ASSESSEMENT OF GROUND DEFORMATION MEASUREMENTS ON ANDEAN VOLCANOES USING RADAR INTERFEROMETRY AND GPS DATA

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INTRODUCTION

Recent studies have demonstrated the potentialities and the limitations of satellite SAR (Synthetic Aperture Radar) interferometry for measuring ground deformations related with volcanic activity (see for instance Zebker et al., 2000). Basaltic shield volcanoes or large calderas appeared as good targets for radar interferometry and studies conducted on these volcanoes have significantly improved the understanding of magmatic fluid migrations at various depths. On the other hand, explosive andesitic volcanoes appeared to be less suited for interferometry studies due to specific geometry or environmental conditions (sleep slopes, vegetation, ice cover, etc.) which may contribute to reduce the quality of the acquired radar data. As a matter of fact, very few studies have been conducted on stratovolcanoes even though significant topographic changes are likely to occur at various scales (lava dome collapse, flank destabilization, etc.). Moreover, the rough field conditions (elevation, access conditions) such as observed on Andean volcanoes, do not allow to properly perform ground monitoring tasks. For such volcanoes, precise geodetic observations are often rare or inadequate to improve our knowledge of ground deformation processes and contribute to hazard mitigation.

In the present study, we have combined SAR interferometry and GPS techniques on some Andean volcanoes with the following objectives :

- to attempt a better quantification and understanding of possible ground deformations associated with lava dome extrusion and collapse,
- to evaluate the potentialities of using satellite interferometric data for ground deformation studies in remote or dangerous areas where geodetic networks cannot be easily maintained,

- to set up precise GPS repetition networks and to determine baseline measurements for a better monitoring of future activities.

We present here the results obtained on Guagua Pichincha and Cotopaxi (Ecuador) and Lascar (Chile) volcanoes and discuss their significance in relation with the current activity and with the potentialities for future monitoring. ERS and JERS datasets have been selected in order to compute interferograms from various time periods (from several years to one day) for coherence analysis between 1992 to 2000. The differential interferograms have been generated with Diapason software (CNES). On these volcanoes, we set up GPS networks and acquired observations using dual frequencies Z-code receivers with full wavelength data. Static or kinematic survey procedures have been used according to the field conditions and the required accuracy. The precise coordinate solutions have been computed according to classical protocols for precise GPS processing.

CASE STUDIES

(1) Guagua Pichincha and Cotopaxi volcanoes (Ecuador)

Guagua Pichincha (4785 m) and Cotopaxi (5911 m) are located in the vicinity of the capital Quito (1,5 Million Inhab.). Both of them have been very active in the historical times, but only the Guagua-Pichincha has undergone eruptive activity within the last decades (repetitive dome growth and destruction). The last reactivation, started during summer 1998 was characterized by a series of phreatic explosions which took place within the 2-km-wide summit caldera hosting a dacitic lava dome. It culminates with a paroxysmal explosion occurred in October 1999 that produced partial destruction of the lava dome and ash fall over Quito. This recent volcanic crisis offered a good opportunity to study ground deformations related with growing lava dome and to evaluate the SAR interferometry method for monitoring such dangerous areas. Moreover, both Pichincha and Cotopaxi volcanoes are representative of South American strato-volcanoes that constitute extreme cases for SAR interferometry applications (steep slopes, variable vegetation, possible ice cap).

Data acquisition (ERS, GPS) : We carried out a first GPS survey on Pichincha volcano in October 1998, consecutively to the reactivation of the Guagua Pichincha. A total number of 34 GPS stations have been determined (21 in the summit area on the eastern side of the active crater) from static or kinematic measurements (figure 1a). The western part of the volcano has not been investigated due to the bad field conditions (absence of access path, dense vegetation) that would require high difficulties for network installation and reiteration. For same reasons, other geophysical monitoring networks are also mainly deployed on the eastern part of the volcano. The GPS network has been partially reoccupied in March 2000 after the major explosion of October 1999. On Cotopaxi volcano, the first GPS observations have been realized by USGS in 1993 (network of 4 stations). In November 1996, we reoccupied the USGS sites and installed 14 new sites distributed from the base of the volcano up to the base of the ice cap (figure 1b). A control survey based on kinematics observations has been realized in March 2000.

Results : The SAR dataset includes ERS images acquired between October 1992 and January 2000. We first attempted to determine from coherence analysis of ERS radar images, the areas where SAR interferometry might be successfully used for ground deformation studies (see results on table below). Despite of the low coherence level of the interferograms, the dataset revealed that no large scale deformation affected the Pichincha volcano before and during the recent volcanic crisis. This result is consistent with our precise GPS measurements realized during 1998-2000 on the eastern part of the volcano up to the caldera rim. By stacking temporal series of amplitude radar images we attempted to obtain a higher resolution of SAR imaging of the summit active zone. This process allowed to evidence morphologic change of the lava dome consecutively to the Oct. 1999 event (figure 2). This study confirms that ground deformations were confined within the caldera and that no important magmatic fluid migration or gaz pressure occurred at shallow levels to produce large scale surface deformation.

	Guagua Pichincha	**Cotopaxi**
SAR interferometry	**(10/1992–01/2000)**	**(05/1992–05/1997)**
ERS availability	poor (1992-2000)	poor (1992-1997)
Spatial coherence	limited (eastern flank, summit)	quite good (below ice cap, lahars)
Temporal coherence	6 months	up to few years (lahars deposits)
Observed changes	within the caldera	none (05/1992-05/1997)
Potentialities	short term deformations	short to mid terms deformations
GPS data	**(11/1998–03/2000)**	**(11/1996–03/2000)**
Network / Baseline	26 stations (since 1998)	18 stations (since 1996)
Network accuracy	Static (1 to 3 cm) - Kinematics (2 to 5 cm)	Static (1 to 3 cm) - Kinematics (2 to 5 cm)
Observed changes	Below network accuracy (< 2 cm horiz.)	Below network accuracy (< 2 cm horiz.)

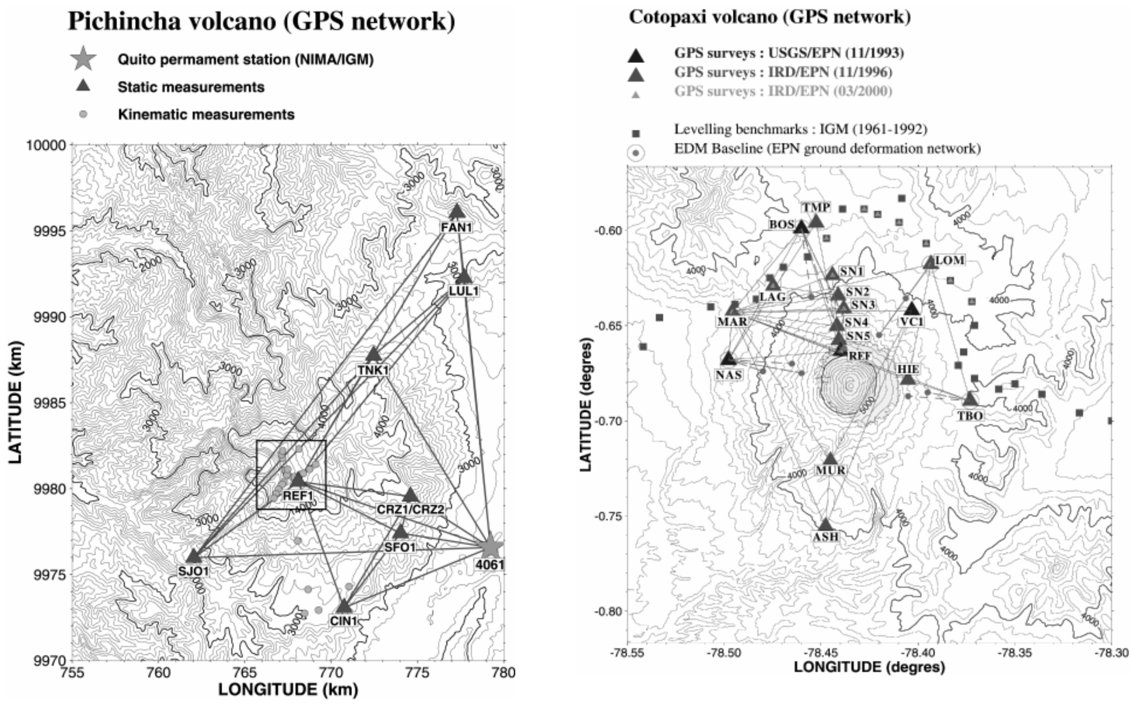

Figure 1 : Topography and GPS networks of Guagua Pichincha (a) and Cotopaxi (b) volcanoes (Ecuador)

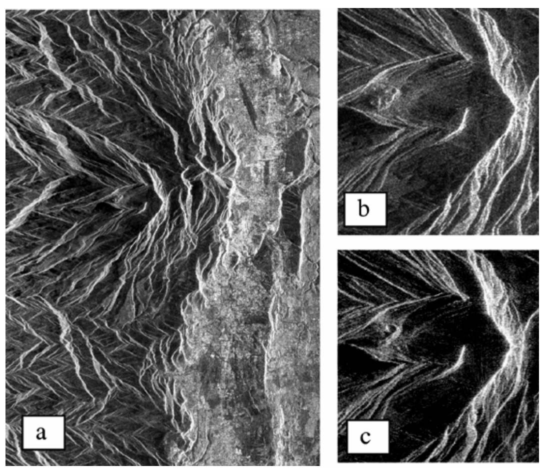

Figure 2 : Example of amplitude radar image on Pichincha volcano and Quito capital (a). Detailed views of the active caldera obtained from stacking of images acquired before (a) and after (b) October 1999 show morphologic changes of the lava dome.

(2) Lascar volcano (North Chile)

Lascar (5592 m) is one of the most active volcanoes of the northern Chilean Andes. Its recent activity is characterized by repetitive dome growth and subsidence (4 cycles between 1984 to 1993) accompanied by vigorous degassing and explosive eruptions of various magnitude Matthew et al. (1997). In April 1993 the largest historical eruption of Lascar produced ash column up to 25 km altitude. Remote sensing and ground based geodetic data are combined here for the first time to enhance if ground deformations are associated with episodes of dome extrusion and collapse and attempt to better constrain the internal dynamics (localization of pressure source for instance). Moreover, due to the absence of vegetation and to arid climatic conditions, this volcano presents the most favorable conditions of for radar interferometry and can be considered as a test site.

<u>Data acquisition (ERS and JERS)</u> : We analysed a series of radar images taken between July 1993 and October 2000. In addition, the use of ERS and JERS data provided a comparative information of the potentialities of different satellite radar data according with the sensor specifications. The longer wavelength of JERS signal (23,5 cm) compared to ERS signal (5,66 cm) is less sensitive to the ground cover and thus presents a better response to the underlying geology. Moreover, as shown on figure 3, the larger JERS incidence angle (35°) reduces the foreshortening and layover effects as observed for ERS satellite (23°). Unlike to ERS for which precise orbits data are available, the low accuracy of the JERS orbits decreases the quality of the interferograms.

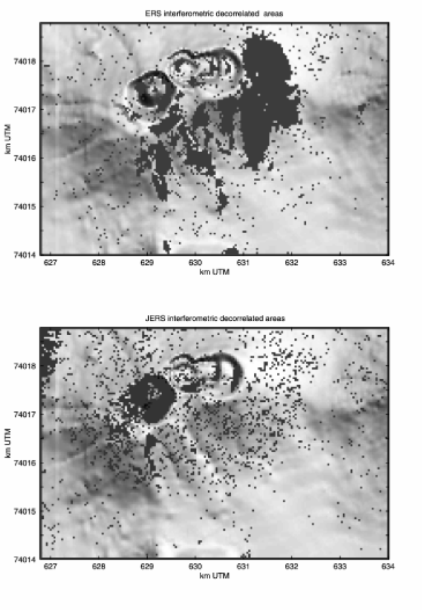

Figure 3 : Comparison of layover and foreshortening effects on Lascar volcano from ERS and JERS data. The black pixels correspond to interferometric decorrelated areas.

<u>Results</u> : The analysis of ERS and JERS data on Lascar confirmed the high quality of ground response to radar imaging. First results also revealed that more precise Digital Elevation Model would be required to better remove local effects of the topography in the summit area and to enhance small scale ground deformation. With this aim, a more precise DEM generated from aerial photogrammetry and constrained by GPS data acquired in early 2002 is in progress.

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