Assessment of SIR-B for Topographic Mapping

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ABSTRACT: The SIR-B synthetic aperture radar (SAR) was launched on board the Space Shuttle in October 1984. As a principal investigator of the data, the Centre for Remote Sensing at the University of New South Wales (UNSW) is undertaking a number of experiments on different aspects of the interpretation and application of SAR data, one of these being the evaluation for topographic mapping. This experiment investigated the geometric accuracy of features derived from SIR-B data, and the detectability of features required for cartographic map scales in Australia. The suitability of radar images for mapping will depend on their inherent geometric fidelity as well as their content and interpretability. A first-order polynomial was found to produce an adequate transformation between image and ground coordinate sets, producing an RMS vector error of some four pixels or approximately 50 m on the ground. This indicated that geometrically SIR-B radar imagery is unsuitable for topographic mapping at scales of 1:100,000 and larger. Analysis of the content, using the times required to digitize the features on the radar images and existing maps as an indicator of the amount of cartographic detail they each contain, showed that at best the radar images contained only 60 percent of the detail that was depicted on the 1:100,000 scale map.

INTRODUCTION

THE AIM of the topographic mapping project carried out by the Centre for Remote Sensing, University of New South Wales, on the Shuttle Imaging Radar-B (SIR-B) data was to investigate the two aspects of geometric accuracy of features derived from SIR-B data, and the detectability of features required for particular cartographic map scales in Australia. Geometric accuracy was investigated by identifying features on the images and current topographic maps at appropriate scales. Formulas transforming the image coordinates to ground coordinates were studied, and the RMS of residuals at the control points following transformation gave a measure of the geometric quality of the data derived from SIR-B images. Suitability of the data for mapping is dependent on an observer's ability to detect specific cartographic features which are required for the particular scales of mapping. An investigation was therefore made on the detectability and interpretability of such features. As scale governs the type of features which must appear on maps, this study acted as a guide as to the map scales which could be compiled from radar data. It is assumed that detectability of 80 to 90 percent of all features must be achieved before imagery can be considered suitable for topographic mapping at the required scale.

CHARACTERISTICS OF RADAR AND SAR IMAGING SYSTEMS

All radar systems measure distances or ranges to objects by the time taken for the emitted radiation from the antenna to travel to the object and back again. The radar beam is emitted, approximately normal to the direction of flight, at an angle from the vertical referred to as the look angle. The electromagnetic radiation is pulsed so that in time, τ, the resolution element in the range direction, R_r, is given by $R_r = c\,\tau/2$, where c is the velocity of electromagnetic radiation and R, the slant range, is found from $R = cT/2$, where T is the total return period of the signal. The azimuth resolution of so-called real aperture radars, R_a, can be approximated by $R_a = \beta R$, where β is the azimuthal beamwidth (radians), and R the slant range from above. Because the azimuth resolution, i.e., the resolution in the along track direction, of real aperture radar is directly proportional to the range of the object, it is also dependent on the altitude of the platform: i.e.,

$$R_a = \beta R = \beta \cdot h/\cos\phi,$$

where

h = the height of the platform, and
ϕ = the look angle.

Radars that use antenna beamwidth for azimuth and range resolution are termed real aperture radars, in contrast to systems using pulse width and a long synthetic antenna to improve azimuth resolution. The latter systems are termed synthetic aperture radars (SAR).

A long antenna or aperture for SAR systems is simulated (synthesized) by using the motion of the platform. Instead of recording only the one signal return from an object, as in the case with real aperture radar, for SAR the returns from a number of pulses are recorded, while the object remains in the beam of the antenna, and are compared to the transmitted signal, enabling the determination of Doppler shift between the object and the platform. It can be shown that the theoretical azimuth resolution of SAR is approximately given by $l/2$ (De Loor, 1983), where l is the length of the antenna and is, thus, independent of the operating altitude and the radar frequency, and will reduce as the length of the antenna reduces. The limits of azimuthal resolution will be constrained, however, because radar complexity, storage, and processor requirements all increase with increasing range and wavelength, and power requirements increase sharply as the antenna length is reduced.

Due to the monochromatic, coherent nature of SAR microwave radiation, the return signal is the vector addition of signals resulting from reinforcement or negation from different elements within the resolution cell (Krul, 1983), thus creating the speckle effect visible on SAR imagery. To reduce this effect, "look extraction" is used during processing whereby the spectrum is divided into a number of segments or "looks" (Curlander, 1986). A single image cell is then formed by summing the intensity of a number of the looks. Processing by look extraction has the advantage of removing some of the speckle but also reduces the resolution from the theoretical value for one look $l/2$, by multiplying it by the number of looks. For SIR-B, where the data are processed to four looks, the theoretical azimuth resolution of 6 m is reduced to around 25 m.

For two objects to be separated in range, the distance, d, between them is given by

$$d = c\tau/2$$

where

c = the speed of light, and
τ = the pulse duration.

This distance is measured as a slope distance to the object and can be converted to a horizontal distance, dg, by

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$$dg = c\tau/2 \cdot \sin \phi$$

where ϕ is the look angle of the radar antenna.

The SIR-B radar data provided by the Jet Propulsion Laboratory (JPL) included three multiple look angle scenes or Data Takes (DT) with look angles of 47 degrees (DT 83.8), 37 degrees (DT 67.8) and 17 degrees (DT 51.8) over the eastern part of Australia. Resolution in azimuth is about 25 m for all three swaths, but resolution in range, being dependent on the look angle, varies from 17 m for DT 83.8 to 58m for DT 51.8. The data were processed to a standard pixel size of 12.5 m. These three data takes were investigated for geometric quality and interpretability as described in this paper.

CHARACTERISTICS AND GEOMETRIC ACCURACY OF SIR-B RADAR IMAGERY

Radar image distortions are described by Naraghi *et al.* (1983). They include "layover" where, for example, two points of different elevations have identical slant ranges and will therefore be projected into the same point on the radar image (Figure 1), the position in azimuth not being affected; ground range nonlinearity caused by a variation in the look angle across the swath; and skew, a second order effect caused by a variation in the rotational velocity of the Earth between near and far range (Curlander, 1984). The latter two effects are substantially eliminated during processing by JPL, but errors arising from the adopted platform ephemeris and the shape of the Earth can lead to small residual errors in the processed data.

Apart from the effects caused by layover, residual errors in geometry of the processed radar images were assumed to be systematic in nature, and could therefore be modeled by a first, or higher, order polynomial. For each control point selected it was, therefore, necessary to correct first the image coordinate in range for the effects of layover before computing the polynomial which would refer to a particular height datum. The magnitude of the displacement (layover) in range, caused by the elevation of terrain above the datum, was found to vary linearly across the swath and to be proportional to the elevation above the datum. The correction for layover could thus be calculated for the near and far ranges and be interpolated for any other point in the swath.

Polynomials or mapping functions were computed, based on control points common to both the image and ground, to transform the corrected range and azimuth or line and pixel coordinates, respectively, on the image, to ground co-ordinates (easting and northing) (Figure 2). Ground coordinates of the common points were derived from maps at suitable scales. The

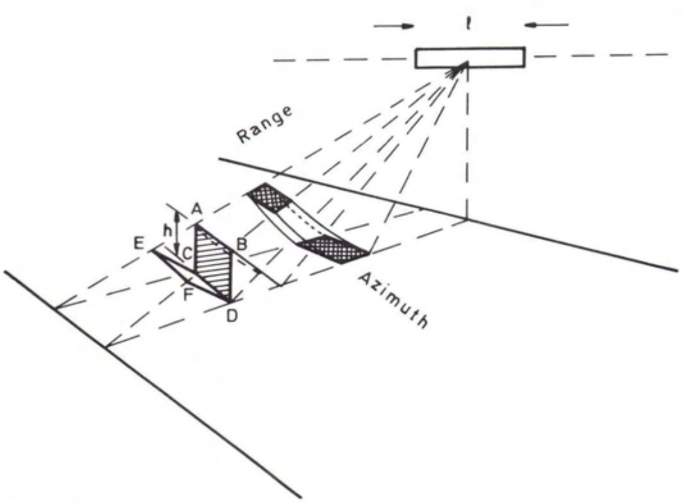

FIG. 1. Schematic diagram of side viewing radar imaging system. Range measured to the top *A-B* of object at height *h* is less than range to its base *C-D* which is equivalent to the range to *E-F*. *ℓ is the length of the antenna.*

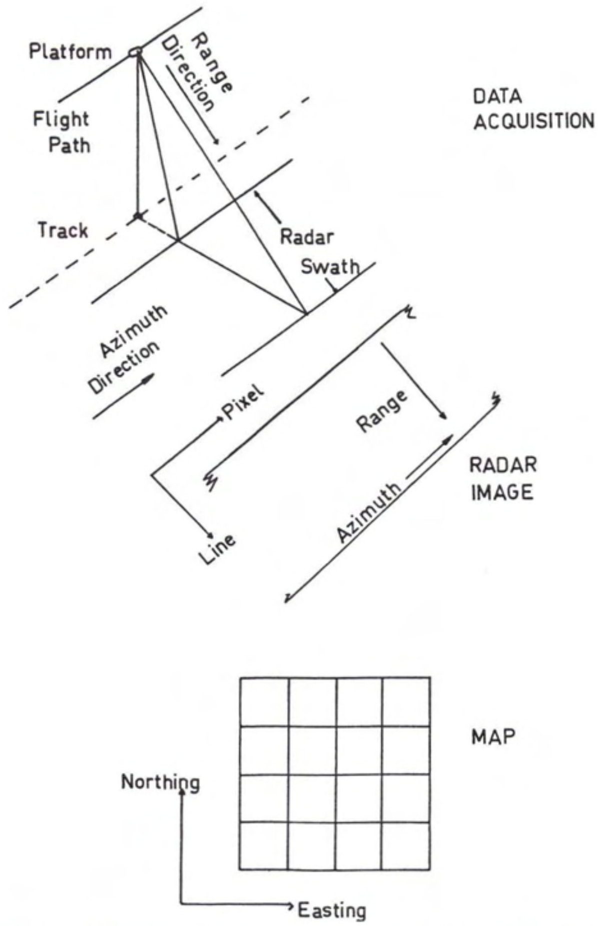

FIG. 2. Relationship between range and azimuth obtained during data acquisition, line and pixel on the processed radar image and northing and easting on a geographic grid, for the same area.

determination of a polynomial, from the coordinates of a limited number of well distributed points common to both the image and the map, allows coordinates in one system to be transformed into the coordinate system of the other. If high order terms as a function of image coordinates were found to exist in the transformation polynomial, then it is probable that significant second or higher order errors would be present in the geometry of the SIR-B data. Tests, however, indicated that in all cases only a first order transformation polynomial was required.

The results summarized in Table 1 show the accuracy of the transformation of coordinates derived on the radar imagery to those of the ground control using an affine transformation, after first determining that the coefficients of the higher powers of the image coordinates in the polynomial were not significant. There was a good distribution of control points for determining the mapping function for the coastal areas, with the majority of points being prominent land features around lakes or along the coast, most of which were at sea level and therefore not subject to errors due to layover. The results for the rural scenes are based on far fewer ground control points due to the topography and availability of features for control, but the control included three points marked with 2-m square metal corner reflectors placed prior to the Shuttle's overpass. Even so, the transformation in the rural areas are only marginally worse than for the well controlled coastal scenes. Dimensions of pixels on DT 83.8 were 12.65 m and 12.82 m in range and azimuth, respectively, revealing about 1.5 percent distortion in scale. For DT 67.8 the pixel size derived was 12.52 m for both range and azimuth, showing no significant scale distortion. It is believed that DT 83.8 was processed early in the SIR-B program whereas DT 67.8 was processed later based on more precise ephemeris

TABLE 1. SIR-B RADAR FITTED TO GROUND CONTROL

DATA TAKE	67.8	83.8	83.8	51.8
SCENE NO.	1	3	1	42
LOOK ANGLE (Deg)	37	47	47	17
LOCATION	COASTAL	COASTAL	RURAL	RURAL
EXTENT OF AREA (sq. km)	800	600	600	900
NO. OF SELECTED CONTROL PTS.	46	68	27	30
NO. USED IN ADJUSTMENT	40	61	18	16
RMS OF RESIDUALS 1:100 000 MAP DERIVED CONTROL	3 PIXELS	3 PIXELS	5 PIXELS	6 PIXELS
RMS OF RESIDUALS 1:25 000 MAP DERIVED CONTROL	4 PIXELS	4 PIXELS	–	–

data. There was no significant increase in accuracy using more "precise" coordinates derived from 1:25,000-scale maps, and it is considered that 1:100,000-scale maps are sufficiently accurate for providing ground control values.

It is concluded that the position of features could be extracted to an accuracy expressed as an RMS to within three pixels in northing and easting as shown in Table 1. This is approximately a vector RMS of four pixels or 50 m on the ground. Because the transformation accuracy is a function of the number and quality of control points available from the data, a large number of artificial control points, e.g., corner reflectors, would be required, particularly in rural areas, to improve the accuracy of transformation.

THEORETICAL MAPPING POTENTIAL OF SIR-B RADAR IMAGERY

The interpretability of features is a more subjective quantity to measure than the geometric quality of the image, but it is usually the factor governing the scale of mapping for which the imagery may be used. The interpretability of features is not only related to the dimensions of the features in relation to pixel size, but also to their contrast against their background.

For an object to have contrast against the background in a radar image, it must return more or less radiation than its surround. The relative increase or decrease in the return produces relatively darker or lighter toned pixels. The radar return of an object depends on its orientation with respect to the beam, its size, its shape (whether it acts as a corner reflector), the look angle of the system, the radar wavelength relative to the size of the object, the surface roughness of the object, and its background. In fact, there are a large number of variables which affect the detectability of features, most of which are related randomly to one another, and so the effect on contrast is unpredictable.

Doyle (1982) formulated the relationship between pixel size and recommended map scale for electro-optical and photographic systems, based on the resolving power of the human eye at normal reading distance of about 25 cm, as seven line pairs per millimeter (lp/mm). For photographic systems, the relationship between ground resolution, *Rm*, in m/lp and image scale number, *Sm*, is given by

$$Rm = Sm/7000 \tag{1}$$

Because about 2.5 pixels are required in electro-optical systems to present the same information as one photographic line pair, the ground resolution, Pm, in metres per pixel is

$$Pm = Sm/17500 = 0.57 \times 10^{-4} Sm \tag{2}$$

The radar image pixel size is fixed at 12.5 m irrespective of actual resolution (Leberl *et al.*, 1985), whereas the ground resolution in range for the higher look angles is approximately the same as the azimuth resolution, 25 m. Accepting 25 m as a more representative pixel size, and therefore adopting $Pm = 30$ m, Equation 2 returns a value for *Sm* approximately equal to 500,000. This indicates that radar imagery, acquired at higher look angles, would be suitable for 1:500,000 scale mapping. At lower look angles, where the resolution in range is reduced by two, radar imagery may be only suitable for smaller scales of mapping, e.g., 1:1,000,000.

These results seem to be supported by Konecny *et al.* (1982) who suggest that, compared with aerial photography, radar images acquired by Seasat cannot be properly interpreted to derive all required topographic features even though radar images show many other features such as metallic objects, e.g., fences, powerlines, and vehicles. It is questionable whether radar imagery is useful for topographic mapping at a scale of 1:250,000; therefore, radar images can only provide supplementary information.

FEATURES DETECTED ON SIR-B IMAGERY

In a radar image the grey tones are determined by the amount of reflected radiation, or backscatter, received by the system. Backscatter conveys not only the position of objects but information about the size, shape, configuration, and electrical properties of the surface and subsurface and is, therefore, dependent on the illumination and scene parameters. For a particular system, however, the average return varies only with the scattering coefficient. The radar scattering coefficient is the measure used to quantify the amount of backscatter for a homogeneous area larger than the antenna beam. The scattering coefficient is used to characterize the backscatter intensity from extended scenes, such as agricultural fields, and is the average radar cross section per unit area.

The differences in the received backscatter are due then to the differences in the scattering coefficients of the point sources in the illuminated area; thus, bright tones in the image will be caused by high backscatter and darker tones by low backscatter. The characteristics of radar backscatter and the terrain surface influence the appearance of terrain features on radar images and, therefore, the ability of cartographers to identify the cartographic features required for mapping.

Although it was found that the amount of detail contained in the SIR-B radar images was variable, some generalizations can be made concerning the content. Generally, linear features, roads, tracks, and railways are only visible if they cut through timber or there are trees growing in their reserve. Railway lines normal to the radar beam saturate the return and appear very bright in the image. Rivers in deep valleys or surrounded by riperian vegetation are indicated by the high return from the side of the valley, especially when normal to the radar beam, or the high return from the lush vegetation, but the exact position of the water course may not be visible.

Boundaries between natural and synthetic surfaces, i.e., rural/town, can generally be detected depending on the amount of vegetation within the built-up area. Between timbered and open country the boundary can also be seen, and differences in the type of timber cover can be shown by tonal variation. Isolated objects acting as corner reflectors stand out as bright pixels, but there is no guarantee that they are buildings. Heavily built-up areas, because of their high radar return, are visible as areas of lighter tones, and the street pattern can sometimes be delineated.

It can, therefore, be concluded that relatively small objects are not detectable on SIR-B imagery even at the higher look angles, and significantly fewer objects are visible at lower look angles because resolution reduces as the look angle decreases. Contrast as well as detectability are dependent on the look angle, orientation with respect to the illumination, the local relief, and the type of country, i.e., open or timbered. It is also apparent that at high look angles the radar is able to discriminate between "smooth" and "rough" surfaces, while at the lower look angles, because of the coarser resolution, the radar provides a view of the geomorphology, and in similar terms is able to discriminate between "rough" and "rougher" surfaces, as shown in Figure 3.

QUANTIFICATION OF THE CONTENT OF SIR-B RADAR IMAGERY

Content and interpretation relate to features which can be detected and then labeled, e.g., road, forest, urban. The amount and disposition of all the features identified on the imagery must portray the ground accurately, given the generalization of detail at particular map scales. This means that radar images need not contain all detail as long as the detail which can be detected is adequate to portray the ground at a particular map scale or scales.

To arrive at a quantitative conclusion on the image content of SIR-B imagery, rather than rely on subjective generalizations, it is possible to plot all the detail that could be detected on the radar imagery and compare the amount and disposition of the plotted features with features identified on suitably scaled maps. Due to the uniqueness of radar geometry, however, which is affected by illumination and image formation, plotting cannot be achieved on conventional stereoscopic photogrammetric equipment without specialized software (Wu and Schafer, 1980). The content of other satellite imagery has been compared with map content by Welch (1982), using the time to digitize the map and the image as a surrogate measure of content. A similar technique was used to determine the map content of SIR-B imagery.

For this part of the project sections of the three overlapping swaths-DT 51.8, DT 67.8, and DT 83.8-were selected in a rural area of southeastern Australia where the terrain is relatively flat and there are a variety of features and densities of vegetative cover. This area was considered to contain a high proportion of cultural detail which would provide a sound basis for comparison with the existing base mapping.

The three radar data takes were registered to the 1:100,000-scale map base and resampled to 25-m pixels. In turn, the detected details on the 1:100,000-scale map, the 1:250,000 scale-map, DT 83.8 (Figure 4), DT 67.8, and DT 51.8 were digitized and stored as separate theme files on a Dipix Image Analysis System, and the time taken to digitize each of the major components was recorded. The ratio of times taken to digitize features on the radar images to those taken to digitize features on the map were used as a measure of the proportion of features detectable on the radar images, as shown in Table 2. This approach also allowed visual comparisons between the digitized data and, thus, revealed features not shown on the current map. Although the percentages shown in Table 2 are only indicative, as some features took longer to digitize yet no additional detail was actually detected, they give a good basis for comparison.

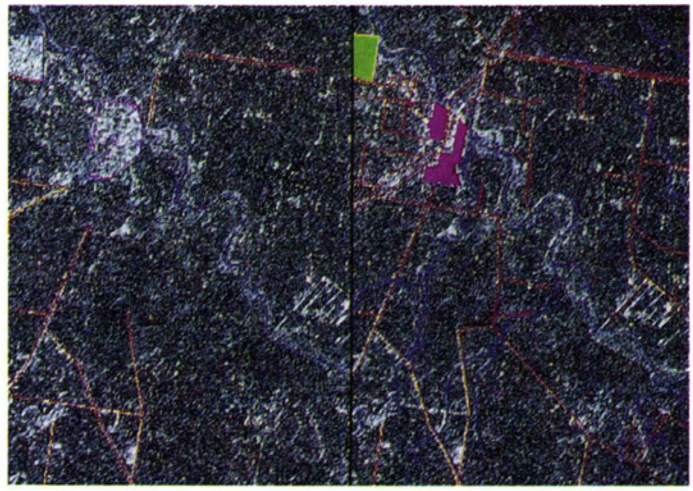

FIG. 4. A section of DT 83.8, look angle 47 degrees, showing the detected linear features, which were highlighted after being digitized to avoid the possibility of duplicating the digitizing and allow a visual comparison with the map.

TABLE 2. PERCENTAGE (%) OF FEATURES DIGITIZED FROM RADAR IMAGES COMPARED TO 1:100,000- AND 1:250,000-SCALE MAPS

DATA TAKE	51.8		67.8		83.8		83.8 51.8	
LOOK ANGLE (Deg)	17		37		47		47 17	
MAP SCALE (K)	100	250	100	250	100	250	100	250
FEATURES								
Roads	12	20	42	70	39	65	36	60
Railways	*	*	33	50	33	50	33	50
Boundaries	32	~	100	~	100	~	100	~
Streams	31	56	17	31	21	38	34	63
TOTAL	23	34	51	53	53	53	59	61

(~) Boundaries are not depicted on the current 1:250,000-scale map.
(*) Feature not detected on radar image.

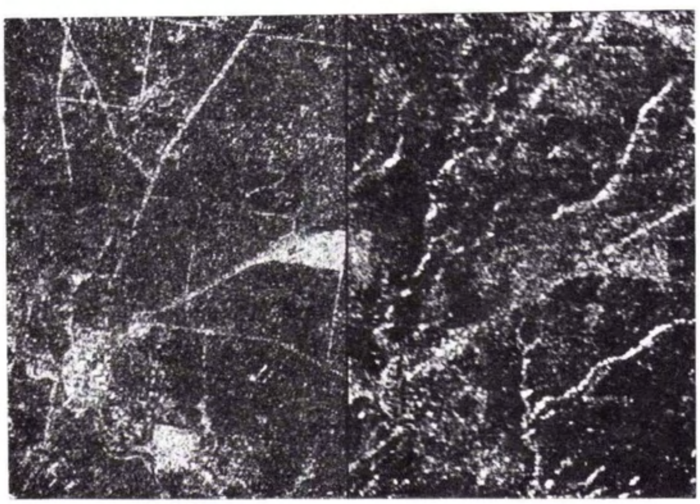

FIG. 3. A section of the terrain imaged at look angles of 37 and 17 degrees, respectively, illustrating the geomorphology apparent on the lower resolution (17 degree look angle) image and the tonal variations caused by differences in surface roughness on the high resolution (37 degree look angle) image.

Both DT 83.8 and DT 67.8 with similar look angles contained similar amounts of detail. Nearly all roads and tracks were detected where there were trees growing alongside them, and it was initially thought that the radar showed roads not depicted on the current map. The major highway and railway, without bordering trees to enhance their presence throughout the scene, were often only vaguely detectable. Where the railway was separated from the road, and trees were growing alongside, it was clearly visible although it could not be interpreted as a railway, but where the road ran alongside the railway, it was impossible to detect two separate features. Examination of aerial photography following this analysis showed that it was the existence of trees along the roads that enabled their detection. Where there were rows of trees growing elsewhere, i.e., as windbreaks, they were wrongly interpreted as roads.

A ground investigation revealed that the trees growing in the road reserves were eucalypts with rather sparse foliage but relatively closely spaced. It was concluded that the tree trunks and the open fields created a corner reflecter effect, thereby increasing the backscatter along the linear features. By contrast, the open fields acted as a specular reflector, and backscatter was minimal. This provided sufficient contrast on the image to enable detection of the linear features described above. Several roads had thick scrub growing in their reserve, but these roads were not detectable. The conclusion was that, as the scrub was essentially foliage, it contained nothing substantial, e.g., trunk or branches, to increase the backscatter to provide the contrast necessary to enable its visual detection.

All vegetation and urban boundaries were detectable, but differentiation between the medium and dense scrub was not possible because they appeared similar on the image. The major river was visible but because of the riperian vegetation its exact course was doubtful, although a later comparison of its plotted position with that digitized from the map showed that the plotted position was not significantly in error. A few of the minor streams were detected by the highlight and shadowing along their banks, but this was essentially a function of their orientation to the radar beam.

On DT 51.8 far less cultural detail and fewer boundaries were detected but, with the lower look angle, more of the river valleys were visible. This indicated that a composite image of two radar scenes (DT 51.8 and DT 83.8) would provide the maximum amount of detail possible. The time taken to digitize the features on the composite image did indeed show that the maximum amount of detail was provided by this image; for a 1:100,000-scale compilation, some 59 percent of detail could be detected compared with 61 percent of detail for 1:250,000-scale compilation.

These values seem to contradict a previous analysis (Welch, 1982), i.e., that Landsat MSS gave only some 40 percent the of detail required for topographic mapping in a similar evaluation. This is explained by the fact that nearly all the roads were detected because of the line of trees along them; where there were no trees along roads, they could not be detected. Also, the rivers and streams were detected by their accompanying vegetation or topography. Additionally, ancillary data would have been required to positively identify certain features, because they could not be correctly interpreted from the radar image alone. A visual interpretation of an area to the south of the study area, where the linear features did not have trees growing alongside them, showed that apart from vegetation boundaries little cartographic detail was visible. The difference in the amount of detail contained in these two areas indicates the variability of content of the SIR-B data and substantiates the claim that radar images are unsuitable for 1:250,000 scale mapping or larger. Nevertheless, in some instances radar images may provide excellent ancillary data for topographic map compilation.

RECTIFICATION OF SIR-B RADAR IMAGES

A computer program for the removal of layover for SIR-B images, which in effect produces a geometrically correct image, has been developed by the Centre for Remote Sensing, UNSW. The program requires that a digital elevation model (DEM) be available so that the amount of layover introduced during acquisition can be compensated. Other constants that need to be entered by the user relate to the position of the platform during acquisition and the Earth's radius (assumed constant for an individual scene), which are provided by JPL with each data take.

As the rectified image is usually required to be related to a standard grid, i.e., a map, the program determines a first order polynomial transform to relate line and pixel values from the radar image to easting and northing coordinates from a map for selected ground control points. The line values used are corrected for layover, as previously described, using the height of each control point. The user selects the area for rectification by entering its coordinates as well as the required grid cell size of the rectified image.

The program uses the inverse of the affine transformation to compute the corresponding line and pixel value in the radar image for each grid cell. The height of this cell in the DEM is used for the interpolation of the amount of layover in range, i.e., image line direction and, finally, the line and pixel value which corresponds with this cell in the radar image. The intensity of the nearest pixel in the radar image, i.e., the nearest neighbor, to that computed represents the ground response from the area covered by the cell. An option also allows for bilinear interpolation of the intensity from the four neighboring pixels. As the process is essentially one of selecting the appropriate response for a grid cell, a response can be selected more than once in the rectified image when areas have not been imaged by the radar due to layover or radar shadow.

CONCLUSIONS

The geometric accuracy of the SIR-B radar was found to be suitable only for 1:250,000-scale mapping and smaller because the RMS vector error from the first order polynomial used to transform the radar data to the map grid was some four pixels, or about 50 m on the ground. Consistent results may not always be possible unless the following requirements are met:

- an adequate selection of common points exists throughout the area on both the image and corresponding maps, and
- a method exists to correct the radar image range values for the displacement caused by layover.

The detection of the cultural detail contained in a radar image is dependent on the large number of factors that determine the amount of backscatter from these features, and then whether the amount of backscattered radiation is sufficient to differentiate the features from their background. A quantitative analysis of the SIR-B imagery indicates that the content of the radar images varies and that theoretically the images are, at best, only suitable for compiling topographic maps at scales of 1:500,000 or smaller. The definition of boundaries and the textural detail of areal features may, however, be useful for thematic mapping.

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