Multiple Incidence Angle SIR-B Experiment Over Argentina: Generation of Secondary Image Products

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***Abstract*—Original radar images may be geometrically and radiometrically distorted. This may be a particular problem when multiple angle imagery is analyzed and there is topographic relief in the area of interest. This paper describes a set of techniques designed to combine a multiple angle radar data set with a digital terrain elevation model, to generate a set of new images called *secondary image products*. These new images are geometrically rectified radar ortho-images, radiometrically rectified images, and stereo ortho-images. These secondary images can then reliably be used for thematic interpretation.**

I. Introduction

SIR-B WAS THE FIRST experiment to address the use of multiple incidence angle radar images for terrain classification and generation of topographic maps. A problem is immediately apparent when one attempts to employ the multiple angle images for interpretation and machine analysis. The individual images do not match one another geometrically, and the variation of image brightness might be controlled largely by the slope-induced variation of incidence angles rather than variations in the response to surface roughness or dielectric constant.

The current paper dicusses methods of image rectification and illustrates results using SIR-B images and digital elevation models. What comes to mind when one plans to perform a geometric rectification of the individual images is to use the set of ground control points that can be identified in a map and each digital image; the image can then be warped in the computer to fit the map geometry. This has been proposed in several instances, e.g., [5], [10]. However, the warping does not consider effects of terrain relief, and the rectified images actually do not fit one another, nor the map. Therefore, this approach is only useful if the imaged area is topographically flat.

To achieve a refined correction one needs to employ information on terrain elevation. If it is in digital form, one calls this a digital elevation model (DEM). Leberl *et al.* [8] performed radar image corrections with film images on a photogrammetric orthoprojector. In this case, the primary image is reprojected onto film in small parts, continuously changing the projection geometry with an optical zoom and Dove prism. The DEM is used to control the optical elements of the reprojection system with a process control computer.

If the image is in digital form, then the reprojection of the image is by a process of resampling. Naraghi *et al.* [9] and Guindon *et al.* [6] demonstrated the concept using digital elevation models extracted from maps.

The SIR-A experiment of 1981 resulted in several sets of overlapping images, most notably over the Greek islands of Cephalonia and Ithaka. These were used to create DEM's from the stereo models formed by the radar images. These and also DEM data obtained from maps were employed with the Greek SIR-A data and data from Northern California to rectify the primary radar images both for geometry as well as radiometry [3].

Methods were developed to match the radar images pixel for pixel with the digital elevation data in order to then correct the radar image. This matching process was based on the use of ground control points and of image simulations from the DEM's. An extensive discussion of a strategy for image rectification can be found in the work of Domik [4] and will be reviewed shortly in Sections III and IV.

Data sets with several images at different look-angles off-nadir did not exist prior to the SIR-B experiment. Therefore, there was limited need and motivation to work on the precise rectification of radar images. A unique quadruple overlap was obtained by SIR-B of an area called Cordòn la Grasa in Argentina. It is with this data set that the previously developed image rectification techniques are demonstrated, leading to a set of secondary radar image products. The demonstration and evaluation leads to recommendations on how to further refine radar image matching techniques.

II. Input Data to Image Rectification

Image rectification will typically follow a rigorous radargrammetric computation involving ground control points, sensor positions in the form of orbit data, and imaging parameters. If a single radar image is concerned, then we will compute a so-called *resection in space*. This

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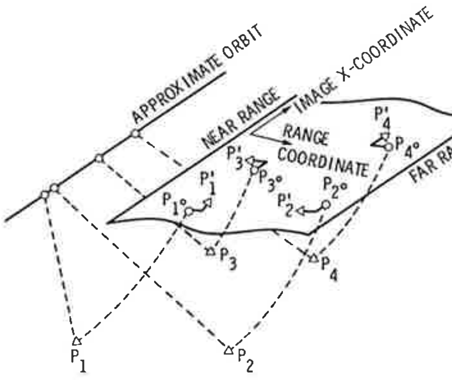

Fig. 1. SAR-resection-in-space. Ground control points $P_1, P_2, \cdots, P_n$ are projected into the image plane with the help of the approximate orbit, producing image positions $P_1^0, P_2^0, \cdots, P_n^0$. The discrepancies P_n^0-P_n' are the basis for a least squares improvement of the orbit and SAR system parameters.

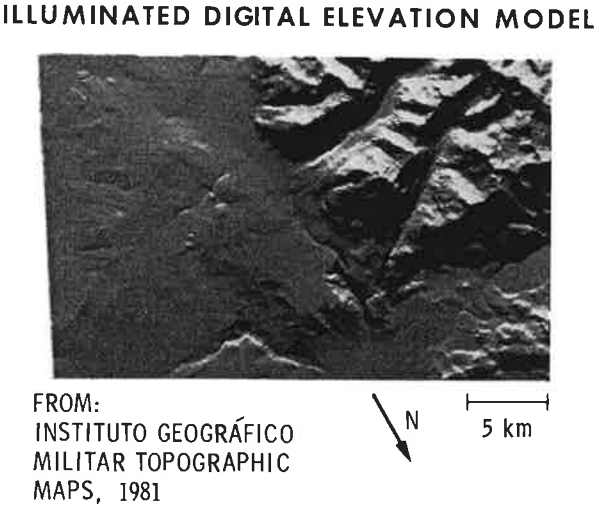

Fig. 2. Illuminated input digital elevation model (DEM) of the test area. The pixel size of the DEM is 50 m × 50 m.

has been discussed in a companion paper (Leberl *et al.*, [7]).

The resection-in-space will provide the following results:

1) coordinates of ground control points in the object system (latitude, longitude, or *xyz*);
2) measured coordinates of the control points in the image, either as image *x*, *y* values or image pixel and line numbers; and
3) refined sensor positions and values for the antenna velocity vectors.

A by-product of the resection-in-space consist of a prediction of the quality of the rectification since it produces values for the residual mismatches between computed image positions of ground points and those measured in the radar images (compare Fig. 1).

Finally, a meaningful rectification will also require a digital elevation model.

The primary radar images of Cordòn la Grasa, Argentina, are shown in Leberl *et al.* [7]. Fig. 2 shows a DEM of the same area.

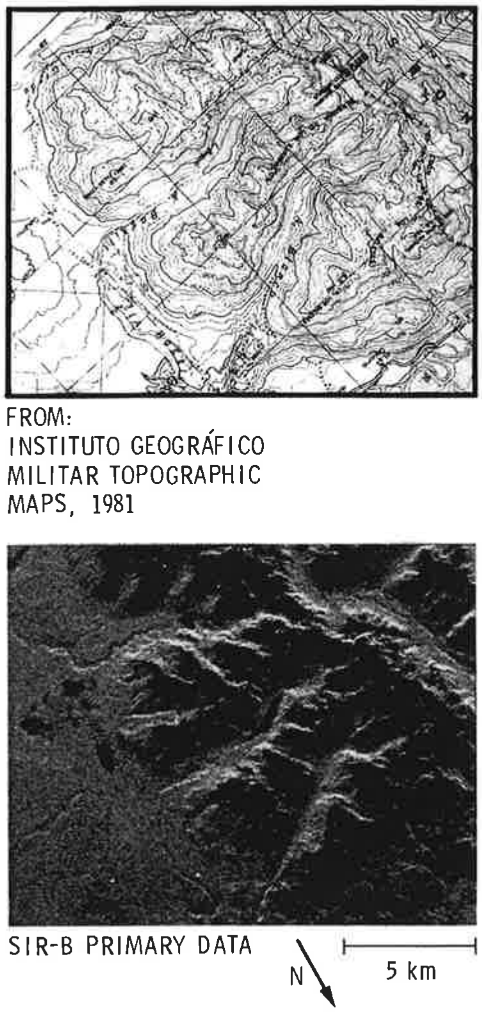

Fig. 3. SIR-B image segment and segment of a map 1 : 100 000. The image is devoid of man-made or other point features in mountainous terrain.

In past efforts of radar image rectification, the above were all of the available inputs. One should stress that ground control points are point features that are uniquely identifiable in both an image and a map. This therefore is limited to man-made features such as road crossings, or to clearly defined natural features such as lake borders.

In mountainous terrain, radar images are devoid of man-made features. Consequently, well identifiable ground control points are often not available (compare Fig. 3). Should the image geometry therefore need correction, one has to resort to other means than straightforward ground control.

III. Geometric Rectification

Rectification of radar images of mountainous areas is prepared in two steps:

1) first a radar image is simulated using the DEM and refined sensor positions;
2) secondly, point features are selected that appear on both the real and the simulated radar image.

The latter are needed in the mountainous regions where point features cannot be identified using a map. As shown

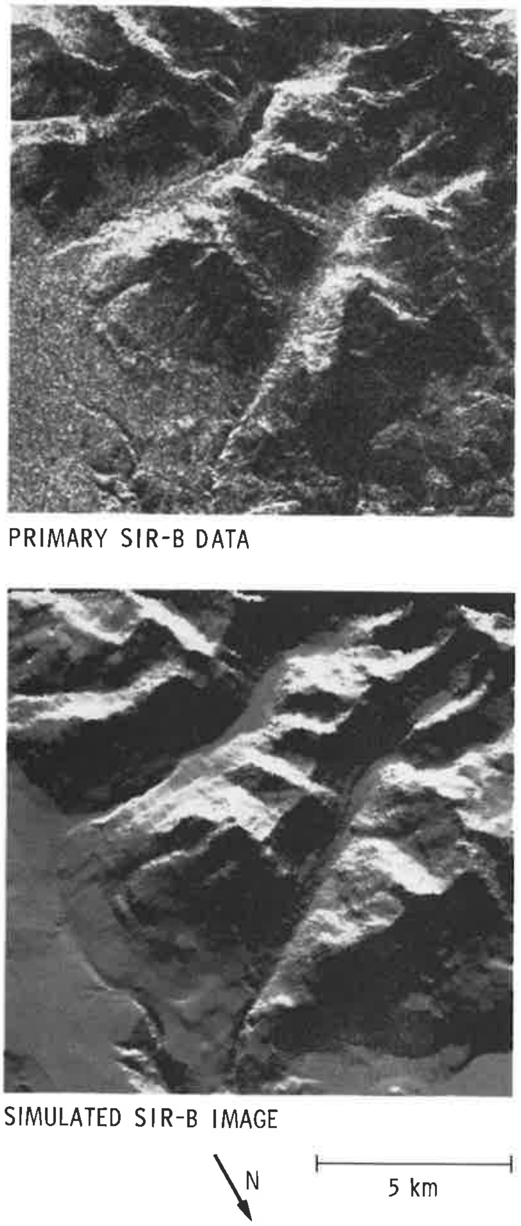

Fig. 4. SIR-B image segment and segment of a simulated image. Simulation is based on a geometric and radiometric model that first computes image brightnesses associated with each DEM-cell, and then computes the DEM-position that belongs to a specific image pixel (simulation algorithms; Domik, [4]).

in Fig. 4, one can find conjugate features in the real and simulated images, essentially taking advantage of the boundary lines between bright and dark slope areas. Available image processing functions (e.g., zoom, grey value enhancement) support the identification of homologue points. In the area shown in Fig. 4, which represents a quarter of the whole scene, approximately 15 points could be easily identified. As a result of the two steps, one now has a dense distribution of ground control points in flatter terrain, and a dense distribution of auxiliary match points in mountainous terrain.

The actual geometric rectification is also in two steps:

1) first the conjugate point features are used to *warp* the radar image so that it fits the simulated image mate;
2) secondly, the real image grey tone encountered at each pixel location of the simulated image can now be simply *resampled* at the address for the rectified image.

Warping is defined as a polynomial fit function and needed if the simulated and real images do not match. A mismatch must be expected in mountainous areas due to the previous absence of identifiable ground control points in the resection-in-space. In flat areas a mismatch would be present if the resection-in-space was unable to remove it due to poor quality control or due to image deformations that cannot be modeled by refining the scanner path and antenna velocity vectors.

Resampling in the second rectification step is defined as a mapping function where elevation at each point is accounted for. This is a straightforward process, as the relation between elevation model and image grey values has been established during the simulation and successive warping.

Fig. 5 shows an uncorrected, warped, and rectified image. After the warp, real and synthetic images match. After rectification the image matches the map. An obvious limitation to the quality of the rectified image exists in areas of excessive slope compression (i.e., *foreshortening*) or in the event of an image layover. A rectified image must present a slope on a larger area than the unrectified original. Therefore, some few input pixels may have to be used to fill a larger number of output pixels. This can lead to *streaky* output areas since the input image is stretched in range direction (compare Fig. 6).

The DEM permits one to quantify the degree to which a radar image will exhibit layover, foreshortening, and image shadows. Table I presents, for the four SIR-B images and the test area of Cordòn la Grasa, a quantitative description of these factors.

Both the warping and rectification are done through nearest neighbor resampling since their simplicity conserves computing efforts.

If multiple images need to be rectified and matched to one another, one might need to resort to a specific sequence of events: one will first rectify a master image to the map as described before. However, subsequent images may need to use more *ground control points* than just those available for the master image. Therefore, additional ground features are measured from the rectified master and subsequent images to enforce a match irrespective of the identifiability of map points. One may well expect that identification of conjugate points is easier between two radar images than it is between image and map.

The flight direction for overlapping images may vary by several degrees. This can lead, in mountainous areas, to differences in illumination and significant differences between the transition from bright to dark on topographic features. Variations in flight direction and look-angles off nadir have been experienced as pertubation factors in identifying matchpoints.

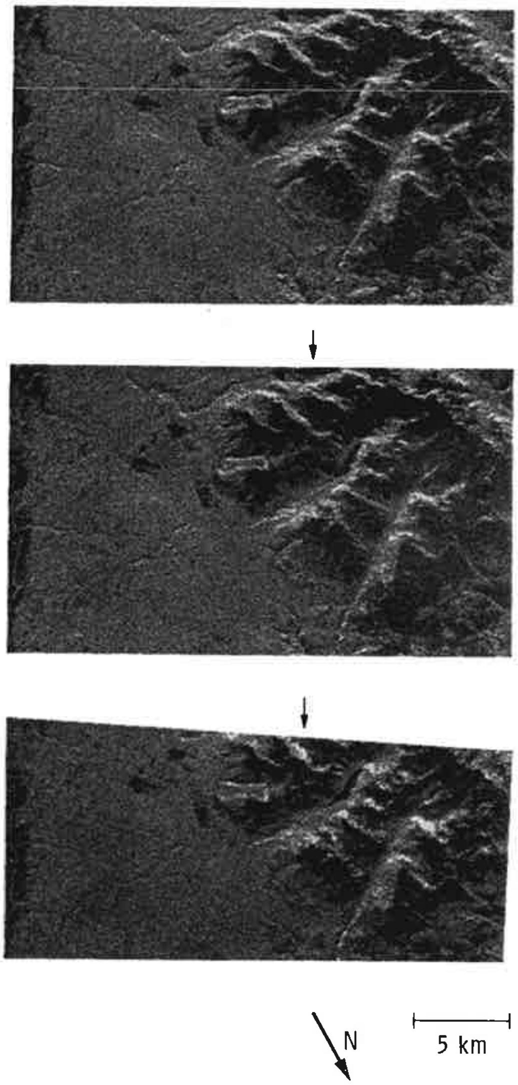

Fig. 5. Image segment in unprocessed form (top), warped with the help of ground control points (middle), and rectified (bottom).

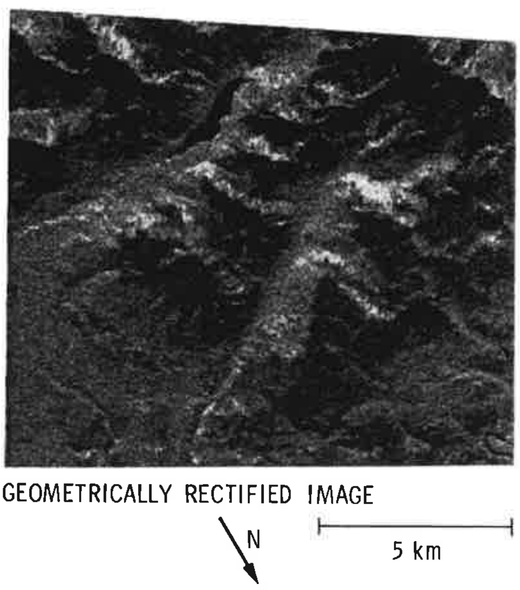

Fig. 6. A compressed slope ("foreshortened") must be stretched into a larger area on the rectified image, potentially leading to poorer image contents.

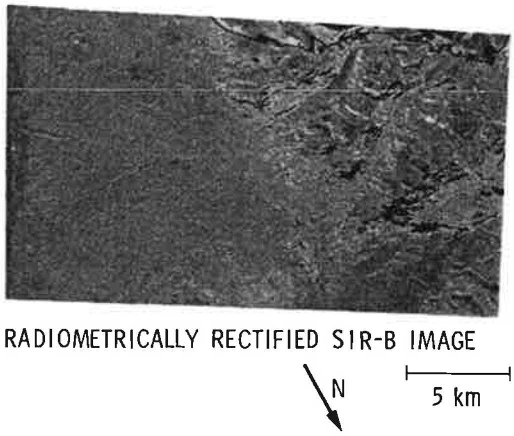

Fig. 7. Segment of a geometrically rectified SIR-B image and its radiometric correction.

TABLE I
SIR-B IMAGES OF CORDÒN LA GRASA AND THE AMOUNT OF IMAGE DISTORTIONS, EXPRESSED AS PERCENTAGE OF PIXELS AFFECTED

DATA TAKE	104.4	88.4	72.4	56.4
CENTER INCIDENCE (°)	59.4	53.7	44.7	33.0
FLIGHT ALTITUDE (km)	233.3	233.6	234.1	233.6
LAYOVER (%)	0.07	0.08	0.14	0.6
FORESHORTENING (%)	12.0	16.1	23.1	34.5
SHADOW (%)	2.4	1.0	0.2	0.1

IV. Radiometric Rectification

Once a geometric relationship has been established between the pixels of a radar image and the height values of a DEM one has the means to create a new radar image where the image grey values are modified: radiometric rectification consists of the computation of a difference image between real radar brightness and those from the simulation. The histogram of difference values needs to be redistributed to obtain a visually meaningful output image, for example, shifting the 0-density number (DN) to 128 and stretching the range of differences over the entire output DN range from 0 to 255.

Fig. 7 presents an example of a radiometrically rectified radar image. One notes the reduction in contrast where the slope-induced brightness variations are eliminated. Effects due to micro-relief cannot be eliminated since the DEM is not sufficiently detailed to include such relief.

V. Other Secondary Radar Image Products

The match between a DEM and set of overlapping radar images permits one to create a number of additional outputs. Table II lists and comments on such potential tools for subsequent thematic image analysis. The applicability of some of these proposed products may vary from purely a presentation of analysis results (see items 9 to 11) to an actual tool in an analysis (see in particular items 2, 5, and 6).

A discussion of the applicability is beyond the scope of this contribution but is reserved for a separate companion

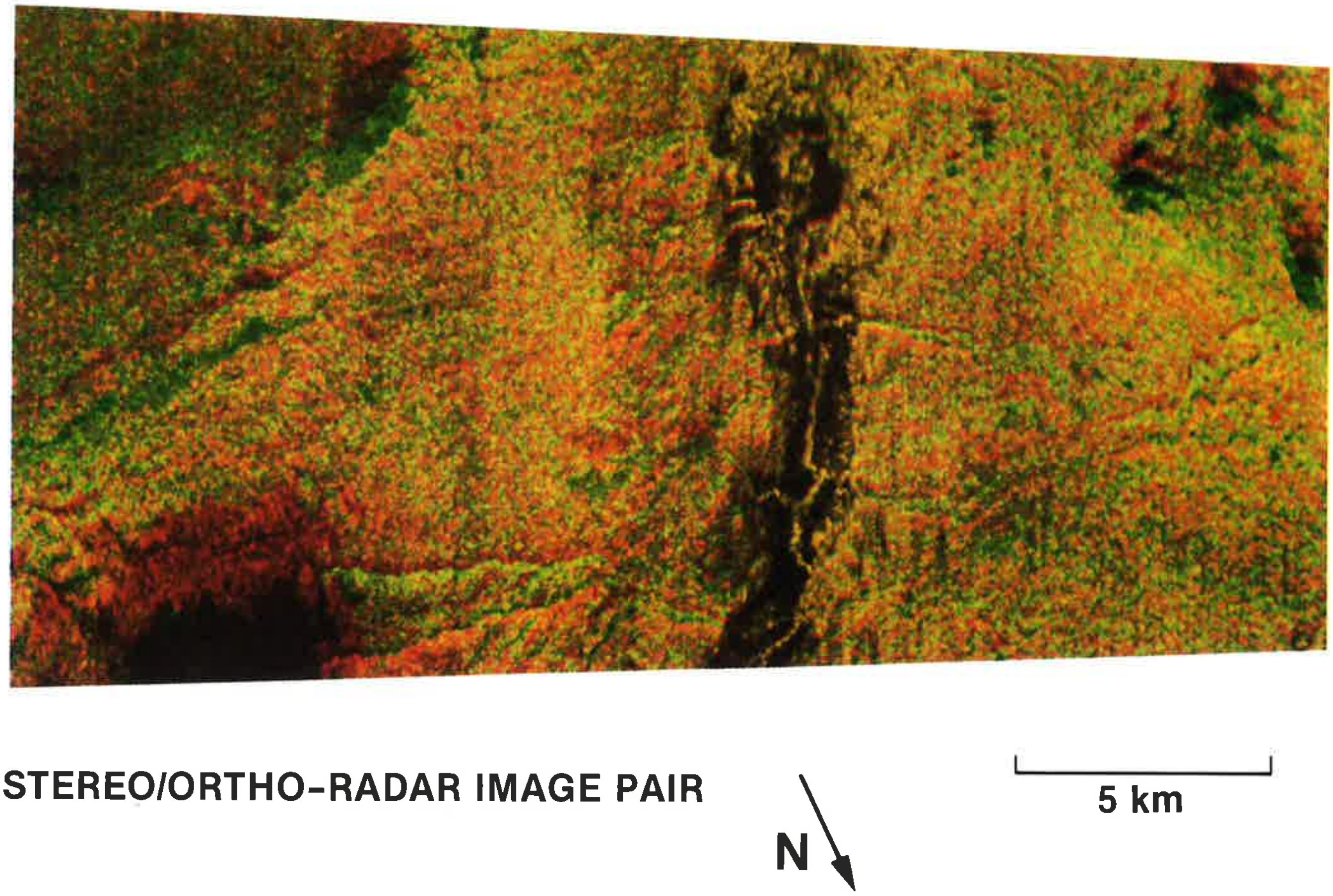

Fig. 8. Example of a stereo ortho-radar-image pair: green image is presented in a map geometry, the red one is intentionally deformed to introduce relief displacement. The two images therefore form stereoscopic parallaxes.

TABLE II
TYPES OF SECONDARY RADAR IMAGE PRODUCTS BASED ON MULTIPLE RADAR IMAGES AND DIGITAL ELEVATION MODEL (DEM)

Type of Product	Comment
1. Ortho-Image	Geometrically rectified black and white image to fit a map.
2. False color from multiple ortho-images.	Use three geometrically matched ortho-images.
3. Simulated radar image	Use of DEM to predict the geometry and radiometry of a radar image, based only on terrain slope and assumed backscatter of surface cover.
4. Radiometrically rectified image	Difference image between simulated and real radar images.
5. False color from multiple radiometrically corrected images.	Use three radiometrically corrected images.
6. Stereo-ortho images from one single image	Create an image pair of which one is geometrically corrected (see 1.), the other is the same radar image but has artificially introduced relief-displacement (so-called "stereo-mate").
7. Stereo-ortho images from two source images.	As in item 6, but the "stereo-mate" is produced from a second overlapping radar image.
8. Composite radar image and DEM	Radar image brightnesses are added to an artificially illuminated DEM to present the relief in conjunction with the radar image.
9. Topographic radar image map	Composite of an ortho-image, contour lines and planimetric detail (roads, settlements, names, legend, coordinate grid etc.).
10. Thematic radar image map	Composite of an ortho-image and planimetric detail from a thematic map.
11. Perspective view of DEM and image density numbers	Same as item 8., but presented as a perspective camera image, to further enhance topographic relief.

paper [1]. It is in this paper that false color image composites are analyzed. Of interest in the current context may be the creation of stereo-ortho images and of a perspective view of topographic relief using three different incidence angle data sets to represent color.

Fig. 8 illustrates a stereo-ortho-image: the concept has been proposed in photogrammetry by Collins [2] and has since found a modest niche in certain applications. The main point of a stereo ortho-image is that one of the two images is geometrically correct. Therefore an interpreter can create an interpretation manuscript on a transparent overlay directly in the map geometry while looking at a stereo-image pair with the help of a simple stereoscope; one thereby avoids complex photogrammetric machinery.

An additional set of advantages is obtained with radar images; that advantage may not be of relevance with photogrammetric data:

1) the stereo ortho-image pair provides vertical exaggeration of the stereo model as desired for optimum viewing;
2) if only a single image were available with a DEM, it is an effective means to support the interpreter with a composite presentation of both the terrain shape and the single radar image.

For a condensed presentation of analysis results and of a composite of several images with a DEM, one may employ a perspective view (item 11 of Table II). The mathematical transformation is a standard tool of computer graphics, simply projecting each point of the DEM via an assumed conversion principal point onto a film plane as shown on the cover of this issue. The figure is therefore only a geometric transformation of the DEM with a false color composite of three radar images.

VI. Conclusion

The digital format of current radar images and terrain data permits one to experiment with new auxiliary image products. This paper reviewed methods to match digital elevation models and radar images, and to create various derived image products from the resulting composite data set. Geometrically and radiometrically rectified radar images and stereo-ortho image pairs may well become useful standard tools for future radar image analysis and thematic interpretations. The use of further secondary products such as false color composites may only be meaningful in an interactive analysis mode with the analyst deciding on various display parameters as work proceeds.

Image maps are already current and accepted standard products of the mapping industry. They are of particular value in featureless areas, and have reached an experimental status with low resolution imagery: examples with Landsat MSS and Thematic Mapper data exist in abundance. It is also standard practice to present reconnaissance-type radar mapping results in the form of image mosaics.

A weakness of currently used radar image rectification methods has been in the dependence on identifiable point features for control purposes. It will be necessary to develop an ability to also employ linear and even areal image features for control. This is certainly a more universal requirement than just for radar images: it may apply to other images of modest resolution as well.

References

[1] J. B. Cimino, A. Brandani, D. Casey, J. Rabassa, and S. Wall, "Multiple incidence angle SIR-B experiment over Argentian: Mapping of forest units," *IEEE Trans. Geosci. Remote Sensing*, this issue, pp. 498–509.

[2] J. Collins, "Stereo-orthophotos," *The Candian Surveyor*, 1969.

[3] G. Domik, M. Kobrick, and F. Leberl, "Analyse von Radarbildern mittels digitaler Hoehenmodelle," *Bildmessung und Luftbildwesen*, vol. 5/84, pp. 249–263, 1984.

[4] G. Domik "Verfahrensentwicklungen zur Analyse von digitalen Seitsicht-Radarbildern gerbirgigen Gelaendes mittels digitaler Hoehenmodelle und Bildsimulation," Ph.D. dissertation, Tech. Univ. Graz, A-8010 Graz, Austria, 1985.

[5] F. Guertin and E. Shaw, "Definition and potential of geocoded satellite imagery products," *Photogrammetr. Eng. Remote Sensing*. vol. 49, pp. 195–199, 1981.

[6] G. Guindon, D. G. Goodenough, and P. M. Teillet, "The role of digital terrain models in the remote sensing of forests," presented at the 7th Int. Symp. Machine Processing Remotely Sensed Data, June 1981.

[7] F. Leberl, G. Domik, J. Raggams, J. B. Cimino, and M. Kobrick, "Multiple incidence angle SIR-B experiment over Argentina: Stereo-radargrammetric analysis," *IEEE Trans. Geosci. Remote Sensing*, this issue, pp. 482–491.

[8] F. Leberl, R. Fuchs, and J. Ford, "A radar image time series," *Int. J. Remote Sensing*, no. 2, pp. 155–183, 1981.

[9] M. Naraghi, W. Stromberg, and M. Daily, "Geometric rectification of radar imagery using digital elevation models," *Photogrammetr. Eng. Remote Sensing*, vol. 49, no. 2, pp. 195–199, 1983.

[10] P. Rebillard and D. Evans, "Analysis of co-registered Landsat, Seasat, and SIR-A images of varied terrain types," *Geophys. Res. Lett.*, vol. 10, pp. 277–280, 1983.

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