Measurement of Surface Microtopography

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ABSTRACT: Acquisition of ground truth data for use in microwave interaction modeling requires measurement of surface roughness sampled at intervals comparable to a fraction of the microwave wavelength and extensive enough to adequately represent the statistics of a surface unit. Sub-centimetric measurement accuracy is thus required over large areas, and existing techniques are usually inadequate. A technique is discussed for acquiring the necessary photogrammetric data using twin film cameras mounted on a helicopter. In an attempt to eliminate tedious data reduction, an automated technique was applied to the helicopter photographs, and results were compared to those produced by conventional stereogrammetry. Derived root-mean-square (RMS) roughness for the same stereo-pair was 7.5 cm for the automated technique versus 6.5 cm for the manual method. The principal source of error is probably due to vegetation in the scene, which affects the automated technique but is ignored by a human operator.

INTRODUCTION

IN RECENT YEARS, there has been an evolution in remote sensing investigations from largely qualitative, descriptive studies to more quantitative analyses involving transformation of the received data into geophysically meaningful quantities such as mineralogical composition, particle size distribution, and surface roughness. Accordingly, recent successes in remote sensing using synthetic aperture radar (SAR) such as Seasat and the Shuttle Imaging Radar (SIR), and the increasing number of planned SAR instruments (e.g., Magellan, EOS, and ERS-1), have led to efforts to understand the relationship between radar backscatter and the corresponding parameters which describe the characteristics of the surface causing the return. Radar backscatter from a surface is dependent on the roughness of the surface, the local incidence angle, and the complex dielectric constant of the surface (e.g., Ulaby *et al.*, 1982). For surfaces with moderate relief and whose electromagnetic properties are similar, the first effect dominates and the radar backscatter can be regarded as a measure of the surface roughness at or near the scale of the radar wavelength, averaged over the SAR resolution cell.

The roughness of geologic surfaces at centimetre to metre scales is important in geology (e.g., Hobson, 1972), geomorphology (e.g., Stone and Dugundji, 1965), planetary geology (e.g., Head *et al.*, 1985) and radar remote sensing (e.g., Schaber *et al.*, 1976; van Zyl *et al.*, 1989). Outcrop geometry and roughness can be used to help identify rock types in the field and on other planets, while the roughness of geomorphic surfaces can be used to deduce the rates and relative importances of some surficial modification processes.

Techniques that have been used to measure roughness of natural surfaces at these scales include surveying (Stone and Dugundji, 1965), templates (Hobson, 1972; Schaber *et al.*, 1980a), laser profiling (Chapman, personal communication, 1989; Chapman, 1985; Garvin, 1988), and close-range stereo-photography (McCue and Green, 1969; Johnson and Kase, 1977; Schaber *et al.*, 1980a, 1980b). Stone and Dugundji (1965) used a plane-table method to make contour maps covering 30- to 40-m areas at 15- to 30-cm contour intervals. The objective of the study was to develop techniques for quantification of microrelief for the study of vehicle locomotion. The resolution of their measurements, while sufficient for their purposes, is not high enough for use in radar backscatter models. Fox (1989) used a standard transit survey to obtain profiles on moraines on the eastern side of the Sierra Nevada. He found a correlation between moraine roughness, age, and radar image brightness.

Laser profiling by aircraft has been used recently by the U.S. Geological Survey and NASA (Chapman, personal communication, 1989; Chapman, 1985; Garvin, 1988), and a commercial helicopter system also exists. These systems can produce long profiles quickly, but their spot sizes are, at best, in the 10- to 20-cm range. These techniques may be useful for extrapolation of high-resolution measurements of limited areas to larger areas, but their resolution is not quite high enough for determination of centimetre-scale effects of geomorphic processes or for direct use in radar backscatter models.

A template is a means to do rapid, high-density surveying over a small area. Devices constructed at the Jet Propulsion Laboratory (JPL) by M. Daily and S. Saunders; at U.S. Geological Survey, Flagstaff, by G. Schaber (Schaber *et al.*, 1980a); and also described briefly in Hobson (1972) are similar to the smaller device used by carpenters to match irregular joints. A linear or square array of vertical rods of equal length is allowed to drop to the surface and the heights of the rods above a horizontally leveled frame are then measured. The major disadvantages of the use of templates for roughness measurement is their limited relief capacity and the large amount of time required to make measurements in areas of difficult access. Elliot (1989) used a template to study surface evolution of moraines in Norway. In contrast to Fox (1989), she found no correlation between roughness and age of moraine. Gaddis *et al.* (1989) found good correlation between template measurements of lava-flow roughness and SIR-B radar image brightness in Hawaii.

Close-range stereo photographic techniques hold the most promise for delivering the required resolution and coverage. These requirements place limits on baseline and height of the photography. McCur and Green (1965) presented topographic maps of Pisgah lava flow with coverage of 300 m but contour interval of 25 cm. These were constructed from low-altitude conventional fixed-wing aerial photography. Lower-altitude, slower-speed photography of archaeological sites were obtained by the Whittlesey Foundation (e.g., Johnson and Kase, 1977) through the use of a tethered balloon system flying at 50 to 800 m. Experience at JPL with a similar system has shown that the logistical problems of helium supply in areas of difficult access, the sensitivity to wind, and the uncontrolled baseline of the system make it unsuitable for work in widely separated field areas. Hand-held stereo photographs have also been used

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(Schaber *et al.*, 1980a, 1980b), but their limited coverage (less than 2 m) makes statistics derived from them suspect.

A technique for acquiring the necessary data using helicopter-borne film cameras has been developed. Two co-boresighted 70-mm metric cameras with 100-mm geometrically calibrated lenses are attached to either end of a 6.2-m boom mounted longitudinally under a small helicopter (Figure 1). The cameras are remotely triggered from the passenger seat. Using Kodak Aerochrome 2448 film developed to a contrast ratio of 1.6, the resulting ground resolution is about 5 mm when the helicopter flies at 20 m above local terrain. Field of view for the cameras is about 15 m at that altitude. The apparatus, originally built for the Canadian Ministry of Forests by Canadian Air Products (Hindley and Aldred, 1981; John Markila, personal communication, 1989), has been used in the southwest U.S. to image control targets and a number of natural sites. The resulting microtopographic data provide input to geomorphic and volcanological studies and electromagnetic interaction models being developed at JPL. These models will provide the connection between radar backscatter, roughness, and geologic processes.

MANUAL DATA REDUCTION TECHNIQUE

Two techniques were used to generate topographic data from the helicopter stereo-pairs: standard manual photogrammetry involving an operator, and an automated digital technique.

The manual stereo measurement technique derives height information from the original positive transparencies, which are mounted on a Kern Instruments DSR-11 Analytical Plotter. The optical axes of the cameras were assumed to be parallel and orthogonal to the stereo base, and scale was derived from camera altitude, which was determined from measurement of the image overlap. Leveling of the terrain coordinate system is not important to the observation of high-frequency relief.

The relevant unknown to be determined is photo scale or, equivalently, platform height. A good estimate of either parameter is obtained from the image overlap as follows (Figure 2):

$$\text{Platform height} = \frac{\text{(focal length)(stereo base)}}{\text{(frame width)}(1 - \text{overlap})} \qquad (1)$$

At a 40 percent overlap and with a focal length of 100 mm, frame width of 70 mm, and stereo base of 6.2 m, platform height is found to be 14.8 m. At a typical height of 20 m, overlap is about 60 percent. At a height of about 9 m, there will be no overlap.

To make the measurements, the plotter is moved automatically to a predefined *x-y* grid location, and the operator translates one image to remove parallax, thereby measuring height. Two types of one-dimensional linear profiles were obtained. The first set of profiles consisted of height measurements spaced 1 cm apart, with each profile spaced 1 m from its neighbor. Profiles were taken in both the *x* and *y* directions, producing 10 to 30 profiles of up to 3000 points depending on the amount of overlap. The second set was also measured in each direction, but at a 5-cm spacing, digitizing one height measurement every 5 cm. The second set of profiles thus formed a two-dimensional digital elevation model (DEM).

Accuracy of the measurements depended on stereo acuity and the base-to-height ratio. Parallax measurement accuracy, dp, was about 6 micrometres on the film. The associated height error, dh, is

$$dh = dp * H^2/(B^*f) \qquad (2)$$

with parallax error, dp, in mm, flying height, H, in metres, stereo-base, B, in metres, and focal length, f, in mm. This results in a height error, dh, in mm. At an assumed 6-μm parallax accuracy, resulting height errors are up to ±4 mm from a flying height of 20 m, with quadratically more error as flying height increases. Under adverse conditions (which produced lack of focus, image motion, poor lighting, and lack of surface texture), errors are estimated to be as high as 6 mm.

Operator time required for determination of each point was less than 0.6 seconds, but operator fatigue prevented sustaining this rate for long periods. Profiles and stereo models such as those used here may be generated in three to ten workdays. The speed of this technique can be greatly increased by measuring in a dynamic mode where the machine profiles the surface continuously, and the operator keeps the measuring mark on the surface. Overshoots, undershoots, and a general inability to keep the measuring mark on the surface in a dynamic mode will lead to a loss of accuracy estimated at 5 to 8 times in this mode, but a surface may be measured in 2.5 hours.

AUTOMATED DATA REDUCTION

A second method was evaluated for production of the profiles and DEM. This technique is a completely automated image-matching technique originally developed for generating accu-

FIG. 1. The stereo-boom mounts longitudinally on a small helicopter. Metric, 70-mm Hasselblad cameras are mounted in each end (note holes). Cameras are operated from the cockpit.

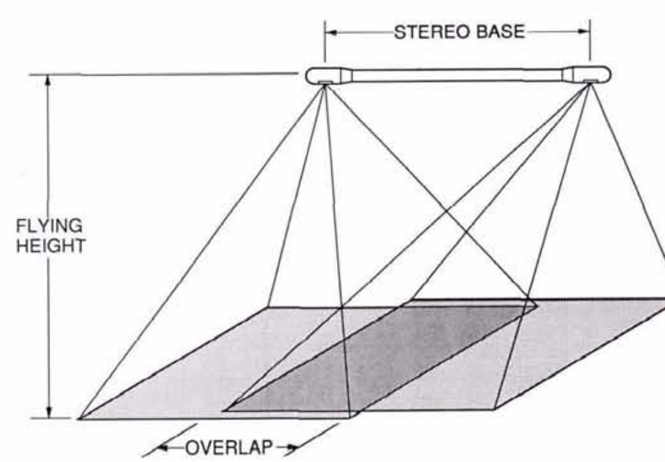

FIG. 2. Stereo geometry for calculations, using Equations 1 and 2 (see text). Stereo base is fixed at 6.2 m, and flying height is typically 20 m, leading to an overlap of about 60 percent.

rate and dense DEMs from SPOT satellite imagery (Muller, 1989; Muller *et al.*, 1988). Positive transparencies were digitized with a fixed pixel size of 16 μm using a pair of RS170 CCD cameras stereoscopically mounted in a Kern DSR-11 Analytical Plotter. This pixel size is equivalent to a spot size of about 3.2 mm on the ground from a platform height of 20 m. The analog-to-digital converter on an Imaging Technology framegrabber interfaced the cameras to a VaxstationII/GPX workstation using 8-bit quantization. The 512-by 480-pixel frames (equivalent to 8.192 by 7.68 mm on the film) were then radiometrically corrected for severe vignetting (Tadrowski, 1988) and mosaicked into an 8-frame by 7-frame mosaic.

The Otto-Chau stereo-matcher (Otto and Chau, 1988), based on a region-growing version of an adaptive least-squares correlation algorithm, originally described by Gruen and Baltsavias (1988), runs on either a single Sun-3 workstation or an ETHERNET of Sun-3 workstations using a task parallelism "farming" technique described in Muller *et al.* (1988). The algorithm involves more than 10^5 floating-point operations per pixel per iteration of the least-squares adjustment process (Muller *et al.*, 1988) but usually converges within one or two iterations. This results in a single Sun-3 execution time of approximately 0.2 seconds per patch of 15 by 15 pixels (the patch size chosen after extensive testing). The distributed version of the Otto-Chau algorithm reduced the execution time of around 32 days to about 7.5 days on five workstations on which there were three other stereo-matching jobs running. A user-selectable grid of 5 pixels was chosen to jump-step the patch in the region-growing process. The planned use of an array of transputers (Muller, 1989; Muller *et al.*, 1988) should reduce this computation time to a few hours.

For the stereo matching described here, tiepoints were generated manually using a digital stereo measurement system developed on a Sun workstation (Muller, 1988). These manually determined tiepoints were determined to approximately 0.3 pixel and were then further refined (with several being rejected) by the Otto-Chau matcher. From ten tiepoints, the stereo matcher generated 231664 matches out of a maximum possible 240000 points.

Using interior orientation parameters supplied by the camera manufacturers and assuming that exterior orientation parameters remained constant between a control target stereo-pair and the test site photography, image coordinates were transformed into ground coordinates. The extensive quality assessment performed for the Otto-Chau stereo matcher on SPOT-DEMs indicates accuracies can be obtained to better than 0.3 pixel root-mean-square (RMS) (Day and Muller, 1988) which is equivalent to 1.5 mm in this photography. Note that this assumes excellent contrast, absence of image motion, and presence of good stereo clues. Given that the base-to-height ratio of the helicopter photography is about 0.3 at 20 m flying height, we can support the expectation of an average height error of at least one pixel, or 3 to 4 mm on the ground.

COMPARISONS OF THE TECHNIQUES

In order to compare the two techniques, two-dimensional, 5-cm topography from each technique for the same stereo pair were linear least-squares fit to remove trends due to unknown helicopter attitude and local terrain tilt. RMS roughness (i.e., standard deviation of the data from the best-fit plane) were then calculated for each. Results for the manual method show an RMS roughness of 6.5 cm. Comparison with a result of 7.5 cm for the automated method yields a relative difference of 16 percent.

The discrepancy includes the inherent errors in the two processes, but is certainly dominated by the fact that topography is mapped differently by the two techniques and is affected by surface characteristics. The test site used for the comparison (Figure 3), an area of pahoehoe lava mantled by aeolian deposits drawn from nearby alluvium, was characterized as a part of the experiment. It is composed of solid material (quartz and basalt sand, 61 percent; gravels, 23 percent; cobbles, 8 percent; and bedrock or boulders, 3 percent) and non-solid vegetation (creosote, low scrub, and grasses with heights less than 1 m, 6 percent) (S. Petroy, personal communication, 1988). The automated technique will either extract heights over the canopy or will produce gaps in the matching process if the surface violates the implicit assumption of contiguity. By comparison, photogrammetric operators tend to use visual interpolation to extract the height field at the underlying surface, except where the vegetation is dense enough to prevent observation of the surface. Thus, it is expected that the automated technique will produce a higher estimate of the surface roughness than the manual technique, as was observed here. At platform elevations typical of aerial photography, this difference is insignificant.

FIG. 3. Mantled pahoehoe surface at Pisgah lava field measured by both the manual and automated techniques. Note bushes (about 1 m in diameter) that are the likely source of disagreement between the two methods.

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