Short Communication

Digital topography of volcanoes from radar interferometry: an example from Mt Vesuvius, Italy

Peter J. Mouginis-Mark, Harold Garbeil

Planetary Geosciences, Department of Geology and Geophysics, SOEST, University of Hawaii, Honolulu, HI 96822, USA

Received: July 20, 1993/Accepted: July 31, 1993

Abstract. A new airborne radar technique can generate digital topographic data for volcanoes at a scale of 10 m spatial and 1–5 m vertical, with a swath width of ~6.4 km. Called TOPSAR, the instrument is an interferometric radar flown on the NASA DC-8 aircraft. TOPSAR data permit the quantification of volcano slopes, volumes, and heights, and as such will be valuable for the analysis of lava flows, domes, and lahars channels. This instrument will be flown over several volcanoes in the near future, providing volcanologists with valuable data sets for the analysis of high-resolution topography. We briefly illustrate the potential use of TOPSAR data through examples from Mt Somma and Vesuvius, Italy.

Key words: Volcano topography – digital elevation models – Vesuvius – radar

Introduction

In several investigations of volcanoes, high quality digital elevation models (DEMs) are required to study either the geometry of the volcano or to investigate temporal changes in relief due to eruptions. Examples include the analysis of volume changes of a volcanic dome (Fink et al. 1990), the prediction of flow paths for pyroclastic flows (Malin and Sheridan 1982), and the quantitative investigation of the geometry of valleys carved by volcanic mudflows (Rodolfo and Arguden 1991). Additionally, to provide input data for models of lava flow emplacement, accurate measurements are needed of the thickness of lava flows as a function of distance from the vent and local slope (Fink and Zimbelman 1986). Visualization of volcano morphology is also aided by the ability to view digital topographic data sets from oblique perspectives (Duffield et al. 1993). Several commercial and public domain software packages allow the generation of oblique views using DEMs.

Until recently, the generation of these DEMs has required either high resolution stereo air photographs or extensive field surveying using the Global Positioning System (GPS) and other field techniques. We briefly describe here a new method that offers the ability to remotely measure the topography of volcanoes using an airborne interferometric radar called TOPSAR (Zebker et al. 1992). This data set is better than existing DEMs derived from digitizing topographic maps because of the high spatial resolution (10 m) and vertical accuracy (1–5 m). TOPSAR data can be collected day or night under any weather conditions, thereby avoiding the problems associated with the derivation of DEMs from air photographs that may often contain clouds. The utility of TOPSAR is illustrated here using data for Mt Somma and Vesuvius, Italy. We conclude by outlining various topographic studies of volcanoes in the Galapagos, Hawaii and Guatemala that will be conducted in the near future. Through a demonstration of their use, we hope to encourage other volcanologists to utilize these and additional TOPSAR data sets in their research.

TOPSAR

The TOPSAR instrument is a C-band (5.6 cm wavelength) radar flown on board a NASA DC-8 aircraft (Evans et al. 1992). TOPSAR comprises two radar antennas that are displaced vertically on the aircraft fuselage to form an interferometer (Zebker et al. 1992). Topographic data collected by TOPSAR have a spatial resolution of 10 m, with a vertical accuracy of 1–5 m depending upon the relief of the target – smoother surfaces will have lower height errors than mountainous areas. TOPSAR swaths are 30 km × 6.4 km in size. These topographic data are acquired concurrently with radar backscatter images at C-band, L-band (24 cm) and P-band (68 cm), which enable surface textures and structure to be investigated in a manner comparable to
Fig. 1. Computer-generated oblique view of Mt Somma and Vesuvius, as viewed from the north. The three valleys studied here in detail (see Fig. 3) were selected as representative of the larger examples on the flanks of Mt Somma, and are labeled 1, 2 and 3. Colors correspond to different elevations (green is low, brown is high) except that areas of high radar backscatter (man-made features) are shown in blue. No vertical exaggeration.

Fig. 2. Slope map for Mt Somma and Vesuvius, generated from the TOPSAR digital terrain data. The slope at each pixel is calculated by taking the square root of the sum of the vertical slope squared and the horizontal slope squared. The vertical slope is calculated first by summing the neighboring three pixels from the row above and subtracting the sum of the three pixels from the row below. This number is then divided by six times the pixel dimension. The horizontal slope is calculated in the same manner using pixels from the two columns adjacent to the pixel in question. The maximum slopes (>48°) on the inner wall of Mt Somma and the summit crater of Vesuvius are average values due to the radar shadowing resulting from the illumination direction (from left in this image). Large arrow points north.
conventional radar analyses of volcanoes (e.g. Gaddis et al. 1989, 1990; Campbell et al. 1989).

TOPSAR measurements differ significantly from DEMs derived from the interpolation of digitized contour maps. In TOPSAR data sets, a height measurement is made at each point (pixel) on the image and therefore the TOPSAR DEM provides a truer representation of the surface relief. We note, however, that in its current configuration TOPSAR does not have any absolute geodetic control, so that each TOPSAR scene must be referenced to a geodetic grid before absolute elevations and regional slopes (i.e., those slopes measured along or across the entire swath) can be resolved.

**Mt Somma Vesuvius**

We illustrate the value of TOPSAR data for volcanological research with examples derived from data collected over Mt. Somma and Vesuvius, Italy, in the summer of 1991. In the case of Mt. Somma (Fig. 1), oblique views of the volcano from any orientation aids in the interpretation of valley systems on the flanks. While the topography of Mt. Somma is well known from ground observations, the ability to view the rim profile and the distribution of the deepest valleys on the flanks provides valuable information that is not as readily apparent from a conventional topographic map.

The TOPSAR data also permit the detailed characteristics of the flanks of a volcano to be investigated by means of a topographic slope map (Fig. 2). Slope maps can be computed from the TOPSAR DEM and can provide valuable input when examining the likelihood that different areas will be affected by volcanic hazards such as pyroclastic flows, lava flows, and lahars. We have found the slopes of the flanks of Mt. Somma to be typically 13-24° at lower elevations, 25-36° closer to the rim, and a maximum value of >48° on the inner walls of the craters. The spatial distribution of slopes has been previously used to identify landslide hazards in non-volcanic regions (Pike 1988), as well as infer the regional geologic processes on the Earth and Venus (Sharpton and Head 1985), and might be useful in volcanology for the prediction of unstable slopes on volcanic domes (Fink and Kieffer 1993).

In this short communication, we want to demonstrate the use of TOPSAR by presenting two aspects of the morphology of Vesuvius, and to point out the potential application of this digital topographic data set to volcano hazard studies. We present two sets of measurements obtained from the TOPSAR data: valley geometry (Fig. 3a), which provides an indication of erosional processes; and downslope profiles (Fig. 3b), which should be useful for identifying differences in the strength of materials due to geologic structure, age, and composition. Knowledge of the dimensions and gradient of valleys may also permit the paths of future density currents to be predicted (Malin and Sheridan 1982; Ishihara et al. 1990), while the depth of incision relative to the width of each valley may be interpreted in terms of the extent of erosion by debris flows (Rodolfo and Arguden 1991). For the shape of the valleys at Mt. Somma, we choose to present the depth to width ratio as a function of slope (Fig. 3a) for three representative valleys. From our morphologic data, there appears to be a trend towards proportionally deeper valleys with increasing slope. In general, for each valley, on slopes >30° depth/width can be twice that on slopes <10°. This may be interpreted to be an indic-
tion of the lower erosive action of the flows (either debris flows or running water) on the lower slopes than on steep slopes, or of deposition on the lower slopes. Analysis of the profiles (Fig. 3b) shows that the slopes of each of the three valleys are quite similar, with slightly steeper slopes for the greatest change in elevation (Profile #2). Potentially, it may be possible to use TOPSAR data to recognize different lithologic units (either different in the mechanical properties or absolute age) by these two analysis methods, since the degree of erosion of materials on a given slope should vary as a function of strength and/or age. In order to explore the physical basis for these relationships, a more rigorous study would be required to identify and evaluate the possible significant variables (e.g. Knighton 1974).

Comparative TOPSAR topographic measurements for valleys on volcanoes such as Mayon volcano, where frequent lahars are generated by heavy rains (Rodollo and Arguden 1991), might be very useful for predicting which parts of the valley wall could be overtopped by individual lahars of a given size. Particularly because radar systems can operate day or night under any weather conditions, the ability to derive quantitative measurements from the high-resolution TOPSAR data show that changes in the geometry of a valley, such as those at Mt. Pinatubo, or dome growth (e.g. at Mt. Unzen; Fink and Kieffer 1993) could be productively studied. In addition, it is possible to measure lava flow thickness using TOPSAR (Evans et al. 1992) and, in combination with data on the local slopes, these data permit an investigation of the rheological properties of the flows in a manner comparable to that presented by Fink and Zimbelman (1986). In some instances, due to the limited number of foreign flights that the NASA DC-8 can make per year, orbital radar interferometry techniques such as those described by Zebker and Goldstein (1986) may have to be used to study some volcanoes.

Future TOPSAR data sets

To date, only a few TOPSAR data sets have been collected over volcanoes; the most potentially useful are the data for the western Galapagos Islands. Recently, several structural and volcanological investigations of these volcanoes have been conducted using air photographs (Chadwick and Howard 1991) and satellite images (Munro and Moguinis-Mark 1990; Rowland and Munro 1992), but the detailed topography of the islands is poorly known. Fernandina and Isabela Islands were imaged in May 1993 by TOPSAR, but at the time of writing the analysis of this data has not been initiated. The use of TOPSAR data to investigate the spatial distribution of rift zones through the generation of slope maps, the measurement of lava flow thickness on different slopes, and the calculation of volumes of cinder cones and summit calderas, should all significantly improve our knowledge of these infrequently visited volcanoes.

Two TOPSAR deployments over Kilauea volcano, Hawaii, took place in August and September 1993. These flights will enable the derivation of a topographic difference map, which should permit the quantitative measurement of the volume of new lava erupted over the intervening month. This will allow an average effusion rate for the volcano to be determined, as well as facilitate the study of the growth of a compound lava flow field. Finally, as part of the Decades Volcano program (Bennett et al. 1992), planning is underway for a TOPSAR deployment to Santa Maria Volcano, Guatemala. We hope to use TOPSAR to aid the analysis of the Santiaguito lava dome, and help with the production of new hazard maps through the construction of detailed topographic maps.

For TOPSAR data acquisitions at other volcanoes, prospective users should file flight requests with the Aircraft Program Manager, MS 240-2, NASA Ames Research Center, Moffett Field, CA, 94035-1000, USA, or contact Dr. Miriam Baltuck, Code Y, NASA Headquarters, Washington, DC 20546, USA.

Acknowledgements. Our use of the TOPSAR data would have been impossible without the collection and reduction of these data by Howard Zebker, Diane Evans, Mike Kobrick (all at the Jet Propulsion Laboratory, California) and the flight crew of the NASA/JPL DC-8. Their assistance in working with these data, and the planning of data acquisitions, is gratefully acknowledged. Comments by Scott Rowland on an earlier version of the text were appreciated. This research was supported by NASA grants NAGW-1162 and NAGW-2468 from NASA’s Office of Mission to Planet Earth. This is Planetary Geosciences paper No. 735 and SOEST Contribution No. 301.

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Editorial responsibility: H.-U. Schmincke