CHAPTER 1

INTRODUCTION

1.1 AMAS - Topographic Mapping Experiment

The Australian Multi-experimental Assessment of SIR-B (AMAS) was a proposal of the University of New South Wales, Centre for Remote Sensing in response to the National Aeronautics and Space Administration (NASA) Announcement of Opportunity, number OSSA-1-82, on Shuttle Imaging Radar-B (hereafter SIR-B). The proposal outlined four experiments which treated different aspects of the interpretation and application of SIR-B data.

AMAS was one of the forty-three proposals from researchers outside the United States which were accepted, and resulted in SIR-B data being acquired for some of the specific Australian sites detailed in the proposal. Part of AMAS was the Topographic Mapping Experiment, under the leadership of Dr JC Trinder, Associate Professor, School of Surveying and Centre for Remote Sensing, University of New South Wales. This work will describe how the aims of the topographic mapping experiment were achieved.

Data from the previous radar missions (Seasat and SIR-A) were made available after acquisition for researchers to evaluate. Early in the SIR-B program selected researchers had the opportunity to request optimum data for their particular field of study. Some 40 SIR-B scenes were acquired for the AMAS and selected scenes were used during the topographic mapping experiment. Most of the SIR-B scenes were acquired during 3 separate data takes, each data take acquired at a different look angle. The three data takes covered a strip of eastern Australia and were provided to the UNSW Centre for Remote Sensing both on computer compatible tapes and as photographic negatives by the Jet Propulsion Laboratory (JPL).

1.2 Aim of the Topographic Mapping Experiment

With the imminent completion of Australia's medium scale map coverage, the maintenance of this coverage through a revision program will include the use of imagery acquired by spaceborne systems because of economic constraints. It was considered that being the first digitally acquired radar data, SIR-B imagery should be evaluated to determine its suitability for such a program. The aim of the topographic mapping experiment was to investigate the 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 evaluated by identifying features on the images and on current topographic maps at appropriate scales. Formulae that transformed the image coordinates to ground coordinates were studied and the root mean square (RMS) of residuals at the control points, after transformation, gave a measure of the geometric accuracy of the data derived from the SIR-B images.

Suitability of the data for mapping is dependent on the map maker's ability to detect specific cartographic features required for mapping at that particular scale. An investigation was therefore made of the detectability and interpretability of such features. As scale and the types of features that appear on maps are related, this study acted as a guide to the scales of mapping which could be compiled from SIR-B data. It was assumed that detectability of 80-90 percent of all features must be consistently achieved before the imagery could be considered suitable for topographic mapping.

1.3 Objectives

Three objectives being:

- To evaluate the geometric accuracy of a single strip of SIR-B data;

- Evaluate the use of composite Landsat and SIR-B images for interpretability of features;

- To determine the scales of mapping for which the SIR-B data is suitable;

were determined so that the aim of the topographic mapping experiment outlined in Section 1.2 above could be achieved.

1.4 Topographic Mapping in Australia

Australia's basic map coverage is comprised of national coverage at a scale of 1:250,000 with a contour interval of 50m (540 map sheets). The current series at this scale is due for completion in 1988. It replaces an earlier uncontoured series that was completed in 1968. There is also coverage of the more settled areas (1640 map sheets) at a scale of 1:1,00,000 with a contour interval of 20m. The remaining 1470 map sheets at this scale are being compiled although there is no printing program at present. If required they could be published on demand when compilation is completed in 1989. By 1989 much of the mapping at these scales will be approaching 20 years old and in need of revision. Due to resource limitations revision is likely to be a slow process unless a new rapid and economic method is devised.

Most urban development in Australia is restricted to the coastal margins, and represents only a small proportion of total map detail at these scales. The inland areas are mostly arid with sparse cultural detail so that the revision requirements in these areas relate to:

- point features such as bores, wells and tanks;

- line features such as roads, fences, power lines and irrigation channels; and

- areal features such as mining activities and settlements.

Depending on the amount of cultural change revision may involve either total re-compilation or only the plotting of new detail. The amount of such change can be determined by one (or all) of the following methods:

- field inspection;

- estimation, based on knowledge of the activities in the area since the map was completed;

- inspection of imagery e.g. satellite.

Post war, aerial photography has been the source of all map detail, with the production of a line map taking up to two years. Even with recent developments in computer assisted methods, whereby aerial photography is still used as the data source, but plotting and scribing are computer controlled, the production time is still only marginally reduced. The ultimate aim of mapping agencies is to reduce the time between data acquisition and map availability as well as providing a cost effective product. Producing maps from satellite data appears to be one way of fulfilling this aim.

1.5 Use of Spaceborne Imagery for Topographic Mapping

The launch of the Landsat series of satellites was a significant advance in the acquisition of imagery on a cyclical basis. This imagery allowed a reduction in the acquisition costs over aerial photography, reduced control requirements, and offered a choice of product i.e. a photographic image or digital data. For topographic mapping at the larger scales however, the nominal 80m pixel of Landsat meant that this imagery was too coarse and the detail required by the cartographer could not be detected. Crane (1986) reported that Landsat imagery has been used with some success to revise mapping at 1:1,000,000 scale, but doubts have been expressed about its suitability as the primary data source for revision of mapping at a scale of 1:250,000. This is because compared with Landsat's nominal 80m pixel size, the equivalent pixel size needed for map compilation at a scale of 1:250,000 is some 14m (Konecny et al., 1982) whereas Welch (1982) suggests a higher resolution of between 5-10m. Landsat 5 contained the Thematic Mapper with a nominal 30m pixel size. The amount of detail that can be detected is greater than for Landsat MSS. With Thematic Mapper's high rate of data capture and lack of on-board recorders data is transmitted to the ground via a Tracking and Data Relay Satellite (TDRS). Only limited imagery of Australia has been acquired as the TDRS necessary for Australia to receive cyclical data was destroyed with the Shuttle in 1986. The satellite SPOT (Systeme Probatoire Observation de la Terre), with 10m and 20m pixels, launched by CNES (Centre National d'Etudes Spatiales) in February 1986, has already acquired a significant amount of imagery which is currently being evaluated.

Airborne radar data was used in the late 1960s for mapping large areas where climatic conditions had restricted image acquisition by optical systems (see Section 2.2). The suitability of radar data for topographic map compilation and/or revision was indicated by Seasat (1978) and SIR-A (1981) imagery. With the added flexibility of the SIR-B system it was considered that its imagery offered greater potential and deserved evaluation.

1.6 Data Processing

For the topographic mapping experiment, display and processing of the digital SIR-B data, supplied by JPL, was carried out on the Aries 2 Image Analysis System developed by DIPIX Systems Ltd, Canada. It is a system dedicated to the display and analysis of digital, spatial data. Although initially designed for Landsat data it has the flexibility to display any digital data in raster form. The DIPIX Image Analysis System software is controlled by the DEC RSX-11M operating system with an applications software package (A2ASP) comprised of modular programs written in Fortran 77. The program modules are designed as menu-driven "Tasks". The DIPIX Image Analysis System input, files and procedures for carrying out particular tasks are not detailed within this report. However, to enable the procedure to be duplicated on a DIPIX Image Analysis System or any other system, sufficient detail has been included. The UNSW CYBER system and software developed by Prof Trinder were used for the analysis of the fit of selected control points in SIR-B image coordinates to absolute map coordinates using a least-squares method. Being specialized, the DIPIX Image Analysis System software did not contain the necessary options needed to evaluate the geometric accuracy of the radar data. A program to produce rectified radar images for display on the DIPIX Image Analysis System was developed in collaboration with Mr J Klingberg, a computer programmer with the Centre for Remote Sensing. Due to the data storage requirements the program was installed on the UNSW VAX 11/780 system. A description of the program is detailed in Chapter 6.

1.7 Glossary

Remote sensing terminology has expanded with the developments in microwave imaging systems. For readers not familiar with radar technology a list of common terms has been included as a Glossary.

CHAPTER 2

REVIEW OF THE APPLICATION OF RADAR IMAGERY FOR MAPPING

2.1 Introduction

The use of Side-Looking Airborne Radar (SLAR) as an airborne imaging system for topographic mapping can be traced back to project RADAM in the early 1970s. While SLAR was suitable as an airborne system it lacked resolution at very high altitudes. It was not until Synthetic Aperture Radar (SAR) became available that this problem was overcome and radar could be considered as a spaceborne system. SAR has generally been used only for specific purposes due to its geometry and resolution, while systems operating in the optical wavelengths have generally provided the imagery for topographic map compilation. Nevertheless, there remain regions of the world that can only be imaged in the microwave wavelengths due to their climatic conditions.

This Chapter provides an overview of the application of spaceborne imagery to mapping. Its focus is on the use of radar data but it examines the more flexible radar systems of the future and indicates how they may contribute to topographic mapping.

2.2 Radar and SLAR

The history of radar can be traced back to 1889 when Heinrich Hertz concluded that solid objects interfered with, and reflected radio waves (Koopmans, 1983a). Definitive investigations of radar, however, did not begin until the 1920s. Radar, an acronym for RAdio Detection And Ranging, was developed by Great Britain during World War 2, in the form of a Plan Position Indicator (PPI), although the United States and Germany had also been conducting studies on its use. Cutrona (1962) detailed how in 1953 the first coherent radar acquisition and data processing system evolved from within Project Michigan. However, it was not until 1967 that the first large scale topographic mapping project with Side-Looking Airborne Radar (SLAR) was flown by Ratheon Autometric over the Darien province of Panama for Project RAMP (RAdar Mapping of Panama) (Crandall, 1969). SLAR was considered ideal for rapidly mapping this area, which was continuously covered by cloud, and for which there existed no maps or aerial photographs. The U.S. Air Force attempted to acquire aerial photography over the area for nearly 20 years (Viksne et al., 1969).

During the late 1960s and early 1970s large parts of the world were covered by airborne SLAR surveys. The best known and largest example of these surveys is Project RADAM (RAdar am AMazonia), where the entire country of Brazil (8.5 million square km) was imaged (Koopmans, 1983b). SLAR has demonstrated its value in a wide range of resource mapping activities such as lithological mapping in geology (Sabins, 1978), agriculture (Ulaby et al., 1980, Fenner et al., 1981), and soil moisture (Dobson and Ulaby, 1981).

2.3 Spaceborne Synthetic Aperture Radar

Prior to the development of synthetic aperture radar (SAR) in the late sixties (Brown and Porcello, 1969), the use of SLAR at very high altitudes was constrained by its resolution in the along-track (azimuth) direction. Using SAR, the azimuth resolution is independent of altitude, and is therefore suited to spaceborne image acquisition. See Section 3.3 for more details. On June 26, 1978, Seasat was launched into orbit carrying the first spaceborne L-band (23.5cm wavelength) SAR. Seasat operated in a 108 degree inclination orbit at an altitude of 786km until its failure, due to electrical problems, on October 10 that year (NASA SIR-B Science Plan, 1982). The radar system carried by Seasat operated with a fixed incidence angle of 20 degrees. It produced a 100km swath with a resolution of about 25m in range and azimuth and some 42 hours of data were collected. Because of the extremely high data acquisition rate, however, data could not be stored on board and was transmitted to one of the five ground receiving stations. All of these stations were located in the northern hemisphere. Nearly all of the data from the Seasat mission, which was optically processed, showed the remote sensing potential of spaceborne SAR.

Following the encouraging results from Seasat NASA incorporated a SAR into its Space Shuttle experiments and SIR-A (Shuttle Imaging Radar-A) was launched on board the Shuttle (mission STS-2) on November 12, 1981, recording nearly 8 hours of data. The SIR-A SAR was essentially similar to that aboard Seasat. The only difference was that SIR-A had a larger incidence angle (50 degrees) which produced a swath of 50km with a lower resolution of 40m in range and azimuth. Both SIR-A and Seasat were fixed parameter systems in that the wavelength, polarisation and incidence angle were all constant. Interpretation of the imagery required the use of the photo-interpreter's tools of tone, texture and context (NASA SIR-B Science Plan, 1982). Elachi et al. (1982) reported that SIR-A was useful in mapping geological structures, in the observation of the oceans' internal waves, and in land-use studies where man-made features were detected because of their corner reflector effect. Canby (1983) showed evidence of radar's ability to penetrate very dry sand such as that found in the Sudan.

SIR-B (Shuttle Imaging Radar-B) was launched on board the Shuttle (mission STS-17) on October 5, 1984. SIR-B was the first imaging radar to allow digitally processed imagery to be acquired at selected incidence angles between 15 and 60 degrees (Landsat Data Users Notes, 1984). It was anticipated that this capacity would assist in the acquisition of backscatter from different surface materials at different incidence angles and enable the determination of the optimum incidence angle for various mapping purposes (Koopmans, 1983a). The change of incidence angle would vary the range (cross track) resolution from 17m to 58m, but the azimuth resolution (along track) would remain constant at about 25m, refer Section 3.3 for more details.

In orbit SIR-B encountered problems with the Ku-band data transmission antenna and the SIR-B data acquisition antenna. Subsequently it developed an electrical malfunction. These problems resulted in 98 percent of the proposed SIR-B data acquisition passes (data takes) being altered and necessitated many other operational changes

Australia was fortunate to have received data over some of its sites. This data included data takes at three different incidence angles that run from north of Sydney, south across NSW and Victoria, to Bass Strait near Wilsons Promontory. The three data takes also overlap for a significant portion, and thus offer a unique data set for investigation.

2.4 Combining Radar and Landsat Imagery

The detection of cultural detail on Landsat imagery is difficult because of the large pixel size and the lack of relief discrimination. Conversely the ground dimensions of radar pixels are much smaller and it has the ability to enhance landforms. Together the information from both systems are complementary. An analysis of the various procedures used to photographically merge Landsat and radar data is given in Harris and Graham (1976). Researchers such as Guindon et al. (1980), Henninger and Carney (1983) and Kux and Dutra (1984) have shown that using merged Landsat and SAR data computer algorithms for classifying land-cover types are improved. Whether map detail is also enhanced on such composites will be investigated as part of the topographic mapping experiment.

2.5 Topographic Mapping from Spaceborne Imagery Acquired by Optical and Electro-optical Systems

Topographic maps are a large scale portrayal of the spatial associations of a selection of diverse natural and man-made features such as roads, boundaries between areal features, waterbodies, elevations, coastlines and settlements. Topographic maps are accurately made to a standard set of specifications (National Mapping Council of Australia, 1975). Thematic maps concentrate on one single attribute or the relationship of several attributes, and are usually produced at smaller scales to less stringent requirements. For the compilation of maps at a scale of 1:250,000 or larger, the imagery from which the position and type of detail is extracted must have a high spatial resolution. Welch (1982) suggests a resolution of between 5-10m, whereas Konecny et al. (1982) suggest the lower resolution of 14m. With the resolution of current space systems, the cartographic products which appear most compatible with the imagery from such systems are image maps and derived thematic maps. Image mapping from space readily lends itself to automation and rapid map production, whereas preparation of line maps may take up to several years.

Conventional line maps, of which topographic maps are one type, include information on names, road classification and feature identification, that cannot be obtained from any airborne/space imagery (Colvocoresses, 1984). Although spaceborne imagery can be used as a basis for, or the limited revision of, line maps, the image data needs to be augmented by data from other sources. The need for auxiliary data is supported by Welch (1982), who reported that the detail detected on Landsat MSS-3 and RBV-3 images amounted to only 40 percent of the detail necessary for map compilation at a scale of 1:50,000, and 40-50 percent of the detail necessary for map compilation at a scale of 1:250,000. Traditional camera systems, where the data is recorded on film, have the capability of producing the highest resolution images whilst maintaining large regional coverage. Such systems have not been used for free-flight in space or cyclical acquisition. Because camera systems simultaneously image a complete frame the spatial geometric fidelity is maintained through precise knowledge of the distortion parameters via for example, camera calibration. The acquired images can be evaluated using existing photogrammetric instruments together with conventional interpretative principles (Konecny et al., 1982). Carrying stocks of various film types into orbit and having to retrieve the exposed film for processing is a major disadvantage. Additionally, there is a degradation in image quality when photographic products are reproduced. There is also the likely possibility of clouds and weather obscuring the ground and rendering such images unusable.

Two camera systems have been used to acquire images from space. The first was the Metric Camera, a Zeiss aerial camera with a 23cm x 23cm format, modified for space operation and included in the 1983 NASA/ESA (European Space Administration) Spacelab mission. It was expected to provide imagery enabling features of 20-30m to be detected and thus suitable for compiling topographic maps at the small scales of 1:100,000 to 1:250,000 (Schroeder, 1982). Meneguette (1985) reported that the imagery was geometrically suitable for map compilation at a scale of 1:100,000, but identification of detail was insufficient for plotting at such a scale. He suggested that the imagery could be used for map compilation at a scale of 1:250,000. Engel et al. (1986), reported that the accuracy of stereo- compilation from the Metric Camera imagery was sufficient to produce maps at a scale of 1:50,000 but the recognition of detail was suitable only for map compilation at a scale of 1:100,000. The second camera system, was the Large Format Camera (LFC), which was operated during Shuttle mission STS-17 in 1984, the same Shuttle which carried the SIR-B system. The LFC had a 23cm x 46cm format (large format) and 30.5cm focal length. Doyle (1982b) suggested that positional accuracy was suitable for topographic mapping at a scale of 1:50,000, but believed that the content was probably more suited to mapping at a smaller scale. Derenyi (1986), and Murai (1986), reported that the accuracy of the LFC imagery was suitable for map compilation at a scale of 1:50,000. However, both believed that as its resolution is only some 10m/lp and as 2-3m/lp is required for topographic mapping, the LFC imagery cannot be used as the sole data source for topographic map compilation.

2.6 Use of Radar Imagery for Mapping

The use of airborne radar for general geoscientific mapping purposes has been reported by several researchers (for example see Lewis, 1968, Nunnally, 1969 and Henderson, 1983). They cited studies focussed on differentiating between land- covers at varying polarisations. Their results give an indication of what might be detected on the SIR-B imagery although the smaller wavelength of the airborne systems would be more susceptible to surface roughness (the SIR-B operated in L-band - 23cm wavelength, compared with the airborne systems which operated in K-band - 2cm wavelength).

Lewis (1968) reported that with like-polarized imagery the discrimination between vegetated residential areas and parks, and non-vegetated urban areas was possible. He also reported that the detection of power lines and railroads when aligned parallel to the flight path was improved. Higher radar returns were received from commercial and industrial areas, while lower returns were associated with open country, pasture and forest. These areas therefore appeared as regions of lighter and darker tones respectively on the radar image. This difference in appearance was reported to be a result of the size, shape and arrangement of objects which were imaged (Lewis, 1968). Horizontal plane surfaces such as grass, parking areas and vacant land, which often comprise the majority of land cover surfaces, combined with the returns from vegetation and frequently dominated the returns from structures. The return from low density residential areas on the urban fringe was indistinct from that of adjacent crops, pasture and forest, as the combination of vegetation and horizontal plane surfaces blurred the urban and non-urban interface. Discrimination of these relatively distinct areas by their appearance on the radar imagery was therefore difficult.

The use of Seasat radar imagery for topographic mapping has been studied. Konecny et al. (1982) suggest that the advantage of radar in being able to penetrate cloud does not compensate for its restricted detectability of general topographic detail. They further report that it is probably not suited for mapping at scales larger than 1:250,000. The topographic mapping experiment will provide a quantitative evaluation of the suitability of SIR-B imagery for medium scale topographic mapping.

2.7 Future Radar Systems

Due to the problems during the 1984 SIR-B mission a re-flight of the SIR-B system was proposed. As a result of NASA's launch vehicle problems, however, the SIR-B re-fly (SIR-B prime) has been cancelled, as it will coincide with the expected launch of SIR-C in 1991. The SIR-B system may be reflown primarily to test the Shuttle's ability to service the Earth Orbiting System (EOS), but data collection will be a secondary consideration.

The operation of the EOS polar platform, post 1994, is expected to provide continuous coverage of the earth using a multi-frequency, quadpolarised, multi- incidence angle radar system. The European Space Agency (ESA) has scheduled the launch of ERS-1 for late 1989. This radar system will operate in C-band (6cm wavelength), VV (vertically transmitted and vertically received) polarized using a 23 degree incident angle. The data will be acquired across an 80km swath with a resolution of 30m. As there will be no recorders on board it will only be possible to access the data in real time. It is therefore desirable that the proposed Australian Centre for Remote Sensing ground station upgrade be completed to enable data reception over Australia. There are also plans for a mobile Japanese station on the Antarctic ice cap to receive data of this region.

The Canadian Government's proposed Radarsat is apparently encountering financial difficulties. It is proposed to operate in C-band (6cm wavelength), VV polarized using a 20-45 degree incident angle. Data with 25m resolution is planned to be acquired across a 130km swath. Near real time data processing is a feature of this system and will allow data to be available within a few hours of overpass. The launch of Radarsat is now in doubt. Japan is developing JERS-1 for launch in 1990. JERS-1 will operate in L-band (23.5cm wavelength), HH polarized using an incident angle of 35 degrees. Data will be acquired across a 75km swath with a resolution of 18m. Of the proposed systems SIR-C offers the opportunity to image the terrain at various combinations, which may assist the detection of features not visible on a single swath. It is proposed that

SIR-C will be a multi-frequency, quadpolarised system able to image at multi-incidence angles. Originally only radar systems operating in L and C bands were to be installed, but now an X-band system (XSAR) developed by the German DFVLR organization is to be added. The EOS polar platform SAR which will provide, for the first time, the ability to collect nine channels of SAR data simultaneously (i.e. all three wavelengths at all three combinations of polarisation - Cimino et al., 1986).

Following data acquisition research will then need to establish the combinations of wavelength, polarisation and look angle that provide the maximum cartographic detail. Research will also be necessary to establish whether this imagery is suitable for the compilation of medium and large scale topographic maps.

CHAPTER 3

CHARACTERISTICS OF RADAR AND SYNTHETIC APERTURE RADAR IMAGING SYSTEMS

3.1 Introduction

Radar remote sensing systems acquire data differently to traditional camera and scanner systems. Radar images are therefore different in geometry and appearance to the images of either of the other two systems. An understanding of the characteristics of radar was therefore required to enable the work to be effectively performed, on the topographic mapping experiment. In this Chapter the basic principles of radar systems are developed leading to the concept of more complex synthetic aperture radar systems.

An overview of the processing of SAR data is given to show the relationship between 'look extraction' and azimuth resolution. As the tones of a radar image are dependent on radar backscatter the factors that affect this aspect are also discussed. Finally, the major differences between a radar image and a passively sensed aerial image are outlined, together with details of radar speckle and texture, which are specific to radar images.

3.2 Basic Principles of Radar

Radar is an active remote sensing system that has four basic components: 1. transmitter 2. antenna 3. receiver 4. recording device. The microwave energy which is generated by the transmitter, in pulses or bursts, is directed at the ground by the antenna. The terrain scatters this incident radiation, some of which is reflected back to the antenna. As the same antenna is shared by both the transmitter and receiver radar is a monostatic system. Subsequent processing of the return signal allows particular characteristics to be extracted and compared (correlated) with a delayed replica of the transmitted signal. The magnitude of the delay is recorded either optically or digitally. To avoid all the return signals being received simultaneously radar imaging systems have their antenna configured to look to the side, hence the original name 'Side-Looking Airborne Radar' (SLAR). The SLAR antenna emits a fan shaped beam with the narrow side of the fan parallel to the 'along track' direction of flight (or azimuth) of the platform. The wider side of the fan is then parallel to the 'cross track' direction of flight (or range). The beamwidth of the antenna b is related to its length and to the wavelength of the emitted radiation in the following way: $b = l / l$ radians where l is the wavelength of the emitted radiation, and l is the length of the antenna. All radar systems measure distances or ranges to objects by using the time taken for the radiation emitted from the antenna to travel to the object and back. The radar beam is emitted, approximately normal to the 'along track' direction, but at an angle from the vertical referred to as the look angle. Its electromagnetic radiation is pulsed such that in time t the resolution element in the range direction Rr is given by: $Rr = c * t / 2$ where c is the velocity of electromagnetic radiation, and R the slant range is found from: $R = c * T / 2$ where T is the total round trip time of the signal. The azimuth resolution of real aperture radar Ra can be approximated by: $Ra = b * R$ where b is the azimuthal beamwidth (radians). Because the azimuth 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 radar platform. Thus $Ra = b * R = b * h / \cos f$ where h is the height of the platform, and f is the look angle. Radars that use antenna beamwidth for azimuth resolution and pulse duration for range resolution are termed real aperture radars. Systems that use pulse width and a long synthetic antenna to improve azimuth resolution are termed synthetic aperture radars (SAR).

3.3 Synthetic Aperture Radar (SAR)

Using the motion of the platform a long antenna for SAR systems is simulated (synthesized). Instead of recording only the one signal returned from an object (as in the case of real aperture radar) in SAR the returns from a number of pulses are recorded, while the object is in the beam of the antenna. The returns are compared with the transmitted signal, enabling the determination of Doppler shift. As the antenna passes over a point, if the time delay and Doppler shift information contained in the returned signals are processed simultaneously, the surface is divided into a coordinate system. The coordinate system consists of concentric circles (time delay) and coaxial hyperbolae (Doppler frequency shift), so that the point can be defined by a unique time delay and Doppler frequency shift (Elachi and Granger, 1982). The resolution is now independent of the range and related only to the accuracy of the measurement of the differential time delay and Doppler frequency shift, thereby improving performance, and making SAR suitable for spaceborne operations. It can be shown that the theoretical azimuth resolution of SAR is given approximately by l/2 (De Loor, 1983) (see Section 3.3 below). Azimuth resolution is now only a function of the antenna length and independent of the operating altitude and the wavelength, and will reduce as the antenna length is reduced. 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 handling considerations increase sharply as the antenna length is reduced. For two objects to be separated in range the distance d between them is given by: Equation (1)..d = c * t / 2 where c is the speed of light t = pulse duration. This distance is measured in a straight line from the elevated sensor to objects in the terrain and is therefore a slope distance. It can be converted to a horizontal distance dg by dividing the slant range by the sine of the look angle f. Thus, dg = c * t/(2 * sin f) In a radar system the range resolution is a function of the slant-range resolution modified by the incidence angle. It is, therefore quoted as a range of values. Azimuth resolution is only dependent on the system and the number of 'looks' and is thus a constant value.

3.4 The Processing of SAR Data - An Overview

The radar pulse has a duration of t and a carrier frequency fo related to wavelength l by fo = c / l For the SIR-B system where the wavelength l is 23.5cm fo is 1.28GHz. As range resolution is dependent on the pulse duration t from equation 1 above, if the pulse duration is reduced the resolution is increased. A shorter pulse duration reduces the amount of energy in each pulse and limits the range of the radar unless the pulse amplitude is increased to compensate. However, a limit on the pulse amplitude is imposed by the electronic capacity of the system. To avoid this problem synthetic aperture radar does not use a simple pulse. Instead a linear chirped waveform or ranging 'chirp', where the frequency increases linearly with time, is transmitted. The carrier frequency remains fo as defined above. At time t, where the time origin is adopted at the middle of the chirp, the frequency f of the chirp is such that: f = fo + at where a is the chirp rate, and a * t = B, the chirp bandwidth. The bandwidth for the SIR-B chirp is 12MHz; less than a 1 percent variation from the central frequency of SIR-B, 1.28GHz. Resolution in range is achieved by comparing the received chirps with a replica of the transmitted chirp. That is, a sweeping waveform is correlated with itself, thus producing a short pulse where the energy of the received signal is compressed into a pulse with an effective width inversely proportional to the bandwidth B. Azimuth resolution is similarly obtained by comparing the azimuth chirp with a replica of itself, thus producing a short pulse with an effective width which can be shown to be equivalent to a distance of l/2 (where l is the antenna length). Unlike the range chirp the azimuth chirp is motion induced and is a function of the Doppler shift caused by the motion of the platform relative to the ground. In practice, however, the azimuth chirp is affected by earth rotation and platform attitude changes. Therefore, the replica is derived from the return signal. From a given transmitted chirp, the set of return chirps from the terrain form a range line of data. As the return chirps are a continuous signal this signal is sampled (range gated) and these samples are stored on magnetic tape. Subsequently this data is transferred to computer memory for processing. The complete set of radar reflections for a given area of terrain will therefore consist of many range lines. Radar returns from a point target in the terrain will occupy a number of computer memory cells (range bins) in each range line and a number of memory cells in azimuth (azimuth bins). Range and azimuth correlation takes this spread of data and compresses it to a single bin corresponding to the return from the point target. This procedure implies that the slant range to a point target is constant irrespective of the position of the platform. In practice the slant range varies quadratically as a function of the distance between the platform and the point directly abeam the object. During data acquisition earth rotation causes a skew effect and together with the continuous slant range variation leads to the range compressed line of data being 'curved' in the memory i.e. the data for the point target migrates across range bins as a function of azimuth. This causes errors following azimuth compression unless this 'Range Cell Migration' is corrected. Therefore, any range migration is corrected following range compression and before azimuth compression. Range migration is not always a significant correction and its effect can be predetermined and a decision made as to whether it will be corrected during processing. A corner turning algorithm is also incorporated in the processing which takes the data written in range line order and rearranges it so that it can be read in azimuth line order. The 'Range Cell Migration' process, uses information on the centre of the radar beam as a function of range, to extract lines of azimuth data corresponding to a fixed value of range (Cumming and Bennett, 1979). The data is now suitably formatted for azimuth compression.

Instead of compressing the entire azimuth signal energy in one operation the Doppler spectrum is divided into several segments or "looks" (Curlander, 1986); this process is called 'look extraction'. A single image cell is then formed by summing the intensity of a number of looks. Processing by look extraction has the advantage of removing some of the 'speckle' inherent in coherent imaging systems. It also has the disadvantage however of reducing the azimuth resolution from the theoretical one look value of l/2 to a value equal to the product of the number of looks and the l/2 value. The reduction in resolution occurs as the signals from a number of resolution elements are combined in one signal of a larger cell. SIR-B is processed to four looks so that the azimuth resolution is reduced from around 6m (l/2) to approximately 25m (4 x {l/2}). The SIR-B radar data provided by the Jet Propulsion Laboratory (JPL) included a swath over the eastern part of NSW and Victoria. The swath consisted of three multiple angle scenes or Data Takes (DT) with look angles of 48 degrees (DT 83.8), 37 degrees (DT 67.8) and 17 degrees (DT 51.8). Resolution in azimuth was about 25m for all three swaths. Resolution in range was dependent on the look angle and varied from 17m for DT 83.8 to 58m for DT 51.8. The data was processed to a standard pixel size of 12.5m.

3.5 Radar Backscatter

The grey tones in a radar image are determined by the amount of reflected radiation (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 sub-surface. It is therefore dependent on the illumination and scene parameters. For a particular system, however, the average return varies only with the radar 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 (i.e. the ratio of the scattering cross section to the actual cross section of the illuminated area). The relationship of all the factors affecting backscatter ‟ can be expressed as follows: ‟ = f (l,P ,f,a,o,E ,T1,T2,V) where the system parameters are: l the wavelength of the radiation, P the polarisation of the system, f the look angle, a the azimuth angle, and the scene parameters are: o the aspect angle, E the complex dielectric constant, T1 the surface roughness, T2 the sub-surface reflectance, V the complex volume scatterer, (from Colwell (Ed.)., 1983) Changing one or several of these parameters will alter the backscatter and result in different information being acquired.

As the carrier frequency of the radar pulse is set by the system electronics the wavelength remains fixed. Additionally, the azimuth angle for a particular orbiting system relative to ground features also remains constant. The depression and aspect angles are inter-related. The depression angle determines how the radar beam strikes the terrain relative to the true vertical whereas the aspect angle determines the local vertical. Thus the combination of depression angle and the aspect angle will indicate how a particular ground surface is oriented to the beam. Radar backscatter is maximized when the sum of the depression and aspect angle is 90 degrees, i.e. the ground surface is normal to the beam. The parameters of complex dielectric constant, polarisation, surface roughness and volume scattering vary with the terrain being imaged and are therefore discussed in more detail.

3.6 Major Factors Affecting Backscatter

3.6.1 Dielectric Constant

The speed at which an electromagnetic wave propagates through a medium is inversely proportional to the magnetic and electric properties of that medium i.e. the medium's permeability and permittivity. In remote sensing the interest is in media that are non-magnetic so that the permittivity will be different and always greater than that of free space (permeability maintains its free space value). The permittivity, also called the dielectric constant, is sometimes given as a complex number, with a real and imaginary part. The so-called complex dielectric constant represents the permittivity of the medium by the real part and the conductivity of the medium by the imaginary part. The dielectric constant of a media is a strong function of its moisture content. Moisture, and to a certain extent the salinity of that moisture, in a media can significantly increase radar reflectivity and thus reduce penetration. Depth penetration is defined as the depth below the surface at which the magnitude of the power of transmission is equal to 1/e (e = 2.718, the exponential constant) of the power just beneath the surface. In a medium with a constant moisture content the wavelength of the radiation must be increased to obtain an increase in the penetration of that medium. The high dielectric constant of water means that even a low soil moisture content will result in little penetration and reduced backscatter.

3.6.2 Polarisation.

All electromagnetic energy has electric and magnetic fields operating at right angles to each other and normal to the direction of propagation. This allows the electric field vector to be polarized in either the horizontal or vertical plane. The mechanism responsible for depolarisation is not definitively known (Sabins, 1978). However, the most widely accepted theory attributes it to multiple reflections at the surface. This theory is supported by depolarisation effects being observed to be much stronger from vegetation than from bare ground. Leaves, twigs and branches that essentially comprise vegetation cause the multiple reflections thought to be responsible for depolarisation. The degree of polarisation of the return signal has been postulated to be a function of object orientation and the Fresnel reflector coefficient. The latter is a function of the complex dielectric constant and the angle of incidence (Lewis, 1968).

3.6.3 Surface Roughness.

The roughness of the surface relative to the wavelength is the major contributor to surface scattering. Volume scattering is caused above the surface by vegetation and below the surface by changes in the soil profile. A surface scatterer can be considered as a homogeneous medium, whereas a heterogeneous medium is considered to be a volume scatterer. A homogeneous medium has a uniform composition in contrast to a heterogeneous medium which is comprised of a large number of discrete and differing components. Radiation striking a surface is either reflected specularly (if the surface is smooth) or diffusely (if the surface is rough). The boundary between these two extremes is a function of three parameters: - the height of the irregularities in the surface, - the periodic nature of the irregularity, and - the grazing angle of the incident ray, (i.e. the angle between the incident ray and the surface).

Rayleigh's criterion relates these factors as follows: $h < l / (8 * \sin G)$ where h is the height of irregularity, l is the wavelength of the radiation, G is the grazing angle. This criterion says that a surface can be considered rough if the RMS of height variations exceeds the quotient of the wavelength and eight times the sine of the grazing angle. In effect the grazing angle determines how much of the irregularity the radiation 'sees'. Approaching at a low grazing angle the radiation would see little height difference even if the irregularity was extreme. Conversely, as the grazing angle increases, the radiation will see more and more of the height difference. The relationship between wavelength and height variation can be considered in terms of their relative dimensions. If the emitted wavelength is smaller than the height variation, then the radiation will be scattered by the terrain. If the wavelength is larger than the height variation, then a greater proportion of the radiation will be reflected specularly by the terrain. Because the radiation sees the irregularity as being larger than the wavelength at all times, at short wavelengths, surfaces will appear rough irrespective of the incident angle. With increasing wavelength, at low grazing angles the surface can appear smooth. As the grazing angle is increased, more of the height difference is detected and the surface appears rougher. At the larger wavelengths then, a rough surface even at high grazing angles will appear to be smooth to the radiation as the wavelength will generally be greater than the height difference. Thus the radiation will be reflected specularly.

In general, backscatter is controlled by topography at lower incidence angles and by small scale roughness at larger incidence angles. For regularly spaced features (such as crops in aligned rows or a particular sea state) the return signal from two parallel rows can be in phase. This results in a reinforced signal. Conversely the return signal can also be out of phase resulting in the return being negated. This phenomenon is known as Bragg scattering and is dependent on the separation of the rows L, the look angle f and the wavelength l of the system. These parameters are related as follows: L * sin f = K (l /2) When K is an even integer value the return signals are in phase; and are out of phase if K is an odd integer value. If the periodic nature of the irregularity is uniform over a large area (for example a ploughed field) then the backscatter is likely to be relatively more than if the irregularity is random. This arises because the beam 'sees' the surface with random irregularities as a more specular reflector. This effect can also be caused by canopy roughness, where a tree canopy or other vegetation canopy appear as a surface to the radar beam. Injecting the wavelength (23.5cm for SIR-B) and the three incidence angles (assuming flat terrain) into Rayleigh's criterion yields the values for the height of the irregularity h as listed below: Look-angle h (degrees) (cm) 17 3.07 37 3.68 48 4.39 Thus a surface with irregularities less than the value of h will be seen as a smooth surface by the SIR-B system and the radiation will be reflected specularly. The above example shows that the relatively long (23.5cm) wavelength of the SIR-B system, irrespective of look angle, is largely unaffected by sub 1cm changes in surface roughness.

3.6.4 Volume Scattering.

Spatial inhomogeneities at scales relative to the radar wavelength create a volume of scatterers (Forster and Trinder, 1985). Vegetation can appear as a random volume of scattering facets. Different layers of material in the soil may also create a volume of scattering elements beneath the surface. Penetration of microwaves into the soil is a function of the dielectric constant which is related to soil moisture content. There is a rapid decline in penetrative depth as moisture content increases, especially at the longer wavelengths. Volume scattering is primarily caused above the surface by such vegetation as leaves, stalks and fruit acting as a very large number of discrete components. In forest areas tree trunks and limbs have a greater scattering effect than their leaves. The tree trunks and limbs provide multiple-path reflections and account for the isotropic (equal at all angles) backscatter from vegetated surfaces.

Backscatter provided by volume scattering is very susceptible to movements in the vegetation. Its magnitude is affected when the canopy is wet by rain or dew which makes the foliage droop and increases the number of reflecting surfaces. In windy conditions the scattering elements are continually moving thus producing a fluctuating return which can add to the overall speckled appearance of the imagery. In dealing with 'natural' targets, the combination of vegetation, soil surface and soil profile contribute to the complexity of the target and form part of the total surface "roughness" (Colwell (Ed.)., 1983).

3.6.5 High Backscattering Mechanisms.

Long linear, flat or rounded metallic objects can lead to a high backscatter especially if normal to the radar beam. Corner reflectors create a higher return by reflecting a relatively greater proportion of the incident radiation back to the receiver. A corner reflector is created by either two or three planes being mutually perpendicular and as corner reflectors are generally man-made they predominate in city and urban areas. Elements which have either a high dielectric constant or a length half the wavelength of the incident radiation can act as antennae. This antenna effect directs a high level of the incident radiation back to the radar antenna.

3.7 Backscatter and Tonal Differences

Differences in received backscatter are due to the differences in the scattering coefficients of the point sources in the area illuminated by the radar beam. Bright tones in the image are caused by high backscatter and darker tones by low backscatter. The tonal variations on a radar image give it the appearance of a black and white passively sensed aerial image whose shading represents the amount of reflected light. However, any further similarity with passively sensed aerial imagery ends there because the basis for high or low radar returns depends on variables related mainly to the wavelength and magnitude of surface roughness.

The tonal variations result in one of the more confusing aspects of radar images. Heavily vegetated and open country on a radar image have the reverse appearance to that on a black and white aerial image. Compared with forests open country is a relatively high reflector of visible light and hence appears bright on a passively sensed aerial image. The radar wavelength generally 'sees' open country as a smooth surface. Thus the majority of the radar radiation (which strikes the terrain at an angle) is reflected away from the sensor. The resultant backscatter is therefore low giving open country on a radar image a dark appearance. Conversely a forest area scatters radar radiation and relatively more backscatter is received by the sensor and hence it appears bright on the radar image. On a passively sensed aerial image forest areas appear dark. These differences must be understood to correctly interpret radar imagery. Furthermore, relief causes slopes facing the radar radiation to reflect a greater amount of radiation. These slopes thus appear bright on the radar image. Slopes that slope away from the radar radiation can be in radar 'shadow', or reflect a reduced amount of radiation, appearing darker on the image. This effect can appear similar to the relief shading on topographic maps.

A special effect of radar is noticeable in built-up areas. The rectangular planes of roads and buildings strongly return the radar beam, whereas streets parallel to the beam reflect the radiation away. The high and low backscatter produces a pronounced speckle effect. Orientation of objects to the radar beam changes the pattern of backscatter and therefore the appearance of those objects in the image. Features which alter their orientation relative to the beam such as rivers and roads also alter their detectability. Streets having a particular orientation may be easily visible whilst those streets running at right angles may not be detectable.

Metallic objects (particularly wire fences or power lines) that are normal to the radar beam can saturate the return and appear as very bright lines on the image. Thus the characteristics of radar backscatter from the terrain influence the appearance of features on radar images. Consequently, it may not be possible to consistently identify these features for map compilation.

3.8 Radar Speckle

Due to the monochromatic and coherent nature of the microwave radiation, the return signal is the vector addition of signals resulting from reinforcement or negation from different picture elements within the resolution cell (Krul, 1983). This creates the speckle effect on SAR imagery which appears as a grainy, granular noisy phenomena of black and white random pixels (Barber, 1983). Although look extraction during the processing of SIR-B data suppresses the speckle (see Section 3.4), the compromise between speckle reduction and resolution results in residual speckle being present in the processed radar images as well as a reduction in image quality.

3.9 Radar Texture

Spectral, textural, temporal, and contextual features are the four most important pattern elements used in human interpretation of image data (Frost et al., 1984). Spectral characteristics describe band to band tonal variations in a multi-band set, whereas textural features describe the spatial distribution of tonal variations in a single band. Contextual features contain information about the arrangements of image segments belonging to different categories, while temporal features describe changes in image attributes as a function of time. Synthetic aperture radar images contain only tonal and textural features. Consideration of the visual interpretation of radar images reveals that the intrinsic spatial variability or 'texture' of the image beyond that caused by speckle is a valuable feature in discriminating different land use types. Texture may be more useful than image tone in interpreting radar images, (Frost et al., 1984, Ulaby et al., 1986). The textural patterns provided by radar as well as the image tone assists the photo- interpreter to discriminate detail. Three components of texture on radar images are micro, meso, and macro texture (Colwell (Ed.), 1983). Micro image texture tends to be random while meso and macro texture are spatially organized. Micro texture is related to the resolution in range and azimuth as well as the number of independent samples. All smooth surfaces will generally exhibit fine (or micro) texture. Meso texture is produced by spatial irregularities of the order of several resolution cells. It is most striking where there is a sharp change in the relative relief of the forest canopy, or where a highly variegated soil-vegetation pattern exists in a marshy environment. Macro image texture permits identification and delineation of bounded homogeneous unit areas. Meso and micro texture are apparent in SIR-B imagery and enable the delineation of the different areas of open country, scrub and plantation from one another.

CHAPTER 4

GEOMETRIC ACCURACY OF SIR-B IMAGERY

4.1 Introduction

A primary need for potential users of radar data is an understanding of the inherent limitations of the use of SIR-B and future radar data for planimetric mapping purposes. The positional accuracy affects both the imagery's mapping potential and the ability to register it to other data obtained from separate SIR-B passes, or to data from other experiments. An understanding of the SIR-B planimetric accuracy will help to define the limits on the use of the spaceborne SAR systems for projects that may require registration with ancillary data, or multi-sensor data (NASA SIR-B Science Plan, 1984). Registration is the spatial transformation (rotation, expansion or contraction) or geometric "rubber-sheeting" of individual pixels to match a reference image or base map. To determine the geometric accuracy of SIR-B imagery, the distortions in the data needed to be established and their effects calculated. The positions of selected features in the radar data when corrected for the effect of the distortions can be compared with their positions in such ancillary data as Landsat and line maps on a geographic grid. As part of the geometric accuracy evaluation (see Section 4.3 below), 2m square metal corner reflectors were positioned in the field at Bowral some 120km south-west of Sydney. The reflectors were positioned prior to the launch of the Shuttle carrying SIR-B, and coordinates obtained by Magnavox satellite receiver. These reflectors created strong signal returns that generally assisted their detection on the SIR-B imagery and enabled the true distances between them to be compared with the distances derived from the radar imagery.

4.2 Distortions in Radar Imagery

The geometry of radar imagery is fundamentally different from both aerial photography and scanner imagery as radar is a distance rather than an angle measuring system. Radar images are therefore range projections (Wu, 1984). Features displayed on radar images are distorted. The distortion inhibits subjective interpretation and precludes quantitative analysis of spatial relationships (Naraghi et al., 1983). The distortion is essentially a function of both the data recording and processing system and the platform and shape of the earth. Such distortion can be substantially eliminated during processing. 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, the projection in azimuth not being affected; ground range non- linearity caused by a variation in the look angle across the swath and skew; and a second order effect caused by a variation in the rotational velocity of the earth between near and far range (Curlander, 1984). The last two effects are substantially eliminated during processing by the Jet Propulsion Laboratory. However, errors arising from the adopted platform ephemeris and the shape of the Earth, can lead to small residual errors in the processed data. Radar imagery, aerial photography and scanner imagery all contain the distortion produced by local elevation variations. Due to relief displacement the aerial photograph and scanner image record the tops of objects away from their true plan position in a radial direction. In a radar image the tops of objects are recorded away from their true plan position in the range direction, towards the sensor. Geometrically, for layover to occur the angle of slope of the terrain must be greater than the radar look angle. Terrain slopes facing the radar will be foreshortened while slopes facing away will appear to be elongated. The displacement caused by layover can be calculated and used to restore objects to their true plan position. Detail in radar shadow, however, is lost.

4.3 Basis of the Evaluation of Geometric Accuracy

Residual errors in the geometry of the processed SIR-B images were assumed to be systematic in nature and could therefore be modelled by a first, or higher degree polynomial. The displacement due to layover was considered separately. For each control point selected it was necessary to correct firstly the image coordinate in range for the effect of layover before computing the polynomial or mapping function which referred to a particular height datum. Polynomials (mapping functions) based on control points common to both the image and ground were computed to transform the corrected line and pixel (range and azimuth) coordinates on the image, to the ground coordinates (easting and northing). Ground coordinates of the common points were derived from maps at suitable scales. The coordinates of a limited number of well distributed control points common to both the image and the map allowed the determination of a polynomial. This polynomial was used to transform the coordinates in one system to the coordinate system of the other. If high order terms as a function of image coordinates were found to exist in the polynomial, then it was probable that significant second or higher order errors were present in the geometry of the SIR-B data. For a good determination of the polynomial and to allow for errors in the SIR-B geometry a large number of common control points were thus located for each of the four SIR-B sections tested.

4.4 Procedure

The geometric accuracy evaluation consisted of five parts:

1. investigation of layover correction algorithms,
2. determination of the relationship between displacement (layover) and elevation,
3. measurement of ground control point coordinates,
4. processing and editing the data sets,
5. evaluation of results.

Sections of the three multiple angle data takes with look angles of 48 degrees (DT 83.8), 37 degrees (DT 67.8), 17 degrees (DT 51.8), over areas near Sydney were used as test sites for this evaluation. The first site, to the north of Sydney, had a predominance of coastal and lake features and was imaged on DT 83.8 and DT 67.8. The second site, a rural area, around Bowral some 120km to the south west of Sydney, was imaged on DT 83.8 and DT 51.8. The Bowral site contained the 12 metal corner reflectors (referred to in Section 4.1) which had been placed as ground control.

4.4.1 Layover Calculation.

As discussed in Section 4.2 relief causes objects in the radar image to be displaced, in range, relative to their true plan positions towards the sensor. The magnitude of this layover effect needed to be determined to allow a correction to be incorporated in the data. The amount of displacement was calculated using the following three algorithms: A simplified calculation. A calculation assuming a flat earth. A calculation assuming a spherical earth. It was concluded that the more rigorous calculation using a spherical earth provided the most accurate determination of displacement, especially where the layover was excessive. This algorithm was therefore adopted for all further layover calculations.

4.4.2 Relationship between Height and Layover Correction.
Instead of separate calculations for each discrete point (as terrain height is a continuous variable), it is preferable to use a simple relationship to calculate layover for different terrain heights. To determine if a simple relationship between layover and height exists the layover correction at heights of 0, 100, 500, and 1000 meters were calculated for each of the three data takes. The quotient of the layover correction and height was then determined. This column indicates that the height and factor increase proportionally within the range of heights where the work was being undertaken. For each data take then, the appropriate near and far range corrections for layover were introduced into the data and a linear interpolation used to calculate the displacement for any position across the swath and elevation above datum.

4.4.3 Selection of Ground Control Points.
Control points were selected with reference to topographic maps at 1:100,000 scale and the radar image displayed on the DIPIX Image Analysis System. The line and pixel value for each point together with its northing and easting, scaled from the map, were recorded for input into data files for later analysis. Although pin-point features were preferred as control points (such as cross-roads and stream intersections), it was found that areal features predominated on the radar imagery and point features were very scarce. The coastal site (DT 83.8 and DT 67.8) contained promontories or points with a very distinguishable boundary between land and water. Water reflects the radar beam away from the antenna and it therefore appeared darker than the adjacent land. Such points proved to be excellent for use as control. They also had the advantage of being close to sea level so that the range coordinates were unaffected by terrain height. Un-sealed roads were visible between trees on the scenes with the largest look angle (48 degrees). Boundaries between timbered and open country were also visible. In places power lines were also visible, but generally this feature could only be detected because of its particular orientation to the radar beam. For the rural scene

(DT 83.8 and DT 51.8) the areal features were valleys and spurs. The radar shadow and highlight effect made accurate location on the radar image difficult. Similarly, these topographic features were not well delineated on the cartographically generalized maps and caused difficulty in the determination of map coordinates. Leberl et al. (1986) reported having similar difficulties. They stated that it became very apparent that the contents of a map at 1:100,000 scale do not, in general, include many details that appear on radar images. On the other hand, maps describe a wealth of features that cannot be identified on the radar images. Therefore, it is preferable to have available another type of reference data such as aerial photography. Orthophotomaps would be even more advantageous as they depict geometrically correct image detail but in Australia orthophotomaps are not nationally available. An attempt was made to improve the accuracy of the scaled map coordinates by using maps at a scale of 1:25,000. However, the generalization of the topographic features in the rural areas did not enable the positions of the control points to be definitively located. This uncertainty of location negated the improvement possible in coordinate accuracy. The data derived from the maps at 1:25,000 scale were therefore tested only for the coastal scene (refer Section 4.4.5).

4.4.4 Processing and Editing the Data Sets.

Software was available to perform a least- squares adjustment of the radar image line and pixel coordinates to the map coordinates. Included was an option to vary the number of polynomial terms as well as the correction to range (line) for the layover effect. The adopted standard errors were 30m for the ground coordinates and 5 pixels for image coordinates. The largest data set (DT 83.8) was adjusted a number of times. Points with residuals larger than the computed RMSE were validated and either accepted or rejected. Once an acceptable data set was found a test was carried out to determine the most significant terms in the polynomial transformation. This test was based on the overall residuals and also the variance of the parameters. Map coordinates derived from the 1:25,000 scale map, with an adopted standard error of 7m, were also introduced. This was to determine, and prove, that the polynomials produced consistent results.

4.4.5 Evaluation of Results.

The results show the accuracies of the affine transformations in relating the coordinates derived from the radar images to those of the ground control. The results for the rural scene (DT 83.8 and DT 51.8) are based on far fewer ground control points due to the topography and availability of features. The control also included three points marked with the metal corner reflectors. Even so, the transformation is only marginally worse for the rural scenes than for the well controlled coastal scenes. Dimensions of pixels on DT 83.8 were 12.65m and 12.82m in range and azimuth respectively. This revealed a 1.5 percent distortion in scale. The pixel size derived for DT 67.8 was 12.52m which indicated no significant scale distortion.

It is understood that DT 83.8 was processed early in the SIR-B program, whereas DT 67.8 was processed later based on more precise ephemeris data. In one DT 83.8 scene, the pixel size calculated between two of the corner reflectors in an area to the south of the scene agreed well with the pixel size from an area to the north of the same scene. There was no significant increase in accuracy using more 'precise' coordinates scaled from the 1:25,000 map; in fact, there was a deterioration of one pixel in the RMS. This was caused by the difficulty in selecting a point on the map corresponding to the centre of an area on the image. At 1:25,000 scale the determination of the actual centre of a feature can vary. Although most re-scaled points had coordinates within 100m of their previous values, there was no guarantee that they represented the objects' centres any better than the initial set of values. Therefore, it is considered that a topographic map at 1:100,000 scale is sufficiently accurate to provide ground control values. Leberl et al., (1986) also found topographic maps at 1:100,000 scale suitable for providing ground control values for their work with SIR-B imagery. Provided there is a reasonable distribution of control points throughout the scene, it is considered that the position of features could be extracted to an accuracy (expressed as an RMS) within 3 pixels in northing and easting. This approximates a vector RMS of 4 pixels or 50m on the ground. Transformation accuracy is a function of the number and quality of control points available from the data. Therefore, a large number of artificial control points (for example corner reflectors) would be required, particularly in rural areas, to improve the accuracy of transformation.

CHAPTER 5

FEATURE IDENTIFICATION USING SIR-B IMAGES

5.1 Introduction

The cartographic content is directly related to the spatial resolution of the radar image data. Studies by Welch (1982) and Konecny et al. (1982) suggest that to satisfy the accuracy and completeness standards for mapping at scales of 1:50,000 or larger necessitates the use of image data acquired by sensors having an instantaneous field of view (IFOV) of less than 5 - 10m. Sensors operating in the optical wavelengths have not yet been developed to achieve such a high resolution in free-flying space operation and are only available for aircraft borne applications. Similarly, with microwave systems, sub 10m resolution is limited to aircraft borne systems. Because of the complexity of SAR, significant increases in resolution seem unlikely in the foreseeable future. Nevertheless, the amount of cultural detail required for map compilation, which can be interpreted in SIR-B imagery has yet to be fully investigated. Three methods of registering Landsat and radar images are evaluated in this Chapter. This is to establish whether more cultural detail can be detected in the composite image. The theoretical potential of radar images for topographic mapping is discussed in Section 5.6 and the content of the radar images is then quantified in Section 5.8, using a method developed by Welch.

5.2 Enhancement of Landsat Images using SIR-B Imagery

The potential of radar data for mapping purposes depends on the information content of the data and on its interpretability. Preliminary work by other researchers at the Centre for Remote Sensing, UNSW, indicated that in Landsat images overlaid with radar images, the aggregate information content was enhanced, thereby assisting interpretation. Two data takes DT 51.8 and DT 67.8 partly overlap in an area south of Sydney also covered by a Landsat scene acquired about the same time as the SIR-B data. Water features along the northern and southern edges provide control for registration. These three data sets were resampled and registered to provide the following composite images which were used for visual analysis: - the Landsat image overlaid with either or both SIR-B images, all resampled to 25m pixels, - the Landsat image overlaid with either or both SIR-B images registered to the base mapping, resampled to 25m pixels. The objective was to establish if the interpretation of cultural features was improved in the composite images.

5.3 Methodology

5.3.1 Feature Reduction.

The DIPIX Image Analysis System uses three colour guns for image display. As two of the colour guns were required to display the radar images only one gun was available for the Landsat image. As three of the four Landsat bands are usually displayed to facilitate feature interpretation, being limited to a single Landsat band reduces the interpretability of cultural features. To maximize the detail in this one Landsat band a principal components transformation (refer Appendix E for more detail) was used. This transformation compresses the data contained in the original 4 Landsat bands into 2 new bands. One new band contained most of the detail and the second new band showed the boundaries between the urban and forest areas more clearly. Either of these transformed bands could then be displayed using the remaining colour gun without a reduction in the interpretability of the detail. The composite images formed using a combination of the two transformed Landsat bands and the two radar scenes (refer Section 5.4) were viewed to establish if the cultural detail was enhanced.

5.3.2 Resampling.

The Landsat image had nominal 80m pixels while the radar images had 12.5m pixels. The pixel size of the SIR-B images however, is 12.5m irrespective of the range and azimuth resolution and this is confirmed by Leberl et al. (1985). Thus while the 80m pixels of Landsat are indicative of its resolution the radar pixel size is fixed during processing. The resolution in azimuth of SIR-B is about 25m and range resolution varies depending the look angle (refer Section 3.3). At a look angle of about 30 degrees, however, the range resolution of SIR-B radar is approximately 25m, the same as the azimuth resolution. Although the two data takes had look angles of 17 degrees and 37 degrees (i.e. a range resolution of 43m and 21m respectively) it was considered that these images could be resampled to 25m with little loss of detail. Resampling the Landsat image to 25m pixels from 80m pixels, did not result in any noticeable loss of definition.

5.3.3 Registration.

For registration of the images the following three approaches were adopted: 1. Radar DT 51.8 registered to radar DT 67.8, then both radar images registered to the Landsat image. 2. Radar DT 51.8 and radar DT 67.8 individually registered to the Landsat image. 3. Radar DT 51.8, radar DT 67.8 and the Landsat image individually registered to the map base at 1:100,000 scale. The first approach made use of points of common detail which appeared in both radar images. DT 67.8 had less layover than DT 51.8 and more points of detail common to the map could also be detected. Therefore, DT 51.8 was registered to DT 67.8 and DT 67.8 subsequently registered to the Landsat image. This required that DT 51.8 be resampled twice whereas DT 67.8 was resampled once. The second approach registered the radar images directly to the Landsat image. Common detail however appeared differently in the two data takes and thus made precise positioning difficult. The resulting registration was less accurate for DT 51.8 which had severe layover. The third approach registered the Landsat image and the radar images individually to the base mapping. In this approach map generalization caused difficulty in the identification of common points. Resampling and registration were performed using the DIPIX Image Analysis System. Transformation polynomials were calculated to link the data sets without any compensation for radar layover. The results indicate that a second degree transformation polynomial only marginally improves registration, and do not show any clear indication as to the best method, although either approach 2 or approach 3 appeared to be more sound than approach 1. During later analysis, approach 3 gave information not apparent from approaches 1 and 2 and thus this method is favoured. However, approach 3 relied heavily on control points associated with the water features. In most areas there may be few such features available for selection thus making registration difficult.

5.4 Analysis of the Composite Images

The three approaches produced three sets of images for evaluation. Each set was made up of the first two principal components of the Landsat scene and the two radar images. This made six composite images per set as follows: 1. Principal component 1 and radar image DT 51.8 2. Principal component 1 and radar image DT 67.8 3. Principal component 1 and both DT 51.8 & 67.8 4. Principal component 2 and radar image DT 51.8 5. Principal component 2 and radar image DT 67.8 6. Principal component 2 and both DT 51.8 & 67.8 Set 1 was obtained by the registration of the two radar images together and then both to the Landsat image. On this set the sides of the valleys facing the radar beam were highlighted and gave some impression of the topography. The water features were clear and reasonably well defined. In the urban region the higher backscatter (brighter tones) indicated a change of surface. However, there was no discernible boundary between the timber and urban areas, and neither were any roads nor tracks in the forest areas visible. Set 2 was obtained by the registration of both radar images separately to the Landsat image. It gave similar results to Set 1. Set 3 was obtained by individually registering the radar images and Landsat image to the base mapping. Results for the Set 3, DT 51.8 composite were again similar to that from Sets 1 and 2. The result from the Set 3, DT 67.8 was unexpected. The radar image appeared to "float" above the Landsat image background, particularly in the forested areas. Clearly defined through the radar 'layer' were forestry tracks and clearings. With the radar antenna set at the lower look angle of 17 degrees the system received the radar return from the tree canopy in advance of the return from the ground. Therefore, the layover effect of the trees obscured the ground detail in the cleared areas. With a higher look angle of 37 degrees the radar return from the cleared areas and the forest canopy is received sequentially which resulted in reduced layover and hence clearings within the forest were visible on the imagery. It was difficult to determine why the same details were not visible on the other Sets with DT 67.8. Repeating the registration did not change the result. The characteristic textural patterns on the radar images consistently showed a distinctive boundary between the open and timbered areas. This boundary was due to the reduced backscatter and therefore darker tones of cleared areas and the higher backscatter and thus lighter tones of the timbered areas.

5.5 Evaluation of Results

Registration of the images to a base map was indicated as being preferable in this investigation. This was due to the improved detectability of tracks and clearings in the composite images formed by this approach. Although numerous points of common detail were available, the layover effect caused by large differences in relief made registration difficult. In areas of little detail and unless the radar image can first be corrected for the layover effect, an acceptable registration may well be impossible. Moreover, if only a few control points can be selected high order transformation polynomials should be avoided in order to prevent distortions being introduced in areas between the control points. The use of a higher look angle radar image registered to a Landsat image provided an enhanced image in this evaluation. It is perhaps doubtful that in this particular evaluation the Landsat image needed any enhancement to aid feature detection. Nonetheless, the ability to register the two data sets indicates that composite images can usually be formed without any prior correction to the radar image. This will allow radar imagery to be used in other investigations together with remotely sensed imagery acquired by other sensors. 5.6 Theoretical Mapping Potential of SIR-B Imagery Doyle (1982b) postulated a relationship between pixel size and recommended map scale for electro- optical and photographic systems. The relationship is based on the resolution of the human eye, at normal reading distance of about 25cm, as 7 line pairs per millimetre (lp/mm). For photographic systems, the relationship between ground resolution Rm in meters per line pair (m/lp) and image scale number Sm is given by: Equation (1)....Rm = Sm / 7000 m/lp As 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: Equation (2)....Pm = Sm /17500 = 0.57 x 10 -4 Sm The radar image pixel size is fixed at 12.5m irrespective of actual resolution (Leberl et al., 1985). As stated in Section 5.3.2 the ground resolution in range for the higher look angles is approximately the same as the azimuth resolution, 25m. By accepting 25m as a more representative pixel size, and therefore adopting Pm = 30m, equation 2 returns a value for Sm of approximately 500 000. This suggests that radar imagery, acquired at higher look angles, would be suitable for mapping at a scale of 1:500,000. At lower look angles, the resolution in range is reduced by a factor of two. Such radar imagery may theoretically be only suitable for mapping at a scale of 1:1,000,000. These results appear to be supported by Konecny et al. (1982). They suggest that compared with aerial photography, radar images acquired by Seasat cannot be properly interpreted to derive all required topographic features. Furthermore, they state that radar images may show many other features such as metallic objects fences, power lines and vehicles. They conclude, however, that the use of radar imagery as the primary data source for topographic mapping at a scale of 1:250,000 is questionable and therefore radar images can only be used to supplement the primary data source. 5.7 Features Detected on SIR-B Imagery The interpretability of cartographic features is a more subjective quantity to assess than the geometric quality of the image. However, it is usually the factor governing the scales of mapping for which the imagery may be used. The interpretability of features is related not only to their dimensions in relation to the pixel size, but also to their contrast against their background. For an object to have contrast against its background in a radar image it must return a different amount of radiation than its surround (Koopmans, 1986). Relatively darker or lighter toned pixels are produced by the relative difference in the backscatter. There is a large number of variables which affect the contrast of features. Most of these variables are related randomly to one another and thus have an unpredictable effect on contrast. The radar return from an object depends on its orientation with respect to the beam, its size, 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. From work on the registration of SIR-B images acquired at different look angles (described in Section 5.3) difficulty was experienced in selecting points of common detail. This was partly due to the effect of layover and the lower resolution of the images acquired at lower look angles. There was also a lack of contrast caused by the longer SIR-B wavelength relative to the general surface 'roughness'. Although the amount of cultural detail contained in the radar images varied, some generalizations on the content can be stated. Generally linear features such as roads, tracks and railways are only visible where their route passes through an area of forest or there are trees growing alongside their route. Railway lines normal to the radar beam saturate the return and appear very bright in the image. Rivers in deep valleys are indicated by the high return from the side of the valley, especially when normal to the radar beam. Where vegetation is growing along, or in some cases in, the river bed there is a high radar return from this riparian vegetation. However, the exact position of the water course may not be detectable. Boundaries between natural and synthetic surfaces for example between the rural and town areas can generally be detected. This depends on the amount of vegetation within the built-up area. The boundary between timbered and open country can also be detected and differences in the type of timber cover can be shown by tonal differences. Isolated objects acting as corner reflectors stand out as bright pixels, but there is no guarantee that they are buildings. Because of their high radar return heavily built-up areas are visible as areas of lighter tones and the street pattern can sometimes be delineated. From these observations it was concluded that relatively small objects are not detectable on SIR-B imagery even at higher look angles. Far fewer objects are visible at lower look angles. This is because the reduced look angle results in decreased resolution. Contrast and detectability were found to be dependent on the look angle, orientation with respect to the illumination, the local relief, and the type of country (e.g. open or timbered). It was also apparent that at high look angles the radar discriminates between "smooth" and "rough" surfaces. A view of the geomorphology is provided by radar at the lower look angles, because of the coarser resolution. Thus "rough" and "rougher" surfaces can be discriminated. It was concluded that all the features required for topographic mapping at a scale of 1:250,000 or larger, may not be detectable on SIR-B imagery. The textural patterns provided by SIR- B, however, may be useful for small scale thematic mapping. 5.8 Quantification of the Content of SIR-B Imagery Content and its interpretation relate to features which can be detected and then labelled e.g. a road, a forest or an urban area. Given the generalization of detail at particular map scales the amount and disposition of all the features identified on the imagery must portray the features on the ground accurately. This means that radar images need not contain all cultural detail, as long as the detail which can be detected is adequate to portray the features on the ground at a particular map scale or scales. By plotting all the detail that could be detected on the radar image compared with the plotted detail shown on the map, the content of the radar image could be determined. Plotting from radar images cannot be achieved, however, on conventional stereoscopic photogrammetric equipment without specialized software (Wu and Schafer, 1980). This is due to the uniqueness of radar geometry which is affected by illumination and image formation. The content of other satellite imagery has been compared with map content by Welch (1982). He used the time taken to digitize the map and the image as a surrogate measure of content. A similar technique was used to determine the map content of the SIR-B imagery. 5.8.1 Methodology. For this part of the experiment a section of the three overlapping swaths, DT 51.8, DT 67.8 and DT 83.8, was selected near Stratford in eastern Victoria. Here the terrain was relatively flat and there were a variety of features and densities of vegetative cover. This area contained a high proportion of cultural detail which could provide a firm 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 25m pixels. In turn, the detail on the 1:100,000 scale map and the 1:250,000 scale map was digitized using the table digitizer connected to the DIPIX Image Analysis System. Then the detected detail on DT 83.8, DT 67.8 and DT 51.8 was digitized from the DIPIX Image Analysis System display using its graphics facility. The five files created during this process were all stored separately as theme files on the DIPIX

Image Analysis System. The time taken to digitize each of the major components was recorded allowing a visible comparison between the digitized data.

The digitizing times shown are only indicative as some features took longer to digitize although no additional detail was actually detected, however, they give a good basis for comparison. The ratio of the times taken to digitize features on the radar images to those taken to digitize features on the map were also computed and recorded. This ratio indicated the proportion of features detectable on the radar images. 5.8.2 Discussion of Results. Both DT 83.8 and DT 67.8 have similar look angles and contained similar amounts of detail. Nearly all roads and tracks that had trees growing alongside them were detected. It was initially thought that the radar showed roads not depicted on the current map. The major highway and railway were often only vaguely detectable without bordering trees to enhance their presence. Where the railway was separated from the road and had trees growing alongside it was clearly visible but could not be interpreted as a railway. Where the road ran alongside the railway it was not possible to detect two separate features.

Following this analysis an examination of the aerial photography showed that the existence of trees along the roads enabled the roads' detection. Rows of trees growing in such other places as windbreaks were wrongly interpreted as roads. Initially it was difficult to differentiate the tree plantations from town areas. When it was realized that both roads and railways converged on the town it then became possible to detect some street patterns. All the vegetation and urban boundaries were detectable. Areas of medium and dense scrub appeared similar on the image, thus these areas could not be discriminated. The major river was visible but because of the riparian vegetation its exact course was doubtful. However, a later comparison of its position with that digitized from the map, showed that its interpreted position was not significantly in error. A few of the minor streams were detected by the highlight and shadowing along their banks, but this effect was essentially because these streams were almost normal to the radar beam. On DT 51.8 far less cultural detail and fewer boundaries were detected. The lower look angle, however, highlighted more of the river valleys. The higher look angle (higher resolution) image provided the cultural detail and the lower look angle (lower resolution) the topography. It was concluded that a composite image of the two radar scenes (DT 51.8 and DT 83.8) could provide the maximum amount of detail possible. The time taken to digitize the features on this composite (DT 51.8 and DT 83.8) image showed that the maximum amount of detail was provided by this image. For compilation at a scale of 1:100,000 some 59 percent of detail was detected, compared with 61 percent of detail for compilation at a scale of 1:250,000. The values of 59 and 61 percent seem to contradict the value of 40 percent determined by Welch (1982) in his analysis of Landsat MSS imagery. As both evaluations were based on the same method as described earlier in this Section, a reason for the higher content of the SIR-B composite was sought. It was concluded that the higher content of the composite radar image was because nearly all of the roads were detected due to their accompanying line of trees. Where there were no trees along the roads they could not be detected. Also the rivers and streams were detected by their accompanying vegetation or the local topography. The precise identification of certain features would have required additional information to that provided by the radar image. A visual interpretation was performed on an area to the south of the study area, where the linear features did not have trees growing alongside them. It showed that apart from vegetation boundaries little cartographic detail was visible. The difference in the amount of detail contained in these two areas indicated the variability of content of the SIR-B data and substantiated the claim by Konecny et al., (1982) that radar images are unsuitable for mapping at a scale of 1:250,000 or larger. This conclusion also supports the results of the theoretical analysis of Section 5.6. In some areas, however, radar images may provide additional information to assist with topographic map compilation. 5.9 Ground Inspection of the Stratford Study Area A ground inspection of the Stratford study area was undertaken following the interpretation of the radar imagery using aerial photographs and topographic maps of the area, to assist the analysis. The bright line on the radar imagery, DT 51.8 and DT 67.8 was created by the backscatter from a section of railway saturating the receiver. The ground inspection revealed it to be a single track raised slightly above ground level by the bed of ballast. A triple strand of telegraph wires, supported at regular intervals by a single wooden cross member mounted on a steel pole, runs parallel to the railway on the northern side of the track. The strong signal return in this area was due to this section of railway being almost exactly parallel to the track of the Shuttle and acting as a hard target. (refer Section 3.6.5 and cf. Lewis, 1968, Section 2.6). It was noticeable that some of the roads had thick scrub growing within their reserves, yet these roads were not detected on the radar imagery. It was also difficult to detect a line of Norfolk pines on the radar imagery even though the general area could be located on the radar scenes. These pine trees which formed a windbreak (that was even difficult to see through) had thick trunks and a mass of thick foliage. In the area where the roads had been detected on the radar imagery because of their accompanying trees, the ground investigation revealed these trees to be tall eucalypts with fairly sparse foliage but relatively closely spaced. It was concluded that the tree trunks and the open created a corner reflector effect thereby increasing the backscatter along the linear features. Conversely the open fields acted as a specular reflector and backscatter was minimal. The variation in backscatter between the trees and the open fields provided sufficient contrast on the image to enable detection of the linear features described above. It was also concluded that the majority of the backscatter came from the tree trunks rather than the foliage, and the more closely spaced the tree trunks the more backscatter. This explains the higher radar return from the eucalypts than from scrub or the Norfolk pines, as the scrub was essentially foliage and the trunks of the Norfolk pines widely spaced. The study described in Richards et al., (1986), which concludes that the trunk of the tree predominately controls backscatter also supports this explanation. The ground inspection reinforced the variability of features able to be detected on the radar imagery. It also showed that accurate interpretation of SIR-B imagery would be difficult unless the interpreter knew the area well.

CHAPTER 6

RECTIFICATION OF SIR-B IMAGES

6.1 Introduction The effect of layover at low look angles or in areas of significant relief, prohibits the accurate registration of radar imagery with other imagery, or even radar images acquired at different look angles. To produce a geometrically correct image I collaborated on the development of a computer program to rectify radar images. My involvement included the production of a layover correction algorithm which is discussed in Section 6.3, as well as establishing the program's procedural requirements.

6.2 Program Requirements

To link the radar image to the map the coordinates of common ground control points from the SIR-B image and a 1:100,000 scale map are manually entered. The map height of each control point is used to compensate for layover prior to the computation of the affine transformation. This transformation links the radar image to the map. Residuals at each of the control points are computed using the transformation as an indication of the quality of each of the selected points. Suspect points may then be deleted or the coordinates of further control points entered, and the transformation recomputed. As the actual rectification is computationally intensive, rectification does not commence until the user considers that the residuals at the control points have been minimized.

6.3 Layover Algorithm

In evaluating the geometric accuracy of SIR-B imagery the range or line coordinate was first corrected for layover. In Section 4.4.2 this correction was shown to be linearly related to the height of the point above datum and the magnitude of the correction was manually calculated before being input into the program as data. To allow the integration of the layover correction with the rectification program the manual calculation needed to be eliminated. The algorithm detailed in Appendix D is an extension of the formula used for the manual calculation shown in Appendix A. As described in Section 4.4.1 the calculation assumes a spherical earth. With a change of look angle, swath width and therefore the distance to the far range also vary. An investigation was therefore undertaken to determine the maximum swath width of the SIR-B system. The largest swath covered by the multi-angle imagery held by the CRS was about 22km and therefore to allow for some variation the maximum swath was adopted as 25km. The amount of layover for a datum of 100m is computed by the program for both the near range and far range i.e. near range plus 25km, and interpolated for any point in between. The ratio of the height of the point to 100m then determines the amount of layover.

6.4 Rectification Program Overview

To compensate for the layover introduced during radar data acquisition a digital elevation model (DEM) is required to provide terrain heights. 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). These are provided by JPL with each data take (DT). As the rectified image is usually related to a standard grid, i.e. a map, the program determines a first order polynomial transformation. The polynomial relates line and pixel values from the radar image to easting and northing coordinates from a 1:100,000 scale map, for selected common ground control points. The line values used are corrected for layover, as previously described, using the height of each control point, as read from the map. The user selects the area for rectification by entering its UTM coordinates as well as the grid cell size of the rectified radar 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 (image line direction) and finally the line and pixel value in the radar image which corresponds with this grid cell. The intensity of the nearest pixel in the radar image to that computed (nearest neighbour) represents the ground response from the area covered by the cell. An option also allows for bi-linear interpolation of the intensity of the 4 neighbouring pixels. The process is essentially one of selecting the appropriate response for a grid cell. Thus a response can be selected more than once to form the rectified image in areas where data was not originally acquired by the SIR-B system due to layover or radar shadow. Provided the basic data and a DEM is available this program should be able to produce a rectified radar image from any digital radar data.

6.5 Accuracy and Interpretability of the Rectified Radar Images

Three images were produced to determine the validity of the program and the interpretability of the rectified images. A section of DT 83.8, look angle 48 degrees, was processed using the nearest neighbour option, but as the height difference in the terrain is small, very little difference could be detected between the original and rectified image. A section of DT 51.8, look angle 17 degrees, where there were height differences of up to 600m was then processed using the nearest neighbour option. In the rectified image a striping effect was apparent because the same intensity value from the original data was selected many times to create pixels in the range direction. This occurred where the layover effect or radar shadow had prevented data being acquired. The same area was processed using the bi-linear option without reducing this artefact. Localized filtering would be necessary to remove this effect and avoid excessively smoothing the whole image. To check the accuracy of the rectified images, the rectified section of DT 51.8 was registered to a 1:100,000 map and displayed on the DIPIX Image Analysis System. By tracing boundaries on the map with the cursor, the position of the boundary overlaid on the rectified image was displayed on the screen. Allowing for errors in registration and digitizing, the map boundaries appeared to lie along the position of the interpreted boundaries on the rectified image. As the rectified images were of a predominantly rural area only generalized topographic boundaries were available so that this check is not conclusive. Overlaying a transparency of the processed image on the map was also considered to be inconclusive as again the topographic boundaries were too ill-defined for a quantitative conclusion to have been made. To enable a reliable accuracy, check, an urban area in a region with significant relief should be rectified. The comparison of the position of common street intersections on a transparency of the rectified image overlaid on the map should indicate the accuracy of the rectification program. As a DEM for such an area was not available this check could not be performed. The rectified images were also registered to their respective original images and displayed using two different colour guns on the DIPIX Image Analysis System. Where the colours mixed little rectification had occurred, but where one colour predominated displacement due to layover had clearly been corrected. On the composite DT 83.8, this only occurred in a few small areas, but on the DT 51.8 composite, the severe layover created large areas of a single colour. These methods do not provide a quantitative measure of accuracy, but as the rectification program incorporates an affine transformation and layover correction as described and used for the geometric accuracy analysis (Section 4.3), the accuracy of the rectification, is probably of the same order i.e. around 50m. The rules for interpreting the rectified images are the same as previously outlined (Section 3.7). On the rectified image however, areas which were not imaged due to layover or were in radar shadow are represented by pixel values created during the rectification process. These pixels do not represent the actual radar response from the terrain and any interpretation or analysis undertaken in these areas must take this into account.

CHAPTER 7

RECOMMENDATIONS AND CONCLUSIONS

7.1 Recommendations

Having found that the SIR-B imagery is unsuitable for topographic mapping at a scale of 1:250,000 or larger, the question of whether future SAR imagery is likely to be useful for topographic map compilation arises. From the earliest days of the space program cartographers have expected that photographs from space vehicles would result in the same increment of productivity which came about with the introduction of aerial photography for the compilation of map detail compared with the time required for intensive ground surveys (Welch, 1982). Studies on SPOT PAN and MSS data indicate that 1:50,000 and perhaps 1:25,000 scale topographic maps can be compiled from these images (Forster, 1986). Radar images with their relative complexity and lack of resolution may therefore be overlooked as a data source for topographic map compilation. Radar, however, has some advantages. As an active system radar is not constrained by sun illumination and the cyclic period of acquisition is halved compared with passive systems which can only record images during daylight. Climatic conditions in some parts of the world prevent imaging at optical wavelengths.

In Australia's northern and southern extremes images in the optical wavelengths are difficult to acquire due to weather patterns. In times of disaster (for example when information on flood extent is required urgently) weather conditions may prevent imaging by optical systems. To image these areas on demand is only possible with radar. The orbits of Landsat and SPOT do not permit images of the majority of the polar regions, and polar weather often restricts image acquisition from optical systems. A further problem, specific to high latitudes, is the periodic lack of adequate solar illumination for optical systems. The radar images from the polar orbiter (due for launch in the 1990s) will acquire coverage of the majority of the polar regions and hopefully will assist Australia's mapping commitments in Antarctica, especially in the mapping of dangerous crevasse areas that hinder exploration. Other advantages would be the provision of data on the sea ice for ship scheduling and routing as well as information on the ice itself.

In regions of Australia where dense forest or tropical vegetation covers the terrain, traditional contouring from aerial photography is difficult. Terrain characteristics have to be inferred from the top of the vegetation by the photogrammetrist. Using a high incidence angle the terrain becomes "visible" in the radar image. Several passes at varying look angles may be required to complete the coverage, because the high incidence angle coupled with large differences in terrain elevation causes layover and loss of ground detail. Although mapping from this data may take additional time a true representation of the terrain should be obtained. SIR-C will acquire multi-band, multi-look angle and quadpolarised imagery (Cimino et al., 1986). This imagery is expected to provide a superior range of options for analysis. Airborne studies have indicated that different features are imaged at different polarisations. Moreover, shorter wavelengths of radiation will be affected by smaller irregularities and therefore reveal textures not detected by the larger SIR-B wavelength. Zebker and Burnett (1986), have produced a short film in which the possible polarisations are synthesized to show that different features can be detected as the polarisation is changed. Therefore, it is strongly recommended that combinations of SIR-C imagery acquired at different look angles, polarisations and wavelengths, be investigated to determine if specific combinations are suitable for the detection of detail for topographic map compilation. Imagery from space is by no means assured. It has become apparent that the lifetime, replacement and delivery of space systems cannot be guaranteed. In the short term our total reliance for imagery should not be placed on one or two systems. Accepting any inherent limitations, all imagery from space should be investigated for use for mapping if required. Radar has some obvious limitations, but it is considered premature to dismiss radar imagery as being totally unsuitable for topographic mapping. The imagery acquired by the next generation of radar systems should also be evaluated for its suitability for topographic map compilation.

7.2 Conclusions

The conclusions reached as a result of the investigations are summarized below for each of the original project objectives.

- The geometric accuracy of a single strip of SIR-B data.
The geometric accuracy of the SIR-B radar was found to be suitable for topographic mapping at scales of 1:250,000 scale or smaller. The RMS error vector from the first order polynomial used to transform the radar data to the map grid was some 4 pixels or about 50m on the ground. The

transformation may not always produce an RMS error vector consistent with these results unless:

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

- Evaluation of the use of composite Landsat and SIR-B images for interpretability of features.
A second order transformation may be used to register the SIR-B images to Landsat images without removing layover from the radar images. At the lower look angles, however, the poorer resolution and increased layover results in a less accurate registration being achieved. Using composite Landsat and radar images, some cultural detail can be detected more easily. A program using a digital elevation model is available on the UNSW VAX 11/780 to rectify radar images. Being able to rectify the radar image prior to registration with other sensor data should improve any analysis performed on such composite images.

- To determine the scales of mapping for which the SIR-B data is suitable.
The detection of the cultural detail contained in a radar image is dependent on a large number of factors. These factors determine the amount of backscatter from features on the terrain, and then whether the amount of backscattered radiation is sufficient to differentiate these features from their background. A quantitative analysis of the SIR-B imagery indicated that the content of the radar images varied, and therefore the images are unsuitable for the compilation of topographic maps at scales of 1:250,000 or larger. However, the definition of boundaries and the textural detail of areal features on the radar imagery may be useful for thematic mapping. Having achieved these objectives, it is believed that the aim of the topographic mapping experiment outlined in Section 1.2 has been achieved. In summary the conclusions are that although the geometric accuracy of SIR-B is suitable for mapping at a scale of 1:250,000 the content of this imagery is only suitable for map compilation at a scale of 1:500,000 or smaller.

CHAPTER 8

REFERENCES

Allan, T.D. (Ed.). 1983. Satellite Microwave Remote Sensing. Ellis Horwood Ltd., London: United Kingdom.

Barber, B.C. 1983. Some Properties of SAR Speckle. In (Allan, T.D. (Ed.). 1983) 129-145.

Barrett, E.C. and Curtis, L.F. 1982. Introduction to Environmental Remote Sensing. Chapman and Hall, London: United Kingdom.

Becker, F. (Ed.). 1983. Radar Remote Sensing, Remote Sensing Reviews. Harwood Academic Press, London: United Kingdom.

Bennett, J.R. and Cumming, I.G. 1978. Digital Techniques for the Multi-Look Processing of SAR Data with Application to SEASAT-A. Proceedings of the Canadian Symposium on Remote Sensing, Victoria. 506-516.

Brown, W.M. and Porcello, L.J. 1969. An Introduction to SAR. IEEE Spectrum. 52-62.

Canby, T.Y. 1983. Satellites That Serve Us. National Geographic. Vol. 164, No. 3, 280-335.

Cimino., J.B., Elachi, C. and Settle, M. 1986. SIR-B - The Second Shuttle Imaging Radar Experiment. IEEE Transactions on Geoscience and Remote Sensing. Vol. 24, No. 4, 445-451.

Clarke, T.F. and Dovey, S. 1986. Landsat Imagery - Its Rectification and Potential Application to 1:250,000 Scale Topographic Map Revision in Australia. Proceeding of the Australian Institute of Cartographers Conference, Melbourne. Session 13B.

Colvocoresses, A.P. 1984. Report of the Committee for Acquisition and Processing of Space Data for Mapping Purposes. International Archives of Photogrammetry. Vol. 25, Pt. A8a, 329-357.

Colwell, R.N. (Ed.). 1983. Manual of Remote Sensing (2nd edn), American Society of Photogrammetry. Falls Church, Virginia: USA.

Crandall, C.J. 1969. Radar Mapping in Panama. Photogrammetric Engineering. Vol. 35, No. 7, 641-646.

Crane, K.C. 1986. Map Revision of Medium Scale Topographic Maps. International Archives of Photogrammetry. Vol. 26, Pt. 4, 538-546.

Cumming, I.G. and Bennett, J.R. 1979. Digital Processing of Seasat SAR Data, IEEE Spectrum. 506-516.

Curlander, J.C. 1984. Utilization of Spaceborne SAR Data for Mapping. IEEE Transactions on Geoscience and Remote Sensing. Vol. 22, No. 2, 106-112.

Curlander, J.C. 1986. Performance of the SIR-B Digital Image Processing Subsystem. IEEE Transactions on Geoscience and Remote Sensing. Vol. 24, No. 4, 649-652.

Curlander, J.C. and Pang, S.N. 1982. Geometric Registration and Rectification of Spaceborne SAR Imagery. Proceedings of the International Geoscience and Remote Sensing Symposium, Munich. FA2 5.1-5,6.

Curran, P.J. 1985. Principles of Remote Sensing. Longman, London: United Kingdom.

Cutrona, J.L. 1962. Synthetic Aperture Radar. In (Skolnik, M.I. (Ed.). 1970) Chap. 25-3.

Derenyi, E.E. 1986. Accuracy of Three Dimensional Co-ordinates Using Large Format Camera Photographs. International Archives of Photogrammetry. Vol. 26, Pt. 4, 14-23.

De Loor, G.P. 1983. Introduction and Some General Aspects of Image Formation in Radar. In (Becker, F. (Ed.). 1983) 3-18.

Dobson, M.C. and Ulaby, F. 1981. Microwave Backscatter Dependence on Surface Roughness, Soil Moisture and Soil Texture. IEEE Transactions on Geoscience and Remote Sensing. Vol. 19, No. 1, 51-61.

Dowman, I.J. 1985. Images from Space: The Future for Satellite Photogrammetry. Photogrammetric Record. Vol. 11, No. 65, 507-513.

Doyle, F.J. 1971. Can Satellite Photography Contribute to Topographic Mapping? In (Holtz, R.K. (Ed.). 1973) 153-160.

Doyle, F.J. 1982a. A Review of Remote Sensing Programs. International Archives of Photogrammetry. Vol. 24, Pt. 7/2, 341-352.

Doyle, F.J. 1982b. Satellite Systems for Cartography. International Archives of Photogrammetry. Vol. 24, Pt. 1, 180-185.

Doyle, F.J. 1985a. The Economics of Mapping with Space Data, ITC Journal. No. 1, 1-9.

Doyle, F.J. 1985b. The LFC on Shuttle Mission 41G. Photogrammetric Engineering and Remote Sensing. Vol. 50, No. 2, 132.

Duchossois, G. 1984. ERS-1: Mission Objectives and System Design. International Symposium on Remote Sensing of the Environment, Ann Arbor, Michigan. 145-153.

Elachi, C. and Granger, J. 1982. Spaceborne Imaging Radars Probe 'In-depth'. IEEE Spectrum. 24-29.

Elachi, C., Brown, W.E., Cimino., J.B., Dixon, T., Evan, D.L., Ford, J.P., Saunders, R.S., Breed, C., Masursky, M., McCauley, J.F., Schaber, G., Dellwig, L., England, A., MacDonald, H., Martin- Kaye, P. and Sabins, F. 1982. Shuttle Imaging Radar Experiment. Science. Vol. 218, 996-1003.

Engel, H., Konecny, G., Lohmann, P. and Schuhr, W. 1984. Topographic Mapping from Spaceborne Metric Camera Imagery. International Archives of Photogrammetry. Vol. 25, Pt. A4, 157-161.

Engel, H., Muller, W. and Konecny, G. 1986. Application of Spacelab "Metric Camera" Imagery for Mapping. International Archives of Photogrammetry. Vol. 26, Pt. 4, 170-182.

Fenner, R.G. and Pel, G.P. 1981. A Parametric Study of Tillage Effects on Radar Backscatter. Proceedings of the International Geoscience and Remote Sensing Symposium, Washington. 1294-1301.

Fiore, C. 1967. Side-looking Radar Restitution. Photogrammetric Engineering. Vol. 33, No. 2, 215-220.

Forshaw, M.R.B., Haskell, A., Miller, P.F., Stanley, D.J. and Townshend, J.R.G. 1983. Spatial Resolution of Remote Sensing Imagery: A Review Paper. International Journal of Remote Sensing. Vol. 4, No. 3, 497-520.

Forster, B.C. 1985. Future Spaceborne Remote Sensing Systems. Proceedings of the Australian Survey Congress, Alice Springs. 109-117.

Forster, B.C. 1986. Analogue and Digital Images for Mapping: Past Trends and Future Prospects. Proceedings of the Australian Survey Congress, Adelaide. 197-203.

Forster, B.C. and Trinder, J.C. 1985. Synthetic Aperture Radar and the SIR-B Program. The Australian Surveyor. Vol. 32, No. 7, 497-522.

Frost, V.S., Shanmaugan, K.S., Holtzman, J.C. 1984. The Influence of Sensors and Flight Parameters on Texture in Radar Images. IEEE Transactions on Geoscience and Remote Sensing. Vol. 22, No. 6, 440-448.

Goodenough, D.G., Guindon, B. and Teillet, P.M. 1979. Correction of Synthetic Aperture Radar and Multispectral Scanner Data Sets. Proceedings of the International Symposium on Remote Sensing of the Environment, Ann Arbor, Michigan. 259-270.

Guindon, B., Harris, J.W.E., Teillet, P.M., Goodenough, D.G. and Meunier, J.F. 1980. Integration of MSS and SAR Data of a Forested Region in Mountainous Terrain. Proceedings of the International Symposium of Remote Sensing of the Environment, Ann Arbor, Michigan. 1673-1690.

Haack, B.N. 1984. L-Band and X-Band Like- and Cross- Polarized Synthetic Aperture Radar for Investigating Urban Environments. Photogrammetric Engineering and Remote Sensing. Vol. 50, No. 3, 331-340.

Harris, G.H. and Graham, L.C. 1976. Landsat-Radar Synergism. International Archives of Photogrammetry. Vol. 7, paper 17-163.

Henderson, F.M. 1983. A Comparison of SAR Brightness Levels and Urban Land Cover Classes. Photogrammetric Engineering and Remote Sensing. Vol. 49, No. 11, 1585-1591.

Henninger, D.L. and Carney, J. 1983. Shuttle Imaging Radar-A

(SIR-A) Data as a Complement to Landsat Multi-Spectral Scanner (MSS) Data. Proceedings of the International Geoscience and Remote Sensing Symposium. Vol. 2, FP-5,7.

Holtz, R.K. (Ed.). 1973. The Surveillant Science. Houghton Mifflin Co., Boston: USA.

Innes, R.B. 1968. An Interpreters Perspective on Modern Airborne Radar Imagery. Proceedings of the International Symposium of Remote Sensing of the Environment. 107-122.

Jensen, H., Graham, L.C., Porcello, L.J. and Leith, E.N. 1977. Side-looking Airborne Radar. Scientific American. Vol. 237, No. 4, 84-95.

Konecny, G. 1984. The Evaluation of Spacelab-1 Photogrammetric Camera Data. International Archives of Photogrammetry. Vol. 25, Pt. A1, 64-69.

Konecny, G., Schuhr, W. and Wu, J. 1982. Investigations of Interpretability of Images by Different Sensors and Platforms for Small Scale Mapping. International Archives of Photogrammetry. Vol. 24, Pt. 1, 11-22.

Koopmans, B.N. 1983a. Side-looking Radar a Tool for Geological Surveys. In (Becker, F. (Ed.). 1983) 19-69.

Koopmans, B.N. 1983b. Spaceborne Imaging Radars, Present and Future. ITC Journal. No. 3, 223-231.

Koopmans, B.N. 1986. Oil Drums as Resolution Targets for Quality Control of Radar Survey Data. International Archives of Photogrammetry. Vol. 26, Pt. 4, 145-147.

Krul, R. 1983. Introduction to the Use of Radar in Remote Sensing. In (Becker, F. (Ed.). 1983) 159-178.

Kux, H.J.H. and Dutra L.V. 1984. Evaluation of SIR-A (Synthetic Aperture Radar-A) Images from Tres Marias Region (Minas Geras State, Brazil) Using Derived Spatial Features and Registration with Landsat Images. International Archives of Photogrammetry. Vol. 25, Pt. A8a, 800-805.

Landsat Data Users Notes, No. 32. 1984. USA: National Oceanic and Atmospheric Administration.

Leberl, F. 1976. Imaging Radar Applications to Mapping and Charting. International Archives of Photogrammetry. Vol. 21, Pt. 3, No. 3-06-137.

Leberl, F., Fuchs, H. and Ford, J.P. 1981. A Radar Image Time Series. International Journal of Remote Sensing. Vol. 2, No. 2, 155-183.

Leberl, F. and Domik, G. 1984. Radar Image Simulation and Its Application in Image Analysis. International Archives of Photogrammetry. Vol. 25, Pt. A3a, 99-108

Leberl, F.W., Domik, G. and Kobrick, M. 1985. Mapping with Aircraft and Satellite Radar Images. Photogrammetric Record. Vol. 11, No. 66, 647-664.

Leberl, F.W., Domik, G., Raggam, J. and Kobrick, M. 1986. Radar Stereomapping Techniques and Application to SIR-B Images of Mt. Shasta. IEEE Transactions on Geoscience and Remote Sensing. Vol. 24, No. 4, 473-497.

Leberl, F.W., Domik, G., Raggam, J., Cimino., J.B. and Kobrick, M. 1986. Multiple Incidence Angle SIR-B Experiment over Argentina: Stereo- Radargrammetry Analysis. IEEE Transactions on Geoscience and Remote Sensing. Vol. 24, No. 4, 482-491

Levine, P. 1960. Radargrammetry. McGraw-Hill: New York. Lewis, A.J. 1968. Evaluation of Multiple-polarized Radar Imagery for the Detection of Selected Cultural Features. In (Holtz, R.K. (Ed.). 1973) 297-314.

Lillesand, T.M. and Kiefer, R.W. 1979. Remote Sensing and Image Interpretation. John Wiley and Sons, Inc : New York.

Lintz, J. and Simonett, D.S. 1976. Remote Sensing of Environment. Addison-Wesley Publishing Co., Reading: Massachusetts.

Lynne, G.J. and Taylor, G.R. 1986. Geological Assessment of SIR-B Imagery of the Amadeus Basin, N.T., Australia. IEEE Transactions on Geoscience and Remote Sensing. Vol. 24, No. 4, 575-581.

Meneguette, A.A. 1985. Evaluation of Metric Camera Photography for Mapping and Co-ordinate Determination, Photogrammetric Record. Vol. 11, No. 66, 699-709.

Murai, S. 1986. Cartographic Accuracy of Stereo Space Photographs Taken by Large Format Camera - A Case Study in Japan. International Archives of Photogrammetry. Vol. 26, Pt. 4, 732-737.

Naraghi, M., Stromberg, W. and Daily, M. 1983. Geometric Rectification of Radar Imagery Using Digital Elevation Models. Photogrammetric Engineering and Remote Sensing. Vol. 49, No. 2, 195-199.

National Aeronautics and Space Administration, Image Radar Science Working Group. 1982. The SIR-B Science Plan. Jet Propulsion Laboratory Publication pp 82-78

National Aeronautics and Space Administration. SIR-B Workshop on Preliminary Science Results. 1985. Papers distributed at meeting at JPL. National Mapping Council of Australia. 1975.

Special Publication 3, Standards of Map Accuracy. (2 edn.). Division of National Mapping, Department of Resources and Energy, Canberra.

Nunnally, A.P. 1969. Integrated Landscape Analysis with Radar Imagery. Remote Sensing of the Environment. Vol. 1, 1-6.

Price, J.C. 1984. Comparison of the Information Content of Data from the Landsat-4 Thematic Mapper and the Multispectral Scanner. IEEE Transaction on Geoscience and Remote Sensing. Vol. 22, No. 3, 272-281.

Rabchevsky, G.A.(Ed.). 1984. Multilingual Dictionary of Remote Sensing and Photogrammetry. American Society of Photogrammetry, Falls Church: Virginia, USA.

Raney, R.K. 1982. Processing Synthetic Aperture Radar Data. International Journal of Remote Sensing. Vol. 3, No. 3, 243-257.

Rebillard, Ph., Elachi, C., Naraghi, M., Soha, J. and Stromberg, W. 1982. Seasat/SIR-A Digital Registration over Algeria. International Archives of Photogrammetry. Vol. 24, Pt. 7/2, 271-276.

Richards, J.A., Forster, B.C., Milne, A.K., Trinder, J.C. and Taylor, G.R. 1982. Australian Multi-experiment Assessment of SIR-B. Australasian Remote Sensing Conference- Landsat'84. 668-676.

Richards, J.A., Sun, G.Q. and Simonett, D.S. 1987. L-band Radar Backscatter Modelling of Forest Lands IEEE Transactions on Geoscience and Remote Sensing. (forthcoming July edition).

Sabins, F.F. 1978. Remote Sensing: Principles and Interpretation. W.H.Freeman and Co.: San Francisco.

Schroeder, M. 1982. Present Status of the Metric Camera Experiment of the First Spacelab Mission. International Archives of Photogrammetry. Vol. 24, Pt. 1, 187-193.

Schultejann, P.A. 1985. Structural Trends in Borrego Valley, California: Interpretation from SIR-A and Seasat. Photogrammetric Engineering and Remote Sensing. Vol. 51, No. 10, 1615-1624.

Shaw, E., Raney, R.K., Langhorn, E.J. and Strome, W.M. 1984. The Canadian Radarsat Program, International Archives of Photogrammetry. Vol. 25, Pt.A1, 251-264.

Skolnik, M.I. (Ed.). 1970. Radar Handbook. McGraw-Hill: New York.

Slama, C.C. (Ed.). 1980. Manual of Photogrammetry (4th edn). American Society of Photogrammetry, Falls Church: Virginia, USA.

Thomson, G.H. 1985. Some Aspects of Image Quality in Satellite Photography. Photogrammetric Record. Vol. 11, No. 66, 717-720.

Trinder, J.C. 1984. Space Programs for Mapping. Australian Journal of Geodesy, Photogrammetry and Surveying. No. 40, 102-105.

Trinder, J.C., Wise, P.J. and Manning J. 1986. The Use of SIR-B and LFC Space Images for Mapping, International Archives of Photogrammetry. Vol. 26, Pt.4, 250-260.

Trinder, J.C. and Wise, P.J. 1986. Cartographic Applications of Space Imaging Systems. Proceedings of the Australian Institute of Cartographers Conference, Melbourne. Session 13B.

Ulaby, K.T, Batlivala, P.P, Bare, Janet E. 1980. Crop Identification with L-Band Radar. Photogrammetric Engineering and Remote Sensing. Vol. 46, No. 1, 101-105.

Ulaby, K.T, Moore, R.K. and Fung, A.K. 1982. Microwave Remote Sensing, Active and Passive. Addison-Wesley Co.: Massachusetts.

Ulaby, K.T., Kouyate, F., Brisco, B. and Lee Williams, T.H. 1986. Textural Information in SAR Images. IEEE Transactions on Geoscience and Remote Sensing. Vol. 24, No. 2, 235-245.

Viksne, A., Liston, T.C. and Sapp, C.D. 1969. SLR Reconnaissance of Panama. In (Holtz, R.K. (Ed.). 1973) 291-296.

Welch, R. 1982. Image Quality Requirements for Mapping from Satellite Data. International Archives of Photogrammetry. Vol. 24, Pt. 1, 50-54.

Welch, R. and Usery, E.L. 1984. Cartographic Accuracy of Landsat-4 MSS and TM Image Data. IEEE Transactions on Geoscience and Remote Sensing. Vol. 22, No. 3, 281-288.

Welch, R. 1985. Cartographic Potential of SPOT Image Data. Photogrammetric Engineering and Remote Sensing. Vol. 51, No. 8, 1085-1091.

Wise, P.J. and Trinder, J.C. 1987. Assessment of SIR-B for Topographic Mapping, Photogrammetric Engineering and Remote Sensing. (forthcoming edition).

Wu, S.S.C. 1984. Current Approaches to the Problem of S-band Radar Mapping. International Archives of Photogrammetry. Vol. 25, Pt. A3b, 1179-1183.

Wu, S.S.C. and Schafer F.J. 1980. Side-looking Radar Using Analytical Plotters. International Archives of Photogrammetry. Vol. 23, 174-179.

Zebker, H.A. and Burnett, F. 1986. Imaging Radar Polarimetry from Wave Synthesis,(A short video produced with the support of the Jet Propulsion Laboratory). Loaned to the Australian Centre for Remote Sensing by AERO PACIFIC, Sydney.

GLOSSARY Where applicable these terms are defined specifically as used in microwave (radar) remote sensing from Colwell (1983), Slama (1980) and Rabchevsky (1984).

ACROSS TRACK : See RANGE DIRECTION.

ACTIVE : A system having its own source of electromagnetic radiation e.g. radar.

ALONG TRACK : See AZIMUTH.

ANTENNA : The device that radiates electromagnetic radiation (EMR) generated by a transmitter and receives EMR from other sources.

AZIMUTH : The direction parallel to the ground track of the platform; also known as the along track direction.

BACKSCATTER : The scattering of radiant energy into the hemisphere of space bounded by a plane normal to the direction of the incident radiation and lying on the same side as the incident ray. Also known as backscattering.

BACKSCATTERING COEFFICIENT : The radar cross-section divided by the minimum resolved area illuminated on the target.

BANDWIDTH : The number of cycles per second between the limits of a frequency band.

BEAMWIDTH : The angle in degrees subtended at the antenna by arbitrary power-level points across the axis of the beam. It is approximately related to the wavelength of the emitted radiation divided by the physical antenna length

BRUTE FORCE RADAR : A radar imaging system employing a long physical antenna to achieve a narrow beamwidth for improved resolution.

CHIRP : An all-encompassing term for the various techniques of pulse expansion - pulse compression applied to pulse radar; a technique to expand narrow pulses to wide pulses for transmission, and compress wide received pulses to the original narrow pulse width and wave shape, to achieve reduction in required peak power without degradation to range resolution and range discrimination.

CORNER REFLECTOR : A dihedral (two-sided) corner reflector formed by two intersecting flat surfaces perpendicular to each other. Radar energy striking one of these surfaces is reflected back to the antenna via the other surface.

DEPRESSION ANGLE : The complement of the angle tilt; in radar the angle tilt is called the look angle.

DOPPLER EFFECT : A change in the observed frequency of EMR or other waves caused by the relative motion between the source and the observer.

ELECTROMAGNETIC RADIATION (EMR) : Energy propagated through space or through material media in the form of an advancing interaction between electric and magnetic fields.

FAST TIME : See RANGE.

LAYOVER : Displacement of the top of an elevated feature with respect to its base on the radar image; also known as equal-slant-range-blur.

LOOK ANGLE : The direction of the look, or the direction in which the antenna is pointing when transmitting and receiving from a particular cell.

LOOK DIRECTION : See RANGE DIRECTION.

LOOKS : Obtaining a view of a feature from more than one direction to minimize fading effects of terrain.

PIXEL : A contraction of the words "PIcture ELement". A data element having both spatial and spectral aspects. The spatial variable defines the size of the resolution cell (i.e., the area on the ground represented by the data values), and the spectral variable defines the intensity of the spectral response for that cell in a particular channel.

POLARISATION : The direction of vibration of the electric field vector of electromagnetic radiation.

PULSE : A short burst of electromagnetic radiation transmitted by the radar system.

RADAR : An acronym for RAdio Detection And Ranging.

RADAR BEAM : The vertical fan-shaped beam of electromagnetic radiation produced by the radar transmitter.

RADAR SHADOW : A no-return area extending in range from an object which is elevated above its surroundings. The object cuts off the radar beam, casting a shadow and preventing illumination of the shadowed area behind it.

RANGE : The distance from the radar to a target; also known as slant range. A shortened name for range direction.

RANGE DIRECTION : The direction to target; also known as the across track direction, look direction or fast time.

RANGE CELL MIGRATION : Where the point target undergoes a migration across range cells as a function of azimuth due to the variation of instantaneous slant range with respect to range cell separation.

REAL APERTURE RADAR : See BRUTE FORCE RADAR.

ROUGHNESS : The average vertical relief of small scale irregularities of the terrain surface.

SIDE LOOKING RADAR : Or SIDE LOOKING AIRBORNE RADAR (SLAR) is an all weather, day/night, remote sensor which is particularly effective in imaging large areas of terrain. It is an active sensor, as it generates its own energy which is transmitted and received to produce a photo-like picture of the ground.

SLANT RANGE : See RANGE.

SLOW TIME : See AZIMUTH.

SYNTHETIC APERTURE RADAR (SAR) : A radar in which a synthetically long apparent or effective aperture is constructed by integrating multiple returns from the same ground cell, taking advantage of the Doppler effect to produce a phase history film or tape that may be optically or digitally processed to reproduce an image.