Violent Volcanic Eruptions: The Horizontal Dimension in Hazard Prediction

Edward S. Gaffney[1]*, Grant Heiken[1], J. Bernard Minster[2], William I. Rose[3]
[1]Los Alamos National Laboratory. Los Alamos, NM USA
[2]University of California, San Diego, CA USA
[3]Michigan Technical University, Houghton, MI USA
*correspondence to: gaffney@lanl.gov or Geophysics, EES-1, ms F665, Los Alamos, NM 87545 USA

Useful prediction of catastrophic eruption needs to be available on a time scale of hours to days. Applications of synthetic aperture radar (SAR) to volcanological problems, especially those related to hazard prediction have concentrated on vertical deformations of the earth's surface (e.g., Massonnet and Sigmundsson, 2000; Zebker *et al.*, 2000). When vertical deformations are related to near-surface dyke intrusion, as at Reunion in 1998 (Sigmundsson *et al.*, 1999) or Fernandina in 1995 (Zebker *et al*., 2000), the time scale to eruption can reach into the range of days, or even less. But this type of deformation usually is related to movement of magma at deeper levels and provides only a general warning that eruption may occur over a period of months or even years.

However, some types of violent volcanic eruptions, such as Mount St, Helens in 1980 (Lipman and Mullineaux, 1981) and Bezymianni in 1956, are more characterized by horizontal deformation prior to eruption. Siebert (1987) has estimated that this type of collapse occurs about four times per century world-wide. Augustine volcano in Alaska is an example of a very active volcano for which lateral blasts may be a recurring mechanism of eruption (Siebert, Beget and Glicken (1995). These are not restricted to andesite-dacite environments; Vallance *et al*. (1995) report lateral blast deposits in Guatemala for both andesitic and basaltic stratovolcanoes. Geodetic (Lipman, Moore and Swanson, 1981) and photogrammetry (Jordan and Kieffer, 1981) measurements at Mount St. Helens indicated that deformation in the weeks before the eruption was primarily horizontal rather than vertical, and therefore would not have been as prominent with present data analysis approaches as it would be with measurement of horizontal strains. The purpose of this paper is to point out the potential and desirability of looking at this type of volcanic hazard from a new angle – the horizontal – as a predictive tool.

Remote sensing practice for volcanic hazards generally involves multispectral images, including COSPEC and lidar, and deformation measurements (Mouginis-Mark, P.J., J.A. Crisp and J.H. Fink, 2000). The latter type has focused on vertical deformation that accompanies magma intrusion below the volcanic edifice and on hydrologic anomalies caused by aquifer pressurization. These measurements are made with a variety of tools including geodetic surveys, surface-mounted strain and tilt meters, synthetic aperture radar (SAR) and lidar.

Several remote sensing techniques may have potential for real-time monitoring of lateral deformation of volcanic edifices with the goal of providing hours-to-days warning of impending catastrophic failure and eruption. Mouginis-Mark, P.J., J.A. Crisp and J.H. Fink (2000) have recently reviewed the field. Methods that seen most pertinent to the present application derivation of lateral deformation results from AIRSAR or space-based SAR, airborne last-return lidar, and ground-based radar arrays or ground-based lidar.

The horizontal velocities seen at Mount St. Helens for about two months prior to the catastrophic eruption were 1.5 to 2.5 m/d ($1.7\text{-}2.9 \times 10^{-5}$ m/s) (Lipman, Moore and Swanson, 1981). These are comparable to line-of-sight velocities of 390 m/a (1.2×10^{-5} m/s) for outflow glaciers from the Greenland and Antarctic ice sheets measured by Goldstein *et al.* (1993) with a 6-day frame separation. Vector velocities, using ascending and descending orbit pairs, up to 300 m/a (9.5×10^{-6} m/s) reported by Mohr, Reeh and Madsen (1998) with 31- and 35-day separations. Both these measurements employed SAR interferometry. Larger velocities up to 2 km/a (6.3×10^{-5} m/s) have been measured by tracking surface features in radar topography images separated by 105 days (Fahnestock *et al*., 1993).

For space-based SAR monitoring of the horizontal *vs.* vertical precursory motions, the critical science measurements would take the form of ascending and descending orbits, with right and left looks, so that there are redundant observations for a vector field displacement determination as Mohr, Reeh and Madsen (1998) did. With an 8-day repeat orbit, and a single instrument, you could get on of these images every 24 days at full resolution (about 25 m), and every 8-days at ScanSAR resolution (about 50 m). The latter may just barely meet the criteria for "hours to days" of warning. But either could serve to alert for the need for more frequent monitoring from other platforms such as AIRSAR or ground-based remote sensing.

AIRSAR could provide more frequent coverage than satellite-based SAR. It would also more readily be configured to be sensitive to horizontal deformations by using lower flight paths and/or using returns from larger incidence angle. Although AIRSAR has been used in volcanological applications (e.g., Ansan and Thouvenot, 1998), applications have been focused on topography, not on either horizontal position or velocity. We feel that there is considerable potential for AIRSAR if applied to such hazard-related volcanological problems as dome growth.

Although it is not as insensitive to effects of weather, another tool that has potential for application to monitoring horizontal deformations which might presage violent volcanic eruptions is late-return lidar (Ridgway *et al*., 1997; Hofton *et al*., 2000). Ridgway *et al*. (1997) used this technique to measure vertical ground deformation in the Long Valley caldera and were able to detect the true ground surface through the trees. Hofton *et al*. (2000) specifically address forested areas in the rain forest in Costa Rica, a land rich in active volcanoes.

Lidar measures the vertical position of the ground surface, and it does not return phase information so it can not be used interferometrically to measure horizontal deformations directly. But it can be used to track surface features in topography images separated in time to derive horizontal deformations, just as was done with radar images of the Greenland ice sheet by Fahnestock *et al*. (1993). The lidar approach has one considerable advantage over radar in that the system is smaller and consumes much less power. This results in substantial cost reductions in implementation.

Finally, we would like to suggest that either the radar or the lidar approach might be deployed as a ground-based system if the objective is to look horizontally. Zhao and Shibasaki (2001) describe such a vehicle mounted lidar system for generation of CAD models of urban landscapes. It should be possible to adapt the same approach for monitoring volcanos. A radar system would not permit synthetic aperture operation to obtain a large effective receiver dimension, but with much shorter ranges (10 kilometers rather than 100s) and array and beam-forming approaches, adequate spatial resolution seems to be possible. The principal advantage of such a system would be that the cost could be reduced to the point where it would be possible for several systems to be stationed at strategic points around the globe where they could be used for rapid response to local volcanic activity. This, we would hope, could provide a cost-effective way to get "high tech" volcanic predictions deployed where they are most needed which will more often than not be in poorly developed regions..

As a final note, a side-looking motion detection system such as we describe would also be useful for continuous, real-time monitoring of initial-stage landslides on a variety of scales.

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