Radar Interferometry Studies of the Earth’s Topography

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Topographic information is required for many geological and geophysical investigations. For example, detailed topographic data alone can be used to map geological structure and thus reveal the effects of tectonic deformation. Additionally, they can be combined with gravity field measurements to constrain models of lithospheric structure and rheology (e.g., Topographic Science Working Group, 1988).

Topography is also an important element in both regional and global geomorphic studies because it reflects the interplay between erosion and the tectonic and volcanic processes of formation. The quantitative analysis of landscapes, whether for regional studies of mountain building and continental erosion (Harrison et al., 1983; Pike and Rozema, 1975) or for detailed analysis of geomorphological processes (Pike, 1988), relies on the availability of a detailed topographic data base that has a uniform spatial resolution and vertical accuracy. Topography is one of the controlling factors in pedogenesis and has a strong influence on soil properties such as soil thickness, pH, soluble salt content, and potential for erosion or accumulation (e.g., Birkeland, 1984).

Topographic information can also be used to investigate hillslope development and the rate of incision of drainage networks (e.g., Bloom, 1991). In addition, Pike [1988] showed that it was possible to correlate the types of terrains susceptible to landslides with their topographic signatures. Another soil-related application is estimation of soil carbon storage, which requires accurate slope information for calculations of areal coverage. Topographic information is also necessary to correct for solar illumination effects and geometric distortions in remote-sensing data. Slope and aspect information is required for accurate estimates of solar radiation and snow melt (e.g., Dubayah et al., 1993) and models of evapotranspiration and mass and energy exchange with the atmosphere (e.g., Band et al., 1992).

For regional- and local-scale investigations, high-resolution digital elevation models (DEMs) can be used. Until recently, DEMs were produced directly from air photos, by digitizing previously produced topographic maps (e.g., Pike, 1988), or by using low-spatial-resolution data sets derived from orbital altimeters (e.g., Sharpton and Head, 1985). However, for many studies, a globally consistent high-resolution DEM is required. Possible options for acquisition of a global data base include spaceborne synthetic aperture radar (SAR) interferometry, laser altimeters, or stereogrammetry (e.g., Topographic Science Working Group, 1988). As a proof of concept for an SAR interferometry mission, a prototype instrument called TOPSAR has been developed to fly on the NASA DC-8 aircraft as part of the Jet Propulsion Laboratory (JPL) Airborne SAR (AIRSAR) system. Data have been acquired over several sites in the United States and Europe. These data have been reduced to DEMs and can be displayed as topographic contour maps coregistered with images of radar backscatter (Figures 1 and 2).

In this article, we describe some of the preliminary results from TOPSAR as examples of the types of analysis permitted by these data. Specifically, these data have been used for rectifying the geometry of SAR images; determining the history of alluvial fan formation in Death Valley, Calif.; and
calculating slope, height, and thickness for lava flows on Mt. Helka, Iceland. We believe that Earth scientists working in a broad range of disciplines will see the potential of such data to assist their research.

**Sensor Description**

Nominally, AIRSAR acquires polarimetric images at P-band (wavelength = 68 cm), L-band (wavelength = 24 cm), and C-band (wavelength = 5.6 cm). This system has been augmented for TOPSAR with a pair of C-band antennas supplied by the Consorzio per la Ricerca e lo Sviluppo di Telesensori Avanzati (CORISTA) in Italy. They are placed vertically on the DC-8 fuselage to form an interferometer [Zebker et al., 1992]. When used, TOPSAR effectively replaces the C-band polarimeter instrument, but the L- and P-band systems are undisturbed and operate together with the topographic mapper, producing simultaneous L- and P-band polarimetric images plus C-band vertically transmitted, vertically received (VV) polarization images.

The interferometric geometry is shown in Figure 3. Surface height, \( z(x) \), is determined from [e.g., Zebker and Goldstein, 1986; Zebker et al., 1992]:

\[
\begin{align*}
  z(\alpha) &= h - p \cos(\alpha) \cos(\alpha-\theta) + \\sin(\alpha) \sin(\alpha-\theta) \\
\end{align*}
\]

(1)

Where \( h = \) aircraft altitude, \( r = \) slant range, \( a = \) baseline angle, and \( q = \) look angle.

Analysis of the topographic data indicates that the pixel-to-pixel random component of the height errors, for instance those due mainly to signal-to-noise ratio and decorrelation effects, are in the 1-m range, while systematic errors due to uncompensated aircraft motion are in the 1- to 2-m range. TOPSAR swaths are 30 km X 6.4 km. The multilook spatial resolution is 10 m; 10 m pixels are derived by first filtering the slant range image to approximate 10-m resolution and then resampling the data to fit a 10 X 10-m true ground coordinate system. The heights derived from this procedure thus represent a "phase center" for all scattering points in the output pixel. For most pixels not dominated by a single bright scatterer, the phase center is very nearly coincident with the center of the pixel in the across and along track directions and some average weighted height in the vertical direction. The magnitude of the latter height bias is highly dependent on terrain type and has not yet been well-characterized. A recent comparison of TOPSAR data acquired in the Mojave Desert, California with U.S. Geological Survey's 7.5' (30-m pixels) DEMs shows agreement to 1-m root mean square in flat regions and better than 5-m rms overall. The principal error is that mountains are displaced horizontally by about 30 m between the two maps; the source of this displacement is not well understood at present; however, we speculate that this is due to aircraft motion effects and not to roughness of the surface, as no systematic dependence is evident.

**Examples of TOPSAR Studies**

**Geometric corrections and calculation of slopes.** In SAR images, foreshortening causes areas closer to the radar (near range) to appear compressed with respect to those farther away (far range). In addition, deviations from a smooth geoid result in local distortions in which the tops of features are displaced relative to their bases. Thus, to achieve accurate coregistration of SAR data to other data sets, images must first be geometrically rectified to a map projection [e.g., Curtander et al., 1987]. It should be noted that the extreme case of foreshortening, layover, causes a loss in data as the top of a feature overlaps and obscures the bottom. Rectification can restore the correct geometry but not the lost data. Figure 4 shows an example of a radar image that has been geometrically rectified using a TOPSAR DEM and the algorithm developed by Madsen et al. [1992]. This algorithm is different from that of Naraghi et al. [1985] in that the SAR image is resampled directly in the processor without producing the intermediate radar slant range image. Similar data acquired over Montespertoli, Italy, have been used to calculate surface slopes to estimate true ground-surface area rather than projected area; such a correction is needed to measure the area to accuracies better than 10-15%.

*Use of topography for studies of alluvial fan evolution.** Landforms in arid regions record the interplay between tectonic forces and climate. When a desert piedmont is dominated by erosional processes, a pediment is formed. Conversely, when aggradation dominates, alluvial fans are formed [Bull, 1991]. The relative rate of uplift versus the rate of aggradation or channel cutting determines the slope of a fan, the area of a fan relative to the drainage basin that formed it, and whether a fan is cut by a trench [Bull and McFadden, 1977]. Changes in uplift rate or climatic conditions can lead to the isolation of the currently forming fan surface through entrenchment and the construction of another fan farther from the mountain front (decreased uplift or increased runoff) or closer (increased uplift or decreased runoff) [Bull, 1964]. Many present-day alluvial fans are therefore made up of a mosaic of fan units of different ages, some as old as early Paleoene. For this reason, determination of the stages of fan evolution leads to a history of uplift and runoff [Hooke, 1972]. To separate the effects of tectonic (uplift) and climatic (runoff) processes on the shapes of alluvial fan units, a modified conic equation developed by Troeth [1981] has been fit to TOPSAR data (Figure 5) for alluvial fans in different arid areas. The function used to determine the height at any point, \( z(x,y) \), is

\[
\begin{align*}
  z(x,y) &= P + \frac{1}{S} \sqrt{(x-x_0)^2 + (y-y_0)^2} + L (x-x_0)^2 + (y-y_0)^2 \\
\end{align*}
\]

(2)

This allows parameters for the apex position \((x_0, y_0)\), apex height \(P\), slope \(S\), and slope curvature \(L\) to be compared with unit age.

![Fig. 2. Contour map superimposed on an image of radar backscatter showing a prehistoric lava flow on the north flank of Helka. TOPSAR measurements of the thickness of the flow front vary from 5 to 33 m, and the cross-flow section shows up to 15 m of relief on top of the flow, with cross-flow undulations up to 4 m high on a horizontal scale of 80-120 m. Along the axis of the flow, pressure ridges <2-m high are typical with a maximum height of 6 m.](image-url)
drainage basin lithology, climate, uplift rate, and soil properties.

Figure 6 shows that for a particular fan in Death Valley, apex position (x₀,y₀) shifts with time due to uplift, segmentation, or stream blockage and slope, S, and radial curvature, L, also change with age. In addition, the original area and volume of a fan unit may be estimated even if the unit is buried by younger units or has been eroded.

Subtraction of the fit from the measured topography allows the amount of dissection to be estimated, which was previously done by counting contour crenulations. This is another measure of age—it can also be used to distinguish fans from pediments [Doebring, 1970], which are diagnostic of tectonically quiescent regions.

Volcanic studies. In July 1991, the TOPSAR system collected a DEM across the volcano Hekla in Iceland, and the surrounding area. Hekla last erupted in January 1991 [Gudmundsson et al., 1992] and represents a good test of the TOPSAR system over volcanic terrains due to the wide variation in surface types (snow, aa lava flows, and ash deposits) and local slopes. We choose to illustrate the capabilities of TOPSAR with two sets of observations of Hekla.

Figure 1 shows the large-scale geometry of Hekla volcano, clearly identifying the two summit craters—we measured the southwest crater to be 50-m deep, and the northeast crater to be 58-m deep—and the north-south versus east-west asymmetry of the volcano. Hekla rises over 600 m above its southern flank and 1000 m above its northern flank. The maximum measured slope is 17.5° for a horizontal distance of 3.62 km at the north flank. Slopes in excess of 10° over distances of 2.5-3.5 km were found on the other flanks of the volcano. These data indicate that the use of a digital topographic data set to measure flank slopes and the geometry of local topographic barriers on other volcanoes could be of great value in assessing damage caused by pyroclastic flows and lahars [Scott, 1989] as well as in enabling the intercomparison of volcano morphology [Pike, 1980]. Although several different techniques, such as stereo air photography and laser altimetry, can be used to produce a DEM of a volcano, the ability of TOPSAR to collect such a data set under any weather conditions, and with a consistent reference datum make the TOPSAR system uniquely valuable in assessing volcanic hazards during an evolving crisis.

However, it is in the analysis of small-scale topographic features (<100-m high) and the derivation of local slopes that the TOPSAR data are most valuable. Figure 2 illustrates a prehistoric lava flow on the north flank of Hekla. Estimates of the thickness of the flow front based on TOPSAR data vary from 5 to 33 m, and the across-flow section is estimated to range from 1 to 15 m of relief on top of the flow, with cross-flow undulations up to 4 m high on a horizontal scale of 80-120 m. Along the axis of the flow, pressure ridges <2 m high appear to be typical with a maximum height estimated at 6 m. Fink and Zimbelman [1986] made cross-axis field measurements of the Pu‘u ‘O‘o lava flows in Hawaii to calculate rheological properties of the flows but recognized the extreme difficulty of collecting such data even for a field-accessible volcano such as Kilauea. For any volcano imaged by TOPSAR, the DEM would permit not only individual cross sections of the flows to be studied, but also the change in cross-sectional shape in response to variations in down-slope gradient. Heights and volumes of cinder cones can also be determined from the TOPSAR data (Figure 2), permitting a quantitative appraisal of cinder cone erosion rates to be made for this or another volcanic area [cf., Wood, 1980]. Although these studies could also be done using a laser altimeter to generate profiles across the lava flows, there are two disadvantages: it is impossible to know for sure where to set up the flight lines to get the most useful data and to get down-slope gradients and across-flow profiles. One must put in a lot of work to ensure a consistent reference datum. Both of these problems are eliminated with TOPSAR.

Further applications of the TOPSAR data in Iceland are the focus of ongoing studies (S. Rowland, personal communication, 1992). Particularly promising is the ability to measure the volume of mohor ridges in southwest Iceland. These features are formed by subglacial eruptions of lava along a fissure system, and may range in length up to ~35 km [Allen, 1982]. Due to the confining pressure of the ice sheet, lava produced at these fissures does not flow downslope, and it accumulates around the vent as palagonitized ash deposits. By measuring the volume of the mohor ridges, and the variation of volume per unit length along individual ridges, we expect to be able to determine the total volume of lava produced per unit length of the fissure. In this way, spatial variations in vent geometry may be investigated and compared to their characteristics inferred in the field after the cessation of activity [Rubin, 1991].

We also recognize several future applications of digital topographic data, particularly TOPSAR measurements, in studying volcanos. Considerable work is underway to understand the growth of lava flow fields in Hawaii [e.g., Walker, 1991; Horr, 1991]. In particular, the rate of growth of pahoehoe flow lobes and flow fields warrants detailed study. It is believed that changes in topography of a few meters magnitude may be caused by lava inflation or the migration of active flow fronts. Such changes can take place over a time scale of hours to weeks over areas of a few square kilometers, mak-

![Figure 3](image-url-for-geometry-for-radar-interferometry)

![Figure 4](image-url-for-example-of-a-radar-image-over-mt-vesuvius-italy)

Fig. 3. Geometry for radar interferometry. Surface topography, z(x); aircraft altitude, h; baseline distance, B; surface topography, z(x); slant range, p; look angle, β; baseline angle, θ; path length difference, δ.

Fig. 4. Example of a radar image over Mt. Vesuvius, Italy, (a) before and (b) after it has been geometrically rectified using a TOPSAR DEM.
Fig. 6. Results of conic fits to Trail Canyon fan units. Units were assigned relative ages and mapped by Hunt and Mabey [1966] on the basis of surficial characteristics and topographic expression. (a) relative apex position (x0,y0) shifts with age due to shifts in source position; (b) older fans are flatter; (c) older fans have less curvature, although all have negative values, indicating they are concave-up.

Fig. 5. TOPSAR data for alluvial fans on the west side of Death Valley, Calif. North is toward the upper right and the swath is about 10-km wide. A shaded relief image has been generated from the topographic data by setting the illumination from the right at 10° elevation. The alluvial fans stand out as fan-shaped, light gray areas with apices in the Panamint Mountains to the left (west). The fans appear relatively uniform except for subtle raised, dissected areas, which represent the oldest units. The fan used for the conic fits is Trail Canyon fan, near the center of the image.

TOPSAR experiment would be an attempt to measure the rate of change of volume and local spatial variations in the rate of growth of the flow field using two or more DEMs derived from TOPSAR and obtained at different times. By comparing these topographic data sets, areas of inflation and areas where new lava flows have been added to the surface should be identifiable, permitting the quantitative assessment of magma production over a known time interval.

Characteristics of lava flows could also be investigated by high-resolution digital topographic data. Again, TOPSAR offers an excellent opportunity to study this aspect of volcanology. To date, only a few numerical models have been developed that incorporate DEM data to predict directions and extents of inundation of moving lava flows over inclined surfaces [Young and Wadge, 1990; Ishihara et al., 1990]. However, theoretical models of lava flow cooling [Crisp and Baloga, 1990] and attempts to reproduce well-documented lava flows [Murro, 1992] show that high-quality DEMs that provide slopes and topographic roughness are crucial to furthering our understanding of lava flow emplacement. Previous digital topographic data have had insufficient vertical accuracy to investigate the effects of obstacles in diverting lava flows, or of pre-existing topographic roughness (undulations in the surface over which the lava flow may travel) on the path of a lava flow. TOPSAR data could thus be used to model the flow of specific eruptions [Murro, 1992] or predict the effects of surface roughness on potential future eruptions.

Conclusions

DEM's acquired using TOPSAR, an interferometric radar sensor, have immediate application to studies of geology and geophysics. We have examined three illustrative examples: correction of remote-sensing observations for local slope and topographic effects, topographic expressions of erosion and uplift in alluvial fans, and use in volcanic studies.

The ability of TOPSAR to collect topographic data for a wide diversity of geomorphologic features represents an exciting tool for furthering our understanding of a broad range of geophysical processes. The advantages offered by TOPSAR over conventional photogrammetric techniques, namely the rapidity of data collection, high spatial and vertical resolution, and the ability to collect contiguous data independent of cloud cover, should also make these data valuable to hydrology, land use, and ecology.

The TOPSAR data described in this paper have been acquired and processed using a prototype processor and are not in a format compatible with currently available DEM data from other sources. However, work is in progress at JPL to make TOPSAR operational and to provide the DEM data in a documented standard format. This product will also provide calibrated P- and L-band polarimetric SAR data coregistered with the DEM data. This product is expected to be available by summer 1993. For TOPSAR data acquisition beyond 1993, prospective users should file flight requests with the NASA Ames Research Center (Code OM) or contact...
Miriam Baltuck at NASA Headquarters in Washington, D.C.

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References