MANOUHER NARAGHI
WILLIAM STROMBERG
MIKE DAILY
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA 91103

Geometric Rectification of Radar Imagery Using Digital Elevation Models

A procedure is described to remove terrain induced spatial distortion in radar imagery.

ABSTRACT: *Geologic analysis of radar imagery requires accurate spatial rectification to allow rock type discrimination and meaningful exploitation of multisensor data files. A procedure is described which removes distortions produced by most sources including the heretofore elusive problem of terrain induced effects. Rectified imagery is presented which displays geologic features not apparent in the distorted data.*

INTRODUCTION

CURRENT WORK in radar image processing for rock type discrimination includes multisensor studies requiring coregistered radar and multispectral scanner (MSS) data sets, (Blom and Daily, 1981). In previous work (Daily et al., 1978; Blom et al., 1981), this registration was achieved by tedious manual identification of tiepoints common to both images followed by rubber-sheet deformation correction based on a polynomial fit to the control point geometry. For the relatively flat sites studied (Death Valley, California and San Rafael Swell, Utah) this technique gave satisfactory results but was extremely laborious. The next generation of multisensor studies will focus on areas of moderate relief and valley-ridge topography. A correct sampling of such topography implies the identification of tiepoints in each valley and on each ridge, which for a Seasat Radar image (100 km on a side) and 2-km mean drainage spacing would require identifying 10^4 tiepoints. This level of effort would be prohibitive in terms of computer and analyst resources. This paper reports first results from an alternative rectification technique that utilizes digital elevation data and a model of radar image distortion.

RADAR IMAGE DISTORTIONS

Radar images frequently display a highly distorted character which substantially inhibits subjective interpretation and precludes quantitative analysis of spatial relationships. This unusual quality occurs in radar imagery largely because terrain variations cause features to be displaced in a direction opposite to that which occurs in natural vision. The peak of a mountain, for example, is displayed in an active radar image at the same location as a point at a lower elevation which is closer to the observer. In conventional photography, on the other hand, the same peak appears in the image plane at a distance further away than the surrounding lower elevations. This difference from normal sight is magnified by the fact that as the system moves more directly overhead the apparent displacement is increased, a behavior strongly at odds with our day to day experience. Normally, we expect to obtain a more accurate rendition of a surface as we view it less obliquely. The unusual appearance of radar imagery is enhanced by other factors. The displaced features are frequently emphasized because they are often facing nearly perpendicular to the direction of illumination. This produces not only a strong specular response but

PHOTOGRAMMETRIC ENGINEERING AND REMOTE SENSING,
Vol. 49, No. 2, February 1983, pp. 195-199.

0099-1112/83/4902-0195$02.25/0

also an accumulation of returns from points along the slope which occur at nearly the same range. In addition, contraction in the near range is produced by the non-linearity of the relationship between range and distance on the surface. In practice, other bothersome radar-unique distortions may occur. A typical example is a second order effect of the Earth's rotation. Skew is introduced by the cross-track motion of the Earth as the sensor moves along its orbit. This effect might easily be anticipated and be removed by the synthetic aperture signal processing. Not as immediately evident, however, is the variation in the doppler frequency of the radar signal produced by the difference in the relative Earth motion from top to bottom of the scene. This difference introduces as second skew appearing as an incremental along-track translation of sequential image rows.

The unusual character of distortions in radar imagery is detrimental to subjective analysis, but it is especially damaging to certain types of quantitative investigations. It precludes digital multispectral analysis and measurements involving spatial relationships (e.g., the generation of geologically useful plots of the angular distribution of linear structures). In general, the unique behavior of radar image geometry has severely limited the use of these data for scientific analysis.

Initial approaches to geometric rectification have dealt with those effects which were most easily removed. Approximate correction of near range contraction reduced the distracting appearance of this effect which is particularly obvious in images with a wide range of viewing geometry. This expanded the usable extent of these data and allowed the construction of mosaics, making possible coordinated examination of broad regions. Controlled polynomial modeling of geometric distortion achieved reasonably accurate rectification of all effects except those due to high frequency topographic components (which, depending on viewing geometry, might be as large as three times the local topographic variation). Images processed in this manner (through registration to map bases or other spatially realistic image data) have, in areas of low relief, been successfully subjected to multispectral analysis.

These limited approaches have significantly enhanced the scientific utility of radar imagery by correcting much of the systematic distortion as well as some of the terrain induced effects. However, the removal of distortion produced by local elevation variations has remained a critical problem. This paper presents the results of a rectification process which has proven reasonably successful in correcting even these high frequency effects.

RECTIFICATION PROCEDURE

The concept underlying this more thorough correction process is to generate a model of the radar system and environment to be used with digital terrain data in order to position each radar image sample at its true location in a convenient mapping projection. Typically, estimates of relevant system variables (sensor position, pointing vector, scale, etc.) are not consistently accurate. So, the concept also employs a "best-fit" approach to determine the values of model parameters. Estimates are obtained which minimize differences between computed and measured locations of a set of control points (tiepoints) in the imagery. To obtain locations of tiepoints in the mapping projection, a simulated image is generated from the digital terrain data. This simulation is a display of the cosine of the angle between the local suface normal and the ray from the nominal sensor location. It exhibits the general appearance of a photograph of the surface illuminated from the sensor position, and it bears a sufficient similarity to the radar image that the requisite number (usually two to three times the number of model parameters) of tiepoints can be found.

Due to a pressing need for spatially rectified radar images, the problem is being addressed in stages. In this way, corrected imagery will be available throughout the development process. The procedure presented here represents the initial phase of the development. It employs commonly available, general purpose spatial manipulation software to accomplish much of the large scale transformation. The task remaining to be performed by new software is thereby simplified, and a working procedure is obtained with a minimum of technology development.

The procedure consists of a preliminary transformation using general purpose routines to perform rotation, scaling, and deskew. The product of this step, a radar image in which the cross-track direction is aligned with the rows of a digital elevation data file, is then subjected to a special purpose program which removes, row-by-row, the remaining distortions.* This two-step process registers the radar scene to the elevation data file. Because the terrain data are presented in a standard Universal Transverse Mercator (UTM) projection, the product of the process is a radar image which spatially corresponds to the topographic map.

More specifically, the row-by-row processing consists of the following steps. (Refer to Figure 1 for a diagrammatic presentation of the procedure.) At each sample location in a row of terrain data, the range to the radar sensor is computed using the simple trigonometric identity relating the range,

* (Digital Terrain data were obtained from the U.S. Geological Survey, National Cartographic Information Center. In these data, elevation estimates were obtained from contour lines on standard 1:250,000 scale USGS topographic maps in UTM projection. Heights were provided in a rectangular array of samples spaced roughly 200 feet apart.)

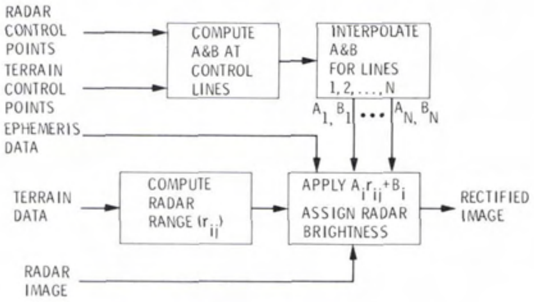
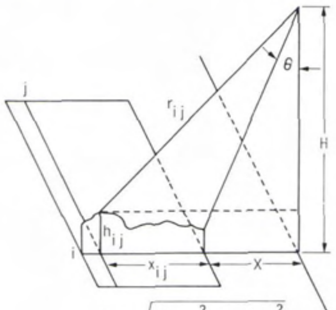


FIG. 1. Processing procedure.



$$r_{ij} = \sqrt{(X+x_{ij})^2 + (H-h_{ij})^2}$$

i = LINE COORDINATE OF TERRAIN DATUM
j = COLUMN COORDINATE OF TERRAIN DATUM
r_{ij} = COMPUTED RANGE AT (i, j)
x_{ij} = CROSS TRACK LOCATION OF (i, j)
h_{ij} = HEIGHT AT (i, j) (ABOVE MEAN SEA LEVEL)
H = SENSOR HEIGHT (ABOVE MEAN SEA LEVEL)
X = GROUND TRACK OFFSET
θ = LOOK ANGLE

FIG. 2. Basic scene geometry.

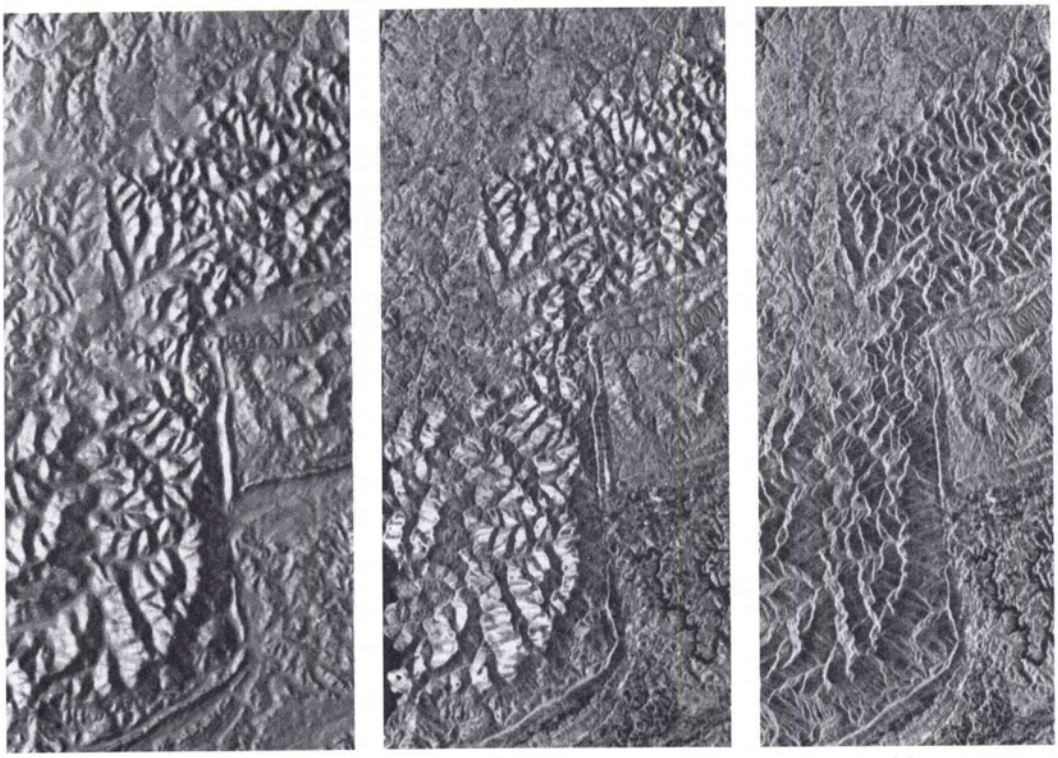
the difference between the nominal sensor height and the topographic elevation, and the surface distance from the nominal sensor point to the terrain sample (Figure 2). The sensor height and subsensor location are obtained from ephemeris data. To convert from range to a coordinate in the radar image, multiplicative (gain) and additive (offset) factors are applied to the range value. The values of gain and offset are determined based on manually located control points in several lines of the data. At these control lines, two corresponding features are identified in both data sets near opposite ends of the line. (Features are identified in the topographic data set using the simulated view described in the discussion of the basic concept.) Gain and offset values are then computed to reconcile the tiepoint locations in the radar and elevation data sets. Tiepoints may be found at any number of lines (two control lines were used to produce Figure 3b). For lines between these control lines, the gain and offset are interpolated linearly. Finally, the radar image brightness at the computed coordinate is obtained by interpolating between the neighboring samples. That brightness is then assigned to the corresponding location in the digital elevation data set.

The gain and offset could be chosen respectively as the nominal image scale factor and the range at the near edge of the image. However, experience has demonstrated that nominal values of these factors as well as those concerning sensor position are far too inaccurate to produce the precision required for this coordinate computation. Further invalidating the use of raw ephemeris data is the fact that small errors in the preliminary geometric manipulation may be manifested as changes in the effective ground track of the spacecraft.

RESULTS

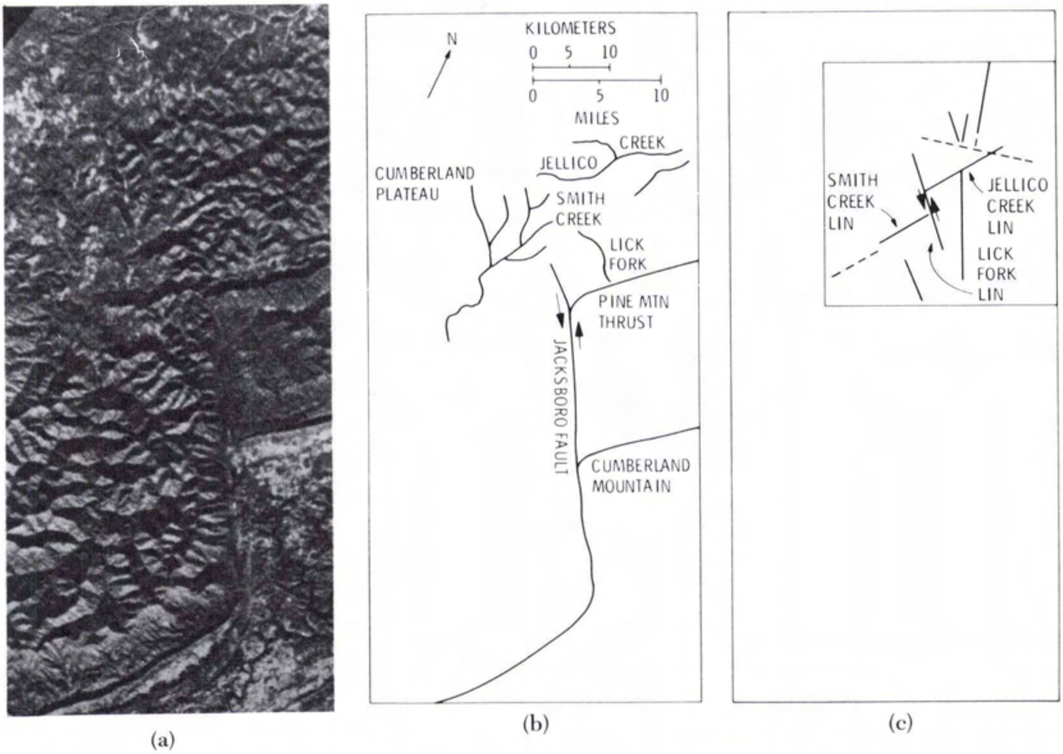
Presented below is an example of the application of the process to a Seasat radar image of an area of the Pine Mountain Thrust of Tennessee. This site contains terrain with elevation variations of up to roughly 1,000 metres. Three images are displayed in Figure 3: a simulation of illuminated topography (described above) (Figure 3a), the radar image geometrically rectified to remove topographic effects (Figure 3b), and the uncorrected radar image (Figure 3c). The simulated image is provided as a reference against which to compare the two radar scenes. Figure 3c has undergone the initial processing step which corrects for rotation and skew. It is displayed, rather than the unprocessed picture, to simplify evaluation of the effects of the rectification process and to emphasize the impact of topography on spatial relationships. In addition, Figure 4 provides a Landsat image of the area (Figure 4a), a sketch map (Figure 4b) in which significant geologic features are identified, and a detailed map of lineaments and faults in the Jellico Creek area (Figure 4c).

The result of the process is the radar image geometrically rectified to the UTM projection in which the topographic data were provided. Among the most obvious effects of the rectification process is the more natural character it has produced in the corrected scene. More significant than this appearance improvement, however, are the changes the process has wrought on the orientation and shape of local features. These differences are particularly apparent in local areas containing bright slopes oriented perpendicular to the incident radiation. The expansion of these faces coupled with the directional changes produced in the neighboring small scale features make the spatial relationship between these two types of structures considerably more understandable. The geometrically rectified radar image (Figure 3b) is also a superior display for identifying lineaments. The block of moderate-relief topography northwest of the Pine Mountain Thrust (see feature map, Figure 4b) shows a number of aligned drainages that are poorly expressed in the unrectified Seasat scene (Figure 3c). Lineaments compiled



(a) (b) (c)

FIG. 3. (a) Simulation of illuminated terrain. (b) rectified seasat image. (c) seasat image.



(a) (b) (c)

FIG. 4. (a) Landsat image. (b) significant feature map. (c) lineament map of Jellico Creek area.

from the rectified scene are shown in Figure 4c. Note that the Lick Fork lineament offsets the Jellico Creek and Smith Creek lineaments approximately 3 kilometres in a left-lateral sense. This geometry is consistent with the Lick Fork lineament being a splay segment (a spur off a major fault commonly occurring near the end of its extent) of the Jacksboro Fault. This relationship is not evident in the Landsat scene (Figure 4a), which is illuminated from the south, but it can be detected on the simulation (Figure 3a), which is illuminated from the west. It is also easily recognized in the rectified radar scene (Figure 3b) but not in the uncorrected Seasat image (Figure 3c).

The generally successful spreading of facing slopes, which is largely responsible for the natural appearance of the corrected scene, is also indicative of the accuracy to which the radar range has been determined. In this computation, errors as small as one or two samples can cause the neighboring darker slopes to be incorrectly expanded. In fact, such mis-registration is visible along the Jacksboro Fault. There, the inaccurate correction which was performed resulted from the failure of the linear gain and offset transformation to compensate for erroneous estimates of local system parameters. It is anticipated that the more sophisticated implementations of the process currently under development will be better able to avoid such problems. The implicit models of global geometry in these models will not be constrained to simple translation, rotation, scaling, and deskew.

Finally, it is interesting to note the strong effect the topography has produced on the left edge of the corrected radar image. The irregularity of this edge occurs because the coverage of the radar image was less than that of the topography. The variations in the edge illustrate the magnitude of the displacements the radar samples experience due to elevation differences, which in that area vary over a range of about 600 metres.

CONCLUSION

Geometric rectification of radar images using digital elevation models is a powerful preprocessing step for spatial and spectral analysis. To fully utilize radar data for multisensor lithologic discrimination, the geometrically rectified scene must undergo a subsequent radiometric rectification to strip out the effect of slope on scene brightness. This brightness correction requires knowledge of the local surface slope and the backscatter curve as a function of terrain slope. Note that the curve as a function of slope is not identical to the curve as a function of look angle, because vegetation tends to grow parallel to local vertical rather than normal to local slope. These geometric and radiometric corrections will be somewhat easier in the future as orbital imaging radars utilize larger look angles.

ACKNOWLEDGMENTS

This paper presents one phase of research conducted at the Jet Propulsion Laboratory, California Institute of Technology, under NAS 7-100, sponsored by the National Aeronautics and Space Administration.

REFERENCES

Blom, R. G., and M. I. Daily, 1981. Radar Image Processing for Rock Type Discrimination, *Digest of the IEEE International Geoscience and Remote Sensing Symposium,* June 8-10, 1981, Washington D.C., Volume 1, pp. 574-581.

Blom, R. G., M. J. Abrams, and C. L. Conrad, 1981. Rock Type Discrimination Using Landsat and Seasat Data, *Digest of the IEEE International Geoscience and Remote Sensing Symposium,* June 8-10, 1981, Washington D.C., Volume 1, pp. 597-602.

Daily, M., C. Elachi, T. Farr, W. Stromberg, S. Williams, and G. Schaber, 1978. *Applications of Multispectral Radar and Landsat Imagery to Geologic Mapping in Death Valley,* Jet Propulsion Laboratory Publication 78-19, March 30, 1978, 47p.

(Received 3 September 1981; accepted 6 September 1982; revised 1 October 1982)

Forthcoming Articles

Peter O. Adeniyi, An Aerial Photographic Method for Estimating Urban Population.

Mike Daily, Hue-Saturation-Intensity Split-Spectrum Processing of Seasat Radar Imagery.

W. Frobin and *E. Hierholzer,* Automatic Measurement of Body Surfaces Using Rasterstereography. Part I. Image Scan and Control Point Measurement.

V. S. Frost, M. S. Perry, L. F. Dellwig, and *J. C. Holtzman,* Digital Enhancement of SAR Imagery as an Aid in Geologic Data Extraction.

P. A. Murtha, Some Air-Photo Scale Effects on Douglas-Fir Damage Type Interpretation.

Ernest H. H. Shih and *Robert A. Schowengerdt,* Classification of Arid Geomorphic Surfaces Using Landsat Spectral and Textural Features.

R. Welch and *T. R. Jordan,* Analytical Non-Metric Close-Range Photogrammetry for Monitoring Stream Channel Erosion.