Digital Processing of Orbital Radar Data to Enhance Geologic Structure: Examples from the Canadian Shield

Penny M. Masuoka
Image Analysis Section, Science Applications Research (SAR), 4400 Forbes Blvd., Lanham, MD 20706
Jeff Harris
Intera Technologies Ltd., 1525 Carling Ave., Suite 600, Ottawa, Ontario K1Z 8R9, Canada
Paul D. Lowman, Jr., and *Herbert W. Blodget*
Geophysics Branch, Code 622, NASA Goddard Space Flight Center, Greenbelt, MD 20771

ABSTRACT: This paper reports a comparative study of digital image enhancement techniques for synthetic aperture radar (SAR) using SIR-B and Seasat images of the Canadian Shield. The best enhancements for highlighting geological structure were found to be (1) a simple linear contrast stretch, (2) a mean or median low-pass filter to reduce speckle prior to edge enhancement or a *K* nearest-neighbor average to cosmetically reduce speckle, and (3) an edge enhancement technique modified from the Moore-Waltz (1983) techniques. Comparative photointerpretation by three analysts confirmed the initial subjective choices. To compensate for radar azimuth biasing, three look directions were coregistered and various ways of displaying the data were tried. The preferred methods of displaying the data were found to be (1) a black-and-white additive image for displaying two coregistered images, (2) a color composite image for displaying three coregistered images, and (3) a principal components analysis for combining more than three images.

INTRODUCTION

ORBITAL RADAR IMAGERY from Seaset and the Shuttle (Shuttle Imaging Radar, SIR-A, SIR-B) has been used successfully for both structural and lithologic investigations (Ford, 1980; Sabins, 1983), demonstrating the potential value of orbital radar for these and other applications in geology. However, the conditions under which orbital radar must operate, in particular, high altitude (generally over 200 km) and ground tracks fixed by orbital mechanics, can detract from the geologic value of the imagery (Lowman *et al.*, 1987). The high depression angles dictated by orbital altitudes generally preclude acquisition of imagery with the extensive shadows typical of airborne radar, and illumination azimuth biasing may be extreme for low-relief terrains (Lowman *et al.*, 1987). Orbital radar imagery of terrain is a strong function of variations in local incidence angle rather than shadowing, for topographic and structural rendition (Ford, 1980), and tonal variations (a major aid in photointerpretation) are often very subdued. Consequently, image enhancement techniques must frequently be used before effective geologic interpretation is possible. We report here a comparative study and evaluation of different digital processing techniques potentially useful for enhancement of radar imagery.

BACKGROUND

Over the past few years, a number of papers have been written concerning digital processing of radar data for lithologic discrimination (Blom and Daily, 1982; Curlis *et al.*, 1986; Rebillard and Evans, 1983; Daily *et al.*, 1979; Evans and Stromberg, 1983; Frost *et al.*, 1983; Shanmugan *et al.*, 1981; Rebillard and Nguyen, 1982; Blom *et al.*, 1981). Fewer papers have addressed the question of digital processing to enhance geologic structure (Daily, 1983; Eppes and Rouse, 1974; Frost *et al.*, 1983; Hirose and Harris, 1985). The two are often incompatible goals because structure is usually expressed topographically whereas lithologic differences are expressed as differences in roughness which in turn affect the texture and tone on radar images.

Daily (1983) used a hue-saturation-intensity technique to improve the visibility of structural features on a Seasat image. Eppes and Rouse (1974) showed that features off-normal could be enhanced by spatial filtering in the Fourier plane of a single look-direction image. Frost *et al.*, (1983) used an adaptive filter to preserve the edges while reducing radar speckle. Hirose and Harris (1985) compared a number of spatial filters for improving image interpretability. Except for two spatial filters tested by Hirose and Harris (1985), this paper compares commonly available techniques previously untested for enhancing structural detail on radar images.

This paper should be of use to other investigators in several ways: (1) Analysts should find this paper to be useful as a checklist or summary of some of the most readily available algorithms which can be used to enhance structural geology on radar images; (2) suggestions have been included for tailoring some techniques which were previously used for Landsat, to radar data; and (3) analysts may find that the enhancements found to be best here will be equally useful in other areas with similar terrain and vegetation cover or with future radar systems.

The factors considered in the selection of enhancement procedures for this study included image contrast, radar speckle, edge rendition, and illumination azimuth biasing. Contrast and edge enhancement techniques that have been developed for Landsat MSS and TM can often be used for orbital SAR as well. By "contrast" we mean the magnitude of brightness differences in the adjacent portions of the imagery. Optimization of contrast at the expense of fundamental tonal or textural variations must be carefully weighed when enhancing SAR images.

Edge enhancement is often used to bring out geologic structure, especially lineaments, faults, or fractures, because they are essentially physical "edges." Lineaments are straight or slightly curved geomorphic features on imagery that may represent faults, fractures, or fractures filled by dikes (topographically expressed by differential erosion). Other linear features which may appear on imagery, such as foliation and strata, may also benefit from edge enhancement.

Speckle is most easily thought of as the granular noise associated with radar that appears as scattered high and low intensity pixels on the imagery. New procedures have been developed over the last several years for reducing the visual

0099-1112/88/5405–621$02.25/0

effect of speckle in radar images (Frost *et al.*, 1982; Lee, 1983). However, we have not yet implemented these algorithms on our system and, therefore, only the smoothing or averaging type of enhancements were evaluated.

Illumination azimuth biasing is the tendency of linear topographic features, that are nearly perpendicular to the illumination direction, to be highlighted (MacDonald *et al.*, 1969; Reeves, 1969; Siegal and Short, 1977). On the radar imagery used in this investigation, linear features within 20° of being parallel to the illumination direction are practically invisible (Lowman *et al.*, 1987); conversely, those within 20° of normal to the look direction are strongly highlighted (Harris, 1986). Therefore, at least two look directions are mandatory for a complete geologic interpretation. The two looks can be interpreted separately or registered and digitally combined into one image before interpretation. Registration is a time-consuming but often necessary procedure. For accurate interpretation of non-linear geologic structures such as folds or domes, all topographic features must be equally well displayed regardless of orientation. (Eppes (1974) suggests spatial filtering in the Fourier plane of a single look-direction image as an alternative to using multiple looks. This method was not tested for this paper.) This paper will consider several methods of combining two or more look directions from coregistered data sets.

GEOLOGY OF THE STUDY AREAS

Figure 1 shows the location of the two Canadian Shield study areas discussed in this paper and Table 1 lists the SIR-B and Seasat SAR imagery used. Because of the prominent and abundant lineaments which occur in several discrete orientations, the Mackenzie Dike Swarm image was selected for testing contrast enhancements, speckle reduction algorithms, and edge enhancements. The Mazinaw Lake area, aside from being a primary test site for the SIR-B study (Lowman *et al.*, 1987), was selected for inclusion in this investigation because there is overlapping coverage for the area, with one SIR-B scene and two Seasat scenes with different illumination directions.

MACKENZIE DIKE SWARM AREA

Figure 2 shows the Seasat scene from which the Mackenzie Dike Swarm 512- by 512-pixel (11-km by 11-km) test site was

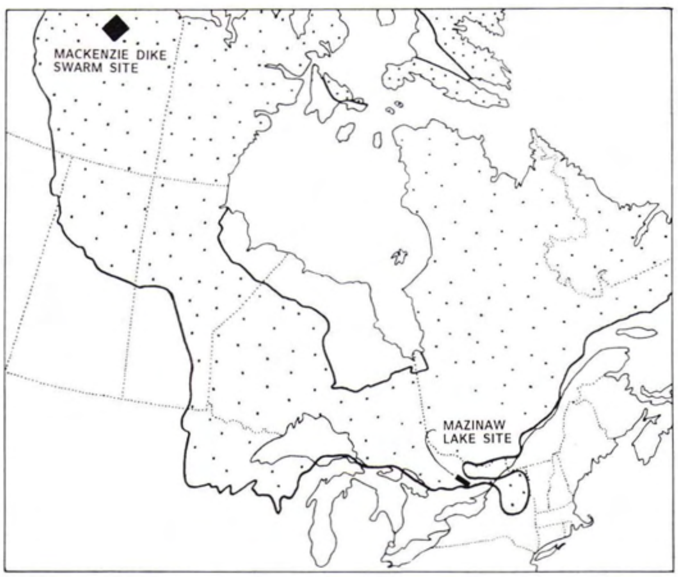


FIG. 1. Location of the Canadian Shield test sites.

TABLE 1. COMPARISON OF IMAGERY USED FOR THIS PROJECT

	SIR-B Data Take AO85.2 Scene 3	Seasat Rev. 1261	Seasat Rev. 263	Seasat Rev. 780
Area	Mazinaw Lake	Mazinaw Lake	Mazinaw Lake	MacKenzie Dike Swarm Area
Pixel size (m)	12.5	16 (azimuth) × 18 (range)	16×18	16×18
Spatial resolution (m)	40	25×25 (4 look)	25×25 (4 look)	25×25 (4 look)
Swath width (km)	25	100	100	100
S/C altitude (km)	225	795	795	795
Incidence angle (degrees)	34.4	23.2 ± 3	23.2 ± 3	23.2 ± 3
Look direction	N50°E	N66°W	N60°E	N40°E

taken. The area, centered on 66° 30′ N, 110°W, is nearly treeless tundra just west of Bathurst Inlet in the Northwest Territories. The terrain is characterized by low relief, much bare rock, thin soil, and glacial features such as the eskers (sinuous ridges) running across the center of the picture. Geologically, the area is in the extreme northern part of the Slave Province, an area of Archean rock similar in dominant age (2,500 million years) to the Superior Province. The region covered by the Seasat scene is underlain by mafic and silicic metavolcanics of the Yellowknife Supergroup, surrounded by Archean granites and granodiorites (Kusky *et al.*, 1986). Early Proterzoic sediments cover the eastern corner of the area, obscuring the lineaments and causing the smoother topography in that area. The prominent lineaments are diabase dikes of the Mackenzie Dike Swarm, intruded about 1220 million years ago, or fracture zones expressed by differential erosion (Lowman *et al.*, in press).

MAZINAW LAKE AREA

The Mazinaw Lake area is a part of the Laurentian Highlands, a glaciated peneplain with local relief of about 300 metres from southeast to northwest. It is covered by mixed deciduous and evergreen forest. Bedrock and talus are exposed in approximately 10 percent of the area. The northeast side of Mazinaw Lake is a steep cliff about 50-m high, which is nearly orthogonal to the look direction, thus producing a bright radar return (Figure 3). The dark line trending northeast just east of Mazinaw Lake is a grassy power line clearing which is a smooth surface at L-band wavelength. Powerlines are not visible on the image because they parallel the radar look direction.

The Mazinaw Lake area is in the Central Metasedimentary Belt of the Grenville Province (Wynne-Edwards, 1972). Geologic structure here is dominated by northeast-trending folds (nearly invisible because they are parallel to the look direction) in high-grade metamorphic rocks, chiefly metasediments, interrupted by diapiric intrusions of granite and tonalite gneiss. The cliff forming the northeast side of Mazinaw Lake is a normal fault scarp cutting across local foliation trends, with Mazinaw Lake occupying the down-thrown side.

PROCESSING METHODS

Processing for the Mackenzie Dike Swarm scene was done on a VAX 11/780 computer using the Land Analysis System (LAS) (NASA Goddard Space Flight Center, 1986) or System 575 image processing software package (International Imaging Sys-

FIG. 2. Seasat Rev. 780 showing the location of the MacKenzie Dike Swarm test site. The entire scene falls within the Slave geological province. Lineaments are due to major fractures and dikes across the area.

tems, 1984). Output images were written to digital tape and an Optronics film recorder (Model 4300) was used to make photographic images.

The coregistered Mazinaw Lake images shown in this paper were processed using an Interactive Digital Image Manipulation System (IDIMS) on an HP3000 computer or a VAX-based Dipix Aries III system.

PHOTOINTERPRETATION METHODS

After all processing was completed, photographic prints of each enhancement were studied by three experienced photointerpreters. In addition, one of the three studied the enhancements interactively on a display screen. Comments made by the photointerpreters are used for comparison purposes in the tables and text which follow.

After the subjective comments were made, the three photointerpreters were given the prints again and asked to draw lineament overlays for each print. O'Leary *et al.* (1976) defined lineament as "a mappable, simple or composite feature, whose parts are aligned in a rectilinear or slightly curvilinear relationship and which differs distinctly from the patterns of adjacent features and presumably reflects a subsurface phenomenon." Some references describing how photointerpreters use radar

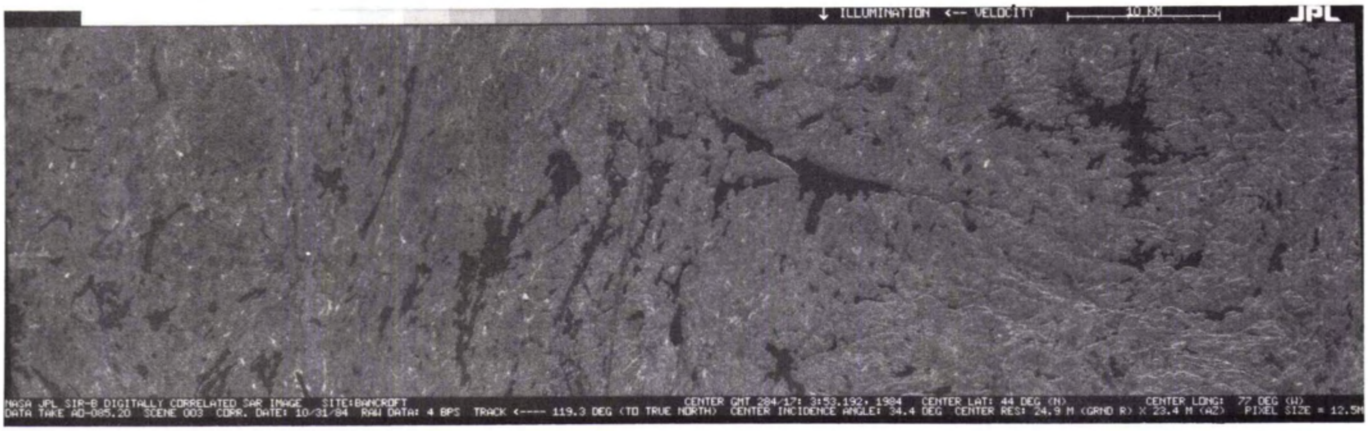


FIG. 3. SIR-B data take A085.2 scene 3 showing the Mazinaw Lake test site. Mazinaw Lake is the large lake slightly right of center.

imagery for mapping lineaments and other geologic structures are Grant and Cluff (1976), Wing *et al.* (1970), Ford (1980), and Gold (1980).

Besides using the O'Leary *et al.* (1976) definition of a lineament, the photointerpreters used the following set of guidelines written specifically for these images in an attempt to keep the photointerpretations as uniform as possible: (1) Lineaments can be black, white, or subtle alignments of gray in the background; (2) lineaments less than 1/2-inch long should not be mapped; (3) line segments separated by less than 1/4 inch can be connected to form one continuous lineament; and (4) To reduce the learning effect of carry-over of information from previously-mapped scenes, the entire set of images should be mapped twice in the same order.

The numbers and lengths of the lineaments were tabulated as shown in Table 2.

RESULTS

CONTRAST ENHANCEMENTS

Contrast enhancements listed in Tables 2 and 3 are in wide use and should be familiar to most image analysts. Differences between contrast-enhanced images are subtle, and selecting the "best" enhancement is a subjective task (analyst, data, and site dependent). Factors influencing the enhancement quality include the shape of the image histogram (the frequency distribution of pixels at gray levels from 0 to 255), the specific features to be enhanced (folds, faults, or lithology), the sensor (Seasat or SIR-B), and the hardware being used to generate the image. Because contrast enhancements are relatively quick and inexpensive to apply, and results are affected by a wide variety of subjective variables, experimentation with several different enhancements for each scene is essential.

For the Canadian Shield radar data, a simple linear contrast stretch (the program TLM or SCALE) was found to be most effective in the photointerpreters' subjective study (Figures 4a and 4b). Both TLM (trackball linear mapping) and SCALE perform a linear stretch of image values between two breakpoints, but TLM is interactive so that results can be seen immediately. Because they both perform the same function, the same enhancement could be made by either program; however, for this project two slightly different enhancements were made. Two of the photointerpreters preferred the TLM image because more background detail was retained although it had less contrast. One photointerpreter preferred the scaled image because of the greater contrast it provided.

Of the three enhancements used in the lineament mapping experiment (Table 2), SCALE performed slightly better than TLM. However, the difference in the average total number of lineaments was only one lineament and is probably due to photointerpreter variation rather than any significant difference in the image enhancement.

SPECKLE REDUCTION ALGORITHMS

The speckle reduction programs tested are listed in Tables 2 and 4, and two images processed to reduce speckle are shown in Figure 4c and 4d. All of these programs were run on the original image data, and the image was then scaled using a 2.5 percent clipping factor at both ends of the histogram. The imagery used in this study was 4-look imagery so that some of the speckle in the original 1-look imagery had already been reduced by the multi-looking process. (See Hirose and Harris (1985), Tomiyasu (1983), and Ford (1982) for more information on multi-looking and its effect on speckle.)

The LOWCAL programs are sliding window local operation processes that work on a user specified size window, usually 3 by 3, 5 by 5, or 7 by 7 pixels. The gray level of the center pixel of the window is replaced by the value obtained by a user-selected function, such as the average of all the pixels. The window is then shifted by one pixel and the process is repeated for the entire image. The following descriptions of the window functions that were used were taken from the LAS User's Manual (NASA Goddard Space Flight Center, 1986).

> *Mean Window* – The center pixel is replaced by the mean of all pixels within the window.
> *Median Window* – The center in the window is replaced by the median of all pixels in the window.
> *K Nearest Neighbor Average* – The center pixel is replaced by the gray level of the average of a user-specified number of neighbor pixles, excluding the center pixel, whose gray levels are closest (in value) to that of the center pixel.
> *Selective Average* – The center pixel in the window is replaced by the average gray level of all neighbors, excluding the center pixel, provided that at least a user-specified number of neighbors have gray level values that differ (in absolute value) from the center pixel by an amount greater than or equal to a user-specified threshold value.

The last routine (CWTGEN-BOX, CONVOLVE) listed in Table 3 is a spatial domain convolution filtering program (CONVOLVE) that uses a weight function (or filter) generated by CWTGEN. In a convolution filtering program, pixels in a window area the size of the filter are multiplied by the corresponding values (weights) in the filter, and the sum of these values replaces the center pixel. When using the CWTGEN-BOX option to generate the convolution filter, the box filter is filled with ones and, when

TABLE 2. A COMPARISON OF ENHANCEMENTS THROUGH PHOTOINTERPRETATION RESULTS

Enhancement	Number of lineaments mapped: User 1	User 2	User 3	Average of all 3	Total length of lineaments mapped by 2 or more users (mm)	Percent of longest total length
Contrast						
Scale	19	18	28	21	640	97
Trackball linear mapping (TLM)	18	16	25	20	587	89
Wallis	15	11	28	18	542	82
Speckle Reduction						
Selective average	21	14	26	20	659	100
Mean filter	19	20	27	22	592	90
K nearest neighbor	20	16	22	19	589	89
Median filter	20	15	21	19	557	85
Box filter	22	17	23	21	513	78
Edge Enhancement						
Laplacian difference	22	18	21	20	650	98
Moore-Waltz (final step)	26	14	24	21	579	88
Compass	20	13	22	18	521	79
Roberts	13	11	27	17	463	70
Edgepix	11	10	22	14	406	62
Difference method	16	13	17	15	392	59
Laplacian filter	12	6	14	11	302	46
Moore-Waltz intermediate step (lines only)	15	8	11	11	286	43
Sobel	5	10	28	14	266	40

TABLE 3. CONTRAST ENHANCEMENT ALGORITHMS TESTED ON CANADIAN SHIELD RADAR DATA

Program name	Program source*	Description	Photointerpreters' comments
TLM	S575	"Track Ball Linear Mapping," a linear contrast stretch	Considered the best contrast enhancement by two photointerpreters. Less contrast than SCALE so that background detail shows well.
LOGARITHM	S575	A logarithmic shaped intensity mapping	Not useful for our radar data. Tends to decrease contrast and de-emphasize lineaments.
H'EQUALIZE	S575	Histogram equalization stretch	May be useful for some images. Very high contrast tends to reduce detail.
WALLIS	S575	Space variant contrast stretch	May be useful for some images but tends to emphasize speckle.
SCALE	S575	A linear intensity stretch between two user-specified values	Considered the best contrast enhancement by one of the photointerpreters.

*S575 is System 575 Software (International Imaging Systems, 1984). LAS is Land Analysis System (NASA Goddard Space Flight Center, 1986).

convolved, the image is replaced by the sum of the pixels in a moving window.

For structural geology, there are two purposes behind using speckle reduction algorithms. One is for cosmetic reasons when the image is to be used for photointerpretation. The other is to reduce the noise that might otherwise be falsely identified as edges by an edge enhancement or edge detection algorithm.

For photointerpretation purposes, the K nearest-neighbor (5 by 5) average (LOWCAL-KNN) was preferred of all of the speckle reduction techniques, by all three photointepreters, because the process appeared to reduce some of the speckle without altering the apparent resolution and detail of the image. All of the other programs tested appeared to reduce the speckle to a greater extent but left the image with blurred edges and a loss of fine detail.

For speckle reduction prior to edge enhancement, either a mean (3 by 3) or median (3 by 3) filter was preferred by the three analysts. Although the selective average filter performed well in the mapping experiment (Table 2), bar-like patterns (filter artifacts) on the image make this enhancement unsuitable for use prior to an edge enhancement.

A qualitative comparison of the mean- and median-filtered (both 3 by 3) Seasat images on the interactive video display screen showed that there is a slight difference between the two. The median filtered image is slightly sharper and has slightly more fine detail than the mean filtered image. This difference is not apparent in the digital enhancements of SIR-B imagery of Mazinaw Lake. This is a surprising result since Blom and Daily (1982) found a median filter to be significantly better than a mean filter for retaining boundaries, edges, and apparent

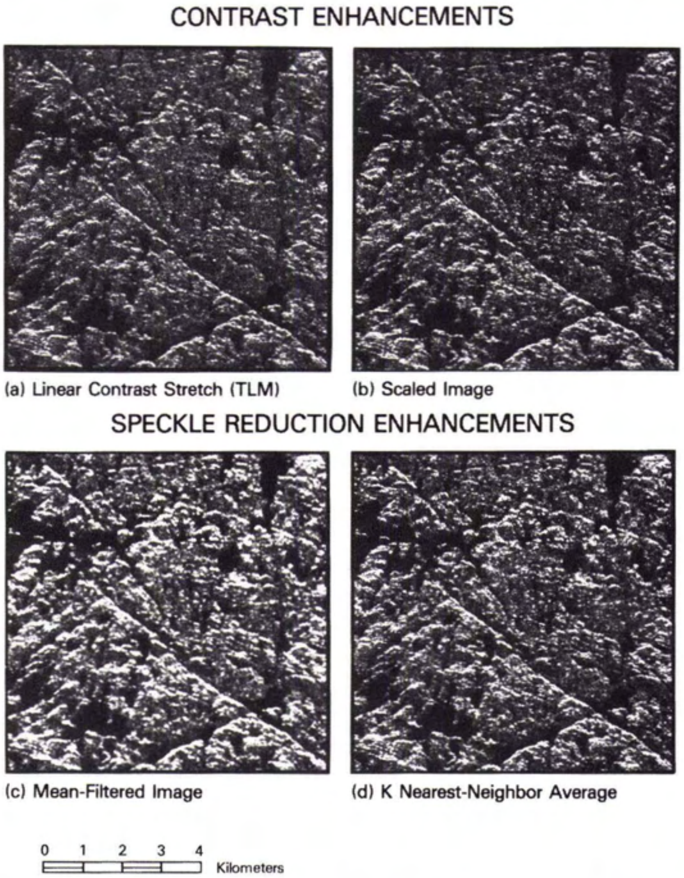


FIG. 4. Contrast and speckle reduced Seasat imagery of the MacKenzie Dike Swarm test site. (a) Linear contrast stretch. (b) Scaled image with 2.5 percent of the values clipped from both ends of the histogram. (c) Mean-filtered image with a 3 by 3 pixel window. (d) K nearest-neighbor average with a 5 by 5 pixel window.

resolution in a Seasat image of the Imperial Valley, California. However, Hirose and Harris (1985) demonstrated that the performance of a filter depends on the target. They note: "when the [median] filter size exceeds the dimensions of the underlying target, its structure is lost since the median value is highly influenced by the larger contribution from the background pixel intensities." Thus, the poor performance of the median filter for the Canadian Shield sites may be due to small targets (lineaments) compared to the agricultural fields studied by Blom and Daily in California. Like the contrast enhancements, it may be necessary to experiment with several filters for each scene.

EDGE ENHANCEMENTS

A variety of edge enhancement procedures were tested on the Mackenzie Dike Swarm image. These are all listed in Tables 2 and 5 and some selected edge enhancements are shown in Figures 5 and 6.

The Moore-Waltz enhancement (Figure 5) is a five-step procedure that was originally developed to enhance lineaments in Landsat data (Moore and Waltz, 1983). The five steps are

(1) generate a low-pass (mean-filtered, 3 by 3 filter size) image;
(2) use a convolution algorithm to derive directional components;
(3) smooth directional components image with a mean (low pass) filter;
(4) extract the prominent line segments (Image brightness distribution is first scaled into a 0 to 255 range. A cumulative histogram is run on the image and all but the highest and lowest 10 to 15 percent of the values are converted to a middle gray value of 128); and
(5) add directional components of step 4 to the original scaled image.

We found the procedure to be effective for the Canadian Shield radar data with one modification in step 2. The Prewitt edge filters shown in Figure 7 were found to be much more effective for enhancing the edges of orbital radar than the filters used by Moore and Waltz for Landsat data. Although there was no apparent difference in using a mean or a median filter prior to the edge enhancement of the Mackenzie Dike Swarm test site, for other areas a median filter may retain more edges.

The "difference method" edge enhancement (Spatial Data Systems, Inc., 1975) (Figure 6a) was performed by shifting the original image horizontally and vertically by one pixel using a copy program and then subtracting the two images. This method was found to give a similar but less useful image than the Prewitt edge filters.

The EDGEPIX program was developed at NASA Johnson Space Center to pick out the edges of agricultural fields using the edge enhancement algorithm given by Moik (1980). Edges are assigned a pixel-brightness value of 255 (white) and non-edges are black (or 0) (Figure 6b). The program may be of value when used in conjunction with other images but two of the photointerpreters who were shown this image found the lack of non-edge information disturbing. It was felt that the textural information not retained by EDGEPIX was important in providing information about the underlying lithology and vegetation and, therefore, assisted in the photointerpretation of the structure.

TABLE 4. SPECKLE REDUCTION ALGORITHMS TESTED ON CANADIAN SHIELD RADAR DATA

Program name	Program source*	Description	Photointerpreters' comments
LOWCAL-MEAN	LAS	Sliding window operation, mean window (3 by 3 pixel window).	Some blurring and loss of fine detail but reduces speckle well. Good for reducing speckle prior to edge enhancement.
LOWCAL-MEDIAN	LAS	Sliding window operation, median window (3 by 3).	Similar to LOWCAL-MEAN but retains a slightly sharper image in some cases.
LOWCAL-KNN	LAS	K nearest-neighbor average (5 by 5).	Best of the speckle reduction methods for photointerpretation. Reduces some speckle but retains fine detail more than other techniques. A 5 by 5 size filter was preferred over a 3 by 3.
LOWCAL-SELECT	LAS	Selective average (3 by 3).	Looks similar to LOWCAL-MEAN. Reduces fine detail and blurs edges. Has a bar-like pattern in the background.
CWTGEN-BOX CONVOLVE	LAS	Box filter (3 by 3).	Similar to LOWCAL-MEAN. Does not show detail well. May be useful to reduce speckle prior to edge enhancement.

*LAS is Land Analysis System (NASA Goddard Space Flight Center, 1986).

TABLE 5. EDGE ENHANCEMENT ALGORITHMS TESTED ON CANADIAN SHIELD RADAR DATA

Program name	Program source*	Description	Photointerpreters' comments
COMPASS	S557	A convolution using a Prewitt edge mask.	Useful for enhancing edges in one direction. (Direction depends on the selection of edge mask.)
Modified More-Waltz (1983) directional enhancement	various	Five step procedure using a Prewitt edge mask (Fig. 7) in a convolution program to extract lines then adding lines back to original image. (North filter was used here.)	Useful enhancement. Brings out some subtle lineaments nearly normal to illumination and some nearly parallel to illumination. Reduces contrast of background area between lineaments.
ROBERTS	S575	An edge enhancement based on the gradient vector of the image.	Not effective for our radar data. Reduces number of linear features in our data.
SOBEL	S575	An edge enhancement based on the gradient vector of the image.	Not effective for topographic lineament enhancement. However, greatly enhances roughness contrasts, i.e., bodies of water.
COPY, ADDPIC	LAS	Image is shifted vertically and horizonally by one pixel and then subtracted from original image. (Difference method).	Looks similar to COMPASS but not as effective; retains less topographic information.
CWTGEN-DIFF, CONVOLVE	LAS	Laplacian difference filter	Highlights lineaments very well. However, image shows many distracting bar-like patterns (filter artifacts), which tend to obscure fine detail.
CWTGEN-LAPLACE, CONVOLVE	LAS	Laplacian filter.	Not effective for our radar data. Suppresses all but the most prominent lineaments. Most detail is lost.
EDGEPIX	JSC	An edge detection algorithm.	May be slightly useful for some areas. Because it is an edge detection program, only edge information is retained. Mostly high contrast edges are detected.

*S575 is System 575 Software (International Imaging Systems, 1984). LAS is Land Analysis System (NASA Goddard Space Flight Center, 1986). JSC is Johnson Space Center.

The remaining programs in Table 4 and displayed in Figure 6c and 6d are all based on some type of convolution algorithm (as discussed previously in the speckle reduction section.)

Of the various edge enhancement procedures tested, the Moore-Waltz (final step) images were preferred by two of the three photointerpreters for structural geologic mapping. The other photointerpreter preferred the K nearest-neighbor average, discussed in the speckle reduction section, over any of the edge enhancements.

Results of the lineament mapping experiment (Table 2) agree with the subjective comments of the photointerpreters (Table 5). Table 2 shows that some of the edge enhancements actually reduced the total length of mappable lineaments by more than 50 percent. The top two enhancements in the lineament mapping experiment (Table 2) were also noted as enhancing the lineaments well in the subjective comments (Table 5). However, in Table 5, the Laplacian difference filter was noted as having bar-like patterns in the image (filter artifacts) that tend to obscure fine detail. Although these bar-like patterns obviously did not affect the ability of the photointerpreters to map major lineaments, they may affect the photointerpretation of other, more subtle geologic structures or lithologies and, therefore, the Moore-Waltz enhancement is preferred. In addition, only one direction of the Moore-Waltz procedure was tested, and additional directional enhancements would undoubtedly increase the number of mappable lineaments.

No attempt was made to determine the geologic significance of the individual lineaments mapped on the images and whether the "important" lineaments could be detected. A comparison of the original and the enhanced images shows that the most prominent lineaments in the original image are retained by even the poorest enhancement. Field experience in other parts of the Canadian Shield has dramatically proven to us that whether or not a lineament is prominent or even visible on a radar image depends on the amount of differential erosion rather than the geological significance of the feature. For example, the Grenville front, a major thrust fault which is the boundary between two geologic provinces, is not visible on SIR-B imagery because of the mylonitization along the fault zone which has caused the fault to be equally impervious to erosion as the surrounding rock units. Therefore, we believe that it is important to map the more subtle lineaments as well as the prominent ones, and an edge enhancement that highlights subtle features as well as prominent ones (such as the Moore-Waltz enhancement) is the "best" enhancement.

METHODS FOR DISPLAYING COREGISTERED DATA

Coregistered data sets can be combined in several ways; for example, (1) by assigning each image a different color and displaying them simultaneously; (2) by adding, subtracting, ratioing, or multiplying two images to get one black-and-white image; (3) by running a principal components analysis; (4) and by using an intensity-hue-saturation (IHS) method (not tried for this study) (Blom and Daily, 1982).

Three orbital radar data sets of Mazinaw Lake were coregistered (Table 1 and Figure 8). Because the Mazinaw Lake area is relatively flat, coregistration was performed successfully by using control points common to the images followed by a geometric correction based on a polynomial fit to the control points. For areas with more relief, it may be necessary to use digital elevation data to obtain an accurate coregistration, as described by Naraghi *et al.* (1983).

Two of the three coregistered images, the SIR-B and Seasat Rev. 263, have nearly the same radar look direction (N50 E and N60 E). The other image, Seasat Rev.1261, has a look direction of N66 W, nearly orthogonal to the other two. Various methods of combining two-and three-look direction data were compared in order to determine which method effectively reduced radar azimuth bias while retaining photogeologic detail.

Various color combinations of the registered data (not

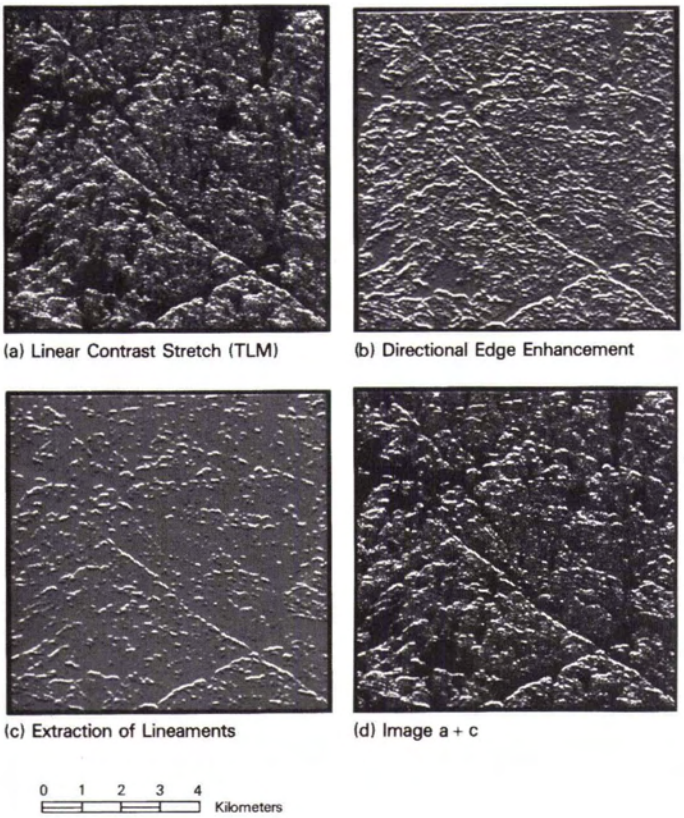


FIG. 5. Steps in the modified Moore and Waltz (1983) directional enhancement. (a) Original image with a linear contrast stretch. (b) Edge enhanced image made by generating a low-pass image (mean-filtered image) to reduce speckle and then using a convolution algorithm with a "north" Prewitt edge mask. (c) Further edge enhancement by using a low pass filter (mean filter) on image (b) and then extracting the trail of the histogram (the brightest and darkest areas). (d) Addition of images (a) and (c).

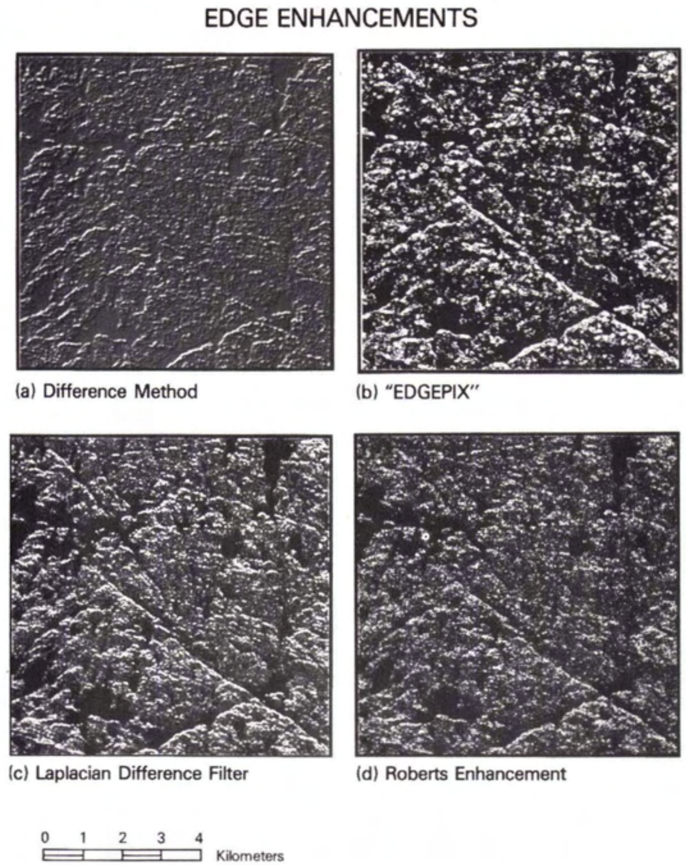


FIG. 6. Edge enhancements of the MacKenzie Dike Swarm area. (a) Difference method of edge enhancement. (b) Image output from EDGEPIX an edge detection program. (c) Laplacian difference-filtered image. (d) A Roberts edge-enhanced image.

1 1 1 1 -2 1 -1 -1 -1	1 1 1 -1 -2 1 -1 -1 1	-1 1 1 -1 -2 1 -1 1 1	-1 -1 1 -1 -2 1 1 1 1
North	Northeast	East	Southeast
-1 -1 -1 1 -2 1 1 1 1	1 -1 -1 1 -2 -1 1 1 1	1 1 -1 1 -2 -1 1 1 -1	1 1 1 1 -2 -1 1 -1 -1
South	Southwest	West	Northwest

FIG. 7. Prewitt edge filters used by the program COMPASS.

reproduced here) were evaluated and found to be effective for combining the information from all three images. For combining only two images, black-and-white additive images were found to retain as much topographic detail as a two-band color composite.

Figure 9 shows a 1024 by 1024 pixel area from Seasat Rev. 1261 and the SIR-B image which includes Mazinaw Lake. The ratio and additive images retain geologic structural information from both of the original images. For example, in the ratio and additive images of Figure 9c and d, the relatively straight southeastern shore of Mazinaw Lake is retained from the SIR-B image and the northeast-southwest trending ridges are retained from the Seasat image. Lakes on the ratio image are poorly portrayed. Patches of smooth water which have the same pixel values on the original images result in a background gray level on the ratio image (Lowman *et al.*, 1987). Where the water is rough (high intensity pixels) on the Seasat image, a division by the lower pixel value SIR-B image gives a bright (higher value) patch. Because some lakes disappeared on the ratio image, the additive image is the preferred product for photointerpretation.

Bryan (1982), using Seasat imagery of an urban area, found that a "difference image" from two different look directions highlights those features that are direction sensitive. Similar results were obtained using coregistered SIR-B and Seasat images of Mazinaw Lake (Figure 10). Although the difference images in Figure 10 are not optimal for photointerpretation (because of the "loss" of the lakes), the images do illustrate azimuth bias and the information added by using nearly orthogonal look directions. In Figure 10a, where the look directions are almost the same, there is almost no residual pattern after subtracting the two images because the two images are so similar. In both Figures 10b and 10c, the original input images for each had almost orthogonal look directions so that the difference images have retained the topographic detail. Correlation coefficients (pixel by pixel) calculated for the image pairs and listed below confirm this observation. (One equals a perfect correlation. Zero means no correlation.)

SIR-B versus Seasat Rev 263 (almost equal look directions) = 0.8
Seasat Rev 263 versus Seasat Rev 1261 (different look directions) = 0.51
SIR-B versus Seasat Rev 1261 (different look directions) = 0.56

A principal components analysis of the three Mazinaw Lake data sets was done, and the resulting images are shown in Figure 11. The first component contains approximately 74 percent

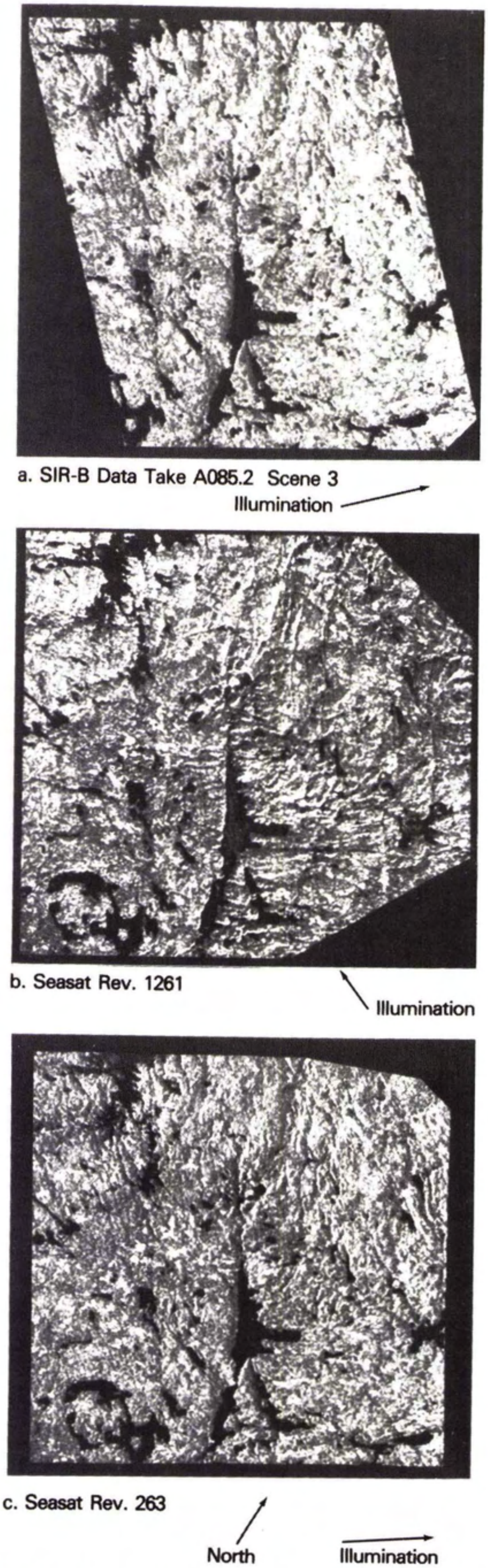


FIG. 8. Coregistered SIR-B and Seasat imagery of the Mazinaw Lake area.

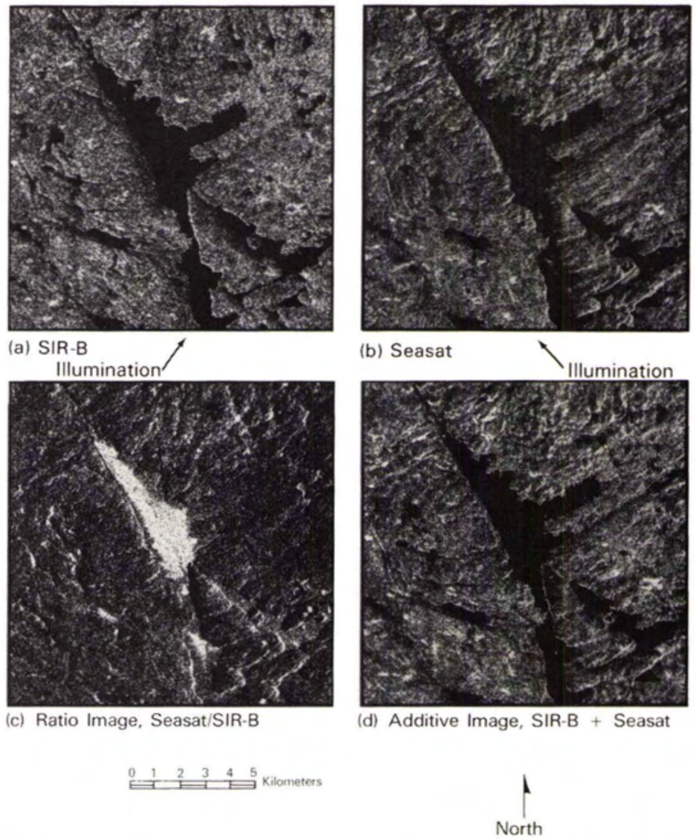


FIG. 9. Orbital radar enhancements of the Mazinaw Lake area (from Lowman *et al.*, 1987). (a) Contrast-stretched section of Mazinaw Lake SIR-B scene. (b) Contrast-stretched section of Mazinaw Lake area, Seasat Rev. 1261. (c) Ratio image, Seasat/SIR-B scenes, Mazinaw Lake area. (d) Additive image, Seasat plus SIR-B scenes.

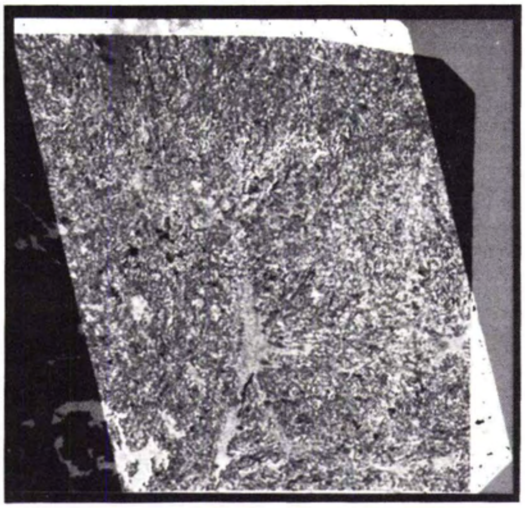
of the variance, the second 20.5 percent, and the third 5.4 percent. The first principal component gives a fairly detailed image of the surface roughness of the three input images (e.g., radar "albedo"). The second component contains most of the topographic and lineament information from the three input images. The third component is essentially the "noise" from all three images. A color composite of all three principal components (not reproduced here) compared to a color composite of all three original images is not a better product for structural mapping. Some lineaments are enhanced; others are not. An additive image containing the first and second principal components without the third component containing the "noise" could be used for a structural geology study.

A principal components analysis would be most valuable for combining more than three look directions. The three components which contain the most geologic detail could be combined in a color composite which would effectively eliminate the "noise" contained in the remaining components.

CONCLUSIONS

The subjectively preferred orbital radar enhancements for highlighting the geologic structure of the two Canadian Shield test sites were found to be

- a linear contrast stretch;
- a K nearest-neighbor average for a cosmetic speckle reduction or a mean- or median-filtered image for greater speckle reduction prior to edge enhancement;
- the Moore-Waltz (1983) directional enhancement using Prewitt edge filters; and

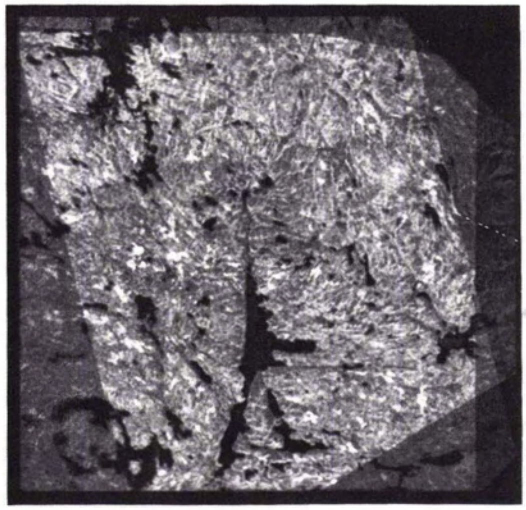


a. SIR-B — Seasat Rev. 263

b. SIR-B — Seasat Rev. 1261

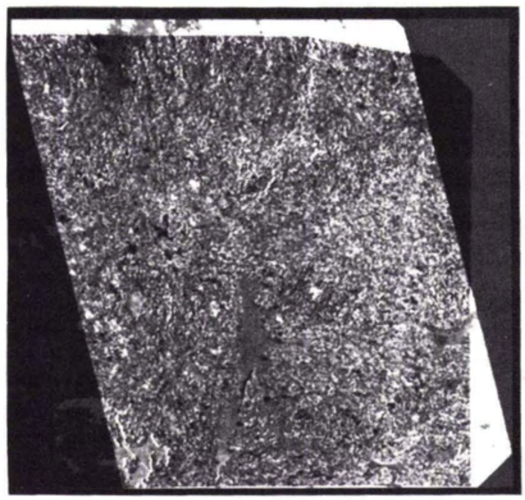
c. Seasat Rev. 263 — Seasat Rev. 1261

FIG. 10. Difference images of the Mazinaw Lake area. (a) There is no meaningful residual pattern (except the black areas which are wetlands present on SIR-B and not on Seasat) as the look directions are about the same. (b) The residual patterns are due primarily to differences in look direction. (c) Again, residual patterns are due to differences in look direction.



a. First Component

b. Second Component



c. Third Component

FIG. 11. Principal component axes from the coregistered images in Figure 7. (a) First component contains approximately 74 percent of total variance. Since it is the combination of three images, it gives a fairly detailed picture. (b) Second component is 20.5 percent of total variance. Notice that the second component "enhances" topography. (c) The third component is approximately 5.4 percent of the variance and contains mostly "noise" from the three input images.

- to reduce azimuth biasing, a black-and-white additive image for combining two coregistered images, a color composite image for combining three coregistered images, or a principal components analysis for combining more than three SAR images.

Results from the photointerpretation experiment (Table 2) confirm the initial subjective opinions. When those enhancements exhibiting bar-like filter artifacts which obscure background detail (the Selective Average filter and the Laplacian difference filter) are not considered, the subjectively preferred enhancements ranked the highest in each category.

These enhancements can and should be combined. For example, three coregistered images could be processed using a K nearest-neighbor average, then contrast stretched prior to being combined in a color composite. Alternatively, the coregistered images could be enhanced using the Moore-Waltz enhancement prior to being combined.

From this study and the study by Hirose and Harris (1985), it is apparent that the value of contrast enhancements and speckle reduction techniques depend on the target (terrain and vegetation cover), the analyst, and possibly the sensor. For these types of enhancements, there is no substitute for the trial-and-error method. future studies will be needed to determine if the same holds true for edge enhancements and methods of displaying multiple look directions.

ACKNOWLEDGMENTS

The authors would like to thank the following people for their assistance and suggestions during the course of this study: Jim Garvin, Tim Kusky, Ravi Kumar, Jeff Newcomer, Don Strebel, Jaime Nickeson, Kathy Wehness, Mark Emmons, and Richard Marcell. Work for this paper was partially supported by the National Aeronautics and Space Administration, Goddard Space Flight Center under contract NAS5-282-00.

REFERENCES

Blom, R., M. Abrams, and C. Conrad, 1981. Rock type discrimination techniques using Landsat and Seasat image data. *1981 International Geoscience and Remote Sensing Symposium*, pp. 597–602.

Blom, R.G., and M. Daily, 1982. Radar image processing for rock-type discrimination. *IEEE Transactions on Geoscience and Remote Sensing*, Vol. GE-20, No., 3, pp. 343–351.

Bryan, M.L., 1982. Analysis of two Seasat synthetic aperture radar images of an urban scene. *Photogrammetric Engineering and Remote Sensing*, Vol. 48, pp. 393–398.

Curlis, J.D., V.S. Frost, and L.F. Dellwig, 1986. Geological mapping potential of computer-enhanced images from the Shuttle Imaging Radar: Lisbon Valley Anticline, Utah. *Photogrammetric Engineering and Remote Sensing*, Vol. 52, pp. 525–532.

Daily, M., 1983. Hue-saturation-intensity split-spectrum processing of Seasat radar imagery. *Photogrammetric Engineering and Remote Sensing*, Vol. 49, pp. 349–355.

Daily, M.I., T. Farr, and C. Elachi, 1979. Geologic interpretation from composited radar and Landsat imagery. *Photogrammetric Engineering and Remote Sensing*, Vol. 45, pp. 1109–1116.

Eppes, T.A., and J.W. Rouse, 1974. Viewing-angle effects in radar images. *Photogrammetric Engineering and Remote Sensing*, Vol. 40, pp. 169–173.

Evans, D., and B. Stromberg, 1983. Development of texture signatures in radar images. *1983 Geoscience and Remote Sensing*, Vol.1, pp. TA-4 6.1–6.6.

Ford, J.P., 1980. Seasat orbital radar imagery for geologic mapping: Tennessee-Kentucky-Virginia. *The American Association of Petroleum Geologists* Bulletin, Vol. 64, No. 12, pp. 2064–2094.

———, 1982. Resolution vesus speckle relative to geologic interpretability of spaceborne radar images: a survey of user preference. *IEEE Transactions on Geoscience and Remote Sensing*, Vol. GE-20, No.4, pp. 434–444.

Frost, V.S., J.A. Stiles, K.S. Shanmugan, and J.C. Holtzman, 1982. A model for radar images and its application to adaptive digital filtering of multiplicative noise. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, Vol. 4, No.2, pp. 157–166.

Frost, V.S., M.S. Perry, L.F. Dellwig, and J.C. Holtzman, 1983. Digital enhancement of SAR imagery as an aid in geologic data extraction. *Photogrammetric Engineering and Remote Sensing*, Vol. 49, pp. 357–364.

Gold, D.P., 1980. Structural geology. *Remote Sensing in Geology* (B.S. Siegal and A.R. Gillespie, eds.), pp. 419–483.

Grant, T.A. and L.S. Cluff, 1976. Radar imagery in defining regional tectonic structure. *Ann. Rev. Earth and Planetary Sci.*, Vol. 4, pp. 123–145.

Harris, J., 1986. A comparison of lineaments interpreted from remotely sensed data and airborne magnetics and their relationship to gold deposits in central Nova Scotia. *International Symposium on Remote Sensing of the Environment, The Fifth Thematic Conference: Remote Sensing for Exploration Geology*, Reno, Nevada, 20 p.

Hirose, T., and J. Harris, 1985. On the improvement of SAR image interpretability using spectral multi-looking and spatial filtering. *International Symposium on Remote Sensing of the Environment, Second Thematic Conference, Remote Sensing for Exploration Geology*, pp. 601–617.

International Imaging Systems, 1984. *System 575 Software Digital Image Processing System User's Manual Version 3.1*, 456 p.

Kusky, T.M., W.S.F. Kidd, D.G. DePaor, C. Simpson, C. Isachsen, D.C. Bradley, and L. Bradley, 1986. On the possible ophiolitic origin of some Slave Province greenstone belts. *LPSC XVIII*, pp. 525–526.

Lee, J., 1983. A simple speckle smoothing algorithm for synthetic aperture radar images. *IEEE Transactions on Systems, Man and Cybernetics*, Vol. 13, No. 1, pp. 85–89.

Lowman, P.D.,Jr., J. Harris, P. Masuoka, V. Singhroy, and V.R. Slaney, 1987. Shuttle Imaging Radar (SIR-B) investigations of the Canadian Shield: initial report. *IEEE Transactions on Geoscience and Remote Sensing*, Vol. GE-25, pp. 55–66.

Lowman, P.D., P.J. Whiting, N.M. Short, A.M. Lohmann, and G. Lee, in press. Basement Tectonics Conference, Kingston, Ontario, August, 1987.

MacDonald, H.C., J.N. Kirk, L.F. Dellwig, and A.J. Lewis, 1969. The influence of radar look-direction on detection of selected geological features. *Proc. Sixth International Symposium on Remote Sensing of Environment*, p. 637.

Moik, J.G., 1980. *Digital Processing of Remotely Sensed Images*. National Aeronautics and Space Administration SP-431, 330 p.

Moore, G.K., and F.A. Waltz, 1983. Objective procedures for lineament enhancement and extraction. *Photogrammetric Engineering and Remote Sensing*, Vol. 49, No. 5, pp. 641–647.

Naraghi, M., W.D. Stromberg, and M.I. Daily, 1983. Geometric rectification of radar imagery using digital elevation models. *Photogrammetric Engineering and Remote Sensing*, Vol. 49, pp. 195–199.

NASA Goddard Space Flight Center, 1986. *Land Analysis System User's Manual, Version 3.1*.

O'Leary, D.W., J.D. Friedman, and H.A. Pohn, 1976. Lineament, linear, lineation: Some proposed new standards for old terms. *Geological Society of America Bulletin*, Vol. 87, pp. 1463–1469.

Rebillard, P., and D. Evans, 1983. Analysis of coregistered Landsat, Seasat, and SIR-A images of varied terrain types. *Geophysical Research Letters*, Vol. 10, No. 4, pp. 277–280.

Rebillard, P., and T.P. Nguyen, 1982. An exploitation of coregistered SIR-A, Seasat, and Landsat Images. *International Symposium on Remote Sensing of Environment, Second Thematic Conference, Remote Sensing for Exploration Geology*, pp. 109–117.

Reeves, R.G., 1969. Structural geologic interpretations from radar imagery. *Geological Society of America Bulletin*, Vol. 80., pp. 2159–2164.

Sabins, F.F. Jr., 1983. Geologic interpretation of Space Shuttle radar images of Indonesia. *American Association of Petroleum Geologists Bulletin*, Vol. 67, pp. 2076–2099.

Shanmugan, K.S., V. Narayanan, V.S. Frost, J.A. Stiles, and J.C. Holtzman, 1981. Textural features for radar image analysis. *IEEE Transactions on Geoscience and Remote Sensing*, Vol. GE-19, pp. 153–156.

Siegal, B.S., and N.M. Short, 1977. Significance of operator variation and the angle of illumination in lineament analysis on synoptic images. *Modern Geology*, Vol. 6, pp. 75–85.

Spatial Data Systems, Inc., 1975. *Computer Eye Handbook of Image Processing*, pp. 36–40.

Tomiyasu, K., 1983. Computer simulation of speckle in a synthetic radar image pixel. *IEEE Trans. on Geoscience and Remote Sensing*, Vol. GE-21, pp. 357–363.

Wing, R.S., W.K. Overbey, and L.F. Dellwig, 1970. Radar lineament analysis, Burning Springs Area, West Virginia – An aid in the definition of Appalachian Plateau Thrusts. *Geol. Soc. America Bulletin*, Vol. 81, pp. 3437–3444.

Wynne-Edwards, H.R., 1972. The Grenville Province. Variations in Tectonic Styles in Canada, *The Geological Association of Canada Special Paper Number 11* (eds. R.A. Price and R.J.W. Douglas), pp. 264–334.

(Received 22 August 1987; revised and accepted 21 January 1988)

New Sustaining Members

Terra Metric, Inc.

8470 Mount Diablo Blvd., Lafayette, CA 94549
Telephone 415-820-9334; fax 415-283-1465

TERRA METRIC, INC. is the sole distributor of Rolleimetric photogrammetric systems in the US. Rolleimetric systems and software are developed and manufactured by Rollei Fototechnic GmbH, Braunschweig, West Germany, recognized worldwide as leader in photographic technology. Rollei Fototechnic's commitment to photogrammetry is extensive and has culminated in the design and production of specialized cameras, photo restitution and image processing instruments.

The cameras, the Rolleiflex 6006 metric and 3003 metric, use the réseau principle to model lens distortion and film deformation. Both cameras come with factory calibration for focal length (at infinity), principle point and radial distortion. Calibrations at specified f-stops are available as an option. Rigorous use of réseau techniques reduces residual image errors to two microns. Rolleiflex cameras are very portable and offer an extensive lens selection, built-in motor drive and all other modern camera accessories including theodolite mounts and underwater housings. Due to its unique electronic shutter, the Rolleiflex 6006 can be syncrhonized with other 6006 cameras within 2-3 milliseconds permitting, therefore, high-speed stereophotography.

The Rolleimetric MR2 photo restitution system allows the user a photogrammetric evaluation of convergent photography taken from any angle of an object by digitizing multiple photographic enlargements and creating accurate X, Y, Z coordinates and two-dimensional plots simultaneously. This process does not require a traditional restitution instrument. Optional bundle adjustment with added parameter features for camera calibrations is also available. Interface programs with interactive graphics programs such as Rolleimetric's CAD program or AutoCad are available. The entire system is designed around MS-DOS operated computers and compatible peripherals.

For industrial applications, Rolleimetric offers a precision image scanner RSl using a high-resolution CCD sensor and the réseau principle for on-line calibration. The RSl is designed as a low-priced scanner for image processing and full or semi-automatic photogrammetric target recording. The image format is 230 mm × 230 mm with a maximum image resolution of 50 K × 50 K pixels.

Additional photogrammetric instruments are in the testing stages including a new digital réseau-scanning camera RSCl.

DAT/EM Systems International

101 E. 8th Street, Suite 130, Vancouver, WA 98660
Telephone 206–695–7005

IN JUNE OF 1984, as the growing need for digital data in the mapping industry became apparent, three mapping firms combined their efforts in a research and development project to create a cost effective system for photogrammetrists, by photogrammetrists, enabling them to achieve data in digital form. The three firms, all having their respective place in the mapping industry, have been associates for many years and have worked together on numerous joint ventures and projects.

With a resourceful and dedicated staff we began development of a computer-aided mapping system, designed around encoded analog stereoplotters. Using AutoCAD software, by Autodesk of California, we developed additional software, allowing for digital data conversion from the stereoplotter directly into AutoCAD with full screen graphics. When compared to the main-frame environment in computer-aided mapping systems today, the relatively low cost of PC's and our software, has proven to be a cost effective tool for our clientele.

Although the DAT/EM System simply grew to meet the mapping needs of three independent companies, it is now marketed by DAT/EM SYSTEMS INTERNATIONAL and is continually placing emphasis on upgrading, and providing additional programs in order to enhance the software. Additionally, custom macros can be developed, by our programmers, for a clients specific needs.