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DEFORMATION ANALYSIS EMPLOYING THE COHERENT PIXEL TECHNIQUE AND ENVISAT AND ERS IMAGES IN CANARY ISLANDS.

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ABSTRACT

Geodetic measurements in volcanic areas are crucial as they serve as input information to the deformation analysis techniques in order to achieve pre-eruption ground displacement predictions. In particular, Satellite Radar Interferometry (InSAR) has been proven to be a useful and powerful tool in this kind of areas. We present some results obtained by applying the Coherent Pixel Technique, an Advanced Differential SAR Interferometry algorithm, which reveal surface deformation episodes in Canary Islands (La Palma and Tenerife Island). The study is carried out by employing DInSAR interferograms concerning the 1992-2008 period corresponding to both ascending and descending images acquired by the ENVISAT and ERS sensors.

1. INTRODUCTION

1.1. La Palma

The archipielago Canary Island is located off the NW coast of the African continent, is formed by seven major islands. We choose La Palma Island as scenario to review previous studies and to apply an advanced InSAR technique because around six eruptions have occurred there over the last 500 years (1585, 1646, 1677, 1712, 1949 and 1971) (see Fig. 1).

Its origins have been studied and several hypothesis have been proposed by different authors ([3], [4], [5], [9] and [12]). All the eruptions have taken place at the Cumbre Vieja ridge and the last eruptions occurred at Teneguia volcano in 1971 (see Fig. 1). Geodetic techniques are used in volcanic monitoring for the measurement of surface displacements in order to control pre- and inter-eruption ground deformation. In this way, usual geodetic studies are carried out using EDM or GPS.

Figure 1. Insets show geographical setting in the Canary Islands and the location in the Atlantic Ocean of la Palma Island. Main figure shows a geological sketch of La Palma (modified from [10]) overlying a shaded relief with the mapped fracture at the summit of Cumbre Vieja volcano and showing the seven historical eruptions: Montaña Quemada (1470-92), Tahuya or Jedey (1585), Tigalate or San Martín (1646), San Antonio (1677), El Charco (1712), Nambroque or San Juan (1949) and Teneguía (1971).

But the GPS technique has a limitation produced by the fact that observation is restricted to a set of discrete surface points.

In order to cover the whole island a Synthetic Aperture Radar Interferometry (InSAR) has been applied. This technique has become over last decade an important remote sensing tool (see e.g. [21] and [23]) for detecting displacement produced by earthquakes, water extraction ([2]) or civil construction. Despite its centimetric precision and the large area covers (100 x 100Km) the InSAR techniques have limitations inherent such as maintining phase coherence in the area (areas with scarce or null vegetation are the best for obtaining "good coherence"), changes over terrestrial surface and the presence of atmospheric artefacts that degrade the quality of the displacements estimation ([29], [14] and [15]). During the years 2006 and 2007, InSAR and GPS obervation were applied to study deformation at La Palma Island and also gravity observation were carried out for structural studies.

In this work, we present a summary of different techniques and results used in La Palma, and the results obtained from an advanced technique InSAR, named Coherent Pixel Technique (CPT), for the period 1992-2008.

1.2. Previous results/studies in La Palma

Since 1994, a geodetic network with Electronic Distance Mesaurement techniques (EDM) has been used to monitor the Cumbre Vieja ridge ([26]). This network was not designed to cover the whole island. For this reason, in 1997 the network was enlarged and occupied using global positioning system (GPS), incorporating the west flank and the southern part of the island as study zones. During 2000 and 2001, several articles appeared as studies of possible different phenomena in La Palma Island. Some of them pointed out the possibility that a landslides might occur on the southern part of the island ([13], [29] and [31]). Other authors disagree with those results ([5] and [6]).

In 2006, a new GPS network covering La Palma Island was defined, complementary to InSAR, in order to study the existence of deformation ([28]). The networks stations were along Cumbre Vieja rift, Cumbre Nueva slope and inside and outside Taburiente Caldera (see Fig. 1), formed by 26 stations. This geodetic control network was observed in November 2006 and July 2007. Data collected for both campaigns were processed with Bernese 5.0 software and GAMIT/GLOBK 10.31. Vertical displacements components were obtained by comparing the results obtained in 2007 with previous coordinates determined by IGN in 1994, and 2006 and 2007 coordinates. Both of them are consistent with InSAR results. ([28]).

For structural studies a terrestrial gravity survey covering the island with GPS observation was carried out. The gravity data was inverted using a non-linear three-dimensional gravity inversion approach to obtain the geometry of the anomalous bodies ([8] and [28]). A total of 317 benchmarks were used. The main results of the inversion model are a large central body with high density and a elongated minima distributed along the rift strucutre in the southern half of the island.

Finally, first work with the InSAR technique shows one interferogram of La Palma Island in the period 1992-1995 ([24]). This interferogram did not have removed the topography as forward cases. In next works, the data used set was formed by six radar images taken by the satellites ERS-1 and ERS-2 covering 1992 up to 1999. Only three interferograms were processed without digital model of the terrain ([14], [15] and [29]). The results revealed deformations no greater than ten centimeters. Almost whole Island is covered by abundant vegetation, meaning that the coherence is not good enough. Lava flows of the last eruptions located to the south of the island are areas with more coherence. The study was extended using more images (up to year 2000) and using the Single Master in order to approach chooses pixels and the Coherent Target Modeling Method (CTM) calculates the temporal coherence of each pixel ([27]). With these methods linear velocities of approximately -4 to -8 mm/year covering an area of about 1 km^2 centered on the Teneguía volcano was obtained. There is an absence of deformation in the northern part of the island. With this same period an estimate map of linear velocity by stacking six independent interferograms has been obtained. In this case, about 9 mm/year of subsidence by means of DORIS software was detected.

1.3. Tenerife

Tenerife is the biggest island of the Canary Island. These are an archipelago of volcanic origin situated 60 km from The African coast. The eruptive system is located in Las Cañadas Caldera and the Teide, a strato-volcano at the northern border of the caldera. A total of 12 eruptions ([11] and [29]) have taken place in the island. Last historical eruptions (last 500 years) have not taken place in the same volcanic edifice (1704, 1706, 1798, 1909). For this reason, whole Island for the study is chosen. Historical eruptions date back from 1706 in Montaña Negra to the most recent, 1909, in Chinyero ([16]), see Fig. 2.

These most recent eruptions are associated with systems of fractures which generally respond to regional tectonics and are concentrated in two basaltic ridges (NW-SE and SW-NE) that converge in the center of the island. In this center Las Cañadas Caldera is located. The Teide-Pico Viejo complex are in the north of this Caldera which are two stratovolcanoes so that Teide has the highest altitude with 3718 m.

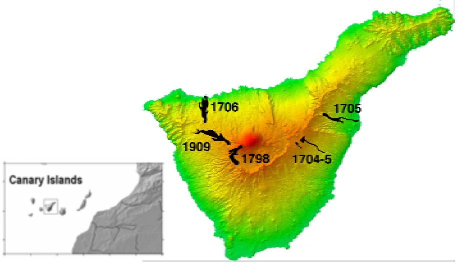

Figure 2. Last historical eruptions detected in Tenerife.

1.4. Previous results/studies in Tenerife

Since 2001, network of National Geographic Institute (IGN) has detected low-magnitude seismic anomalies around the Tenerife Island, increasing during the years 2004 and 2005. After analysis of geochemical and seismic data of 2004 existence of magma movement is assumed. It may be a precursor mechanism of increased seismic activity. The anomalies observed during 2004-2005 is characterized by a large number of epicentres within the Tenerife Island. Thus, from April to December 2004 195 events have been located, five of them felt by the population between May, July and August of that year, and over 350 until February 2006. In total we have over 3000 recorded events.

The model proposed by Almendros et al. ([1]) argues that the pattern of seismicity observed may be due to magma intrusion beneath the northwest flank of Teide. Both interpretations of gravity and seismics are consistent and similar, but have limitations as to the description of the characteristics of the sources due to its short time span, and to study their temporal variations. This reactivation produces surface gravity ([19]).

Using several terrestrial observation techniques (with a limited spatial coverage) as geodetic micronetwork, levelling network, gravimetric campaings for structural studies, gravimetric tidal observations, thermal anomalies, fumarolic activity and different gasses at the top of the Teide ([11]) clear anomaly has not been detected previously to 2004. However, previous geodetic studies of deformation [17] by using InSAR technique have been able to detect two areas of subsidence mainly located in the northwest part of the island, Pinar de Chio and Garachico ([14], [15], [16], [17], [18], [29], [30] and [32]).

2. CPT: COHERENT PIXEL TECHNIQUE

Satellite Radar Interferometry (InSAR) has been proven to be a useful and powerful tool in tectonic areas for surveying subtle surface deformations over several years related to geodynamic phenomena. An advanced DInSAR observation technique, called the Coherent Pixel Technique (CPT), is being applied to study the existence of deformation areas in order to obtain mean velocities and time series of deformation.

This advanced technique InSAR, DInSAR, use a set of interferograms obtained from several images which permit minimize the impact of atmospheric artefacts and the residual topographic on the estimation of deformation. For more details see [7], [20], [22] and [25].

3. RESULTS

3.1. La Palma Island

First we have processed a stack of 15 ascending images from the period 2004-2007 from ENVISAT sensor. Pixels with a coherence greater than 0.3 in more than 45% of the interferograms are used. Fig. 3 and 4 shows linear deformation velocity and displacements time series of six selected pixels from different areas (A-F). We obtain stability in A, B and E areas. In C, D and F we obtain LOS displacements around + 4 cm in 4 years.

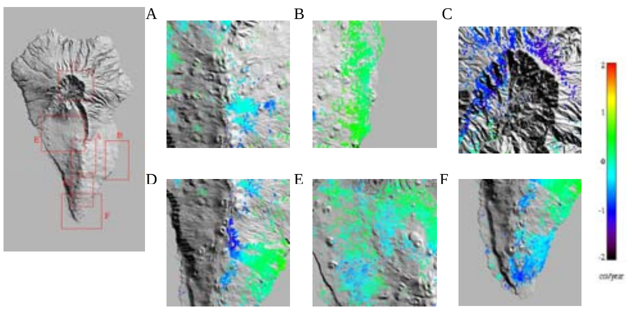

Figure 3. Deformation map. Darker colour means positive and softer colour means negative LOS velocity of displacement.

Eight different points have been selected in order to represent their temporal deformation series (see Fig. 4).

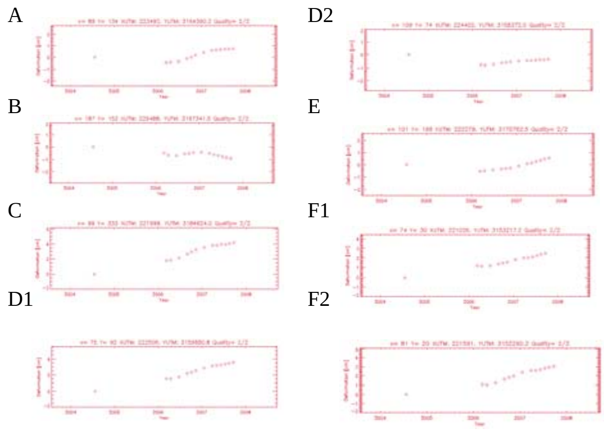

Figure 4. Time series of selected pixels.

The second set is formed by 18 descending covering 2006 up to 2008 from ENVISAT sensor. Pixels with coherence greater than 0.35 in more than 55% of the interferograms are used. Fig. 5 and 6 shows linear deformation velocity and displacements time series of six selected pixels from different areas (C, D, E and F). We obtain stability in E area. In D and F we obtain LOS displacements around -2 cm and -4 cm in 2 years. And in C we see LOS displacement of around 2 cm in 2 years.

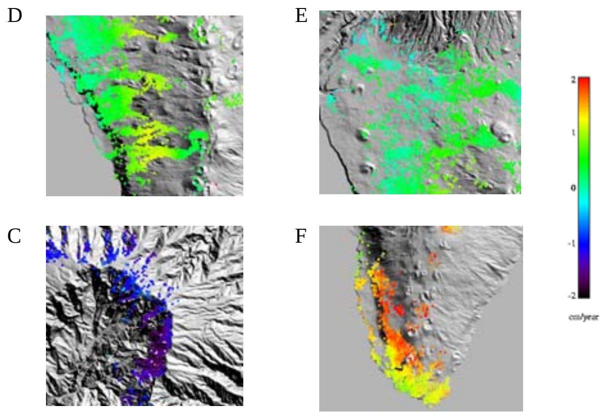

Figure 5. Deformation map. Darker colour means positive and softer colour means negative LOS velocity of displacement.

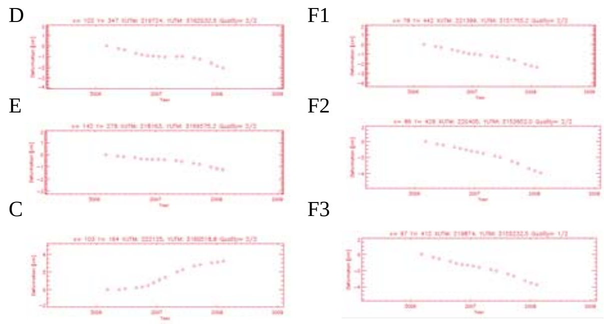

Figure 6. Time series of selected pixels.

A final data set is formed by 16 descending images covering 1992 up to 2000 from ERS sensor. The processed interferograms have a maximum perpendicular baseline of 350 m and time baseline of 1200 days. The linear deformation velocity map (see Fig. 7) for the selected pixels of the processed area shows a clear deformation zone in the south of the island. Six different points have been selected in order to represent their temporal deformation series (see Fig. 8).

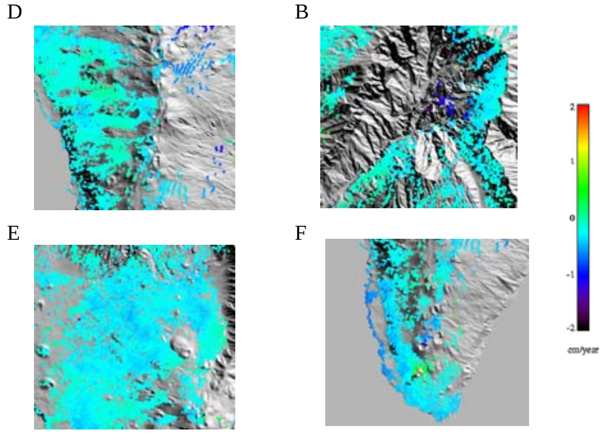

Figure 7. Deformation map. Darker colour means positive and softer colour means negative LOS velocity of displacement.

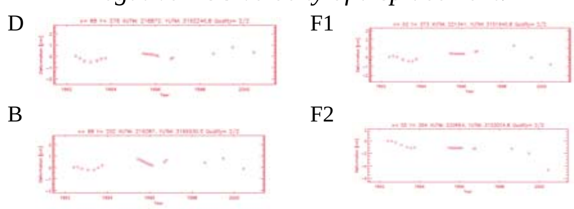

Figure 8. Time series of selected pixels.

3.2. Tenerife Island

We have processed a stack of 19 ascending images from the period 2003-2008 from ENVISAT sensor. Pixels with coherence greater than 0.5 in more than 45% of the interferograms are chosen. Fig. 9a and 9b shows linear deformation velocity and displacements time series of six selected pixels from different areas (A, B and C). In A area we obtain LOS displacements around -2 cm and -8 cm in 5 years. In B, LOS displacements around -4 cm in 5 years. And in C, LOS displacements around 4 cm in 5 years.

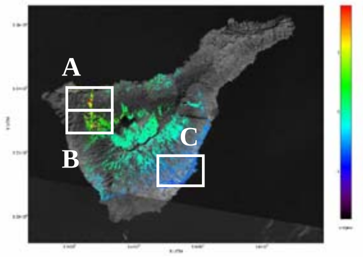

Figure 9a. Deformation map.

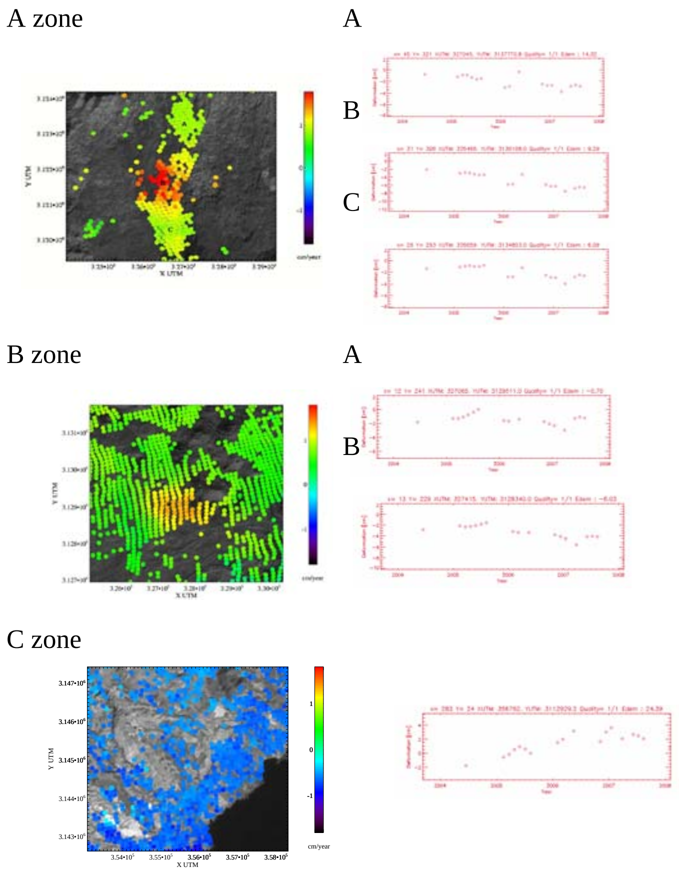

Figure 9b. Deformation map and time series of some selected pixels of different areas.

On the other hand, we have processed a stack of 25 descending images from the period 2004-2008 from ENVISAT sensor. Pixels with a coherence greater than 0.5 in more than 50% of the interferograms are chosen. In all areas we obtain LOS displacements around -4 cm in 4 years.

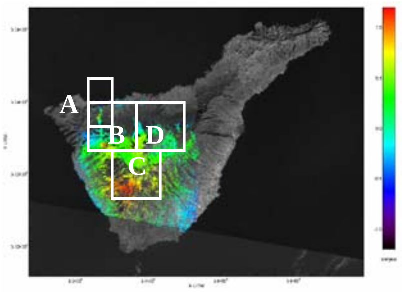

Figure 10a. Deformation map.

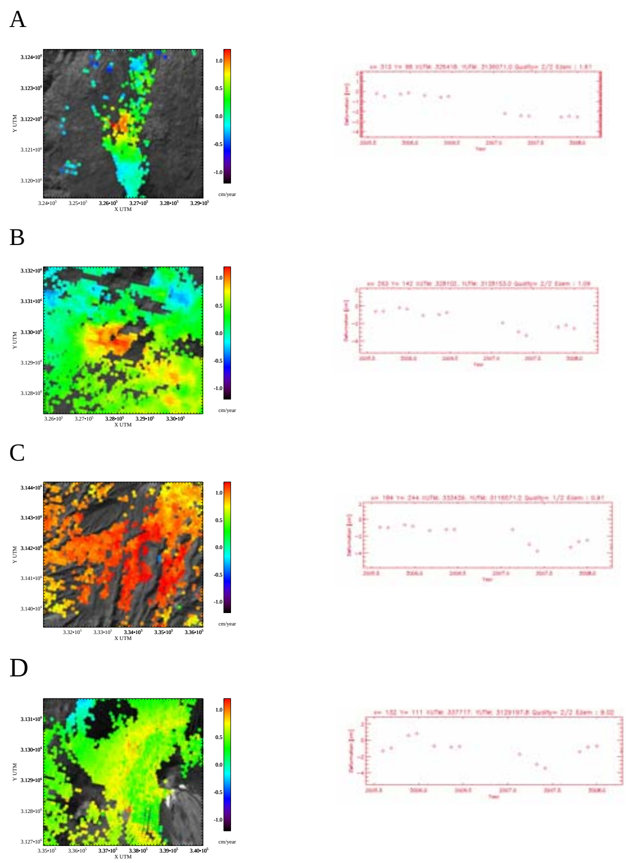

Figure 10b. Deformation map and time series of some selected pixels of different areas.

4. CONCLUSIONS

In this work the Coherent Pixel Technique has been applied for the study of displacements in La Palma and Tenerife Islands. This technique is based on the pixel selection criterion, a coherence threshold and the non-restricted generation of the intereferometric pairs.

In the case of La Palma Island, we studied three set of images. First, we study ascending images from 2004-2008 period using data from ENVISAT. We detect two deforming areas with a maximum value of LOS displacement of about 4 cm in 4 years. We also study descending images from 2006-2008 using data from ENVISAT. We detect displacements at the same areas with a minimum value of LOS displacement of about -4 cm in 2 years. Finally, we study descending images from 1992-2000 using data from ERS. We detect one deforming area with a minimum value of LOS displacement of about -4 cm in 8 years. These results are consistent with results described by [28].

In the case of Tenerife Island, we study two set of images. First, we study a set of ENVISAT ascending images for 2003-2008 period. We detect three deforming areas with a maximum value of LOS displacement of about 4 cm in magnitude. We also study a set of ENVISAT descending images for the period 2004-2008. We obtain displacements in four areas with a minimum value of LOS displacement of about -4 cm in 8 years. These results are consistent with the obtained by [18].

A more detailed comparison of results must be done for both Island as well as an interpretation of the detected displacements.

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REFERENCES

1. Almendros, J., Ibañez. J.M., Carmona, E., & Zandomeneghi. (2007). Array analyses of volcanic earthquakes and tremor recorded at Las Cañadas Caldera (Tenerife Island, Spain) during the 2004 seismic activation of Teide volcano, *J. Volcanol. Geotherm. Res.*, 160, 285-299.
2. Amelung, F., Galloway, D.L., Bell, J.W., Zebker, H.A. & Laczniak, R.L. (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.
3. Anguita, F., & Hernán, F. (1975). A propagating fracture model versus a hotspot origin for the Canary Islands, *Earth and Planetary Science Letters*, 27, 1119.
4. Anguita, F., & Hernán, F. (2000). The Canary Islands origin: a unifying model, *Journal of Volcanology and Geothermal Research*, 103 , 1–26.
5. Araña,V. & Fuster, J. M. (1974). La erupción del volcán Teneguía, La Palma, Islas Canarias. *Estudios Geol.* Vol. Teneguía. 15-18.
6. Araña, V. & Ortiz, R. (1991). The Canary Islands: tectonics, magmatism and geodynamic framework. En: Magmatism in extensional structural settings. The Phanerozoic African Plate. *Springer-Verlag*. Berlín, 209-249.
7. Blanco-Sánchez, P., Mallorquí, J.J., Duque, S. & Monells, D. (2008). The Coherent Pixels Technique (CPT): and advanced DInSAR technique for non linear deformation monitoring, *Pure appl. Geophys.*, vol. 165, pp.1167-1193.
8. Camacho, A.G., Fernandez, J., Gonzalez, P.J., Rundle, J.B., Prieto, J.F. & Arjona, A. (2008). Structural Results for La Palma Island using 3D gravity inversion. *J. Geophys. Res.* 114, B05411, doi:10.1029/2008JB005628
9. Carracedo, J.C., Day, S.J., Guillou, H. & Pérez Torrado, F.J. (1999). Giant quaternary landslides in the evolution of La Palma and El Hierro, Canary Islands. *J. Volcanol. Geoth. Res.*, 94 (1-4), 169-190.
10. Carracedo, J.C., Badiola, E.R., Guillou, H., De La Nuez, J. & Pérez Torrado, F.J. (2001). Geology and volcanology of La Palma and El Hierro, Western Canaries. *Estudios Geol.*, 57, 175-273.

11. Charco, M., Luzón, F., Fernández, J., Tiampo, K.F. & Sánchez-Sesma, F.J. (2007). Three-dimensional indirect boundary element method for deformation and gravity changes in volcanic areas: Application to Teide volcano (Tenerife, Canary Island), *Journal of geophysical research*, vol. 112, B08409.
12. Dañobeitia, J. J. & Canales, J. P. (2000). Magmatic underplating in the Canary Archipelago, *Journal of Volcanology and Geothermal Research*, 103, 27–41.
13. Day, S., Carracedo, J.C., Guillou, H. & Gravestock, P. (1999). Recent structural evolution of the Cumbre Vieja Volcano, La Palma, Canary Islands: Volcanic rift zone reconfiguration as a precursor to volcanic flank instability?. *J. Volcanol. Geoth. Res.*, Special Issue, 94 (1-4), 135-167.
14. Fernández J., R. Romero, D. Carrasco, F. Luzón & V. Araña. (2002a). InSAR volcano and seismic monitoring in Spain. Results for the period 1992-2000 and possible interpretations. *Optics and Lasers in Engineering*, 37, 285–297.
15. Fernández, J. & Luzón, F. (2002b). Geodetic volcano monitoring in Canary Islands. Present and news perspectives, *Fisica de la Tierra*, 14, 109-126.
16. Fernández, J., Yu, T.-T, Rodríguez-Velasco, G., González-Matesanz, J., Romero, R., Rodríguez, G., Quirós, R., Dalda, A., Aparicio, A. & Blanco, M.J. (2003). New geodetic monitoring system in the volcanic island of Tenerife, Canaries, Spain. Combination of InSAR and GPS techniques, *Journal of volcanology and geothermal research*, 124, 241-253.
17. Fernández, J., Romero, R., Carrasco, D., Tiampo, K.F., Rodríguez-Velasco, G., Aparicio, A., Araña, A. & González-Matesanz, F.J. (2005). Detection of displacements on Tenerife Island, Canaries, using radar interferometry, *Geophys. J. Int.*, 160, 33-45.
18. Fernández, J., Tizzani, P., Manzo, M., Borgia, A., González, P.J., Martí, J., Pepe, A., Camacho, A.G., Casu, F., Berardino, P., Prieto, J.F. & Lanari, R. (2008). Gravity-driven deformation of Tenerife measured by InSAR time series analysis, *Geophysical Research Letters*, Vol. 36.
19. Gottsmann, J., Wooller, L., Martí, J., Fernández, J., Camacho, A.G., González, P.J., García, A., & Rymer, H. (2006). New evidence for the reawakening of Teide volcano, *Geophysical Research Letters*, vol. 33, doi: 10.1029/2006GL027523.
20. Herrera, G., Tomás, R., Lopez-Sanchez, J.M., Delgado, J., Mallorquí, J.J., Duque, S. & Mulas, J. (2007). Advanced DInSAR analysis on mining areas: La Union case study (Murcia, SE Spain), *Engineering Geology*, Vol. 90, No. 3, pp. 148-159.
21. Lanari, R., Lundgren, P. & Sansoti, E. (1998). Dynamic deformation of Etna volcano observed by satellite radar interferometry, *Geophys. Res. Lett.*, 25, 1541-1544.
22. Mallorquí, J.J., Mora, O., Blanco, P. & Broquetas, A. (2003). Linear and non-linear long-term terrain deformation with DInSAR (CPT: Coherent Pixels Tehcnique), *Proc. of FRINGE 2003 Workshop. ESA*, p. 1-8.
23. Massonnet, D. & Feigl, K.L. (1998). Radar Interferometry and its applications to changes in the Earth's surface, *Rev. Geophys.*, 36, 441-500.
24. Massonnet, D. & Sigmundsson, F. (2000). Remote sensing of volcano deformation by radar interferometry from various satellites, In Mouginis-Mark, P. J., Crisp, J. A., and Fink,J. H., editors, *Remote sensing of active volcanism, Geophysical Monographs* 116, pages 228, 207–221. AGU, Washington DC.
25. Mora, O., Arbiol, R. & Palá, V. (2006). Advanced DInSAR techniques for monitoring terrain displacements, *5th European Congress on Regional Geoscientific Cartography and Earth information and systems water*, Session 11- Oral presentation.
26. Moss, J., Mcguire, W., & Page, D. (1999). Ground deformation monitoring of a potential at La Palma, Canary Islands, *J. Volcanol. Geotherm. Res.*, 94:251–265.
27. Perlock, P.A., González, P.J., Tiampo, K.F., Rodríguez-Velasco, G., Samsonov, S. & Fernández, J. (2008). Time evolution of deformation using Time Series of differential interferograms: Application to La Palma Island (Canary Islands), *Pure and applied geophysics*, 165, 1531-1554.

28. Prieto, J.F., González, P. J., Seco, A., Rodríguez-Velasco, G., Tunini, L., Perlock, P. A., Arjona, A., Aparicio, A., Camacho, A. G., Rundle, J. B., Tiampo, K. F., Pallero, J. L. G., Pospiech, S. & Fernández, J. (2008). Geodetic and Structural Research in La Palma island, Canaries, Spain: 1992-2007 results, *Pure and Applied Geophysics*, Volumen: 166 N.8/9**.**
29. Romero, R., Fernández, J., Carrasco, D.,Luzón, F., Martínez, A., RodríguezVelasco, G, Moreno, V., Araña, V. & Aparicio, A. (2002). Synthetic aperture radar interferometry (InSAR): Application to ground deformation studies for volcano andseismic monitoring, *Fisica de la Tierra*, 14, 55-84.
30. Rodríguez-Velasco, G, Romero, R., Yu, T.-T., Gonzalez-Matesanz, J., Quirós, R., Dalda, A., Aparicio, A., Carrasco, D., Prieto, J.F. & Fernández, J. (2002). On the monitoring of surface displacements in connection with volcano reactivation in Tenerife, Canary Island, using space techniques, *Fisica de la Tierra*, 14, 85-108.
31. Ward, S. N. & Day, S.J. (2001). Cumbre Vieja volcano–potencial collapse and tsunami at La Palma, Canary Islands. *Geophys. Res. Lett.*, 28(17):3397–3400.
32. Yu, T.-T., Fernández, J., Tseng, C.-L., Sevilla, M.J. & Araña, V. (2000). Sensitivity test of the geodetic network in Las Cañadas Caldera, Tenerife, for volcano monitoring, *J. of Volcanology and Geothermal Research*, 104, 393-407.