

ON THE MONITORING OF SURFACE DISPLACEMENT IN CONNECTION WITH VOLCANO REACTIVATION IN TENERIFE, CANARY ISLANDS, USING SPACE TECHNIQUES

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ABSTRACT

Geodetic volcano monitoring in Tenerife has mainly focused on the Las Cañadas Caldera, where a geodetic micronetwork and a levelling profile are located. A sensitivity test of this geodetic network showed that it should be extended to cover the whole island for volcano monitoring purposes. Furthermore, InSAR allowed detecting two unexpected movements that were beyond the scope of the traditional geodetic network. These two facts prompted us to design and observe a GPS network covering the whole of Tenerife that was monitored in August 2000. The results obtained were accurate to one centimetre, and confirm one of the deformations, although they were not definitive enough to confirm the second one. Furthermore, new cases of possible subsidence have been detected in areas where InSAR could not be used to measure deformation due to low coherence. A first modelling

attempt has been made using a very simple model and its results seem to indicate that the deformation observed and the groundwater level variation in the island may be related. Future observations will be necessary for further validation and to study the time evolution of the displacements, carry out interpretation work using different types of data (gravity, gases, etc) and develop models that represent the island more closely. The results obtained are important because they might affect the geodetic volcano monitoring on the island, which will only be really useful if it is capable of distinguishing between displacements that might be linked to volcanic activity and those produced by other causes. One important result in this work is that a new geodetic monitoring system based on two complementary techniques, InSAR and GPS, has been set up on Tenerife island. This the first time that the whole surface of any of the volcanic Canary Islands has been covered with a single network for this purpose. This research has displayed the need for further similar studies in the Canary Islands, at least on the islands which pose a greater risk of volcanic reactivation, such as Lanzarote and La Palma, where InSAR techniques have been used already.

1. INTRODUCCION

Geodetic measurements are used in volcanic monitoring because ground deformation measurement techniques can permit control of pre-eruption ground displacements. Even though volcanic activity in Tenerife is characterized by the fact that eruptions do not normally occur more than once in the same volcanic structures, geodetic monitoring has mainly focused on the Caldera de Las Cañadas, where there is a geodetic micronetwork and a levelling profile. The theoretical and observational results of the existing network sensitivity analysis showed that the network should be extended to cover the whole island for volcano monitoring purposes. The observation of such a network is more operational if Global Positioning System (GPS) is used, even though it still provides point specific measurements. Furthermore, Synthetic Aperture Radar Interferometry (InSAR) is also suitable for ground deformation monitoring of active areas (Massonnet et al. 1995; Lanari et al. 1998; Amelung et al. 1999; Fruneau and Sarti 2000; Wright et al. 2001) due to its centimetric precision and the large area covered by only one image (100 km² for ERS satellites). InSAR is a space technique that uses the phase differences contained in two radar images, acquired from separate orbits and at different times, to obtain a ground displacement image of the area under study, known as interferogram or fringes pattern. One of the limitations in using classical InSAR techniques is maintaining phase coherence in the area

under study (Lu *et. al.*, 1998; Romero *et al.*, 2002a). Therefore, “good coherence” (good quality phase) is required to obtain a good quality interferogram and be able to monitor a volcanic area with InSAR. The good existing coherence of volcanic areas makes them very suitable for application of InSAR techniques. However, in other areas vegetation is so dense that InSAR cannot be used to monitor ground displacements, at least in the radar frequency employed by the ERS-1 and ERS-2 satellites used in this study. Another limitation stems from the fact that, in principle, this technique cannot be used to obtain the three components of the possible displacements because what it actually measures are changes in the ground segment distance, and from there, knowing the image acquisition geometry, their projections over the horizontal and vertical directions. The GPS observation would be a good alternative for areas lacking good coherence, and in other areas it helps to validate and complement the results of InSAR observations. This paper aims to define and verify the applicability of a new geodetic monitoring system in Tenerife, GPS plus InSAR. This system must consider not only the technical optimisation of the monitoring systems, but also their economic and scientific profitability. The system must be effective enough to allow us to monitor any existing ground movement in the island.

2. GEOLOGICAL SETTING

The Canary Islands are a group of seven oceanic islands and some islets, of volcanic origin, that have emerged from a transitional crust of varying thickness (Banda *et al.* 1981). For example, the eastern edge is 15 Kms and 12 Kms thick near the island of La Palma.

The magmatic activity began in the pre-Miocene, as reflected in the basal complexes that exist on a few islands, and formed by a mixture of plutonic and volcanic rocks, sediments and a dense network of dikes that run through them. Deposited on top of these complexes is a series of basic volcanic materials, in rather thick lava flows, which constitute the ancient series that outcropped on all the islands, albeit with varying ages within the Miocene. They are examples of fissure eruptions with shield volcanoes, remains of which are still to be found on a few islands.

These emissions were followed by series of basic and salic materials that abounded on islands such as Gran Canaria and Tenerife, with intermediate ages of the Miocene-Pliocene.

The most recent volcanic series are to be seen on all the islands (except for Gomera) and correspond to basic lava flows. The series effused in monogenetic structures with strombolian-type eruptions and at different times

(Plio-Quaternary). The volcanic eruptions on the Islands were of strombolian type, preceded by local earthquakes and lasted weeks and/or months (Solana, Aparicio 1999). The most recent manifestations include the historic eruptions of Lanzarote (Tinguatón, 1824), Tenerife (Chinyero, 1909) and La Palma (Teneguía, 1971).

The magmatism is of undersaturated alkaline type, and constitutes an example of OIB, albeit with certain continental features (Araña y Ortiz 1991), such as its projection in the continental intraplate volcanism area.

There are several, often highly divergent theories as to how this volcanism came into being, but most authors argue either that there is a hot spot that moves temporarily, or that volcanism is produced by rifting with more or less vertical mobility in the blocks.

More recently (Anguita and Hernán 2000) put forward a theory that seeks to combine all these tendencies, defining the existence of a residual thermal anomaly in the upper mantle from an ancient plume, which would explain the absence of the geochemical and geophysical features of this type of processes. According to this theory, the magma came out through the subsequent fractures associated to the Mesozoic rift, which would explain the structural identity of the Atlas and the Canary Islands. The islands rose up during the compression stages, and the magmatic cycles were generated in the expansion stages.

On Tenerife, the historic eruptions have been fissural type eruptions that generated a cone (Garachico-Montaña Negra (1706), Chahorra (1798), Chinyero (1909)) or several aligned cones such as Siete Fuentes (1704), Fasnía (1705) and Arenas Negras (1705) or the eruption of 1430(?) in the La Orotava valley. The activity in these historic eruptions of Tenerife was always of the strombolian type, with limited lava flows. Furthermore, the most recent eruptions are associated to systems of fractures that condition the emission of magmas through dikes that are barely one metre thick, although the dikes of salic composition are much thicker. These dikes are associated to systems of deep fractures that generally respond to regional tectonics. In other cases, the dikes are located in shallow radial or circular fractures in large volcanic structures. Regional fractures in Tenerife are mainly to be seen in two basaltic ridges (NW-SE and SW-NE) that converge in the central region of the island. The local circular or concentric fractures are associated to the formation of calderas in the island's central volcano, Cañadas. There are also major radial fractures associated to the eruptive systems of the Teide-Pico Viejo volcano (in the central structure) and the Pedro Gil volcano (on the SW-NE ridge).

3. GEODETIC SURVEYS PERFORMED UP TO 2000

Up until 2000, geodetic studies have been conducted that apply directly or indirectly to volcanic monitoring. The National Geographical Institute (IGN) has installed a large amount of infrastructure in terms of geodetic benchmarks and levelling itineraries. In 1994 the IGN built and observed the archipelago's geodetic network and, in 1997, the fourth order geodetic network (Blanco *et al.*, 2000). The former has properly monumented benchmarks, with a forced centre whose coordinates have been determined very accurately in the REGCAN-95 geodetic system (Caturla, 1996), as part of the REGENTE (Red Geodésica Nacional por Técnicas Espaciales - National Spatial Technique-Based Geodetic Network) project (Regidor-Gutiérrez *et al.*, 2000; Quirós *et al.*, 2002) for the Canary Islands, which sought to create a frame of reference on which to establish the previous traditional observations and the future GPS observations of densifications. The campaign ended with 13 stations on the Island of Tenerife, 3 of which form part of the network linking the islands. In designing the connection network, the Maspalomas fiduciary station defined on the ITRF93, epoch 1994.9, was taken to be fixed and used as the basis for the REGCAN95, which in turn served as the basis for the ROI (Lower Order Network) observed using classical and GPS techniques. The official altitudes are orthometric, and GRS80 ellipsoidal heights are also available and were used in this paper.

Furthermore, purpose-designed traditional networks have been set up in the Las Cañadas area and the Teide. In the Las Cañadas caldera is a 17-benchmark geodetic network (Sevilla and Martín, 1986; Sevilla *et al.*, 1986; Sevilla and Romero, 1991; Sevilla and Sánchez, 1996), observed six times since 1982 in order to detect possible crystal movements associated with volcanic reactivation (Figure 1). The network is located on the south-western part of the Caldera, where there are two zones of different morphological characteristics with strong differences between them. The network was designed not only to study ground deformations, but also to check the different caldera formation hypotheses. High-precision measurements have been made of horizontal and vertical angles and of distances. Also a levelling profile exists in the same zone which is connected to the geodetic network (Sevilla *et al.*, 1996). It consists of 52 points distributed along two itineraries: a main ring, 10690 metres long, and another secondary ring, designed in such a way that it can be linked to the geodetic network. It was set up in 1994 and has been observed several times using precision trigonometric levelling. The comparison of numerical values for geodetic magnitudes derived from the different surveys shows that during the period from 1985 to 2000, no

differences big enough to indicate the existence of deformations in the area were detected (Sevilla, M.J., 2002, personal communication).

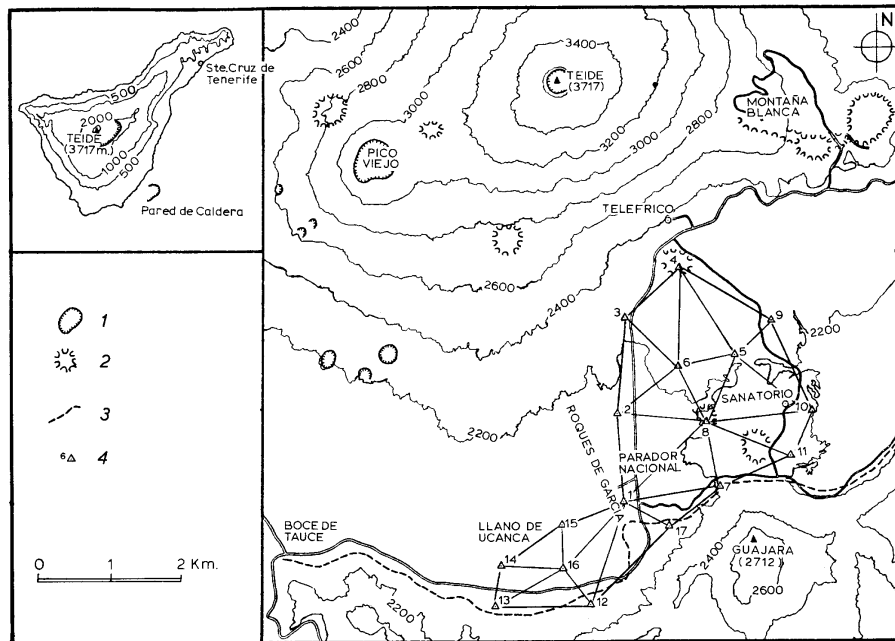


Figure 1. Location of the geodetic network in Las Cañadas, Tenerife island (Sevilla et al., 1986). Meanings are: 1= Teide and Pico Viejo craters and basaltic cones; 2= salic emission centers and domes; 3= base of the caldera wall; 4= geodetic station.

Fernández et al. (1999) study the application of different geodetic techniques to volcanic activity monitoring in the Teide volcano in Las Cañadas Caldera using theoretical analysis. This analysis takes into account the crustal structure of the area, its geology, and its known volcanic activity to estimate the deformation and gravity changes that could precede eruptions. The deformation model used includes the existing gravity field and vertical changes in the crustal properties, but considers spherical point source (centre of expansion plus point mass). They used their methodology on the Teide strato volcano. They worked at the lowest level of Las Cañadas Caldera, studying a smaller work zone instead of the whole Caldera or island, thus not having to consider topography. Therefore the results described by Fernández et al. (1999) give only an approximation to

the most suitable geodetic monitoring system. Having taken into account the theoretical results, financial aspects and existing activity, they propose the most appropriate method for continuous monitoring of the Teide volcano with a relative gravimeter and a clinometer installed in the middle of the area in question, supplemented by re-observation of the existing geodetic network Caldera.

On account of the two limitations of the work described by Fernández *et al.* (1999), namely the kind of source considered (point magma intrusion) and the limitation in size of the zone studied, Yu *et al.* (2000) extended it to consider a wider zone and a more realistic source, a dike, considering the fact that in Tenerife, most recent eruptions (< 3 My) have been fed by dikes. They changed the depth and location of dike to study the variation of the displacements produced. They found the size and location of the intruded dike to play a major role in determining both the displacement pattern and magnitude. When the dike is close to the surface, there is an inversion of the surface displacement pattern and very large surface displacement at certain benchmarks. Such phenomena could serve as precursors of such dike eruptions. Their study shows clearly the need to extend the existing geodetic network to cover the whole island for volcano monitoring purposes. A clear selection should be a global GPS network.

4. APPLICATION OF RADAR INTERFEROMETRY IN TENERIFE

InSAR techniques were applied on Tenerife to detect possible ground deformation produced by a volcanic reactivation. Therefore images had to be selected in order to cover a long time in a homogeneous way (similar time span between images). The 18 SAR images chosen (Table 1, in Romero *et al.*, 2002b) were taken by the European Space Agency satellites ERS-1 and ERS-2 from 1992 to 2000. Due to the large area imaged by only one SAR image, the whole island can be seen in one of them, so the whole risk area can be monitored with only one image.

High coherence was obtained (as expected before processing the SAR images) due to the volcanic nature of Tenerife, and because vegetation has not covered the whole island. Thus, the highest coherence appears in the area of the Las Cañadas Caldera and where the last eruptions occurred on the island (NW-SE and SW-NE ridges), whereas the lowest coherence appears in areas covered by abundant vegetation, located on the north of the island, from Punta Teno (on the west) to Punta Anaga (on the east). Nevertheless, the coherent areas outnumber the non-coherent ones, so fringes appeared in all of interferograms, proving that InSAR can be used on Tenerife island.

The images were processed with EPSIE2000 software (Martínez and Moreno, 1997). When the topographic fringes had been removed from interferograms (using a Digital Elevation Model with 25 m pixel spacing), 21 differential interferograms were obtained showing two patterns of fringes on the northwest of the island (Romero *et al.*, 2002b, Fernández *et al.*, 2002a). These fringes appeared in most differential interferograms, so they cannot be an atmospheric error (Romero *et al.*, 2002b), and increased with time, so they must be caused by deformation. They are located in the region where the most recent eruptions have occurred and outside usually observed areas (Figure 2). Both of the deformations, which we have called Garachico and Chío respectively, are subsidences that increased from 1992 to 2000. The size of the Garachico deformation is about 3 fringes (each fringe represents 3 cm of vertical deformation, so the Garachico deformation is 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 is about 1 fringe (3 cm of vertical deformation) between 1993-2000, and 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). The Garachico deformation subsided at a rate of about 1 cm/year from 1992 to 2000, whereas the Chío deformation shows similar deformation in 1992-1998 interferogram and 1998-2000 interferogram, so it has increased in these last years.

Another important result provided by the differential interferograms is that no deformation was found in the Las Cañadas Caldera area, thus confirming the information achieved from ground geodetic data.

5. NEW GLOBAL GPS NETWORK

Due to the need to extend the geodetic network to make it more sensitive and to the results obtained with the SAR technology, it was decided to establish and observe a global GPS network. This type of observations was chosen because it provides the required levels of precision and poses few problems for carrying out the routine monitoring functions. The first factor taken into account in its design was that the network had to have a homogeneous density that covered the whole island of Tenerife. Furthermore, to facilitate its observation without raising the cost, it should not have too many stations. Since one of its main functions was to be the routine monitoring and control of possible deformations through regular observations, we had to guarantee that the observations could be repeated in future campaigns, and that the results could be compared, so wherever possible the

vertices had to be properly monumented and have a forced centre. 17 of the vertices already installed by IGN on the island were selected. Figure 3 displays the monumentation of these vertices. We also used the permanent station at Santa Cruz de Tenerife (TENE) which, despite being in the test phase, was configured to suit our requirements. This station is part of the RECORD (Radiodifusión Española de CORrecciones Diferenciales - Spanish

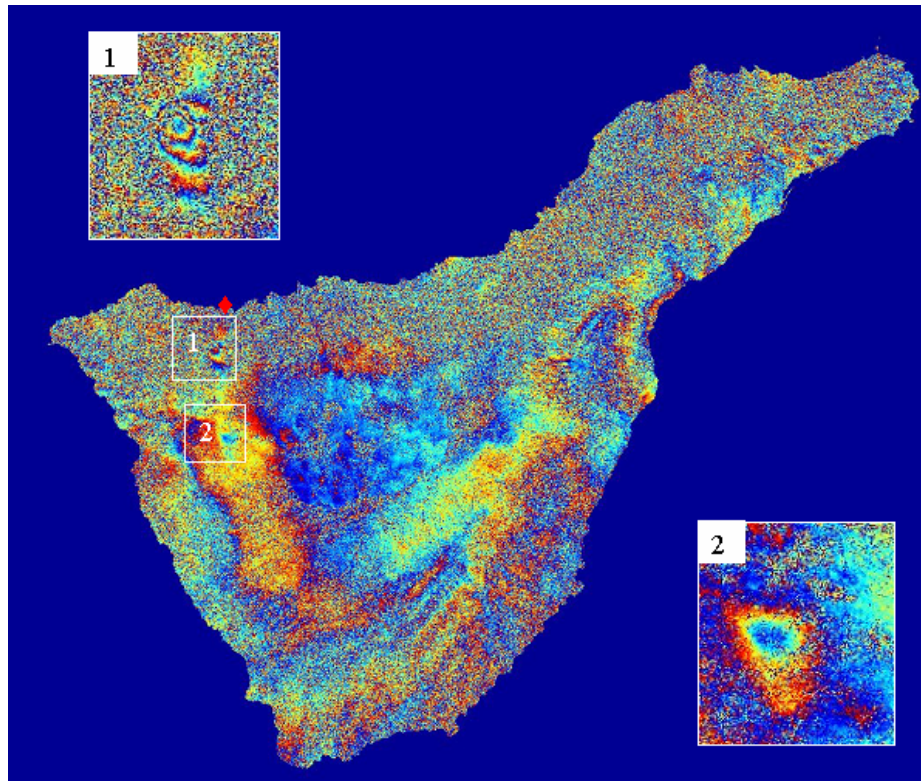


Figure 2. Differential interferogram from Tenerife island corresponding to 2agu96-15sep00. Any fringe can not be seen at the area of Las Cañadas, so there is not any deformation from 2agu96 to 15sep00. 1) and 2) corresponding to Garachico and Chío subsidences, respectively, from 20jul93-15sep00 differential interferogram ($B_{\perp} = 180$ m; $\Delta d = 2614$ days). At Garachico subsidence there are 3 fringes, it is to say, ≈ 9 cm of ground subsidence from 20jul93 to 15sep00; at Chío subsidence there is 1 fringe, it is to say, ≈ 3 cm of ground subsidence from 20jul93 to 15sep00.

Broadcasting of Differential Corrections) project and is formed by three GPS stations consisting of two Ashtech Z-12R and an SCA-12/IM integrity monitor (González-Matesanz and Dalda, 2000). Apart from its main function of broadcasting differential corrections, this station forms part of the Canary Islands network processed by the IGN and formed by the stations in Maspalomas, Tenerife, La Palma and Rabat (Morocco). Using Bernese 4.0 gives a daily and weekly solution of coordinates and velocities. Despite being a permanent station that provides daily observations, we decided that it would only be used in the sessions in which the rest of stations are nearby, thus permitting a far better correction of the troposphere effect in the GPS observations, by avoiding such long baselines. Figure 4 displays the geographical distribution of the general network vertices.



Figure 3. Geodetic vertex of IGN.

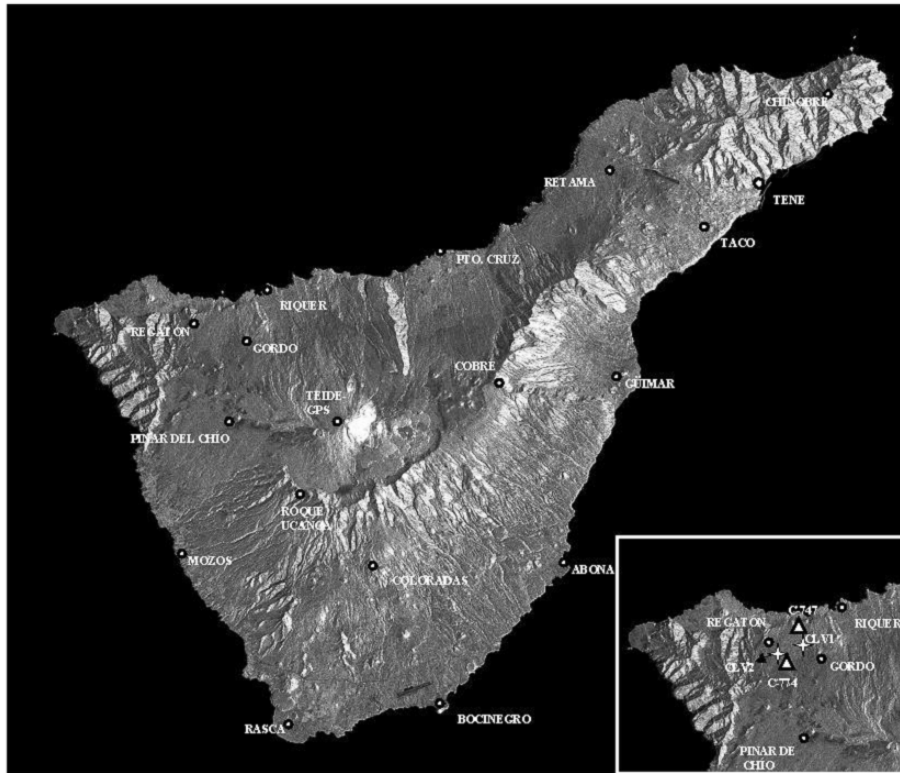


Figure 4. Global GPS network and densification (right lower corner).

As explained earlier, one of the reasons for setting up the network was to check the deformations determined by InSAR. Consequently the main network was densified in the area to the south of Garachico, one of the two areas where deformations had been detected. However, since the Pinar de Chío station (C152) is very close to the centre of the Chío zone, where the smaller of the deformations was detected, and in view of the difficulties posed by the terrain, it was decided not to include any more stations.

This densification (Figure 4, detail in lower right-hand corner) consists of four points: two from the island's fourth order network (747 and 774), permitting comparison with previous observations, albeit without a high level of precision, and two new points indicated by nails, CLV1 and CLV2.

This network was observed for the first time in six sessions between 5 and 12 August 2000, with a total of 27 independent baselines. The observation calendar and sessions are displayed in Table 1. The survey was planned with long observations: five hours in the general network vertices and two in the densification network, the latter being shorter due to the shorter length of the baseline vectors observed. Four or five receivers were used simultaneously in each session. Bifrequency receivers (5 Ashtech Z-12 receivers and receivers installed in TENE) were used to make the observations.

The data collected during the 2000 survey were processed using Bernese 4.2 software (Beutler *et al.*, 2001) with precise ephemerides computed by the Centre for Orbit Determination in Europe (CODE), one of the present eight International GPS Service for Geodynamics (IGS) analysis centre. This type of ephemerides increases the precision of baseline computations by around 100, expressed in ppm (see Beutler *et al.*, 2001, page 126, Table 8.1) and therefore enhances coordinate computation precision. Furthermore, the precise orbits are computed at the International Terrestrial Reference Frame (ITRF), and as a consequence, all the computed baselines and so the resulting coordinates will be in it as well. Therefore the results are directly comparable with the coordinates in the REGCAN95 system, the materialization of the ITRF93. Meteorological field data was not used to compute the wet component of the tropospheric effects. Instead, we used the data itself to estimate the tropospheric parameters.

The data was processed on a session basis and then finally adjusted to obtain 3-D coordinates, using the procedure established by the software, Bernese 4.2. The global network and densification data were processed separately, due to the noticeable baseline length differences between them. To fully guarantee that our results were included in the 1994.9 REGCAN-95 reference system, the Chinobre (C121), Teide (C161) and Bocinegro (C291) stations were considered fixed in calculating the global network. The reason for this is that they belong to the Canary Islands Connection network (Caturra, 1996), and according to different studies, there is no displacement on any of them (Fernández *et al.*, 2002b). The coordinates obtained from the Regatón station (C15C) in the global process were taken as fixed for the densification subnetwork. This station was chosen as the fixed reference station because it is very close to the deformation, but outside it. The resulting coordinates have a mean accuracy of 1-2 mm and 7 mm in the horizontal and vertical components respectively (Fernández *et al.*, 2002b). The global network and the densification have two stations in common: Regatón (C15C) and Riquer (C151). The results of both adjustments for C151 are totally equivalent (Tables 2 and 3).

The adjustment has been constrained to REGCAN95, so no transformations are required before comparing the coordinates obtained from this process with the REGCAN-95 coordinates. Table 4 displays the results of these comparisons for the global network, and Table 5 shows the densification results. We define a significance value, $\Delta = 1.5(N^2 + A\Delta^2)^{1/2}$, where N and E are the northern and eastern components of the differences obtained, respectively.

Table 1. (a) Survey carried out in 2000 of the geodetic GPS networks in Tenerife; **(b)** distribución de stations observed at the different sessions(after Fernández et al., 2002b).

(a)

Dates	Number of					Observations
	Sessions	Receivers	Stations	Baselines	Parameters	
5-12 Aug	6	6	22	27	526	10647

(b)

OBSERVATION OF STATIONS						
STATION	SESSION					
	1	2	3	4	5	6
C202	X	X				
C152	X					
C201		X	X			
C213		X				
C151		X	X			X
C161		X				
C211			X	X		
C291			X			
C281			X			
TENE				X	X	
C163				X		
C162				X		
C110				X	X	
C122					X	
C121					X	
C11A					X	
C15C						X
C747						X
C774						X
CLV1						X
CLV2						X
C15A						X

We have chosen this value because experience shows that altimetry is approximately between 1.5 and 2 times worse in accuracy than planimetry, and also because it would be difficult to assure whether the vertical component discrepancies between the two networks are significant unless there is a good redundancy of observations. This significance value is an example of the degree of reliability of the vertical component results.

Table 4 shows that, broadly speaking, there are no major differences, these being taken to mean differences in excess of 3 cm and at the same time larger than twice the mean square error of the difference. There are exceptions at four stations: C152 (Pinar de Chio), C110 (Pto. de la Cruz), C11A (Chinobre), and C201 (Mozos), where the new coordinates indicate a decline in the altitude of the station, which we will discuss in further detail below.

The first station is located in the second deformation zone described in section 3. The vertical component results obtained with GPS compare favourably with the results obtained by Interferometry SAR (Carrasco et al., 2000; Fernández et al., 2002a; Romero et al., 2002a) and therefore confirm them. Besides, since it provides the three components, unlike SAR, we can clearly see that the subsidence is accompanied by a 2 cm. westward horizontal displacement.

At the next two stations, there is larger subsidence (10 cm in C110, Puerto de la Cruz, and 13 cm in C11A, Retama), which had not been detected with InSAR, which is not surprising because they are low coherence areas. In both cases there has also been horizontal movement, 3 cm towards the N and E and only N respectively. The first station is located on a breakwater in the port, which may be settling at least partially, or it may be the geodetic pillar that is settling. As a matter of fact, there are fractures that might corroborate these hypotheses. The second is located to the north of the island, very close to the zone where the largest volume of ground waters was extracted on the island of Tenerife until the end of the Eighties (Canary Islands Regional Government and Tenerife Regional Council, 1989). The location of possible deformations in areas of low coherence for SAR studies shows that the two techniques complement one another in monitoring deformations on the island, underscoring the importance of the monitoring methodology described in this paper.

Station C201, Mozos, is also located in an area of very low coherence and there was information about possible displacements with SAR. In principle, the zone where this station is located has no other type of known anomaly, although it is also the zone with the smallest difference, 3.3 cm of vertical subsidence, without any horizontal displacement. If one adds this to the possible error in the antenna height measurement, probably of several milli

metres, this result might well be very close to the significance limit, and would need to be checked later.

Table 2. Coordinates of the Global Monitoring Network stations observed on the island of Tenerife during the 2000 campaign, determined with the REGCAN95 system. Precisions in metres. The stations whose coordinates have not been assigned a level of precision have been considered fixed. See text for more details. (Fernández et al., 2002b)

STATION		LATITUDE	LONGITUDE	ELLIPSOIDAL HEIGHT
NAME	CODE	(° ' ")		(m)
PTO. DE LA CRUZ	C110	28 25 11.23444 ±0.001	-16 32 59.79794 ±0.001	53.125 ±0.006
RETAMA	C11A	28 29 20.69587 ±0.001	-16 23 28.81989 ±0.001	718.872 ±0.006
CHINOBRE	C121	28 33 31.31975	-16 10 31.59700	954.074
TACO	C122	28 26 30.48506 ±0.001	-16 17 35.27801 ±0.001	410.971 ±0.006
RIQUER	C151	28 22 48.04581 ±0.001	-16 43 02.53887 ±0.001	209.987 ±0.005
PINAR DE CHIO	C152	28 16 08.36215 ±0.002	-16 44 58.32821 ±0.002	1641.339 ±0.011
GORDO	C15A	28 20 20.60078 ±0.001	-16 44 25.70851 ±0.001	1169.834 ±0.008
REGATÓN	C15C	28 21 02.65978 ±0.002	-16 47 39.10352 ±0.001	844.727 ±0.007
TEIDE GPS	C161	28 16 20.95258	-16 38 34.41225	3755.627
GÜIMAR	C162	28 18 49.01676 ±0.001	-16 22 38.53034 ±0.001	324.307 ±0.009
COBRE	C163	28 18 09.51566 ±0.001	-16 29 34.57105 ±0.001	2304.382 ±0.008
MOZOS	C201	28 08 51.05396 ±0.001	-16 47 41.21977 ±0.001	131.604 ±0.004
ROQUE DE UCANCA	C202	28 12 19.98625 ±0.001	-16 41 00.29237 ±0.001	2155.196 ±0.007
ABONA	C211	28 08 55.25889 ±0.001	-16 25 41.46419 ±0.001	68.488 ±0.005
COLORADAS	C213	28 08 46.53489 ±0.001	-16 36 47.78716 ±0.001	1462.361 ±0.006
RASCA	C281	28 00 45.64814 ±0.001	-16 41 35.41958 ±0.001	197.951 ±0.006
BOCINEGRO	C291	28 01 51.56155	-16 32 28.04723	81.157
STA. CRUZ TENERIFE	TENE	28 28 21.15281 ±0.001	-16 14 50.47003 ±0.001	97.388 ±0.006

Table 3. Coordinates of the DZ densification network stations observed during the 2000 campaign, determined with the REGCAN95 system. Precisions in metres. The Regatón station, whose coordinates have not been assigned a level of precision, has been considered fixed. See text for more details. (Fernández et al., 2002b)

STATION		LATITUDE	LONGITUDE	ELLIPSOIDAL HEIGHT
NAME	CODE	(° ' ")		(m)
RIQUER	C151	28 22 48.04582 ±0.001	-16 43 02.53884 ±0.001	209.986 ±0.005
REGATÓN	C15C	28 21 02.65978	-16 47 39.10352	844.727
747	C747	28 21 34.86872 ±0.001	-16 45 27.61189 ±0.002	652.766 ± 0.008
774	C774	28 19 48.21762 ±0.001	-16 46 21.66940 ±0.001	1129.852 ± 0.008
CLAVO 1	CLV1	28 21 08.98689 ±0.001	-16 45 23.28181 ±0.001	766.732 ± 0.008
CLAVO 2	CLV2	28 20 24.72780 ±0.001	-16 46 35.23901 ±0.001	954.582 ± 0.007

The differences displayed in Table 5 indicate that the only significant coordinate variations have been recorded at the fourth order station C747, which in this case indicate that the station has risen. However, this result is unreliable because the station is located on the roof of a small water tank, which at first appeared not to be in use any more, and the height of which varies depending on the level of water in the tank (see Fernández et al., 2002b). New points must be included in DZ in future campaigns. However, since the points are new, there would be no previous observations and since the range of the expected displacements is small for one year intervals, several reobservations are needed to reliably ratify the deformation. For more details and discussion in the GPS results, see Fernández et al. (2002b).

6. DISCUSIÓN AND MODELLING

One question that remains open is the determination of the possible causes of the deformations we have found. The nature of such causes could differ from one area to another and could be (Fernández et al., 2002b): compacting of the lava emitted during the last eruptions, subduction post eruptions caused by the emptiness of the magma chambers, volcanic reactivation, this subsidence possibly having been caused by a dike (Yu et al., 2000), or the

extraction of water from water tables. The first two causes seem very unlikely to produce the observed deformation about one century or more after the end of the eruptions. Volcanic reactivation does not seem very feasible either, considering the absence of seismic activity in the area covering both DZs or

Table 4. Differences in cm, with precisions, between coordinates obtained in 2000 and 1995 for the repeated stations of the general global GPS network. $\Delta = 1.5(N^2 + E^2)^{1/2}$ (after Fernández et al., 2002b).

00-95				
STATION	North (N)	East (E)	HEIGHT	Δ
	cm	cm	cm	cm
PTO. DE LA CRUZ	-3.5 ±1.5	-2.9 ±1.5	-10.0 ±2.1	6.8
RETAMA	-3.2 ±1.5	+0.3 ±1.5	-13.0 ±2.1	4.8
TACO	+0.2 ±0.3	-1.9 ±0.3	-0.3 ±1.8	2.9
RIQUER	-1.3 ±0.2	0.0 ±0.2	-1.2 ±1.1	2.0
PINAR DE CHIO	+0.6 ±0.4	-2.1 ±0.4	-4.9 ±1.9	3.3
GORDO	-3.9 ±1.5	-1.0 ±1.5	+0.9 ±2.2	6.0
REGATÓN	-2.5 ±1.5	+0.7 ±1.5	+0.6 ±2.1	3.9
GÜIMAR	-1.0 ±0.3	+0.4 ±0.3	-0.9 ±1.8	1.6
COBRE	-1.5 ±0.3	-0.1 ±0.3	+0.2 ±1.7	2.3
MOZOS	+0.1 ±0.2	-0.4 ±0.2	-3.3 ±1.3	0.6
ROQUE DE UCANCA	-1.4 ±0.3	-0.6 ±0.2	-1.8 ±1.3	2.3
ABONA	-0.5 ±0.2	-0.8 ±0.2	+0.6 ±1.3	1.4
COLORADAS	-0.2 ±0.3	-0.5 ±0.3	+0.4 ±1.6	0.8
RASCA	-0.8 ±0.2	-0.3 ±0.3	-2.4 ±1.3	1.3

Table 5. Differences in cm, with precisions, between coordinates obtained in 2000 and 1995 for the repeated stations of the densification micronetwork in DZ1. $\Delta=1.5(N^2+E^2)^{1/2}$ (after Fernández et al., 2002b).

00-95				
STATION	North (N)	East (E)	HEIGHT	Δ
	cm	cm	cm	cm
RIQUER	-1.2	0.1	-1.3	1.8
	± 0.2	± 0.2	± 1.0	
C747	0.0	2.4	+5.7	3.6
	± 0.9	± 0.7	± 1.8	
C774	-4.9	1.4	+7.3	4.3
	± 2.5	± 1.4	± 4.7	

the non-observation of any important gas anomalies until now. As regards the last possible cause, it must be stressed that a large number of galleries have been drilled in the subsoil of much of the island to draw drinking water for the island's inhabitants (Gobierno de Canarias and Cabildo Insular de Tenerife, 1989). Nowadays it is difficult to distinguish the real cause from the others with absolute certainty. Different geodetic and geophysical experiments are being prepared to determine the origin and evolution of the subsidence (Fernández et al., 2002a).

Besides, the deformations found are located in areas where large amounts of groundwater have been drawn since 1925 (Gobierno de Canarias and Cabildo Insular de Tenerife, 1989). This leads us to think that the groundwater decrease may be at least partly to blame for the displacements observed. In order to test this hypothesis, we will try to interpret the displacements using the model developed by Geertsma (1973) and used in similar problems by Xu et al. (2001) and Le Mouélic et al. (2002). We will only consider the vertical component of the displacement in our study. A future, more complete model should also consider the horizontal components not analysed in this study, which only seeks to establish or discard whether there is any connection between the two phenomena, the deformations observed and the extraction of groundwater.

The model assumes that the reservoir is a circular disk of radius R and height h buried parallel to the flat earth surface at depth D . The elastic earth is treated as an elastic half-space with Poisson's ratio σ . Thus the vertical component of the displacement of the surface u is

$$u = (2\sigma - 2)\Delta h R \int_0^\infty e^{-D\alpha} J_1(\alpha R) J_0(\alpha r) d\alpha \quad (1)$$

where r is the radial coordinate along the surface with origin above the centre of the reservoir; Δh is the variation of the height of the reservoir due to its recharge or compaction, and α is the integration variable. Vertical axis is considered positive inside the medium.

Consequently, to model this deformation information is required about the depth, radius and height of the reservoir and the elastic properties of the reservoir rock. As the first step, we could consider the elastic parameters determined by Fernández et al. (1999) who used the crustal model of Bosshard and MacFarlane (1970), in the central part of the island of Tenerife, which consists of three layers overlying the mantle. They located level zero at the base of the Teide (Caldera de las Cañadas), approximately 2000 m above sea level, which is the area of most recent activity and greatest risk. They followed the method described by Fernández and Díez (1995) to assign elastic properties to the different layers of the crustal models, making some minor corrections in densities according to the geologic data of each island. They gave as properties for the 3.5 km of the crust in their cortical model (from 2 km over sea level to 1.5 km below it) a density of 2100 kg m^{-3} , and Lamé parameters $\lambda = 8 \cdot 10^9 \text{ Pa}$ and $\mu = 7 \cdot 10^9 \text{ Pa}$. Therefore the Poisson's ratio is $\sigma = 0.27$.

Furthermore, the information available (Cabildo Insular de Tenerife, 2002) can be used to obtain an approximation of the depth and radius values of the underground aquifers in order to use the model described. We will annotate the values of DZ1 with subindex 1 and the value of DZ2 with subindex 2. We get $D_1=0.4 \text{ km}$, $R_1=2 \text{ km}$, $D_2=1.2 \text{ km}$ and $R_2=3 \text{ km}$, and using the values tabulated by Geertsma (1973) for the perimeter

$$A = R \int_0^\infty e^{-D\alpha} J_1(\alpha R) J_0(\alpha r) d\alpha, \quad (2)$$

for values of $\rho=r/R$ and $\eta=D/R$, for $\rho_1=\rho_2=0$, we will get $\eta_1=0.2$ and $\eta_2=0.4$, which give $A_1=0.8039$ and $A_2=0.6286$ as the values of the maximum vertical deformation u_{\max} in $r=0 \text{ km}$. By finding the value we get the expression of the water table variation

$$\Delta h = \frac{u_{\max}}{(2\sigma - 2)A}. \quad (3)$$

Replacing the maximum subsidence values in the period 1993-2000 in DZ1 and DZ2, 10 and 4 cm respectively, (values obtained from the InSAR and GPS results, averaging values in the case of DZ2), we estimate water table variation values for that period $\Delta h_1 = -8.5$ cm and $\Delta h_2 = -4.4$ cm, consistent with the water table decline estimated by the Tenerife Water Authority (Consejo Insular de Aguas de Tenerife, 2002).

7. CONCLUSIONS

This paper describes the design of a new geodetic-based volcanic reactivation monitoring methodology for the Island of Tenerife. The results show that combining Interferometry SAR (InSAR) with geodetic monitoring techniques is a highly effective way of detecting displacements that might be eruption precursors. This technique makes up for the limited spatial coverage of specific geodetic observations. As a matter of fact, the application of InSAR on the island (processing of images from the period 1992-2000), has served to detect two unexpected movements in areas beyond the reach of the traditional geodetic network: one large movement to the south of Garachico town, and a smaller one in the Chío area.

However, Interferometry SAR has certain limitations because it does not provide information in low coherence areas, such as areas of dense vegetation. Besides, at present it cannot be used to obtain the three components of possible displacements. That is why it must be supplemented with other techniques, in particular GPS networks, which provide the required levels of precision far more easily than other traditional techniques (Gudmundsson et al., 2002). In this case, only point specific measurements are available, but the combination of both methods permit effective detection of displacements. The annual economic cost of the GPS observations and SAR images for the whole island is very similar to the cost of the observation, using terrestrial techniques, of the monitoring infrastructure installed in Caldera de Las Cañadas.

Therefore a GPS network covering the whole island of Tenerife has been designed and observed. The network was observed in August 2000 using relative static observations during periods of 5 and 2 hour, depending of the longitude of the baselines. The results obtained are accurate to one centimetre in height and to a few millimetres in horizontal coordinates, and have confirmed the deformation detected by InSAR in Chío, and revealed others that had not been detected by InSAR, in sites with abundant vegetation. This again shows that the two techniques complement one another, and should be included together in an efficient monitoring methodology. However, the GPS

results obtained in the deformation zone to the south of city of Garachico are not definitive enough to confirm the displacements detected using InSAR due to several factors, mainly the non-existence of previous observations in the stations included in the deformation areas. Therefore future observations will be required and more stations will have to be added, including at least one point in the central zone where a higher annual deformation value (around 1 cm/year) is expected based on the radar interferometry results.

Considering the results obtained, it is quite clear that the new system should be included to carry out systematic, functional monitoring of the island, in order to detect future possible deformations, and also to confirm and study the evolution of those already detected. This study shows that similar studies should be conducted on the islands with the greatest risk of eruption, such as Lanzarote and La Palma, where InSAR techniques have already been applied (Romero *et al.*, 2002b, Romero *et al.*, 2003, Fernández *et al.*, 2002a, Carrasco *et al.*, 2000), and where InSAR should be supplemented with other methodologies, such as GPS, to cover the most densely vegetated areas.

One of the possible reasons for the detected displacements could be the extraction of groundwater all over the island. This idea is strengthened by the fact that the displacements have been detected in two of the areas where large amounts of water have been drawn from the ground. A first attempt has been made to model this with a simple model (Geertsma, 1973) that can only be regarded as an approximation to the real problem on the island of Tenerife, due both to the type of reservoir and the medium considered (homogeneous and without fractures). However, the results obtained are coherent with the ground water level variation on the island in the period in question, so the two phenomena could be related to one another. However, there is clearly a need to continue with this research, with further monitoring of the displacements in order to study their evolution, and further interpretation in order to find more and different data (gravity, gases, etc), real, detailed and up-to-date information about the evolution of the ground waters, and developing models that represent the island's characteristics more accurately.

Finally, it must be stressed that this research is also very important, not only for studying the displacements that might be associated, at least partly, to the extraction of groundwater, but must be capable of clearly distinguishing them from other displacements on the island's surface that might be linked to a future magmatic reactivation.

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