

Operational use of InSAR for volcano observatories : experience from Montserrat

G.Wadge¹, B.Scheuchl^{1,5}, L.Cabey^{1,2}, M.D.Palmer³, C. Riley³, A. Smith⁴, N.F.Stevens¹

1. ESSC, University of Reading, Reading RG6 6AL, UK
2. Montserrat Volcano Observatory, Montserrat
3. Space Department, DERA, Farnborough, GU14 0LX, UK
4. Phoenix Systems, South House, 21-37 South St, Dorking, RH4 2JZ, UK
5. Dept. of Electrical and Computer Engineering, University of British Columbia, Vancouver, British Columbia, Canada

Abstract

Volcanoes as targets for InSAR vary greatly in the quality of their returned phase signal. There are two end-member volcano types from this perspective. Basaltic, low-relief shield volcanoes with frequent effusive eruptions and shallow magma reservoirs generally give excellent coherence and large magnitude ground deformations (~1m) that can be easily detected and modelled. However, their individual (lava flow) deposits tend to be too thin (<10m) for accurate InSAR measurement. In contrast, silicic volcanoes with substantial relief, infrequent eruptions and deeper magma reservoirs tend to be more difficult targets because of greater vegetation cover, layover/shadowing and small magnitude deformation signals. New deposits, however, can be thick (~100m) and can, potentially, be measured with sufficient accuracy by InSAR. Sometimes silicic volcanoes continue to erupt for years, usually explosively and dangerously, and present a long-term challenge to the local observatory. Here we report early experiences in learning how useful InSAR can be in such a case – the 1995-99 eruption of Soufriere Hills volcano, Montserrat. We found that the volcano became a more accessible target to ERS InSAR with time as more of its slopes were covered by deposits and became coherent. We were able to map the thickness of these deposits in this way. However, the summit lava dome did not become coherent and hence could not be measured by InSAR. Long-term coherence was also limited, partly because of decorrelation effects due to ash fall/erosion and this also limited the ability to build up a time series of differential movements. The ERS repeat cycle is not optimum for volcano monitoring but could provide some useful operational support if data can be acquired fast enough (local reception/fast transmission). Local processing is also probably desirable because of the benefits of immediate interaction with other scientists concerned with crisis management.

1. Volcano InSAR

Radar interferometry has the potential to make a major impact on the way that volcanologists monitor the behaviour of active volcanoes. Studies of volcano InSAR to date have been largely retrospective. In particular, they have mainly explored data

spanning eruptions when large surface strains have occurred (Massonnet et al., 1995, Jonsson et al., 1998, Sigmundsson et al., 1999). Studies of data collected during pre-eruption or syn-eruption periods have been rarer and none done in real-time. However, from the perspective of an operational volcano observatory it is just this capability that is needed. This paper discusses some of the issues surrounding this way of using InSAR. We take the experience of the 1995-99 eruption of Soufriere Hills Volcano on Montserrat and look at the needs of the Montserrat Volcano Observatory (MVO) that might have been met by InSAR data had they been available to them at the time.

Soufriere Hills Volcano is an andesitic stratovolcano in the Lesser Antilles island arc. It is typical of the silicic “end-member” types of volcano whose characteristics control the quality of the information retrieved by InSAR (Table.1).

Table 1. InSAR Characteristics of End-Member Volcanoes

InSAR Characteristics	Volcano Type	
	<i>Basaltic, shield/caldera, with recent lava cover</i>	<i>Silicic, high relief, with vegetation cover</i>
<i>Foreshortening/Layover</i>	Low	High
<i>Coherence</i>	High	Low
<i>Ability to measure deposit thickness</i>	Low	High
<i>Ability to measure surface deformation</i>	High	Low

Generally, INSAR techniques have a higher likelihood of success at basaltic volcanoes than at silicic volcanoes, because of topography and surface cover effects. The exception is that the creation of thicker deposits on silicic volcanoes (e.g. lava domes) can produce deposits on the 100m scale, making them potentially easier to measure than basaltic deposits, which are often less than 10m in thickness.

2. Operational Needs of a Volcano Observatory : MVO

MVO was established in 1995 after the start of the 1995-99 eruption of Soufriere Hills Volcano. Monitoring techniques were adapted and devised during the succeeding years, to measure a variety of phenomena including seismicity, surface deformation, topographic change and gas plume chemistry. The character of the eruption; a gradually accelerating effusion of a Pelean lava dome and its repeated collapse to form pyroclastic flows (Young et al., 1998) , coupled with the small size of the island and the proximity of the population at risk meant that the acquisition of timely data used to inform decision

making was imperative. InSAR could have potentially supplied MVO with such data on topographic change and surface deformation.

During the Soufriere Hills eruption a lava dome grew in a complex, piecemeal fashion (Watts et al., 2000). It was observed that the section of the dome currently growing was at greatest risk of collapse and generating pyroclastic flows on that sector of the volcano. Hence knowledge of the current locus of growth and its rate was needed. Unfortunately, the lava dome was covered with clouds much of the time, making some monitoring techniques – ground photography, theodolite and helicopter survey difficult or impossible and yielding only a small number of surveyed positions every month or so. A more frequent (say, weekly) method of collecting a denser sample of the new topography would have been of great benefit. Surface deformation at Soufriere Hills was measured by a number of ground-based techniques including GPS, EDM and tiltmeters (Jackson et al., 1998, Shepherd et al., 1998, Mattioli et al., 1998). Difficulties associated with these measurements included: loss of stations after inundation by pyroclastic flows, poor spatial sampling of the deformation field and lack measurement sites in the far-field (> 5 km). Differential InSAR would have been a way for MVO to complement the other techniques and alleviate some of these difficulties.

3. Data Availability and Timeliness

Spaceborne SAR data of the eruption period at Soufriere Hills are available from the ERS, Radarsat and JERS satellites. The one JERS pair of the volcano with a useable baseline is from 19 July to 15 October 1996, though the coherence is not very good despite the L-band wavelength of the radar. The cost of phase-preserved data and poor orbit control of Radarsat for interferometry made us restrict this study to ERS data from mid-1997 to mid-1999.

Montserrat is on the very edge of the reception range for the ERS ground reception station at Cotopaxi, Ecuador. As a result only ascending pass data are acquired. Fortunately, the volcano falls within the overlap of two ascending tracks (Track 075/Frame 033 and Track 347/Frame 315). Hence there are two sets of ascending pass data, one in the near- and one in the far-range with separations in the 35-day cycle of 19 days and 16 days. Although they cannot be mixed interferometrically the two sets do increase the frequency of sampling. Judging from contemporaneous, continuous GPS measurements on Montserrat (G. Mattioli, pers. comm.) the time of acquisition of the ascending pass data (about 02:40 hrs) is a time of relative stability in tropospheric water vapour content change compared to that at descending pass. This may mean that tropospheric noise would tend to be lower in the ascending pass data.

Some of the baseline separations of the ERS-1 and -2 pairs from the two ascending tracks are too large for interferometry. 58 of the 66 frame 315 pairs available between July 1997 and November 1998 have useable baselines and the corresponding numbers for frame 333 are 37 out of 45 possible pairs. More constraining is the overall quality of phase coherence due to temporal, ground surface and baseline decorrelating factors. We

find that for the same period the number of interferograms with any distributed coherent areas reduces to 17 and 5 for frames 315 and 333 respectively. Some of the volcanological factors for this reduction in data availability are discussed in the next section.

For this study we received our data in the UK via ESRIN at Frascati on CD-ROM. This route added time to the delay between sensor imaging and reception for InSAR processing. In figure 1 we plot the rate of sensor acquisition of data that proved to be capable of generating useable interferograms, the actual time of reception of these data by us and a notional “ideal” data reception rate of useable inteferograms of 1 per week.

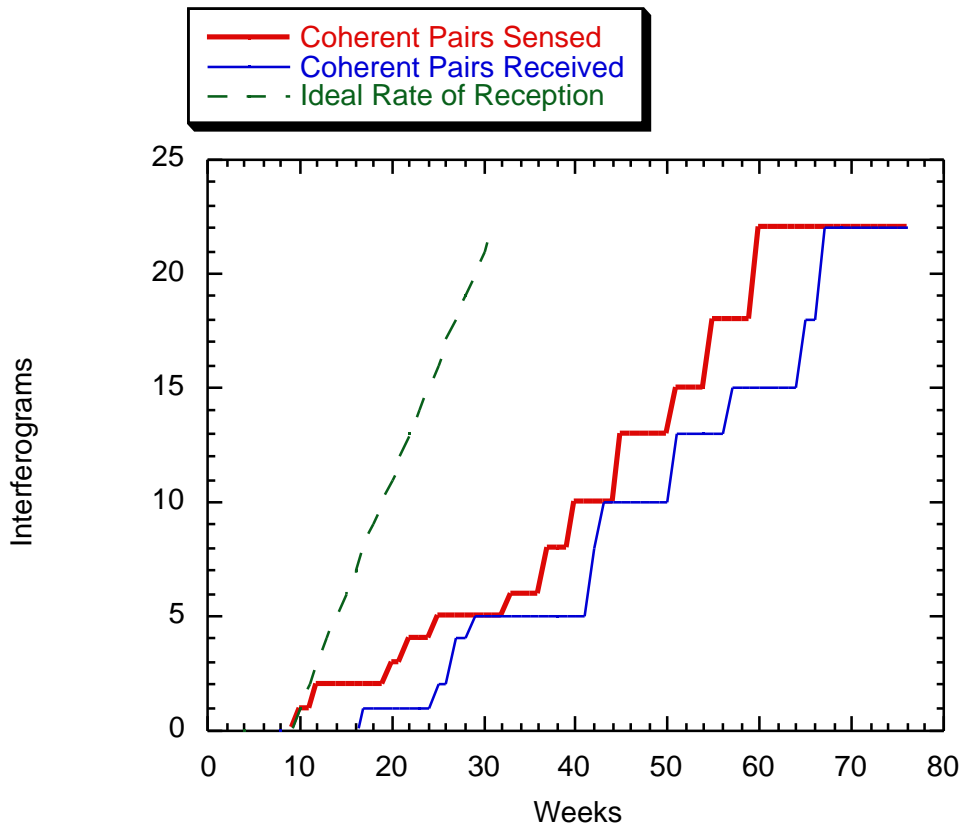


Fig.1. Plots of the rates of sensing and data reception for ERS interferograms of Soufriere Hills Volcano, Montserrat. Week 1 starts at 14 July 1997. The reduced rate after about week 60 is partly caused by the reduced rate in ascending pass acquisitions by ESA at that time. The “ideal rate” refers to the notional reception of one new interferogram per week..

4. Volcanological Information Quality

Like many andesitic volcanoes in the tropics, Soufriere Hills does not erupt frequently (the last eruption was about 400 years ago) and was mainly covered in forest at the start of the 1995-1999 eruption. This forest cover was removed from the summit area during

the phreatic phase of the eruption in 1995. Starting in March 1996 pyroclastic flows began to flow down the volcano's radial valleys removing the forest there (e.g. Wadge and Haynes, 1998). This process accelerated in 1997 and by the time lava stopped being erupted in March 1998 more than half of the volcano was covered in new deposits from pyroclastic flows, up to many tens of metres thick in the valleys. During the latter part of 1998 and 1999 the dome continued to collapse intermittently generating new pyroclastic flow deposits.

The surfaces of these deposits are very coherent at C-band compared to the surrounding forest and so as the area of pyroclastic flow deposits increased so did the overall coherence of the volcano. This trend continued into 1999 when the best interferograms to date were collected. Generally, coherence is reduced rapidly on the deposit surfaces beyond 35 days separation. This is probably due to rainfall-induced erosion on the steeper slopes and deposition on the lower slopes, sometimes via mudflows. The area that tends to show the longest-term stability is around Spanish Point and the airport in the northeast. This is an area of low (radar back)slope away from river channels. The 5 tandem (ERS-1/-2) pairs collected to date have, expectedly, the best coherence. Wadge et al. (2000) have shown from these interferograms that:

- The 25/26 September and 11/12 October 1997 pairs record the passage of pyroclastic flows, during the 24 hour period, as areas of no coherence where they cross earlier flow deposits.
- The lava dome remains incoherent (except on its lowermost slopes) even over 24 hours in May 1999 (Fig. 2).
- It is possible to measure the topography of the lower slopes of the volcano from these tandem data. By differencing the results from the pre-eruption topography the thicknesses of the pyroclastic flow deposits have been measured at up to 85m in some valleys.

The inability of 24 hour repeat-pass interferometry to record stable phase returns on a hot, unstable dome is disappointing, but not surprising considering the experience with ordinary lava flows (Stevens et al., 2000). It will be interesting to see at what stage of cooling the dome does become stable.

There are two probable components to the surface deformation field at Soufriere Hills Volcano during the 1995-99 eruption: a near-field (< 1km radius), high level (< 1km depth) component recorded by tiltmeter, broadband seismometer and EDM due to dome/conduit pressurisation (Voight et al., 1999; Shepherd et al., 1999), and a far-field component recorded by GPS due to elastic/finite strain crustal deformation in response to magma chamber pressure changes (Mattioli et al., 1999). Some of the near-field deformation has a cyclicity of about 8 hours, is almost entirely recovered and hence is not amenable to routine InSAR measurement. Near-field deformation is also difficult to measure because there are few coherent surfaces < 1km from the volcano, particularly during 1997, the period of greatest activity. Differential InSAR at Soufriere Hills over 35 days periods shows some interesting initial measurements (Wadge et al. 2000) of the far-field. But the lack of many long-term interferograms (>> 35 days) with large signals and the poor spatial coverage particularly during the early part of the eruption is restrictive.

Use of permanent scatterers (Ferretti et al., 2000) may be a way to improve the temporal resolution of the deformation signal.

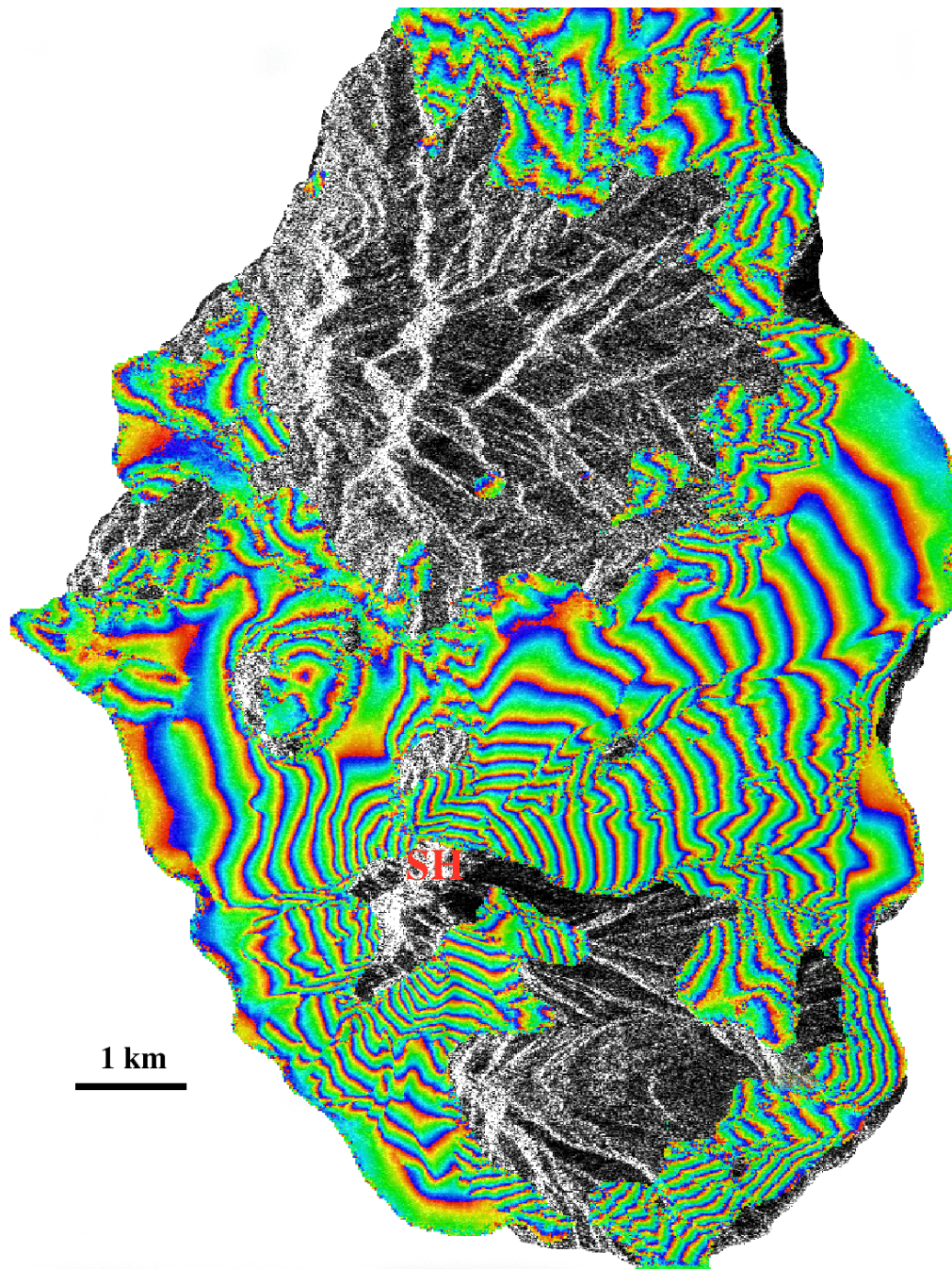


Fig.2 Slant-range ERS tandem interferogram of Montserrat for 4-5 March 1999. Each fringe represents about 45m of relief. The amplitude image is shown for areas where coherence is less than 0.2. Note the lack of coherence over the new lava dome of Soufriere Hills Volcano in the south central part of the island.

5. Conclusions

- The silicic “end-member” type of volcano is inherently more difficult to monitor by InSAR than the basaltic type, but useful volcanological information can still be obtained, probably operationally.
- For C-band repeat-pass InSAR the quality of data will improve during long-lived (years) eruption as more vegetation is destroyed.
- The low repeat frequency of the current generation of spaceborne imaging radars and the high rate of temporal decorrelation at active silicic volcanoes, means that to even approach the nominal operational frequency required (1/week) then data integration strategies are needed, including multi-track, multi-pass and multi-sensor. In addition local data reception (or same day transfer) and processing at the observatory will be required.
- The topographic growth of lava domes such as at Soufriere Hills cannot be mapped by repeat-pass InSAR. A single-pass spaceborne interferometric radar is required.
- ERS InSAR at Soufriere Hills is capable of measuring (i) the thickness of pyroclastic flow deposits on the volcano flanks, (ii) the opportunistic mapping of pyroclastic flow outlines in tandem data, and (iii) possibly a component of the far-field surface deformation.

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