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PSInSAR as a new tool to monitor pre-eruptive volcano ground deformation: Validation using GPS measurements on Piton de la Fournaise

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[1] The Permanent Scatterers Synthetic Aperture Radar Interferometry (PSInSAR™) is a technique, which aims at ground deformation mapping with millimetric precision. In the framework of the Globvolcano ESA project, we evaluated a PSInSAR derived approach to monitor ground deformation in highly active volcanic areas, based on the example of Piton de La Fournaise. The Permanent Scatterer (PS) velocities show two main areas of deformation: (1) the eastern flank displaying old lava flow subsidence (0.05–0.13 $m.y^{-1}$); and (2) the summit cone highly disturbed by eruptions. The PS time series for the summit area agree with the cGPS trends with small long-term (weeks/months) ground displacements preceding eruptions (0.05–0.35 $m.y^{-1}$) and large rapid ground displacements linked to eruptions. Despite some limitations, such as the loss of coherence during the most rapid ground displacements and lava flow emplacement, PSInSAR and its derived approach provide a reliable inference of the volcano ground deformation over large areas. **Citation:** Peltier, A., M. Bianchi, E. Kaminski, J.-C. Komorowski, A. Rucci, and T. Staudacher (2010), PSInSAR as a new tool to monitor pre-eruptive volcano ground deformation: Validation using GPS measurements on Piton de la Fournaise, *Geophys. Res. Lett.*, *37*, L12301, doi:10.1029/2010GL043846.

1. Introduction

[2] Ground deformation monitoring, in the field (e.g., GPS, tiltmeter…) and from space (Interferometric Synthetic Aperture Radar: InSAR), is routinely used to detect subtle precursors of volcanic unrest. Field networks allow the real-time continuous analysis of ground deformation dynamics at specific locations, whereas InSAR provides a complementary estimate of ground deformation on a large spatial scale with weekly/monthly data sampling rates [*Dvorak and Dzurisin*, 1997]. In some cases, InSAR and field networks fail because large scale deformation are not spatially well-constrained by local field networks and conventional InSAR is sometimes unsuccessful because of large deformation rates and/or dense vegetation.

[3] For the GlobVolcano ESA project, which aims to provide Earth Observation products to support volcano observatories in their monitoring activities (http://www.globvolcano.org), the Permanent Scatterers Synthetic Aperture Radar Interferometry (PSInSAR™) has been recently applied on a few active volcanoes. PSInSAR is a technology that has been developed for precise ground deformation mapping, using satellite-borne radar images. It uses a sparse grid of phase stable radar targets (Permanent Scatterers, PS), acting as "natural" reflectors with the aim of reducing the atmospheric noise and the decorrelation of pixels with time sometimes observed with conventional InSAR [*Hooper et al.*, 2004]. In recent years, Persistent Scatterer techniques have been also developed following the lead of PSInSAR [*Hooper et al.*, 2007]. PSInSAR and its derived techniques have started to be used for geological hazard assessment [e.g., *Ferretti et al.*, 2001], and also applied to a few active volcanoes [e.g., *Hooper et al.*, 2007], a context where the method still needs to be fully validated.

[4] Because the ground surface modifications during eruptions may lead to the loss of radar coherence of many pixels, we developed an evolution of the standard PSInSAR in order to apply this technique to highly active volcanic areas. The high eruptive frequency of the Piton de La Fournaise volcano (La Réunion Island), with a mean of two eruptions per year [*Peltier et al.*, 2009], especially well monitored on the field, makes it a particular suitable area to develop, test and validate new techniques. This paper presents an application of a PSInSAR derived approach for detecting and monitoring ground displacements at Piton de La Fournaise; and evaluates the potential application of this technique to active volcanoes by comparing PS time series with field GPS data.

2. Methods

2.1. PSInSAR Method

[5] InSAR uses Synthetic Aperture Radar (SAR) images acquired at different times and views to generate maps of ground deformation, using differences in the wave phase returning to the satellite [*Curlander and McDonough*, 1991]. Conventional InSAR has demonstrated its powerful capabilities to detect ground displacements on volcanoes, notably in our studied area at Piton de La Fournaise [*Sigmundsson et al.*, 1999; *Froger et al.*, 2004; *Fukushima et al.*, 2005]. But sometimes temporal and geometrical decorrelations of pixels (low signal to noise ratio in the phase change estimate) occur as observed in areas with dense vegetation and/or with large deformation rates.

[6] PSInSAR has been developed to determine better mm-scale displacements of individual features on the

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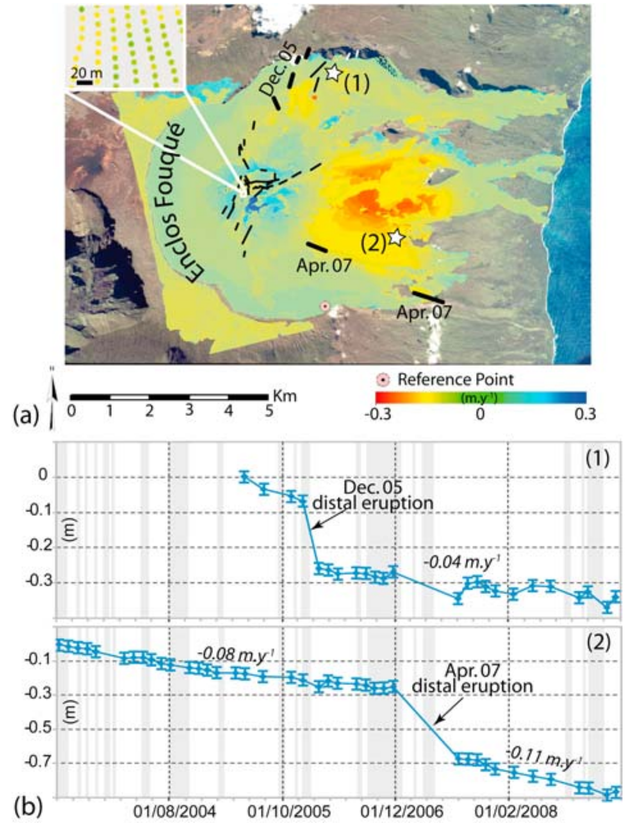

Figure 1. (a) Compilation of average velocities for distinct PS sites for the period between 2003 and 2009 (Swath4 track 127: Incidence angle (δ): 34.24, Azimuth angle (θ): 14.73). For each pixel, the average rate of the longest temporal cluster available is shown. Stars represent the location of the PS time series displayed in Figure 1b. Black lines represent eruptive fissures of the studied period. (b) PS time series in the LOS between 2003 and 2009 for two selected sites. Each time series consists of one temporal cluster of variable duration. Grey areas represent eruptive periods.

ground in otherwise non-optimum conditions using all data collected over the target area by a SAR satellite [*Hooper et al.*, 2004]. The Permanent Scatterers (PS) are high radar reflecting objects for which spectral response does not change significantly during different acquisitions. Dispersion due to temporal and geometrical decorrelation phenomena is thus minimized using PS as measurement points. When a significant number of independent radar-bright and radar-phase stable points (PS) exists within a radar scene and enough radar acquisitions have been collected, displacement time series and displacement rates of each PS can be calculated along the SAR Line Of Sight (LOS) with respect to a reference point, supposed to be stable [*Hooper et al.*, 2004]. Typically, precision ranges from 0.1 to 1 mm.y^{-1} depending on the quality of the processed dataset (acquisition frequency) and on the distance to the reference point.

2.2. PSInSAR Derived Method Applied at Piton de La Fournaise

[7] Conventionally, PSInSAR uses all the collected images and selects the pixels that show a trend in time consistent with the applied velocity model to compute time series and an average displacement rate. In the case of highly active volcanoes the application of this approach would cause the loss of the majority of the pixels due to large variations of the effective displacement rate during eruptive or seismic events. To circumvent such limitations, we developed a PSInSAR derived method. The new approach still relies on the use of point-wise stable radar targets but (1) uses a spatial filtering to estimate the time series and (2) does not apply any evaluation and removal of the atmospheric phase screen (see details in auxiliary material).[1]

[8] 1. A non linear spatial average has been performed such that for each filtered pixel that can be affected by a strong change of reflectivity, different temporal clusters of acquisitions have been identified to avoid the loss of the point because of the lack of coherence. Each temporal cluster is independent from the others because it represents a set of measurements for a distinct PS point. Clusters must thus be processed separately.

[9] 2. Deformation and atmospheric noise contributions to the interferometric phase present similar spatial and temporal behavior. It is thus not possible to correctly separate them. The time series filtering, based on a statistical analysis of the interferometric phase, can lead to a large underestimation of the deformation. In volcanic areas the amplitude of deformation varies from several centimeters to meters whereas the amplitude of the atmospheric disturbance is on the order of few centimeters. Thus this impacts only slightly the quality of the final result. We performed thus no atmospheric noise filtering. The precision of a single displacement measurement increases from millimeters to centimeters, and the average deformation rate precision depends on the number of acquisitions composing the temporal cluster during which the pixel is considered as coherent.

[10] At Piton de La Fournaise, Swath2 and Swath4 Envisat ASAR datasets were processed both in ascending and descending tracks. The descending dataset has been discarded because most of the computed interferograms starting from descending mode acquisitions do not show coherent signal due to geometrical decorrelation and foreshortening problems linked to the topography of Piton de La Fournaise and the satellite angle of view. In this study we focus on the Swath4 Track127 results (44 acquisitions from 07/05/2003 to 07/10/2009) processed inside the area of Enclos Fouqué where recent activity occurs. All PS datasets were processed using a reference point not affected by rapid deformation (latitude: −21.282, longitude: 55.734), which has been selected on the basis of single interferograms. Our dataset consists of 244445 points shown in Figure 1a.

2.3. GPS

[11] Since 2004, the volcano observatory of Piton de La Fournaise (OVPF/IPGP) has implemented a continuous GPS (cGPS) network. The cGPS network includes ten Trimble NetRS or Topcon GB-1000 stations installed on stainless steel rods cemented in the bedrock or on concrete pillars located around the summit cone or at its base, and two reference stations (ENCg, GITg) located 5 km from the summit (Figures 2 and 3). Data are acquired at intervals ranging from 1s to 30s as a function of the level of activity.

[1]Auxiliary materials are available in the HTML. doi:10.1029/2010GL043846.

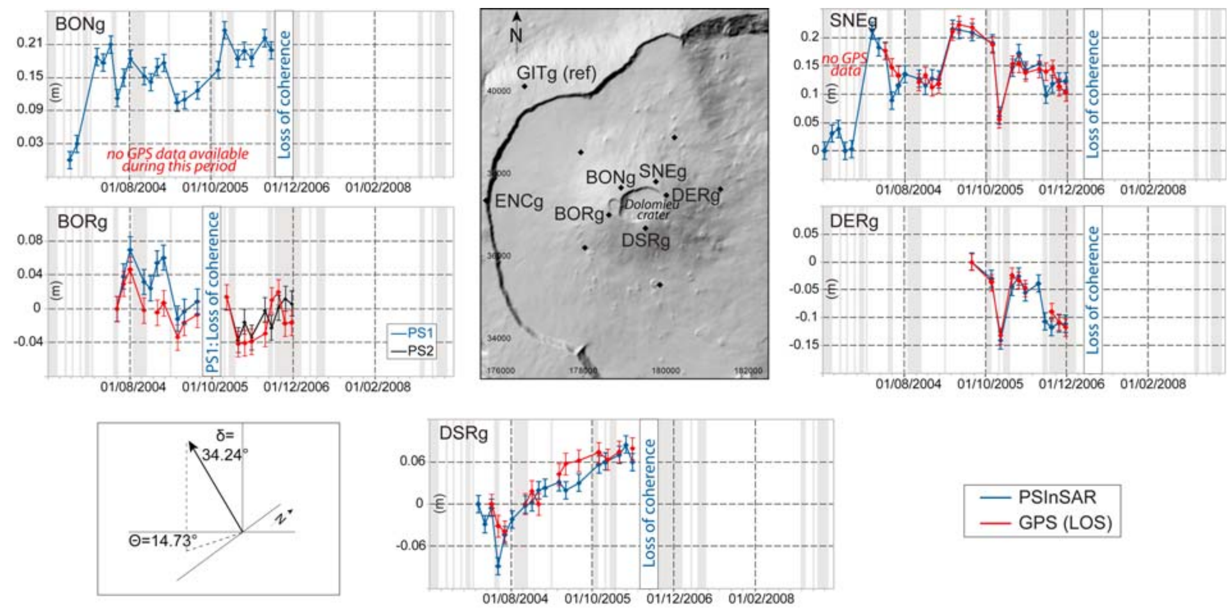

Figure 2. Comparison between PS (Swath4 track 127) and cGPS time series, represented as ground displacements in the LOS, around the summit crater. Grey areas represent eruptive periods.

The position of each station is calculated relative to the GITg reference station and is given in a tri-dimensional referential (X, Y and Z components).

3. Ground Deformation Field at Piton de La Fournaise Measured by PSInSAR

[12] The PS velocities covering the 2003–2009 period presented on Figure 1a allows us to identify two main areas in the ground deformation field at Piton de La Fournaise (1) the eastern flank affected by old lava flow subsidence and (2) the summit cone highly disturbed by eruptive activity.

3.1. Lava Flow Subsidence

[13] On the eastern flank of the volcano that is less often disturbed by eruptions, PS time series reveal evidence for old lava flow subsidence (Figure 1b). During the recent activity of Piton de La Fournaise, lava flows have mainly covered the north-eastern, eastern and south-eastern flanks of the

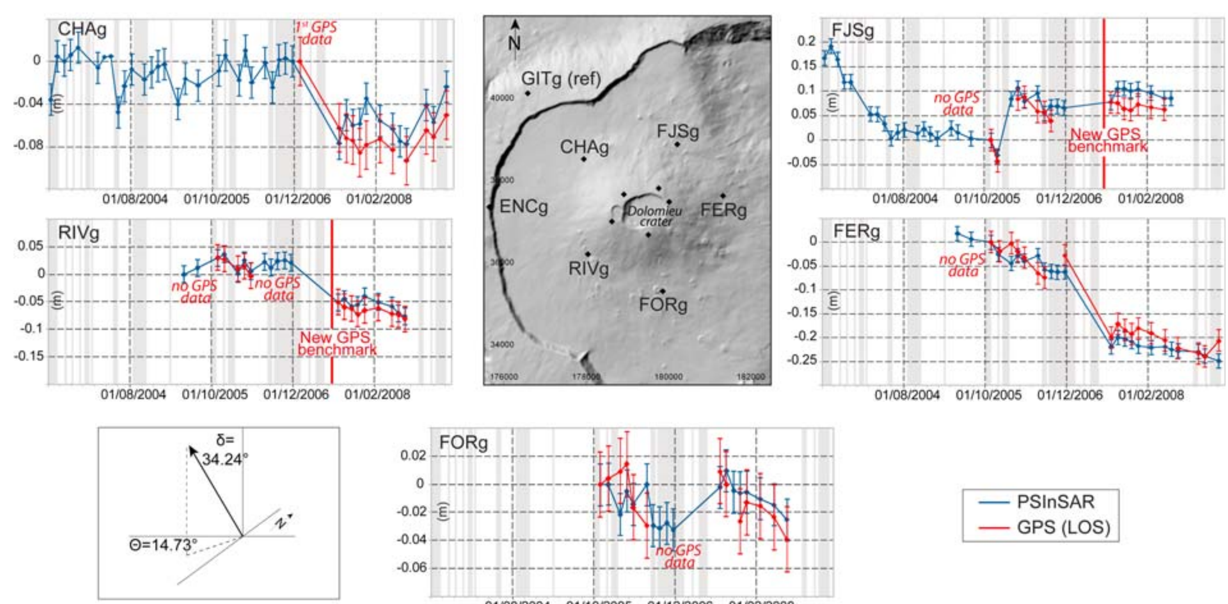

Figure 3. Comparison between PS (Swath4 track 127) and cGPS time series represented as ground displacements in the LOS, at the base of the summit cone. Grey areas represent eruptive periods.

volcano. Depending of the thickness and the age of the lava flows, their displacement is comprised between −0.04 and −0.11 m.y^{-1} in the LOS; 0.05–0.13 m.y^{-1} in pure subsidence if we assume no horizontal motion (Figure 1b). Lava flow subsidence is the result of ongoing thermal contraction and compaction of the lava flow and/or the substrate. It has been detected previously by conventional InSAR at Piton de La Fournaise (~0.2 m.y^{-1}) [*Froger et al.*, 2004; *Tinard*, 2007] but also at Etna (~0.022 m.y^{-1}) [*Briole et al.*, 1997] and Fernandina, Cerro Azul and Sierra Negra on the Galapagos (~0.033 m.y^{-1}) [*Amelung et al.*, 2000].

[14] The subsidence rates of old lava flows are more or less constant over the studied time interval and are only disturbed by major distal eruptions (Figure 1b). Distal eruptions are defined by *Peltier et al.* [2009] as eruptions located more than 4 km from the summit on the north-eastern or south-eastern flank of the volcano (see location on Figure 1a) and are accompanied by strong ground deformation. The high displacement rates observed to the east (Figure 1b) were linked to the large eastern flank motion generated by the April 2007 distal eruption [*Augier et al.*, 2008].

3.2. Summit Cone Deformation

[15] The cGPS data are available around the summit cone to validate some PS time series. We compared on Figures 2 and 3 the cGPS time series recalculated in the LOS of the satellite with the corresponding PS time series located at proximity. We reported for each cGPS location the longest time series not disturbed by loss of coherence of the PS. The displacements inferred from PS agree with the cGPS ground data. The trends are similar within the error bar of the two methods with a RMS error of 0.018m on the whole time series. The two time scales of ground displacements mentioned by *Peltier et al.* [2009] at Piton de La Fournaise are noticeable; (1) large rapid ground displacements linked to eruptions and (2) small long-term (weeks/months) ground displacements recorded during inter-eruptive periods (Figures 2 and 3).

[16] 1. When an eruption occurred between two satellite acquisitions, large displacements are visible on the PS time series. For instance between 02/11/05 and 17/12/05, a period including an eruption on the northern flank, −0.13 m of displacement in the LOS was recorded both by PS and cGPS at SNEg; the same kind of displacement was observed at DERg with −0.11 m and −0.09 m recorded by PS and cGPS, respectively (Figure 2). The largest discrepancies between the two methods are linked with some of these eruptive periods and probably with the loss of coherence of the PS signal due to the rapid ground displacement rates (e.g., SNEg, BORg on Figure 2, FORg on Figure 3). For instance for the May 2004 eruption, a displacement of −0.09 m (between 21/04/04 and 26/05/04) in the LOS was recorded at SNEg by PS, against −0.03 m by cGPS (Figure 2). Note that part of the discrepancy between the two methods can be linked with the reference point which is distinct for the two methods.

[17] 2. Each eruption has been preceded by long-term summit inflation that lasts between 1 to 6 months [*Peltier et al.*, 2009]. Pre-eruptive deformation of the summit cone is especially well visible at BORg; for instance a displacement rate of 0.35 m.y^{-1} (0.25 m.y^{-1} by cGPS (Figure 2)) in the LOS was recorded by PS before the August–October 2004 eruption. A similar slight increase of the signal in the LOS of the satellite has been systematically recorded before each eruption when enough PS data are available to deduce a trend (at least three measurements) at BORg (0.1 to 0.35 m.y^{-1}), BONg (0.1 to 0.35 m.y^{-1}), DSRg (~0.1 m.y^{-1}) and RIVg (~0.06 m.y^{-1}) whereas a decrease has been recorded at SNEg (−0.06 to −0.18 m.y^{-1}) and FJSg (~−0.1 m.y^{-1}) located north-east of the summit (Figures 2 and 3).

4. Discussion

[18] During the studied period, Piton de La Fournaise was very active, and even between eruptions deformation has been recorded both by cGPS and PS. The fact that the comparison between PS and cGPS trends yields similar results during such a strong deformation period provides a robust validation test of the method for its applicability on highly active volcanoes (Figures 2 and 3). The best results are obtained where displacement rates are slow and continuous (high coherence of PS with time), as observed during the pre-eruptive unrests (Figures 2 and 3) or on the eastern flank, an area less often disturbed by eruptive activity (Figure 1b).

[19] The main limitations of the use of PSInSAR techniques to quantify the deformation field on such an active volcano are caused by the irregularity of the deformation trends and the coverage of the ground surface by new lava flows. In the summit area, a loss of coherence is sometimes observed when the displacement rates are too fast, i.e., during dyke injections that feed eruptions close to the PS (Figure 2). On the eastern and north-eastern flanks, some PS time series were interrupted as a result of emplacement of new lava flows on the surface containing the PS, which then led to a loss of coherence (e.g., in February 2005 for PS(1) on Figure 1b).

[20] Even with these limitations, PSInSAR techniques provide an overall estimation of the volcano ground deformation field over large areas with a much greater set of points than field networks, especially during inter-eruptive periods. This technique can detect the centimeter displacements observed in the weeks/months prior to the Piton de La Fournaise eruptions. Efficient and accurate volcano monitoring requires a determination of the true direction of PS motion. The true vertical and easting components can be estimated only with a dataset acquired in both ascending and descending orbits. In our case, no descending PS dataset is available, so only the cGPS velocity field can be used to evaluate the contribution of the horizontal and vertical displacements to the PS measurements. At Piton de La Fournaise, periods of unrest typically involved summit inflation characterized by outward horizontal displacements in the same range of value than uplift at the summit but more than two times higher than uplift at the base of the cone [*Peltier et al.*, 2009]. So with a LOS vector in S4 of N −0.14317, E −0.54423, Z 0.82663, a signal increase is expected for PS sites located on the western flank of the summit cone (e.g., closed to the cGPS of BORg, BONg, CHAg and RIVg (Figures 2 and 3)), whereas a decrease of the signal in the LOS is expected for PS sites located on the eastern flank at the base of the cone (e.g., closed to the cGPS of FJSg and FERg) during volcano unrest.

[21] Even with a monthly data acquisition, this study demonstrates that PSInSAR and its derived approaches can

be used as a valid ground deformation monitoring tool in volcanic area, notably where no field network is implemented, and especially to detect long-term displacements that precede volcano unrests. As PSInSAR technique limitations appear mainly when the displacement rate is too strong, it is likely that during volcano unrest characterized by low rates of volcano inflation, PSInSAR techniques will provide even more robust estimates of the deformation field with long temporal time series. PSInSAR technique alone, or in combination with cGPS data, will give us complementary data to investigate the ground deformation associated with eruptive unrests over large areas and thus to better constrain the deformation sources and manage volcano crises.

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