SPACEBORNE RADAR IMAGERY - ITS ACQUISITION, PROCESSING AND CARTOGRAPHIC APPLICATIONS.

by P. Wise

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ABSTRACT

To date the main cartographic use of spaceborne remote sensing techniques has been through the application of passively sensed data from instruments such as cameras and scanners.

In the next few years considerable actively sensed satellite radar coverage of Australia is planned. These satellite systems are to be flexible in terms of varying look angle, differing emitted frequencies and multipolarization. This flexibility should allow acquisition of pseudo muitispectral data and improve the formation content for cartographic applications.

The maximizing of potential benefits from this expected wealth of remotely sensed data will require users to apply the specialized techniques necessary for handling actively sensed imagery. This paper is not a definitive work on radar. Rather it seeks to stimulate awareness of radar remote sensing by providing an overview of radar systems and the process of data acquisition and imagery formation. The interpretation of radar imagery is also discussed and the variability of the topographic content of radar data is demonstrated.

Introduction

Several space missions carrying synthetic aperture radar (SAR) systems are planned for the 1990s. The European Space Agency's ERS-1, the Japanese JERS-1 and the United States' Shuttle Imaging Radar - C (SIR-C) are due for launch in 1991. These are to be followed by Canada's RADARSAT in 1992 and the United States' polar platform(s) in 1994. Table 1 gives the planned launch dates and sensor operating characteristics of these systems.

These missions promise an extensive radar coverage of Australia that should have greater application than the brief glimpses from the SIR-A and SIR-B missions of 1981 and 1984. The digital data acquired by future SAR systems will enable the generation of imagery on both photographic and magnetic media.

To allow direct reception and processing of ERS-1 data the receiving and processing facilities of the Australian Centre for Remote Sensing are being upgraded (Fensom, 1987). An Australian proposal to acquire radar data from the SIR-C mission has been presented to the United States National Aeronautics and Space Administration in response to the Announcement of Opportunity on Shuttle Imaging Radar - C. Australia's data reception arrangements for the other systems are yet to be formalized.

Radar images differ in geometry and appearance from images acquired by camera or scanner systems. These differences result from the data acquisition process. Thus an understanding of radar characteristics is necessary for effective data analysis.

PARAMETERS	ERS-1	SIR-C	JERS-1	RADARSAT	EOS
Planned Date for Launch	1991	1991	1991	1992	1994
Swath Width (km)	80	15-90	75	100	33-100
Look Angles (deg)	23	15-55	35	20-45	15-60
Frequency (GHz)	5.3	1.25 5.3 9.6	1.28	5.3	1.28 5.3 Other
Polarization Direction (H, horizontal - V, vertical)	VV	HH VV VH HV	HH	HH	Unknown
Range Resolution (m)	30	10-60	18	25	17-58
Azimuth Resolution (m) (after processing to the indicated number of looks)	30	30	18	28	30
Number of looks	4	4	Unknown	4	4

Table 1 : Proposed Launch Dates and the Radar Sensor Operating Characteristics of Future SAR Systems.

Principles of Radar

Radar (RAdio Detection And Ranging) is an active remote sensing system which illuminates the terrain by generating its own microwave energy. The four basic components of the system are:

1. transmitter
2. antenna
3. receiver
4. recording device.

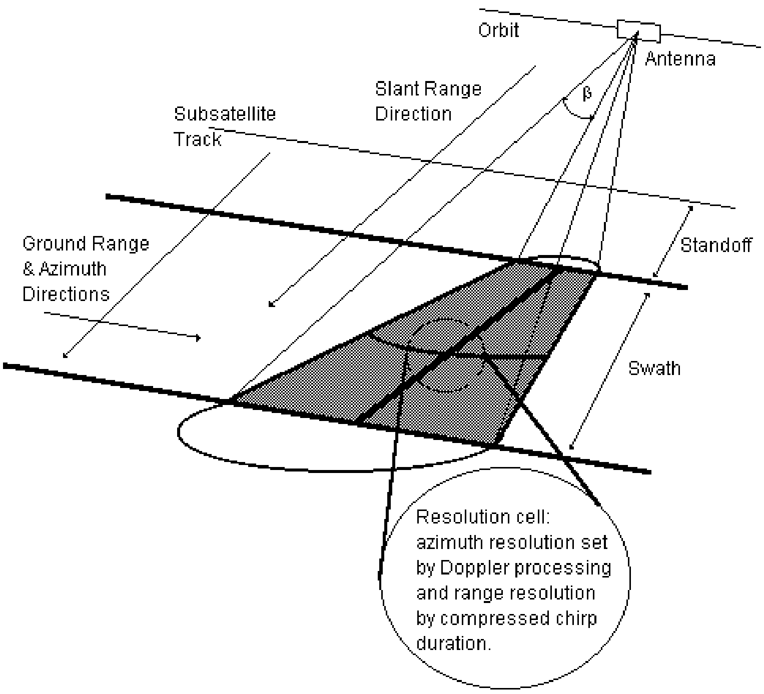

Figure 1 : Schematic Diagram of the Side-Looking Radar Imaging Process.

The microwave energy which is generated by the transmitter, in pulses, is directed at the ground by the antenna. The terrain scatters this incident radiation, some of which is reflected back to the antenna. Processing of the return signal allows particular characteristics to be extracted and correlated with a delayed replica of the transmitted signal. The magnitude of this delay is generally recorded either optically or digitally. However, all future satellite radar systems will record their data 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 parallel to the cross track direction of flight as shown in Figure 1 above. The azimuthal beamwidth of the antenna ß is related to its length and to the wavelength of the emitted radiation in the following way:

$$ß = \lambda \backslash l \quad \text{(radians)} \tag{1}$$

where λ 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 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 (ø). The electromagnetic radiation is pulsed that in time τ the resolution element in the range direction Rr is given by:

$$Rr = c * \tau / 2 \tag{2}$$

where c is the velocity of electromagnetic radiation. The azimuth resolution Ra of real aperture radar can be approximated by:

$$Ra = ß * R \tag{3}$$

where ß is the azimuthal beamwidth in radians and R the slant range is found from

$$R = c * T / 2 \tag{4}$$

where T is the total round trip time of the signal.

Because the azimuth resolution 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,

$$Ra = ß * R = ß * h / \cos ø \tag{5}$$

As

$$R = h / \cos ø \tag{6}$$

where h is the height of the platform and ø is the look angle.

Radar systems that use antenna beamwidth for azimuth resolution and pulse duration for range resolution are termed real aperture radars.

Synthetic Aperture Radar (SAR)

Radar system that use pulse width and a long synthetic antenna to improve azimuth resolution are termed synthetic aperture radars (SAR).

Using the motion of the platform a long antenna for SAR systems is synthesized. Instead of recording only the one signal returned from an object (as with real aperture radar) in SAR the returns from a number of pulses are recorded, while the object is in the beam of the antenna. Thus the synthetic antenna assumes a length directly proportional to the velocity of the platform times the period between emitted pulses.

The return signal contains range and azimuth information. The range information is given by the time delay of the returned pulses and azimuth information is encoded in the Doppler frequency shift that the signal undergoes as the object comes closer to, and then recedes from, the radar antenna. Comparing the return signal with the transmitted signal enables the determination of Doppler shift.

It can be shown that the change in azimuth to the object is a function of the Doppler frequency shift. The location of the object is thus defined by a unique time delay (range) and Doppler frequency shift (azimuth) (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 also be shown that the theoretical azimuth resolution of SAR is given approximately by l/2 (De Loor, 1983), where l is the length of the antenna, as discussed 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:

$$d = c * \tau / 2 \quad (7)$$

where c is the velocity of electromagnetic radiation and τ is the 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 by dividing the slant range by the sine of the look angle ø. Thus,

$$dg = c * \tau / (2 * \sin ø) \quad (8)$$

In a SAR system the range resolution is function of the slant-range resolution modified by the incidence angle. Therefore, it is quoted as a range of values. Azimuth resolution is dependent only on the system and the number of looks and is thus a constant value.

The Processing of SAR Data

As range resolution is dependent on the pulse duration τ from equation (7) above, if the pulse duration is reduced the resolution is increased. A shorter pulse duration normally reduces the amount of energy pulse and limits the range of the radar unless the energy of the pulse is increased to compensate. However, a limit on the energy of the pulse is imposed by the electronic capacity of the system.

To avoid this problem synthetic a radar does not use a simple pulse. Instead a pulse where the frequency increases linearly with time is transmitted. This pulse is known as a chirp.

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 a function of the Doppler shift caused by the motion of the platform relative to the ground. In practice, however, the azimuth chirp transmitted from satellite systems is affected by earth rotation and to a lesser extent platform attitude changes. Therefore, the replica is derived from the return signal.

From a given transmitted chirp the 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. For satellite systems the data storage may be on board or the data directly down-linked to a ground station where they are recorded. Subsequently these data are transferred to computer memory for processing. The complete set of radar reflections for a given area of terrain therefore consists of many range lines. Radar returns from a point target in the terrain 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.

During data acquisition earth rotation causes a skew effect and, together with the continuous slant range variation, leads to the compressed line of data being curved in the memory. That is the data for the point migrates across range bins as a function of azimuth. This causes errors following 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.

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 added advantage of removing some of the speckle inherent in coherent imaging systems. However, it also has the disadvantage 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. For example, ERS-1 data will be processed to four looks so that the azimuth resolution is reduced from 7m (l/2) to 30m (4 x {l/2}) approximately.

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 relationship of all the factors affecting backscatter ȍ can be expressed as follows (from Colwell (Ed.). 1 983):

ȍ = ƒ(λ, P, ø, ő, ờ, E, T1, T2, V) (9)

where the system parameters are:

λ	the wavelength of the radiation,
P	the polarization of the system,
ø	the look angle,
ő	the azimuth angle;

and the scene parameters are:

ȍ	the aspect angle,
E	the complex dielectric constant,
T1	the surface roughness,
T2	the sub-surface reflectance
V	the complex volume scatterer.

Changing one or several of these parameters will alter the backscatter and result in different information being acquired.

An examination of these parameters shows that, for a particular system, several parameters remain constant. The carrier frequency of the radar pulse is set by the system electronics and thus the wavelength remains fixed. In addition, the azimuth angle for a particular orbiting system relative to ground features 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 aspect angle 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, that is, the ground surface is normal to the beam.

The parameters of complex dielectric constant, polarization, surface roughness and volume scattering vary with the terrain being imaged. Their interaction and influence on backscatter is a subject of ongoing research. The total effect of all the system and scene parameters, however, influence backscatter and result in the tonal variations in a radar image.

Mapping from Radar Imagery

In 1967 the first civilian large scale topographic mapping project was flown by Ratheon Autometric, with Side-Looking Airborne Radar (SLAR), over the Darien province of Panama for Project RAMP (RAdar Mapping of Panama) (Crandall, 1969). SLAR was considered ideal for mapping this area, which was continuously covered by cloud, and for which there existed no maps or aerial photographs. The U.S. Air Force had previously attempted, for nearly 20 years, to acquire aerial photography over this area (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, 1983).

SLAR has since demonstrated its value in a wide range of resource mapping activities. These activities include lithological mapping in geology (Sabins, 1978), studies of agriculture (Ulaby et al., 1980, and Fenner et al., 1981), soil moisture mapping (Dobson and Ulaby, 1981) and the photographic merging of airborne SAR and Landsat imagery, for improved interpretability, by Harris and Graham (1976).

The spaceborne SAR systems Seasat, SIR-A and SIR-B were essentially experimental and their areas of coverage limited. Nevertheless, their data have attracted considerable research. For example, Blom and Daily (1982) evaluated the processing and analysis of Seasat data as well as merged Landsat and Seasat data for improved rock type discrimination. SIR-A data was used by Frost et al. (1983) and Soesilo and Hoppin (1986) to discern geological information. Following the 1984 Shuttle flight, with SIR-B on board, Swart (1986) and Wang et al. (1986) investigated these data for the determination of soil moisture content, and Richards et al. (1987) has attempted to develop computer models to predict the interaction of microwaves with forested areas. In addition, researchers such as Guindon et al. (1980), Henninger and Carney (1983), Kux and Dutra (1984) and Kessler (1987) have shown that, using merged Landsat and SAR data, computer algorithms for classifying cover types are improved.

Although SAR imagery has now evaluated for a wide variety of resource mapping applications, little topographic mapping has been generated. Apart from the limited SAR coverage, a major reason is SAR's inherent variability in showing topographic detail.

The interpretability of topographic features is the factor governing the scales of topographic mapping for which any 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. An added complexity to the interpretation of radar imagery is its inherent distortion. This distortion inhibits subjective interpretation and precludes quantitative analysis of spatial relationships (Naraghi et al., 1983).

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 projections (Wu, 1984). Features displayed on radar images are distorted. The distortion is essentially a function of both the data recording and processing system and platform and shape of the earth.

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, 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. However, errors, from the adopted platform ephemeris and the shape of the Earth can lead to residual errors in the processed data.

Radar imagery, aerial photography and imagery all contain the distortion produced by local elevation variations. In a radar image relief displacement causes the tops of objects to be recorded away from their true plan position in the range direction, towards the sensor. Whereas the tops of objects are recorded away from their true plan position in a radial direction in the more familiar imagery from aerial cameras and scanners. In radar this displacement is known as layover. 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.

Terrain lying behind local elevations, as seen from the sensor, may not be recorded as lies in radar shadow. In Australia there are few areas of extreme local height variation this effect will rarely be apparent on satellite radar imagery over this continent.

Backscatter and Tonal Differences

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 lighter toned pixels are produced by the relative difference in the backscatter. There are a large number of variables which affect the contrast of features, as discussed above. 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 (refer to equation (9) above).

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 generated by a particular system and the 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 following the normal laws of physics. 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 face away from the radar radiation can either reflect a reduced amount of radiation or can be in radar shadow thus appearing darker on the image. This effect may appear similar to the relief shading on topographic maps.

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

As well as tonal features, synthetic aperture radar images contain textural features. 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. Frost et al. (1984) and Ulaby et al. (1986) both suggest that texture may be more useful than image tone in interpreting radar images.

Features Detected on SIR-B Imagery

SIR-B imagery over eastern Australia was evaluated for its topographic content (Wise, 1987). This evaluation revealed that some generalizations on the content of SAR imagery could be stated.

Generally linear features such as roads, tracks and railways are only visible where their route passes through an area of forest or where there are trees growing alongside their route. Railway lines normal to the radar beam saturate the return and appear very bright in the image. That is, they act as a hard target. 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.

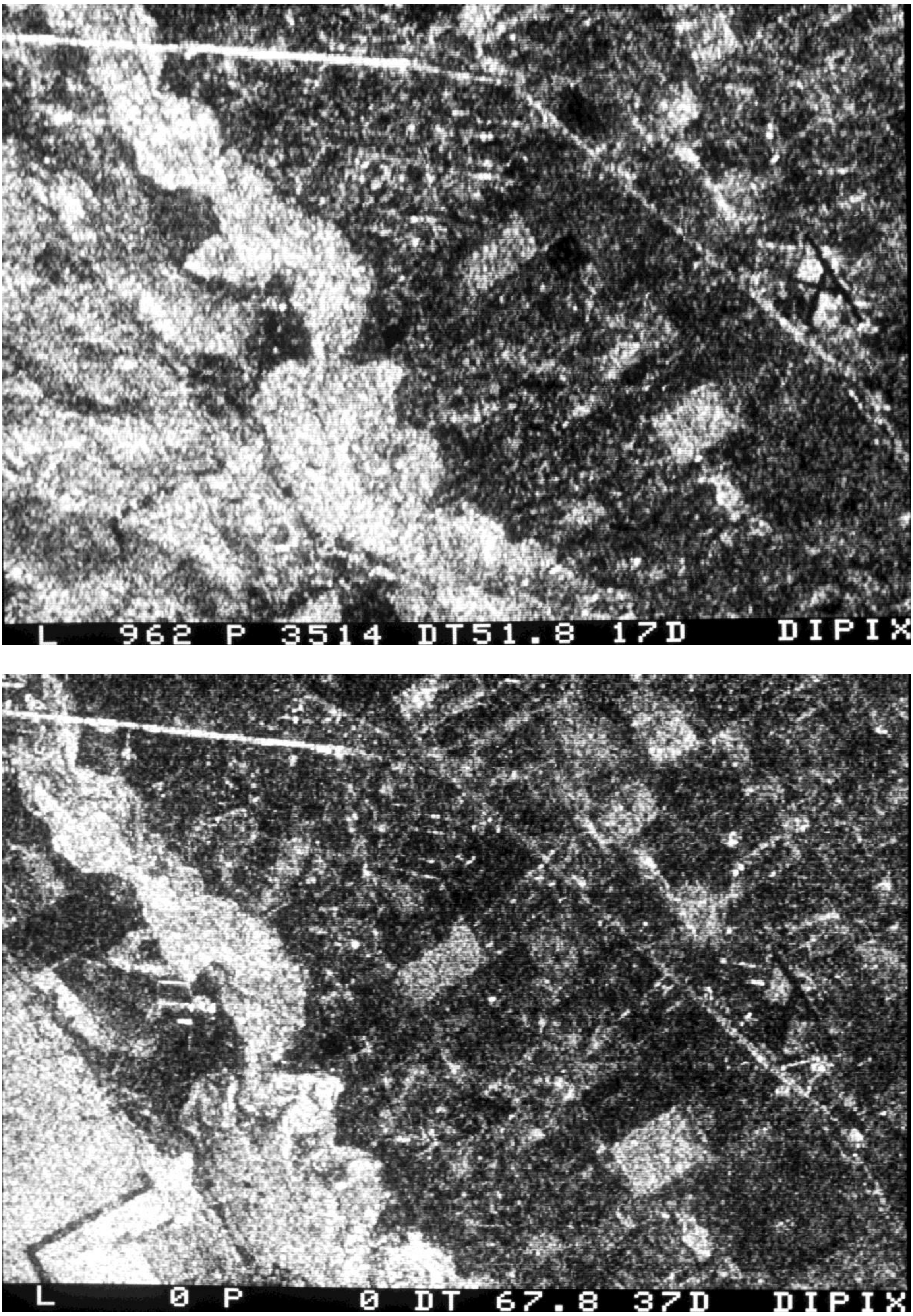

Figure 2 : Sections of two separate SIR-B Data Takes at different look angles of the same area around Sale, Victoria. DT 51.8 acquired at a look angle of 17 degrees and DT 67.8 at 42 degrees.

Boundaries between natural and synthetic surfaces, for example between rural and urban 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.

A view of the geomorphology was also provided in the SIR-B imagery at the lower look angles, because of the coarser resolution. Thus rough and rougher surface be discriminated. In general, backscatter is controlled by relief at lower incidence angles and by small scale roughness at large incidence angles.

The variability of features detectable on radar data is observable in Figure 2 above. The same area, near Sale in Victoria, was imaged by the SIR-B system at look angles of 42 and 17 degrees respectively. At a look angle of 42 degrees (DT 67.8), the radar resolution cell is approximately 25 m square. In comparison, the resolution cell of DT 51.8, acquired at angle of 17 degrees, is approximate by 45 m by 25 m and thus provides less discrimination. Nevertheless, the larger resolution cell may highlight the geomorphology and the drainage patterns.

The bright line at the centre of both images is a section of railway that parallels the Shuttle's ground track and thus acted as a hard target. In the higher resolution scene (DT 67.8) the boundaries between forested and open country are more clearly visible whereas the underlying geomorphology can be seen in the lower resolution image. Within the forested areas, on the higher resolution scene, differing forest types are detectable by their different tones and textures. It is also noticeable that the riparian vegetation is brighter in this image. However, because of the openness of the country, only vague indications of roads and paddock boundaries are detectable, even on the high resolution image. For mapping, maximum detail would be contained in a composite of these two scenes.

This single example demonstrates how the variation in look angle affects the appearance of features on radar images. Research by Haack (1984) and Lewis (1968), using radar data acquired by aircraft has indicated that it is likely that more detail can be detected if an area is imaged at more than one frequency and polarization. The acquisition of similar data from space, however, by multifrequency, multipolarization and multilook angle radar systems is still some years away, and unlikely to be routine until the launch of the polar platforms of the Space Station. Combinations of the acquired data sets, that provide the maximum feature detail, will then need to be established.

Future SAR Imagery

The next SAR system that is likely to have a significant impact on mapping applications will be SIR-C. In addition to multilook angle, SIR-C will have both a multifrequency and multipolarization capability permitting the transmission and reception of any combination of horizontal and vertical polarized signals. With minor modifications SIR-C can be flown aboard the platforms of the Earth Observing System (EOS).

The EOS SAR will provide, for the first time, the ability to collect nine channels of SAR data simultaneously (that is, all three frequencies at all three combinations of polarization (Cimino et al., 1986). Following data acquisition, research will determine whether this imagery is suitable for the compilation of medium and large scale topographic maps.

Summary

Radar is a complex remote sensing system. It is active in the sense that it emits its own energy which is reflected by the terrain and recorded by the system. Terrestrial feature positions are encoded in the backscatter. The amount of backscatter generated by the combined characteristics of the terrain features and the radar system determines image tone.

Imagery is formed by compressing the recorded data in range and azimuth, interposing the range cell migration correction, and output as either digital data or photographic products.

The expected increase in radar imagery coverage of Australia promises to yield a significant supplement to the cartographic information presently provided from passive remote sensing systems. However, the complexity endemic to the imagery is not restricted to its acquisition. Specialized techniques are also required for its interpretation. Because of the variability of the content of radar imagery its interpretation involves a quantum leap up the learning curve, compared with the adaption of interpretation techniques from aerial photography to data acquired by passive scanning sensors. Nevertheless, with the advent of cyclical radar data acquisition it is considered that there is considerable potential for cartographers to benefit from investing in the resources necessary to gain a working knowledge of radar imagery.

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