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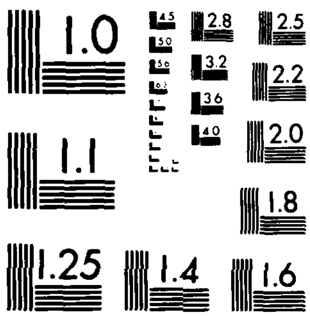
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RADC-TR-84-54
In-House Report
March 1984

ASPECTS AND APPLICATIONS OF SAR IMAGERY FOR MENSURATION

Scott J. Wheeler

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ROME AIR DEVELOPMENT CENTER
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This document provides a brief introduction to those aspects of SAR image properties and signal processing operations related to the use of SAR images for point measurement purposes. Geometrical properties of the image and math models are considered. An analysis of problems which may be encountered in SAR measurement applications and potential research to solve these problems is addressed.

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INTRODUCTION

The advantages of synthetic aperture radar (SAR) for image interpretation have been exploited for some time. The all-hour, all-weather, high-resolution capabilities of SAR have proven to be an excellent reconnaissance source. Recently, attention has been focused on the use of SAR images for the extraction of accurate point location information. The use of SAR capabilities for measurement purposes will greatly enhance both civilian and military users' ability to accurately map or locate point information in extreme conditions.

Prior to the full-scale, wide-spread implementation of SAR imagery as a source of accurate geographic information, it is necessary to understand the imaging system and the images it produces. The knowledge of system capabilities and limitations will lead to a more direct, cost-effective, and successful approach to the use of SAR imagery for measurement purposes. The following report provides a brief introduction to those aspects of SAR with which those interested in utilizing SAR for analysis or measurement purposes should be familiar.

SAR basics and processing are introduced to provide insight into the imaging process. Image characteristics as related to stereo-viewing are discussed to emphasize some of the difficulties which must be dealt with when using SAR. The remaining sections explain the current understanding of SAR image geometry and errors followed by recommendations on future work which should be done to help provide important information necessary to intelligently develope SAR for analysis and measurement purposes.

1.0 SAR Basics

A synthetic aperture radar (SAR) image is the end product of two dimensional signal processing techniques. The position of points measured on a SAR image are expressed in range (cross track) and azimuth (along track) coordinates. Figure 1-1 shows the sensor geometry for a SAR image. From the figure it can be seen that the radar imaging system is side looking and that the image produced is offset by a distance R_b (range bias) from the flight line. Range and azimuth resolution are independent of one another. Range resolution is a function of the ability to measure distance to a ground point. This is related to round trip signal time. Azimuth resolution is related to the ability to measure the angle to a ground point from the sensor. Resolution is not dependent on distance from the sensor and is uniform across the entire image provided the signal-to-noise (S/N) from the most distant point is sufficiently high.

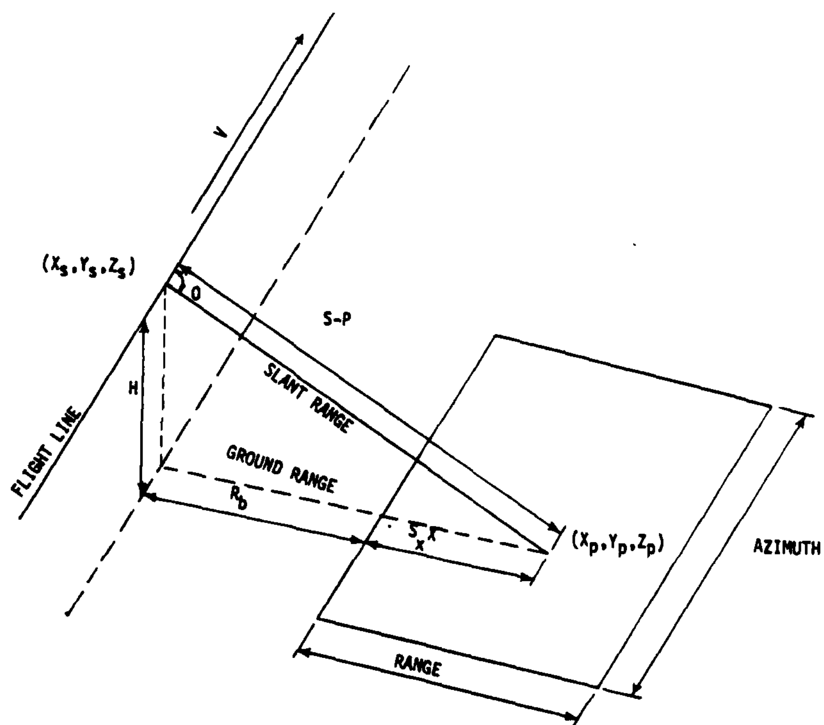


FIGURE 1-1

1.1 Range Resolution

Range resolution is determined by the amount of time taken for a transmitted radar pulse to travel from the sensor, to the ground, and back. This time is given by Equation 1-1.

$$t = {}^{2d}/c \qquad 1\text{-}1$$

d = distance

c = speed of light

Points more distant from the sensor will take longer to return the signal and points closer will take less time. The technique used to obtain high range resolution is to transmit very short pulse lengths to reduce overlapping of signals from adjacent points (ambiguities). In real systems, techniques are used which make long pulses appear much shorter during processing. This enables an increase in transmitted power and a corresponding increase in S/N ratio. These techniques are described briefly in the signal processing section (Sec. 2). Range measurements are presented in two different formats, dependent upon the sensor used to produce the image. Slant range format displays range along a line between the radar location and the ground point. Ground range displays range along a line between the ground nadir and the ground points being imaged.

1.2 Azimuth Resolution

Azimuth resolution is the primary advantage gained over normal radar imaging by using synthetic aperture techniques. In a real aperture radar system, azimuth resolution is controlled by regulating the antenna beam width. Beam width is directly related to antenna size (aperture); a large antenna produces a narrow beam width. The narrow beam width of a large antenna results from the fact that any large antenna is made up of many small radiators with known phase relationships between them. The antenna design adjusts these phase relationships to produce an interference pattern which results in destructive interference away from the antenna axis and constructive interference on axis. This results in a high power, narrow beam width antenna pattern.

It is impractical to build a large antenna system for an airborne imaging system. Signal processing techniques and the use of a coherent wave radar make the generation of a synthetic aperture, which performs similar to a large real aperture, possible. A synthetic aperture is constructed through the simultaneous processing of many return signals from a moving radar system with a small real aperture (i.e., wide beam width). It is helpful to think of each pulse of the radar as an individual radiator of a large antenna. Since the pulses cannot be transmitted simultaneously, and the exact phase relationships between them are not known, the results from each pulse cannot merely be summed to produce a narrow beam pattern. The individual returns are stored and processed after data from the entire synthetic aperture length has been acquired.

Signal processing techniques used to achieve desired azimuth resolution are commonly called "doppler processing" or "doppler beam sharpening". Processing for improved along-track resolution is based on doppler frequency shifts in the signal. Doppler frequency shifts refer to the apparent increase or decrease in signal frequency of a reflected wave due to relative motion between the object and the radar. This is analagous to the well known acoustic doppler shift which causes sound emitted from an object traveling towards an observer to sound higher pitched and objects traveling away to sound lower pitched than the actual sound being emitted. It is important to note that only relative motion is important. It does not matter if either the object, observer, or both are moving.

For an airborne sensor, surfaces of equal doppler frequency shift are projected as cones centered on the flight line with their vertices located at the sensor. The intersection of these surfaces with the ground are called isodops and are parabolic lines passing through points which will exhibit equal frequency shift relative to the sensor. These lines are shown in Figure 2 and the equation for doppler shift is given in equation 1-2.

$$f_d = 2vf_c/c \cos \theta \qquad \text{1-2}$$

c = speed of light

v = velocity of sensor

f_c = frequency of transmitted signal

θ = angle between flight line and ray to point.

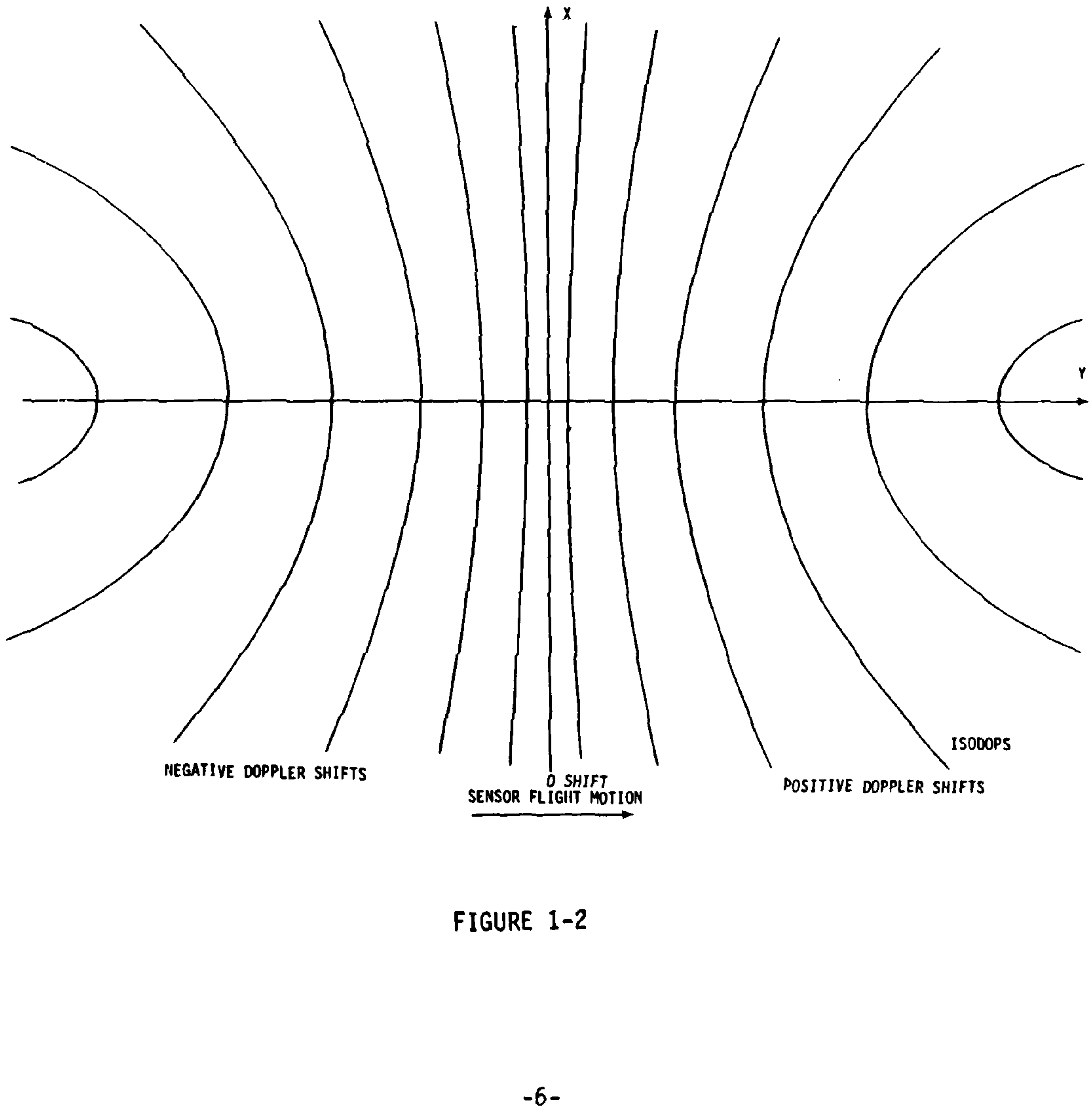

X
Y
ISODOPS
NEGATIVE DOPPLER SHIFTS
0 SHIFT
SENSOR FLIGHT MOTION
POSITIVE DOPPLER SHIFTS

FIGURE 1-2

Azimuth resolution is obtained by separating the various frequency components of (frequency analyzing) the return signal and utilizing the frequency of interest to obtain information about a specific point. From this discussion, it can be seen that coherent radar is essential because the frequency content of the transmitted signal is known. A non-coherent system would not yield meaningful results when the return is frequency analyzed since it would be impossible to determine the doppler frequency shifts. In actual systems, a particular doppler frequency is chosen as the shift of interest. The angle from the flight line to the doppler cone of interest is known as the squint angle.

Signal processing is done once the entire phase history for a particular point has been collected. Phase history is a record of the doppler frequency shift of the point from the time it enters the real aperture field of view to the time it leaves it. Figures 1-3 and 1-4 show the imaged ground area and image representation of that area for a squint angle of 90 degrees and less than 90 degrees respectively. 90 degree squint angles are frequently used since this is the only angle which will yield a linear relationship between the image and the ground. Table 1-1 lists some of the more important terms pertinent to the understanding of SAR which will be helpful throughout the remainder of this document.

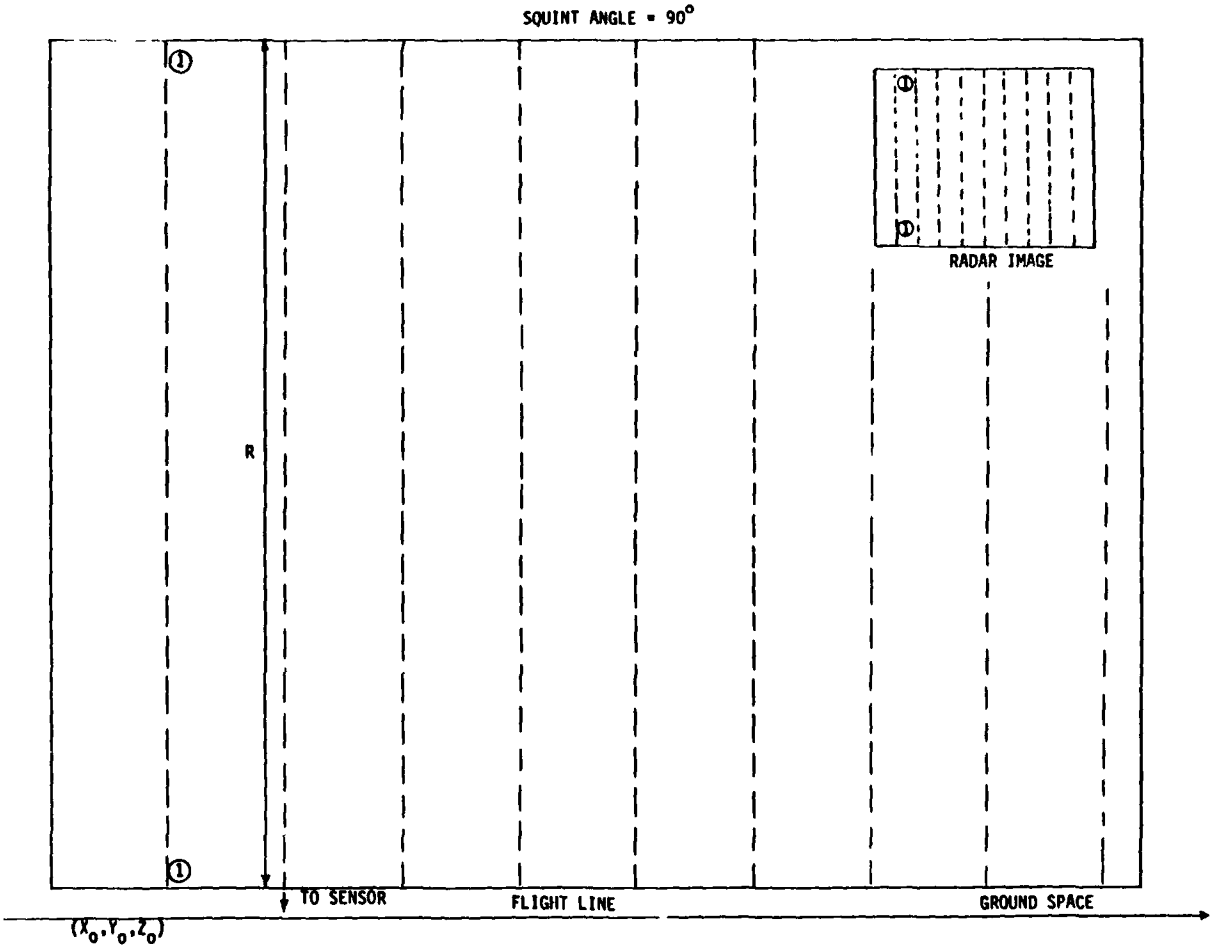

SQUINT ANGLE = 90°
①
①
R
①
①
RADAR IMAGE
TO SENSOR
FLIGHT LINE
GROUND SPACE
(X_o,Y_o,Z_o)

FIGURE 1-3

SQUINT ANGLE < 90°

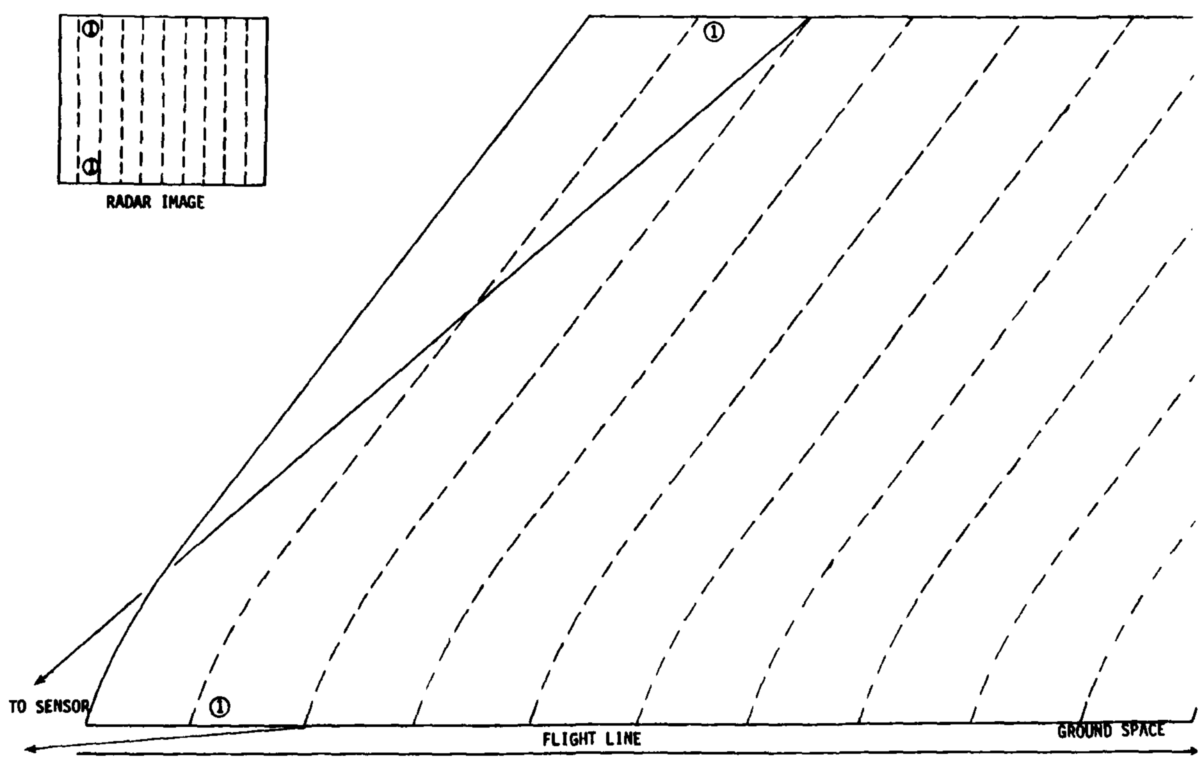


FIGURE 1-4

FREQUENTLY USED SAR TERMS

Range	Measure of distance from sensor, cross track or y resolution on image.
Azimuth	Measure of along track distance on image determined through doppler processing.
Range Bias	Ground distance from nadir to near edge of imaged region.
Slant Range	Range measured along line from sensor to ground point.
Ground Range	Range measured along ground from nadir to ground point.
Beam Width	Actual physical width of antenna beam on ground.
Coherent Wave	Radar emission of uniform controlled frequency signal.
Squint Angle	Angle to doppler cone representing frequency shift being analyzed.

Table 1-1

Phase History	Stored record of changing frequency shift of a ground point as it passes through the real aperture beam over many pulses.

Table 1-1 (Cont'd)

2.0 Signal Processing

When using synthetic aperture radar imagery, or any other type of image, for interpretation and measurement purposes, it is important to understand what the image represents and how it was created. This understanding of actually what the image represents will increase one's ability to utilize SAR imagery in a productive way. This section provides a brief introduction to the theory and techniques used to produce a SAR image.

As was mentioned previously, a SAR image is the result of systematic signal processing operations performed on a collection of radar returns. The returns are assumed to have known frequency shift characteristics and be from a target within the area being imaged. Currently there are three signal processing techniques commonly in use to generate SAR images. One technique uses optical methods and the other two are electronic. Optical techniques record the radar returns containing the doppler phase histories on a film storage medium. Image generation is later accomplished using optical processing techniques which utilize coherent light and holographic techniques. The two electronic techniques are analog and digital processing. Analog processing analyzes and decodes the signals through the use of electronic filtering systems to modify and analyze the radar returns and produce an image. Digital processors use digital functions and processing to analyze SAR data. In all cases the transmitted signal from the coherent radar is identical.

2.1 Transmitted Signal

In order to accomplish the desired signal processing operations, it is necessary that the properties of the transmitted signal be known. Doppler processing is based on the signal frequency shift due to relative target sensor motion. For this reason, it is necessary that the source signal be highly coherent in its frequency so that the carrier signal can be separated from the doppler frequency information. The term coherent radar comes from this requirement. In coherent radars, all signals used in transmission or within the system as references are generated in the local oscillator. The local oscillator produces a continuous highly coherent source of radar waves. Frequencies other than the local oscillator frequency are obtained by upshifting or downshifting the output of the local oscillator to the desired frequency. The output from the local oscillator is shown in Figure 2-1. The coherency of the transmitted source is what makes azimuth resolution through doppler processing possible.

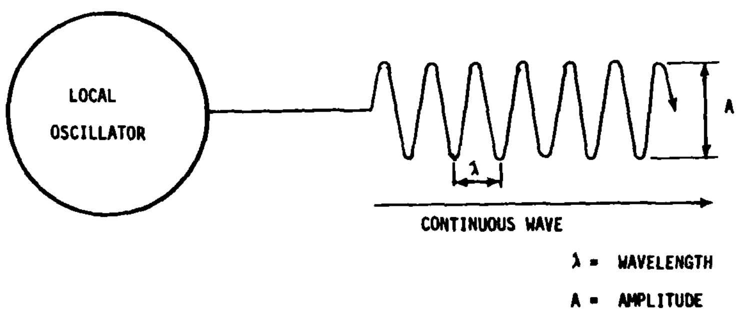


FIGURE 2-1

Range resolution, as mentioned previously, is controlled by limiting the transmitted pulse length. When a pulse is transmitted, a finite amount of time is taken for the pulse to travel from the sensor to a ground point and back to the receiver. Points further away from the sensor will take longer to return to the receiver. If a pulse could be generated of zero or near zero length, the return from each ground point would arrive in succession and at any given point in the return the wave would represent only the return from a single ground point . Since it is not possible to generate pulses of zero length, ambiguities are introduced into the return. Figure 2-2 shows the return signal from two transmitted pulses, one having a hypothetical duration of 0 and the other of t. As can be seen from the diagram, the returns from point 1 and 2 overlap when the pulse is of duration t. This condition causes ambiguities to occur in the return signal. It is still essential to remember that the shorter the signal, the fewer the number of ambiguities and the higher the achievable resolution.

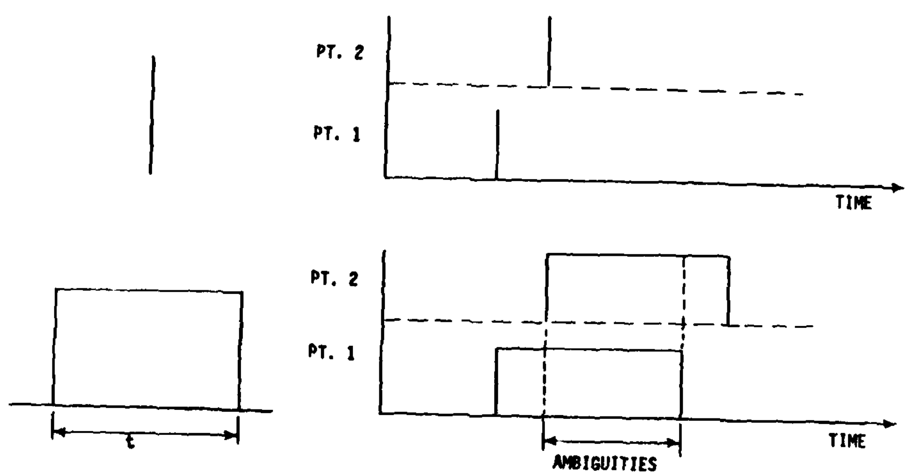


FIGURE 2-2

In order to achieve meaningful information from a radar signal, the signal-to-noise ratio of the return must be above a minimum required level. Signal-to-noise ratio is the ratio of the received signal strength to the strength of non-useful clutter (noise) in the signal. S/N is increased by increasing the energy in the transmitted signal. This is done either by increasing transmitter power or increasing pulse duration. In an airborne system, high transmitter power is often difficult to achieve and pulse lengths must be made longer to compensate for the lack of transmitter power. The solution to this problem has been found by using a frequency modulation technique known as chirp. Chirping the transmitted signal allows long pulse duration with processing techniques that make the pulse appear short and enable subsequent improvements in range resolution.

When a signal is chirped, it is frequency-modulated in a linear manner around a central carrier frequency. Figure 2-3 shows the transmitted and returned signals for points 1 and 2 shown in Figure 2-2 when a chirped signal is used. The important thing to notice is that, although signals from points 1 and 2 are being received simultaneously, the frequency of the returned signals at any instant in time are not equal. A frequency analysis to remove the frequency modulation will result in the separation of the returns from points 1 and 2. The separation of signals from points 1 and 2 is identical to the results that could be achieved with a very high power transmitter and a short pulse duration.

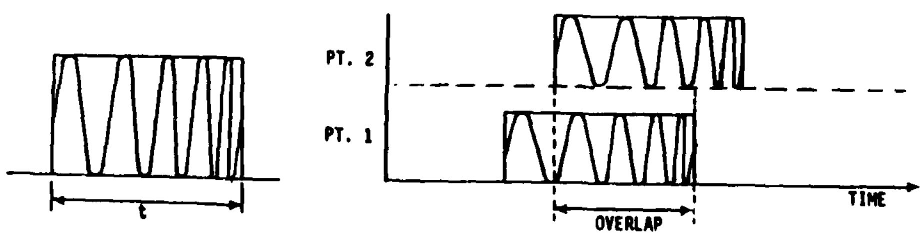


FIGURE 2-3

Since doppler processing is dependent on the phase histories of ground points, the results of many pulses must be used in processing. The time between successive pulses must be adjusted such that the returns from the area of interest are received between the transmission periods (this is shown in Figure 2-4). The frequency with which the pulses are transmitted is known as the pulse repetition frequency (PRF). In airborne sensors, the return pulse is usually received prior to the transmission of the succeeding pulse. In spaceborne sensors, several pulses may be transmitted before the return from a pulse arrives.

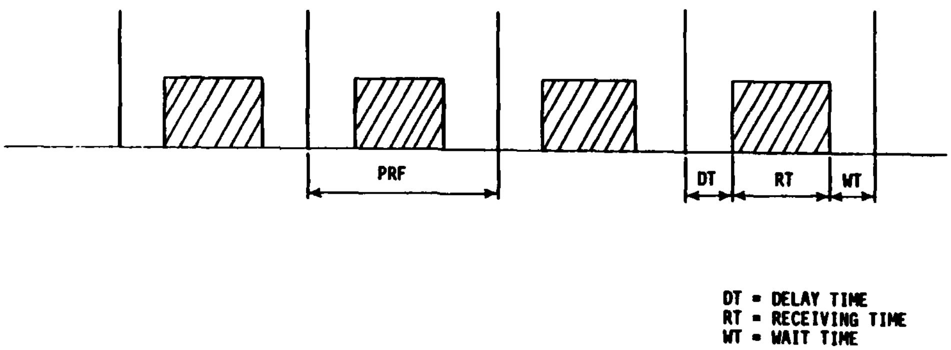


FIGURE 2-4

2.2 Return Signal

The return signal from a coherent radar contains the frequency modulated signal from the transmitter with doppler frequency shifts mixed in. The doppler frequency shifts correspond to the relative radial velocities of the various ground points. The collection of the various pulse returns containing the doppler histories for the ground points of interest is a two-dimensional phase history of the ground points. The within pulse phase history is the result of the linear frequency modulation to improve range resolution and the between pulse phase history is the result of the ground points doppler frequency shift as it passes through the radars field of view. The objective of the signal processing system is to produce an accurate ground representation from the assembled two-dimensional phase histories.

2.3 Optical Signal Processing

Optical signal processing systems utilize film to store radar returns for subsequent processing. The amplitude of the returned pulse is used to modulate the intensity of a light source which is swept across the film as the return from the closest to furthest imaged points arrive at the sensor. The film (Figure 2-5) is advanced at a rate proportional to the velocity of the aircraft (rate of image motion). The resultant signal film contains all of the two-dimensional phase history information contained in the returned pulses.

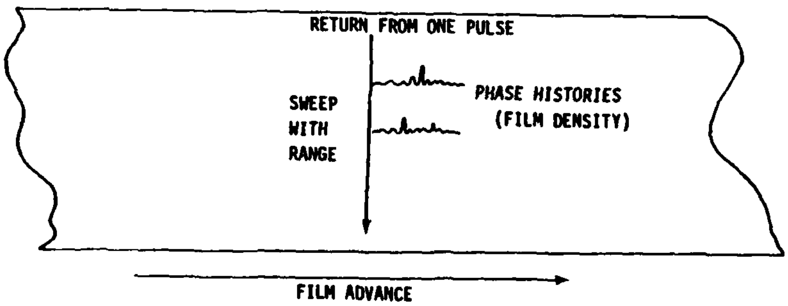


FIGURE 2-5

Processing of the signal film is analagous to processing a hologram and, as such, optical SAR processing is sometimes called holographic processing. In a standard hologram (Figure 2-6), an object is illuminated by a reference light source. The light source is also incident on a film upon which the reflected light from the object is falling. The combination of the reference and reflected sources produces an interference pattern on the film. When a copy of the reference light source is projected through the exposed film, a real image of the illuminated object is produced. The optical hologram idea can be used to process SAR signal films.

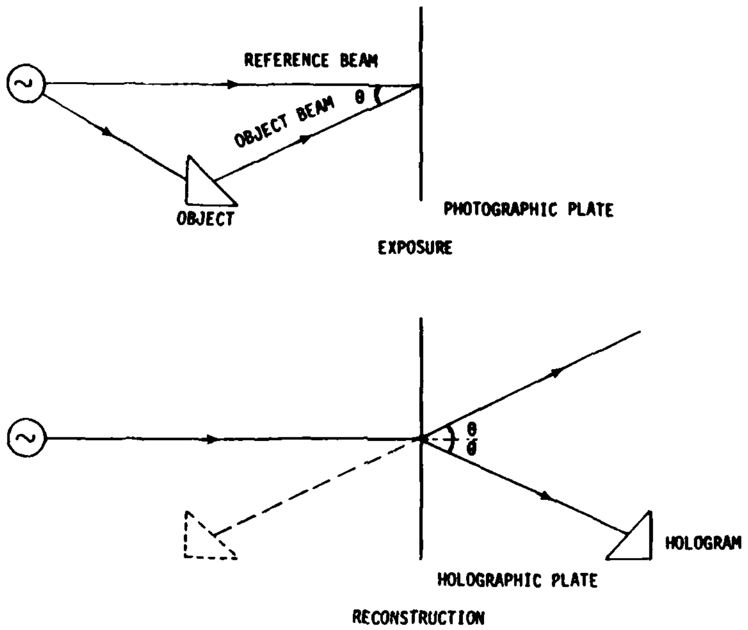


FIGURE 2-6

The exposed signal film can be viewed as the holographic plate. Processing of the phase histories in two dimensions is necessary in order to reproduce a representation of the ground. What this means is that the ability to discriminate points either visibly or through frequency analysis is needed. To understand the analogy between SAR optical processing and holograms, a reference signal and target must be specified. The reference signal is the known doppler and range chirp frequency sweeps for each range resolution element, and the target is the collection of ground points possessing a known doppler frequency at a particular location.

Optical processing consists of illuminating the signal film with a coherent light source which contains the frequency shift information. The resulting image will be the processed phase histories. If the frequency components of the resulting image are determined they will now correlate directly with point ground location. The latter process is accomplished by passing the resultant image through a lens element to separate the frequency components. This is done in both along track and cross track directions to separate range and azimuth elements. The resulting frequency analysis is then masked to allow only the frequencies corresponding to the squint angle and range frequencies desired to image on the map film.

The diagram in Figure 2-7 shows a simplified schematic of a typical SAR optical processing system. A great number of airborne SAR systems utilize optical processing techniques. Optical processing has been used to a large extent as the primary SAR processing technique until recently when, with the introduction of spaceborne SARS and the need for real time processing, electronic processinq systems began to enter the signal processing scene.

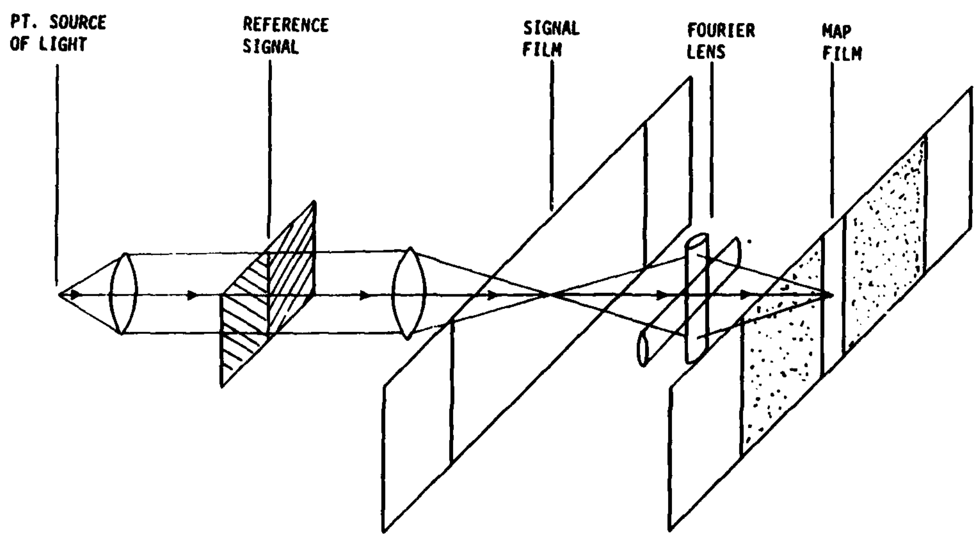


FIGURE 2-7

2.4 Electronic Signal Processing

Electronic signal processing techniques do all of the return signal processing electronically. Processing of the range and azimuth resolution are independent operations. In optical processing these operations are carried out simultaneously; in electronic processing they are processed sequentially. There are two types of electronic signal processing, analog and digital. In both forms of processing the frequency modulation introduced to increase range resolution is processed first. The demodulated signal can then be broken into individual elements by "range gating" the signal. Range gating breaks the signal into small elements; the waveform in each element corresponds to a range resolution cell.

Azimuth and range processing are orthogonal operations on the same set of data. Range processing can be done as the signal is returned and then, upon completion of range gating, stored until all data on the point is acquired. When using range gating techniques it is assumed that any ground point remains in the same range gate for all pulses. Since the range and azimuth processing are orthogonal operations, the data is read into memory along a pulse and read out along a range gate in what is called a corner turn memory. This is shown in Figure 2-8.

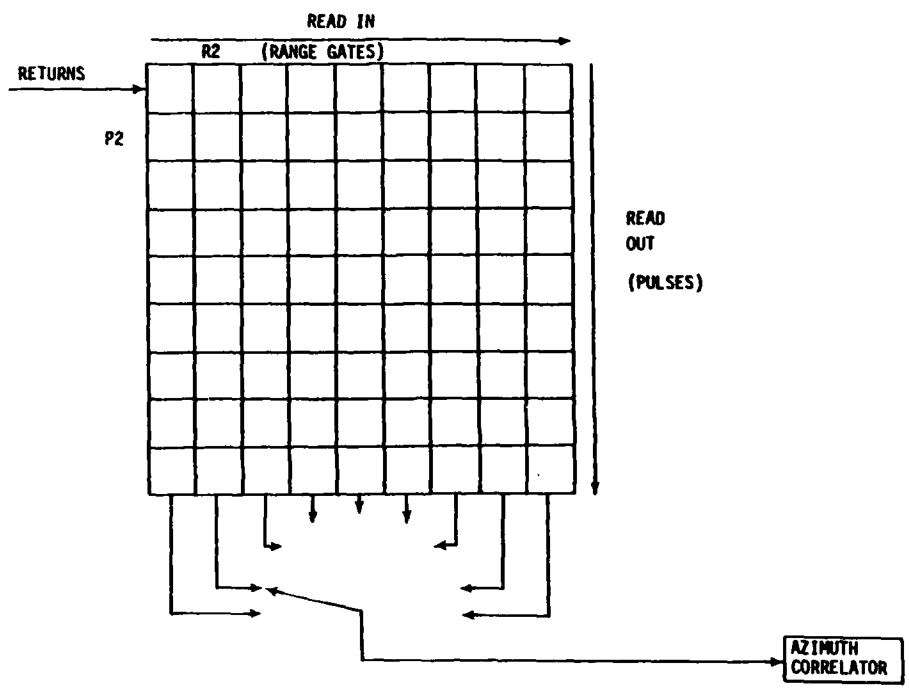

READ IN
R2
(RANGE GATES)
RETURNS
P2
READ
OUT
(PULSES)
AZIMUTH
CORRELATOR

FIGURE 2-8

All points within a particular range gate will have identical doppler frequency histories (phase histories) as they travel from one side of the real aperture beam to the other. The only difference between the doppler phase histories for adjacent points will be in time. For any given pulse, the ground points within a range resolution cell will exhibit a different doppler frequency shift corresponding to the position to which the point has progressed in the real aperture antenna beam. Figure 2-9 shows the frequency shifts of several points across the nine pulses shown in Figure 2-8. Only one point is present in every pulse. Since the expected doppler history is known, it is possible to "match filter" the signal histories in order to force all of the information about a particular point into a single frequency. When this is done, the frequency components of the resultant signal correspond directly to a ground azimuth point. The final azimuth resolution is now dependent on the ability to detect different frequency components within the signal.

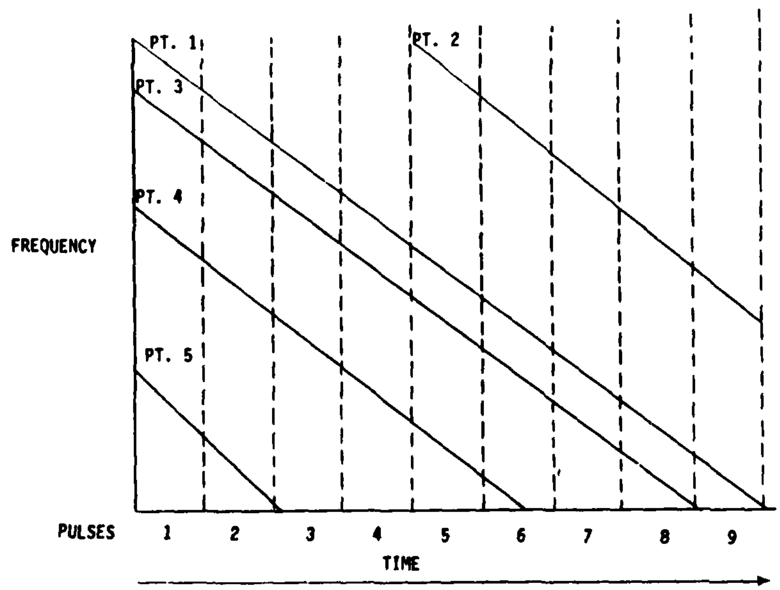
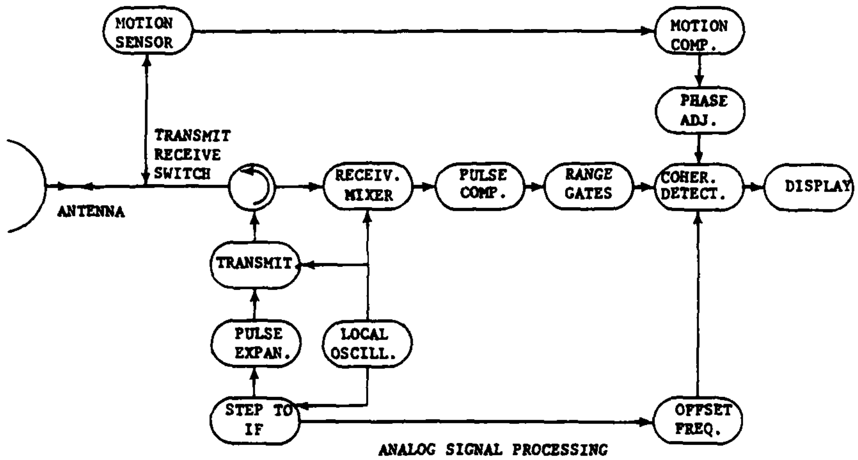
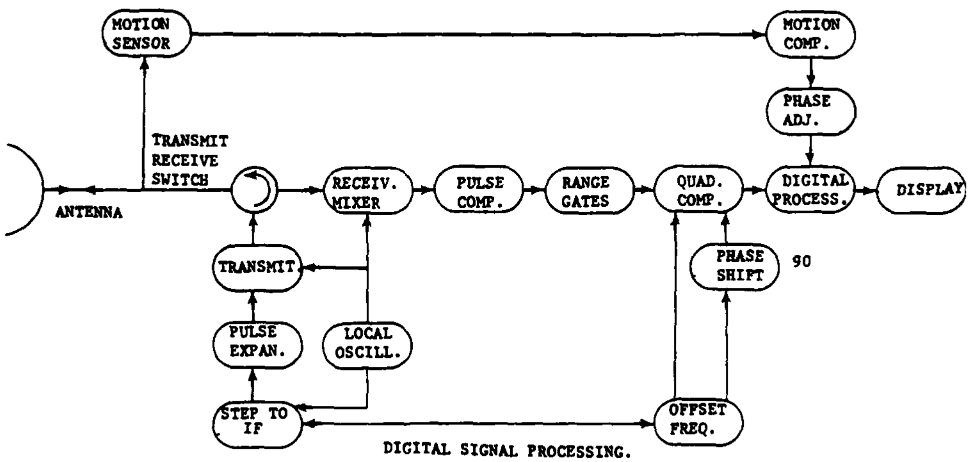


FIGURE 2-9

In Figure 2-10, a block diagram of an analog and digital SAR processing system is shown. Table 2-1 describes the function of the various components of the analog system. The doppler processing technique is the primary difference between digital and analog processing systems. Mathematically, both systems are the same and the end product of both systems contains the same spatial information. In order to utilize the frequency information in the signal, it is necessary to transform the signal from time vs amplitude to frequency vs amplitude. Mathematically, this transformation is called the Fourier transform of the signal. In actual this is done using a set of narrow bandpass filters in analog processors and discrete fast Fourier transform techniques in digital processors. Bandpass filters only allow specific frequencies of the input signal to pass through them. Digital fast Fourier transform produces a discrete frequency amplitude representation of the signal.



ANALOG SIGNAL PROCESSING



DIGITAL SIGNAL PROCESSING.

FIGURE 2-10

COMPONENTS OF AN ANALOG SAR PROCESSOR

LOCAL OSCILLATOR

The local oscillator is a source of stable, highly coherent, and continuous waveforms. This component is the wave generator which makes coherent wave radar possible. In many radars, this source is either stepped up or down to produce all the needed wavelengths.

f_{lo} = frequency of coherent source waves from local oscillator

STEP DOWN TO INTERMEDIATE FREQUENCY (IF)

This component reduces the frequency of the local oscillator to some lower frequency which is offset from zero center frequency. This frequency is supplied to the pulse expansion and coherent detector components.

f_{if} = intermediate frequency

PULSE EXPANSION

The intermediate frequency is expanded to produce a linear frequency modulation from some low frequency to some higher one. The difference between the low and high frequency is Δ . This time varying frequency will allow an increase in transmitted power without a lowering of receiver bandwidth and subsequent reduction in range resolutions.

$$f_m = \pm \Delta/2$$

Table 2-1

TRANSMITTER

The transmitter combines the frequency modulated signal with the local oscillator signal to produce a time varying signal with a carrier frequency given by RF. This signal is the transmitted signal from the radar

$$f_{rf} = f_{if} + f_{lo}$$

$$\text{Trans Signal} = f_{rf} \pm \Delta/2$$

SWITCH

This switch alternately uses the radar antenna to either transmit or receive.

RECEIVER MIXER

The signal received from the target is combined with the local oscillator signal. Filtering of the combined signal will remove the local oscillator from the return and will leave the following frequency.

$$f_{rc} = f_{if} \pm \Delta/2 \pm f_d$$

$$f_d = \text{doppler shift}$$

PULSE COMPRESSION

The linear frequency modulation introduced from the pulse expansion component is removed from the signal via a delay mechanism (either via a filter with specified convolution function or via digital techniques). This results in large amplitude coherent waves which can be range gated for higher resolution.

Table 2-1 (Cont'd)

$$f = f_{if} + f_d$$

RANGE GATES

The compressed pulse is separated according to time which directly corresponds to distance from the sensor. Hence, cross track (range) resolution is taken directly from this step. Doppler signal processing is now needed in order to improve along track resolution.

MOTION SENSOR

The antenna length swept out by the generated synthetic array is assumed to be straight. Since all of the data processing assumptions are based on this fact, it is essential that any aircraft motion other than a straight line be compensated for. The doppler frequencies of incoming signals must be adjusted for any detected motion. The motion sensor measures any of these unexpected and random motions.

MOTION COMPENSATION COMPUTER

The motion compensation computer determines what frequency shifts are necessary to correct the received signal for unexpected sensor motion.

PHASE SHIFTER

The motion compensation signal is generated and adjusted for combination with the received signal.

OFFSET FREQUENCY

The f_{if} which has been phase corrected to match the return phase

Table 2-1 (cont'd)

which will remove the f_{if} component from the signal to leave only doppler information for detection.

COHERENT DETECTORS

Doppler phase histories are processed to improve the azimuth resolution across the image. Information from multiple pulses in the same range gate are processed together to yield this resolution. Doppler processing methods are the primary difference between digital and analog systems and are the heart of any SAR processing system be it optical or electronic.

DISPLAY

The final CRT, hardcopy, or digital image produced as a result of processed range and doppler information.

End of Table 2-1

In analog systems the return signal is processed through filters with specially designed response functions. "Matched filters" are used to remove chirp and doppler frequency sweeps and narrow "bandpass filters" are used to obtain the frequency information in the signal. A matched filter is designed such that its response function, when given a pulse input, is an inverted, time delayed, and amplitude reduced version of the signal to which it is matched. Figure 2-11 shows the response of a filter designed to remove an expected doppler frequency shift and the signal after it has been passed through the filter.

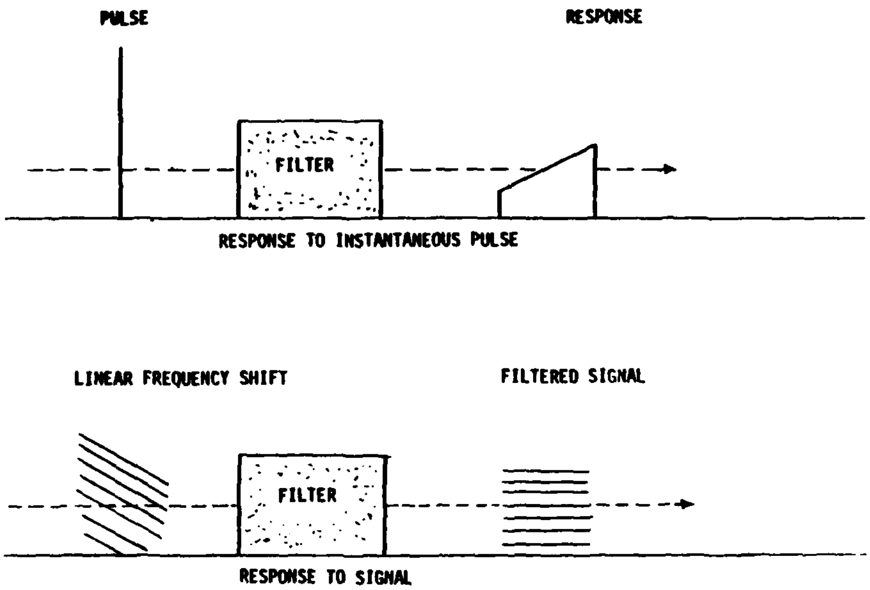


FIGURE 2-11

The signal from the matched filter is frequency analyzed by passing it through a set of bandpass filters. In the doppler shift processing phase, each bandpass filter corresponds directly to an azimuth resolution cell. Azimuth resolution in these systems is directly related to the accuracy and bandwidth of the filters used.

Digital SAR processing systems perform the same operations on the return signal but the operations are carried out on the digital representation of the signal. The matched and bandpass filtering functions are done using discrete digital functions and digital representations of a real filter response function. Convolution, (filter response to a known input signal) is accomplished by convolving the incoming signal with a filter response signal. The convolution function is often performed in the frequency signal domain since this reduces the number of operations necessary to compute the output signal. A typical digital filter is shown in Figure 2-12. The incoming and filter response signal are converted to frequency domain via discrete fast Fourier transform (DFFT) functions, the convolution is performed, and the resultant function is transformed back to time domain via inverse discrete fast Fourier transform (IDFFT) functions.

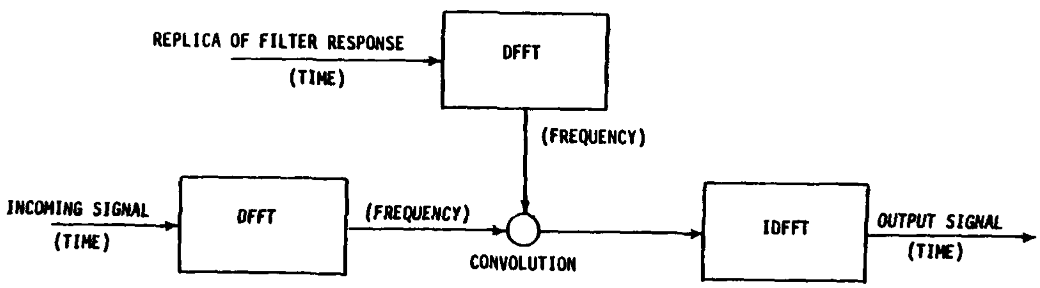


FIGURE 2-12

Digital frequency analysis is done using discrete Fourier transform functions. Transformation to the frequency domain will allow the extraction of the doppler information. The digital processing block diagram (Figure 2-10) contains an extra step to convert the signal into its quadrature components. This step changes the representation of a wave to its complex form given in equation 2-1.

$$\emptyset = \cos w + j \sin w \qquad 2\text{-}1$$

w = angular frequency

j = imaginary component

This is done since the Fourier transform function requires that the wave be represented in this form.

2.5 OUTPUT OF SIGNAL PROCESSING

The output of the signal processors described above is a spatial representation of the ground targets radar reflectance. The spatial accuracy is dependent upon many signal and signal processor characteristics, some of which will be discussed later. The final product may be in the form of a digital or hardcopy image. If a digital image of an optical processor's output is desired, the processor's output must be digitized. If a hardcopy image of an electronic processor's output is needed, it must be printed.

3.0 SAR Image Characteristics and Stereo-viewing

SAR images have several unique characteristics which distinguish them from photographic images. Effects such as range foreshortening, radar layover, and radar shadow all affect the quality of the radar image. These image characteristics also impact the ability of a viewer to fuse conjugate pairs of imagery for stereo-viewing. The following section describes the characteristics of SAR imagery and the conditions necessary to view radar imagery in stereo.

3.1 Range Foreshortening

Range foreshortening causes two slopes of equal ground length to appear as different lengths in the image. The apparent length of the slope is dependent upon its slope angle relative to that of the incoming wave. Smaller angles of incidence between the wavefront and the slope result in greater range foreshortening. Figure 3-1 illustrates the range foreshortening of a hillside facing the sensor.

3.2 Radar Layover

Radar layover is caused when the radar signal reaches the top of an object before it reaches the bottom. This corresponds to a condition where the terrain slope is greater than the angle of incidence. This phenomena can cause confusion when interpreting an image since the top of the mountains may be imaged before valleys etc. Figure 3-2 shows the conditions for which radar layover can occur.

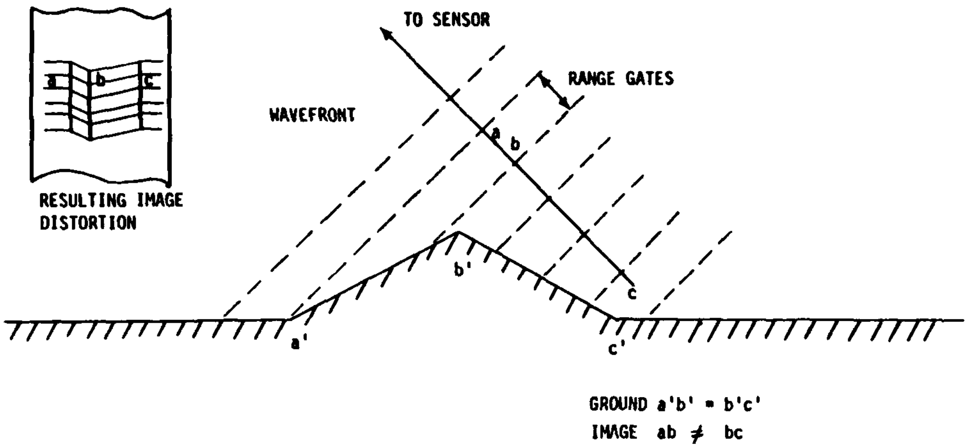


FIGURE 3-1

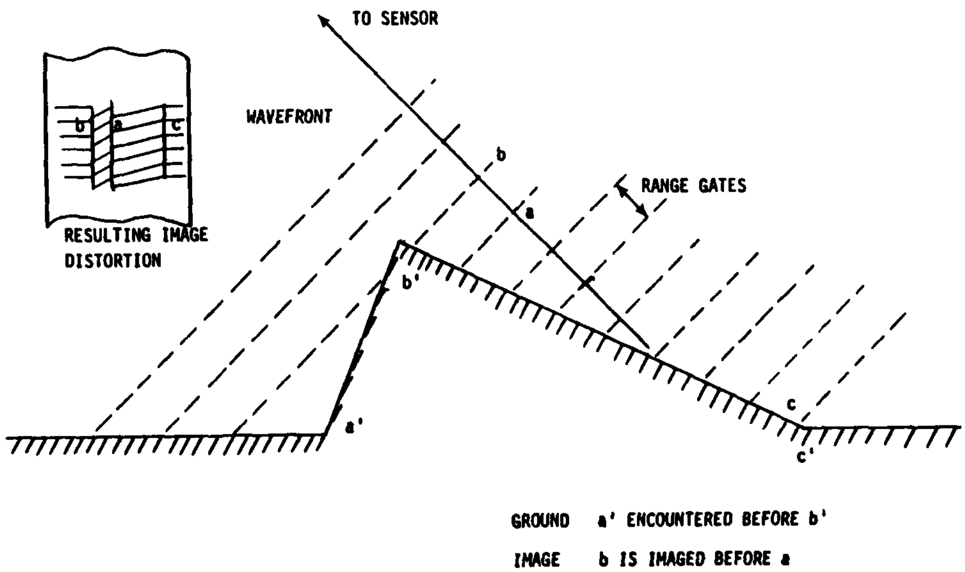


FIGURE 3-2

3.3 Radar Shadow

Shadows in a radar image are analogous to those in an aerial photograph. Since radar is an active sensor, the shadows appear at the side of the terrain most distant from the sensor. Shadows are present whenever the terrain slope exceeds the complement of the angle of incidence. Figure 3-3 shows the effect of shadow on the radar image.

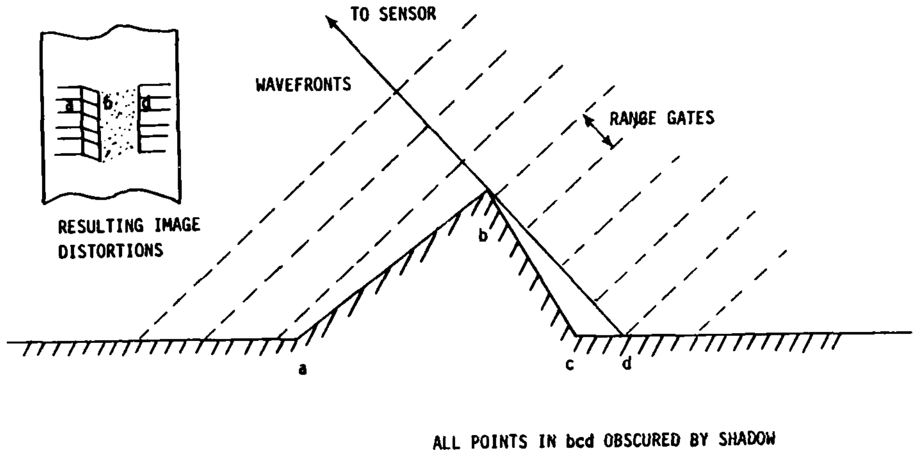


FIGURE 3-3

3.4 Stereo-viewing

The ability to view conjugate radar images in stereo is dependent upon the characteristics of both images. Single flight line stereo cannot be realized with synthetic aperture radar. If different squint angles are used on the same flight line the resulting relief displacements would be equal and at 90 degrees towards NADIR. This results in zero parallax and no stereo perception. (Leberl, 1972).

It is theoretically possible to obtain elevation data from any two SAR images covering the same area and originating from different flight lines. The characteristics of SAR images however, do not allow stereo perception from all flight line arrangements. In fact, surprisingly few arrangements can lead to good stereo perception in a SAR image pair. Leberl concluded that successful radar stereo-viewing depends on:

The stereo arrangement

The look angles off nadir

The stereo intersection angle

The ruggedness of the terrain.

The terrain and viewing geometry interact in determining good stereo-viewing. Flight line configurations which are ideal for stereo-viewing in one terrain type may be prohibitive in another. It is necessary to assess the imagery configuration for each application to insure stereo perception.

There are an infinite number of stereo configurations possible. Two basic ones, same side, and opposite side configurations are shown in Figure 3-4. If a three dimensional model is to be visually perceived, it is necessary that the images be sufficiently similar and the retinal disparities be less than one degree. In order to make accurate measurements, a large stereo intersection angle is needed. In SAR images, stereo perception is rarely possible using the opposite side configuration. The geometry of the arrangement is strong but the opposite shadowing of elevated objects makes the images highly dissimilar except in regions of very low relief.

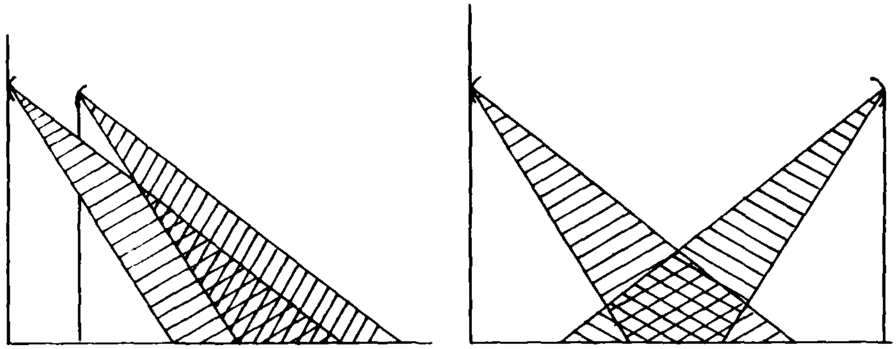


FIGURE 3-4

Same side configurations have similar appearances and stereo fusion is easier for most terrain configurations. Same side configurations, as seen from the diagram, also have a poor geometric strength due to their low angle of intersection. There is a trade-off between stereo-viewing and geometric strength. Other flight line geometries may yield both strong geometric strength and good stereo but more investigation is necessary to determine optimum ranges for these configurations.

Range foreshortening and radar layover can also cause problems in stereo-viewing. The problems caused by these characteristics are the result of confusion and distortion which may reduce the ability of the viewer to see stereo. The similarity between the images, in some cases, may be reduced to the point where stereo-viewing is impossible. In any application where stereo SAR coverage is desired, image, terrain and flight line characteristics must be taken into account in order to arrive at the optimum combination for stereo-viewing.

4.0 SAR Geometry

When using imagery to determine ground point locations, it is necessary to relate ground point coordinates to exposure station coordinates using rigid geometrical conditions. In synthetic aperture radar imagery, there is no "exposure station" as conventionally used in frame images. A SAR image is constructed over a period of time (t) during which the sensor is continuously moved past the target being imaged. Although there is no exposure station, the concept can still be used to relate a particular ground point to the sensor's location or "instantaneous exposure station." This point can be considered as the location from which a point was imaged. Instantaneous sensor position can be determined from a group of several image parameters provided the following assumption is true.

> The 3-dimensional acceleration of the sensor throughout the period of time that an image is being formed is uniform.

If the image y coordinate is measured parallel to the flight line, then the product of scale factor times y can be used to determine the time t from the initial imaging point.

$$(S_y)(y) = t \qquad 4\text{-}1$$

S_y = Azimuth Scale Factor

y = Measured y coordinate

t = Elapsed time

The sensor position (S) at time t can now be stated simply as in equation 4-2.

$S = S_\theta + \dot{S}_0 t + \ddot{S}t^2/2$ 4-2

$S_\theta = (X_{j\theta}, Y_{j\theta}, Z_{j\theta}) =$ 4-3

Position at t_θ

$\dot{S}_0 = (V_{jx\theta}, V_{jy\theta}, V_{jz\theta}) =$ 4-4

Velocity at t_θ

$\ddot{S}, = (A_{jx\theta}, A_{jy\theta}, A_{jz\theta} =$ 4-5

Acceleration

The geometric conditions which apply to SAR imagery are derived from the range sphere and doppler cone which define a particular SAR image point. The range sphere is a sphere with center at the sensor position. All points on the surface of the sphere lie at equal distance from the sensor. The doppler cone is a cone centered on the flight line with its apex at the sensor. All points on the cone exhibit the same doppler shift relative to the sensor. The intersection of the doppler cone and range sphere define a circle (Figure 4-1). Stereo intersection of SAR imagery is the determination of the intersecting point of circles from two separate images to determine the three dimensional coordinates of the imaged point.

The distance of a point (P) from the sensor (S) defines the range sphere. This is given as

$R = \quad P - S$ 4-6

The doppler cone is defined by the angle from the flight line to its surface. The squint angle is the angle between the vehicles velocity vector

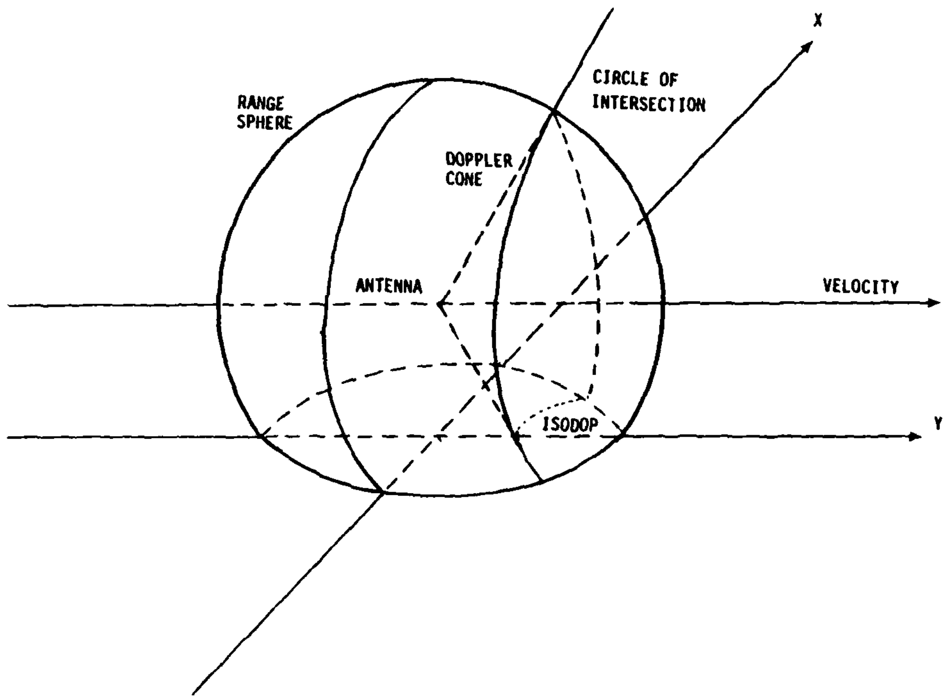

X
CIRCLE OF
INTERSECTION
RANGE
SPHERE
DOPPLER
CONE
ANTENNA
VELOCITY
ISODOP
Y

FIGURE 4-1

and the sensor to point position vector. Its cosine is found by dividing the dot product of the vectors by their product of their magnitudes. This is given below in equation 4-7.

$$\cos\theta = \frac{(\dot{S}) \cdot |(P - S)|}{|\dot{S}| \quad |P - S|} \qquad 4\text{-}7$$

4.1 Parallax and Relief Displacement

The geometric interpretations of parallax and relief displacement on SAR images are dependent upon the format in which the image is presented. Figure 4-2 illustrates the difference between slant range and ground range relief displacement. Similarly, Figure 4-3 shows the difference between slant range and ground range parallax.

Relief displacement in SAR imagery is towards the sensor. This is caused by returns from the top of the object, which is closer to the sensor, returning to the antenna before it returns from the bottom. The relief displacement for an object presented in ground range is given in Equation 4-8.

$$Dr_g = h \cot \emptyset \qquad 4\text{-}8$$

h = object height

Ø = look angle

The relief displacement in slant range is given in Equation 4-9.

$$Dr_s = h \cos \emptyset \qquad 4\text{-}9$$

From these equations, it can be seen that the relief displacement depends on the object height and the look angle to the object.

When using parallax in the classic photogrammetric sense, we are

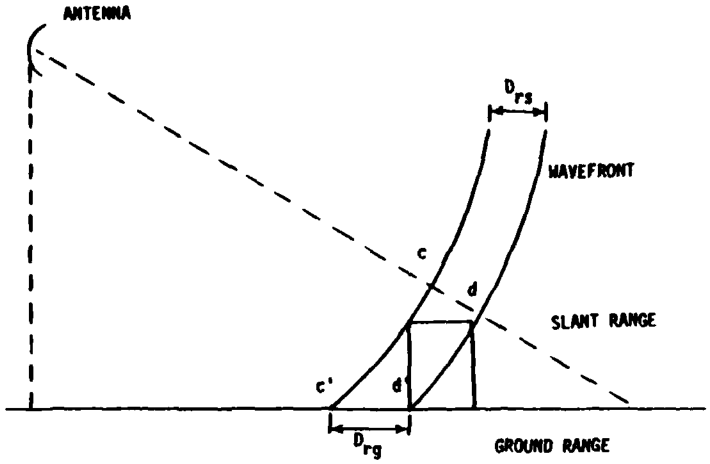


FIGURE 4-2

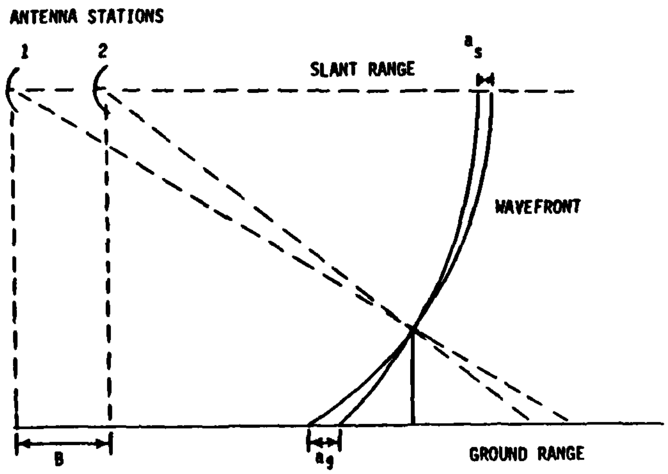


FIGURE 4-3

accustomed to the idea that points of equal elevation, within a stereo model, will exhibit identical parallax. This is not the case for SAR images. In ground range, all points on the datum plane will exhibit equal parallax regardless of their range. Points above and below the datum will exhibit parallaxes which are dependent on both their range and elevation difference from the datum. Assuming equal flying height and parallel flight lines for the image pair, the ground range parallax is given in equation 4-10.

$$a_g = x - x' = (X-h\ (H/X))-((X-B)-h(H/(X-B)\ )) \qquad 4\text{-}10$$

x,x'= measured coordinates (ground distance)

X=local ground range of point

H=antenna height above datum

h=point elevation from datum

B=air base

In slant range presentation the parallax of all points, including those on the datum plane, is dependent upon the points range and elevation from the datum plane. The slant range parallax equation is given by equation 4-11.

$$a_s = x-x' = ((H-h)^2 + X^2)^{1/2} - ((H-h)^2 + (X-B)^2)^{1/2} \qquad 4\text{-}11$$

The variation of parallax with range is shown in Figure 4-4. X parallax is used since the adopted convention is X perpendicular to the flight line and Y parallax to it.

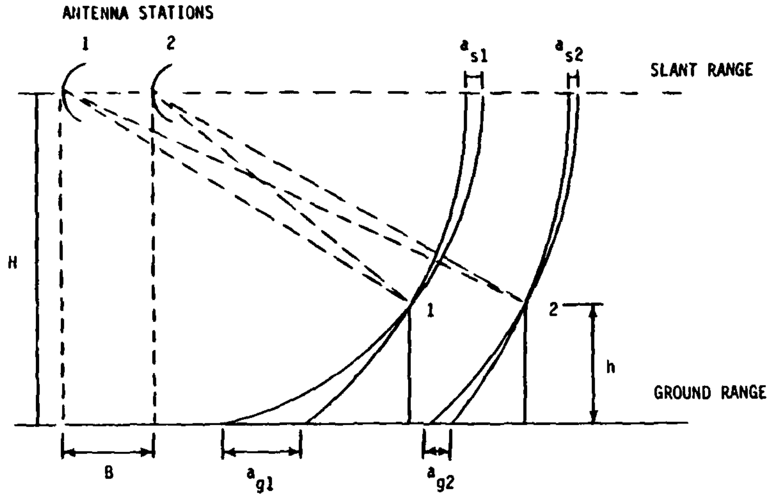

ANTENNA STATIONS
1
2
a_{s1}
a_{s2}
SLANT RANGE
H
1
2
h
GROUND RANGE
B
a_{g1}
a_{g2}

FIGURE 4-4

4.2 Data Adjustment

Data adjustments similar to resection procedures on photographic imagery can be performed on SAR imagery. Two condition equations are developed which relate x (range) and y (azimuth) image coordinates to ground coordinates. Constraint equations are sometimes added to the adjustment depending upon the particular circumstances.

The first condition equation considers the straight line distance (range) between the sensor and ground point. Simply stated the condition says that the image to ground point distance is the same whether it is determined from image measurements or from the displacement vector in space coordinates. The equation for the ground range condition is given in equation 4-12.

$$H^2+(R_B + S_x X)^2 -((X_{si}-X_{gi})^2+(Y_{si}-Y_{gi})^2+(Z_{si}-Z_{gi})^2)=0 \quad 4\text{-}12$$

(X_{si}, Y_{si}, Z_{si}) = Sensor Location Coordinates

(X_{gi}, Y_{gi}, Z_{gi}) = Ground Point Coordinates

S_x = X Scale factor

X = Measured Image Coordinate

R_B = Range Bias

H^2 = Sensor Height

For slant range, the elevation term (H^2) is dropped. Time is implicit in this equation since the sensor location (S) is a function of time.

The second condition equation considers the doppler squint angle of the SAR processor. This condition states that the squint angle is the same regardless of whether it is determined from the received doppler shift or space geometry. Equation 4-7 is the cosine of the squint angle as determined by the geometry. The cosine of the squint angle as a function of the doppler shift is:

$$\cos\theta = K/\dot{S} \qquad 4\text{-}13$$

$$K = f_d c/2f_c \qquad 4\text{-}14$$

f_d = Doppler Shift

c = Speed of Light

f_c = Carrier frequency

From equations 4-7 and 4-13 the doppler condition is

$$\frac{\dot{S} \cdot / P - S /}{/ \dot{S} / \; / P - S /} \; -K/\dot{S} \qquad 4\text{-}15$$

For every point measured on the imagery four equations, one range and one doppler equation for each of the two images, are added to the adjustment. Known ground points establish the control for the adjustment. Parameters commonly solved for in an adjustment procedure are given in Table 4-1. The actual adjustment procedure solves for the unknowns by using the condition equations and applicable constraint equations in a generalized least squares solution.

	COMMON ADJUSTMENT PARAMETERS
$S(X_{si}, Y_{si}, Z_{si})$	Sensor position at t_o
$S(V_{xsi}, V_{ysi}, V_{zsi})$	Sensor velocity at t_o
$S(A_{xsi}, A_{ysi}, A_{zsi})$	Sensor acceleration
R_B	Range Bias
S_x	X - Scale factor (range)
S_y	Y - Scale factor (aximuth)

Table 4-1

In some specific cases, doppler squint angle and transformation coefficients may be solved for as parameters. If this is done, then more ground control points may be added to the adjustment procedure to maintain the desired accuracy.

5.0 Errors in SAR Images

Error evaluation of SAR images includes errors introduced by the radar and processing systems and any measurement errors. Measurement errors and blunders of the type frequently encountered in photogrammetry are not discussed in this section since they are well understood and independent of the type of imagery used. System errors which result in a degradation of the image quality are quite different from the errors present in a photographic imaging system. Both random and systematic errors are introduced by SAR imaging systems.

Most of the errors which affect the output of the SAR signal processor are phase errors. Phase errors are present whenever the phase history of a ground point does not match its predicted phase history (reference function). Phase errors may result in an unexpected frequency sweep (doppler phase history), or the shift of a target between two or more range gates as it passes through the real aperture antenna beam. In either case, the error results in mismatching the phase history information within a range gate with the expected phase history. The major causes of phase errors are given in Table 5-1. The magnitude of each phase error source is dependent upon the particular conditions for an image. Since these errors are variable in nature, the combined systematic errors are usually considered as the total phase error.

PHASE ERRORS
Curvature of Radar Wavefront
Curvature of the Earth
Motion of the Sensor
Motion of the Target
SAR Radar System Phase Errors
SAR Processing System Phase Errors
Wave Propagation Errors

Table 5-1

Other errors and sources of distortion are caused by scintillation from corner reflectors, high reflectance from surfaces whose roughness closely matches the wavelength of the radar signal, and a decrease in signal-to-noise ratio due to inaccurate antenna pointing. These errors are discussed in more detail below.

5.1 Phase Errors

5.1.1 Curvature of the RADAR Wavefront

The curved wavefront propagating from the radar antenna can contribute to the phase errors present in the received signals. If the curvature of the wave is large, a point will be in one range gate at the edge of the real antenna beam and another at the beam center. This condition, shown in Figure 5-1, will cause information about a point to migrate between range gates as it passes through the real aperture antenna beam. The variation in slant range as the point passes through the real aperture antenna beam is known as range walk.

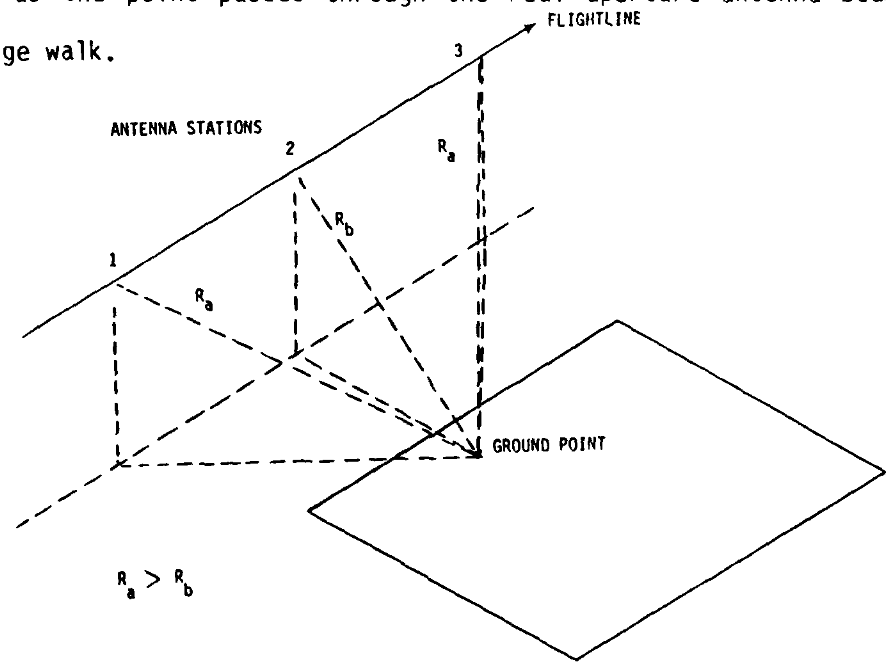


FIGURE 5-1

In most cases, wavefront curvature alone will not be a significant source of phase errors. Due to the distance of the antenna from the ground, the wavefront closely approximates a straight line across the beam width. The effect of wavefront curvature becomes less significant as the sensor to target distance increases providing the beam width is maintained.

5.1.2 Earth Curvature

Earth curvature can also cause range walk in a synthetic aperture data array. As in wavefront curvature, this affect is small. If the radar to ground distance is such that an iso-range line can be approximated by a straight line parallel to the sensor flight line, no range walk will occur when the surface being imaged is flat. If the surface is curved, the straight iso-range line will be tangent to the surface at only one point. Assuming that the sensor maintains a constant flying height, this indicates that the slant range to a target will be greater at either side of the real aperture beam than in the center. The severity of the introduced error is dependent on antenna beam width and surface curvature. This is illustrated in Figure 5-2.

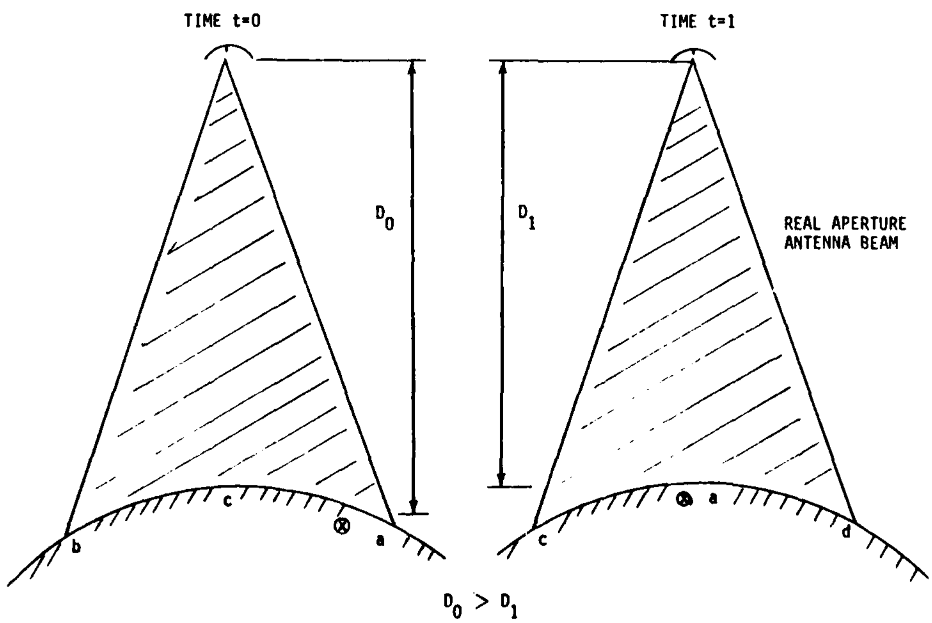


FIGURE 5-2

5.1.3 SAR Vehicle Motions

The motion of the radar platform makes doppler processing possible but random or undesirable platform motion may introduce error into the acquired data. The reference functions used in SAR processors are directly related to vehicle velocity. Any unexpected change in vehicle velocity will result in either range walk, an unexpected frequency shift in the return signal or both.

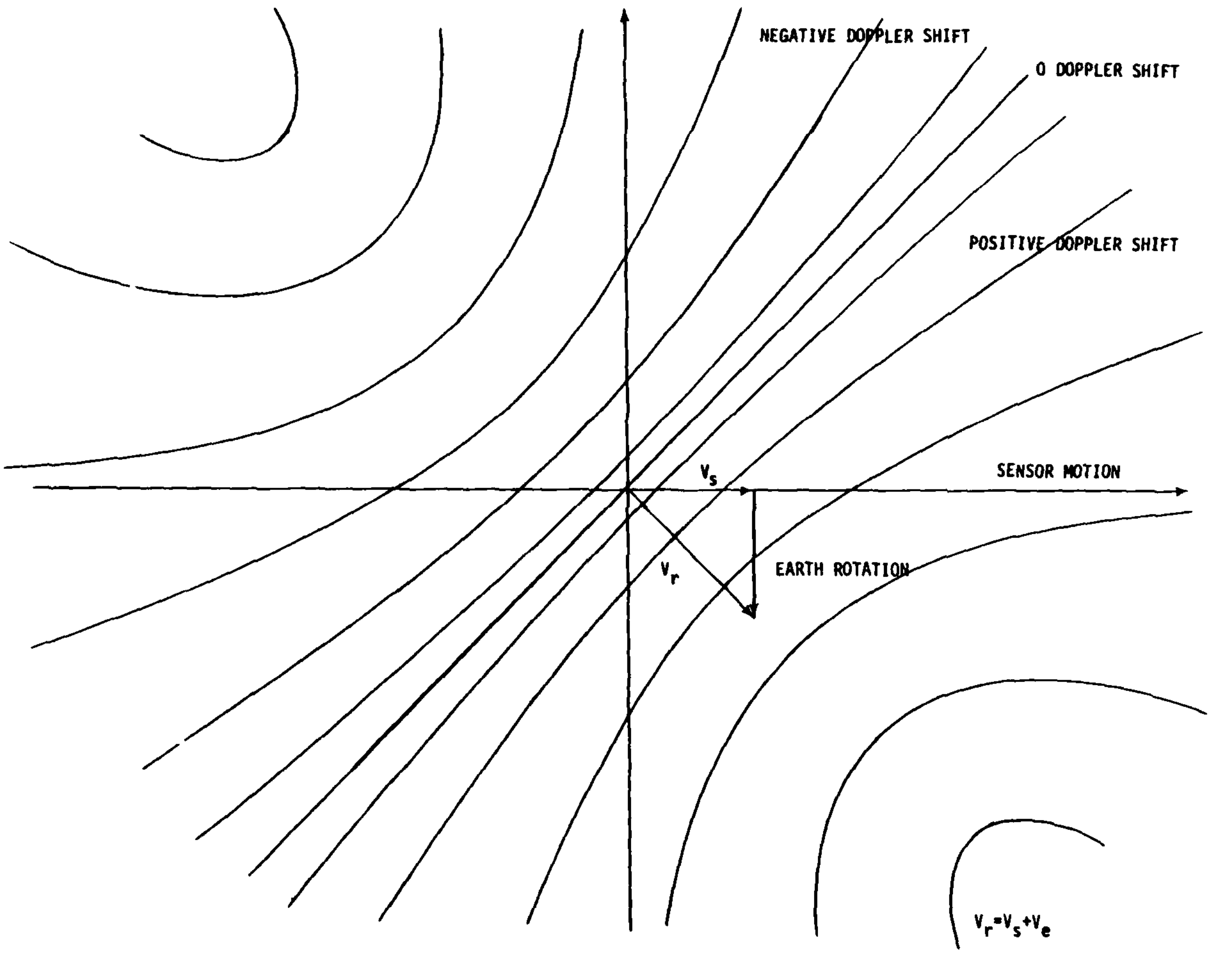
Some range walk may be caused due to a curved platform path resulting from linear but unequal accelerations in the X, Y, and Z directions. If this occurs the error will be systematic and can be corrected. Random variations in the platforms acceleration will cause an unpredicted shift in the returned signals. If the reference function does not match the actual doppler phase history the filtering will not correctly modify the signal for frequency analysis and image blurring will result. If this occurred the output of the filter in Figure 2-11 would not be flat and a matched filtering would not be accomplished.

Higher order vehicle motions such as non-uniform acceleration are an important issue in the math modeling of doppler frequency shifts. In the math model condition equations given previously the acceleration is assumed constant throughout the time period during which the data for an image is collected. If any non-constant acceleration of the sensor occurs during data acquisition the math model will not accurately represent the actual physical condition and point location errors will result. Computational results must be watched carefully to insure that higher order vehicle velocity terms, if present, are taken into consideration in processing are also included in math modeling.

5.1.4 Target Motion

Target motion phase errors are highly dependent on sensor altitude. In low altitude images targets moving across the surface being imaged will exhibit different doppler shifts than non-moving points immediatley adjacent to it do. This is due to the different radial velocities which the moving and non-moving objects have relative to the sensor. As a result of the shifted phase histories of moving objects they will quite often appear displaced from their true location on the imagery. An example of this error is the displacement of a moving train relative to its tracks.

High altitude and space craft SARS have complex phase errors across the entire image since the entire area being imaged is moving due to Earth rotation. In most high altitude situations, the zero doppler isodop will not be perpendicular to the flight line but at some angle to it. This angle will be the angle at which the ground points, due to the combined effects of the sensor motion and earth rotation, exhibit no radial velocity. Figure 5-3 shows an example of the rotated isodop pattern. The issue is further complicated due to the fact that the doppler shift at any given angle to the sensor also varies with latitude. Complex signal processing schemes which include variations and adjustment to the reference functions and squint angle are used to correct for Earth rotation. Uncorrected large scale target motion such as Earth rotation may result in a blurred or meaningless image.



NEGATIVE DOPPLER SHIFT
0 DOPPLER SHIFT
POSITIVE DOPPLER SHIFT
V_s
SENSOR MOTION
V_r
EARTH ROTATION
$V_r = V_s + V_e$

FIGURE 5-3

5.1.5 Radar and Processing System Phase Errors.

When electronic or optical systems, such as those used in the SAR radar and processor, are used to analyze the radar returns, the signal is modified as it passes through each component of the system. In an ideal system the signal change as it passes through the components would be small, known, and calibrated out. In most processors and radars the phase errors added to the signal by the system are small but some unexpected signal modifications do occur in both the radar and processing systems. These errors consititute the system phase errors and, although hopefully small, do contribute to the combined phase error.

5.1.6 Propagation Phase Errors

Propagation errors include any change in the radar signal which occurs during the interval in which the signal is traveling to and returning from the target. Errors introduced during this time consist of added noise, frequency shifts due to a change in the transmission medium and various other atmospheric phenomena. If the propagation errors are assumed constant across the image they may be considered systematic and be included as part of the total phase errors.

5.1.7 Corrections for Phase Errors

Systematic phase effects may be corrected prior to signal processing by adding or subtracting the phase errors to the returned signal. Two techniques are commonly used to determine the phase errors. One method involves representing slant range as a Taylor series expansion. The higher order terms in the series will represent the phase errors in the data. Another method approximates the phase errors as a phase error function. A parameter is included in the model for each source of phase error and a best fit function across the synthetic aperture length is found.

Random phase errors are impossible to correct. Any random phase error will be incorporated into the image produced. This could be manifested as image blur or object displacement. It is possible that the effects of random phase errors may be reduced through multi-look processing as described below.

5.2 Non-Phase-Related Distortions and Errors

5.2.1 Scintillation

Scintillation is a very high reflected radar signal which is the result of the addition of the radar signal reflections from several points on a properly oriented corner reflector. The strong returns result when signals reflect from different faces of the reflector towards a common point. The signals then combine and reflect back towards the sensor. This combined signal can be quite strong and can cause a very bright return on the image which obscures other points around it. Scintillation can be reduced in a radar image by the use of multi-look processing. This is done by forming two or more separate images from different portions of the synthetic array and combining them to produce the final composite image. A loss in resolution occurs when multi-look processing is done but a more accurate representation of the target area's radar reflectivity is produced.

5.2.2 Rayleigh Speckle

Rayleigh speckle is observed over targets that have a surface roughness comparable to the radar wavelength. The reflectance of such targets is usually higher than most other targets in the image. A large number of Rayleigh scatterers can sometimes be found in a radar image producing a speckled appearance across the image. Multi-look processing may have some impact on the reduction of Rayleigh speckle.

5.2.3 Antenna Pointing Errors

Although it has been stated that antenna pointing is not related to the doppler shift exhibited by ground points, it is still necessary to consider antenna pointing. The highest signal-to-noise ratio is achieved when the center of the real aperture antenna beam is pointed at the isodop representing the squint angle to be used in processing the signal. Errors in antenna pointing can reduce the achievable resolution in the image but cannot be corrected for after processing has been completed. In most SAR applications, a 90-degree squint angle is used with a side-looking antenna.

6.0 The Use of SAR for high Accuracy Point Positioning

The preceding sections of this paper have attempted to give a general introduction to the production of a SAR image, and to the aspects of the imagery which may have an impact on its use for mensuration purposes. The widespread use of SAR imagery for these purposes appears inevitable when the potential advantages offered by such imagery are considered. Before the potentials of SAR images can be fully exploited, however, several areas of concern which demand further study remain. As current efforts on the implementation of SAR math models and the study of SAR geometry proceed, and new work is undertaken to investigate the specific problems identified by these efforts, the task of implementing SAR images for mensuration applications should proceed smoothly.

6.1 Potential Advantages of SAR Imagery

There is little doubt that obtaining accurate geographical location data from SAR is highly desirable. Very high resolution can theoretically be achieved with SAR techniques by increasing the length of the synthetic array which is flown. Although some limitations are imposed, which limit the actual array length, the achievable resolution is applicable to many measurement needs.

A radar sensor is not dependent on external sources to illuminate the target area. This means that sensing is possible at any time of the day or night. The wavelengths used in a radar system are, in most cases, not absorbed to a significant degree by the atmosphere regardless of its turbidity. This enables successful radar operation in all weather. These unique properties of a radar sensor, and SAR signal processing, offer the potential for an all day, all hour, high resolution imaging system.

The applications of such a system to both military and civilian users are many. With the current generation of electronic signal processors, near real time processing of the imagery is possible. The advantages of SAR for interpretation purposes has been exploited for some time. The identification and clarification of those aspects of SAR pertinent to measurement accuracy should soon enable the expansion of SAR imagery applications to include accurate point location information.

6.2 Potential Problems in SAR Measurement Applications

6.2.1 Viewing and stereo fusion

Section 3 describes the major characteristics of the SAR image and the conditions necessary for stereo viewing of SAR images. Rapid extraction of elevation data requires that the imagery be viewed in stereo. Although the mathematical and geometric conditions hold true for any flight line configuration, the need for stereo fusion limits the number of usable flight lines. In order to fuse images which contain areas of moderate relief the direction of the radar shadows must be approximately parallel. This condition limits most stereo coverage to parallel same side flight lines. Parallel same side configurations are viable but the geometric strength of figure is low due to a small intersection angle.

Further complications to the viewing of radar stereo can be introduced by the confusion caused by radar layover and range foreshortening. In order to achieve good stereo-viewing and adequate geometric strength of figure, the optimum conditions which permit good stereo viewing and provide accurate measurements need to be determined.

6.2.2 Math Modeling

Mathematical models developed for SAR images are based on the assumptions that vehicle acceleration and doppler squint are maintained constant over the period of data collection for an image. The effects of higher order velocity terms or a change in squint angle across an image may be important. Processor characteristics may affect the constant doppler assumptions and the assumptions may not be the same for all processors. The accuracy and correctness of SAR math models should be determined as the results for computations performed using these models becomes available.

6.2.3 Phase Errors

The phase errors described in the previous section are either corrected by the signal processing system or passed through as random phase errors which occur as image blurring or location errors on the image. Considerations which may cause problems in measuring SAR images concern the completeness with which systematic phase errors are removed from the signal and the effects of random phase errors. Primarily, it must be verified that the processors are providing images which are correct according to the math models.

6.3 Future Directions in the Use of SAR for Measurement Purposes

Research and development efforts devoted to the investigation of synthetic aperture radar for measurement purposes should be concentrated on solving the specific problems identified by current projects investigating SAR math modeling and SAR geometry.

Ideal flight line configurations and stereo-viewing procedures should be formulated soon since the determination of this information will be directly applicable to other work. These efforts will utilize the results obtained through the analysis of measurements made on SAR images.

Error analysis performed on the results obtained from the math models will aid in determining the correctness of the models used and in the identification of error sources in the imagery. Any errors found should be carefully investigated to quantify their effect on the accuracy of the computations. Ongoing work in these areas should continue to ensure the successful implementation of SAR imagery for measurement applications.

Due to the limited scope and unclassified nature of this report, it is possible that some of the work recommended above may have been completed. Further work should be done to investigate and identify potential sources of needed information in both the classified and open literature prior to undertaking full scale investigation of the topics above.

SUMMARY

In the past, attention has been focused on the potential advantages held by synthetic aperture radar in accurate point positioning applications. SAR holds the potential for an all-hour, all-weather, high-accuracy imaging system. In order to utilize SAR imagery for this purpose, it has become necessary to closely consider those things related to SAR which may have an impact on point positioning accuracy. The current status of "Radargrammetry" and the need for further work in this area is discussed in the body of this report.

A synthetic aperture radar image is the result of signal processing performed on a collection of radar returns from a coherent wave radar. The special properties of a coherent wave radar enable the synthesis of a very long antenna which will yield a very high resolution radar image. Imagery can be produced by processing the collection of returns either optically or electronically. Optical processing uses film and coherent light to process the signal data. Electronic processors utilize either analog or digital techniques to produce a SAR image.

The images produced by SAR processing have distinct characteristics which differentiate them from photographic images. Range foreshortening, radar layover, and radar shadow are all related to the sensor ground geometry. The unique characterististics of SAR images can make stereo-viewing of SAR images difficult. Very few flight-line configurations exist which will provide adequate imagery for stereo-viewing and measurement purposes. There is a trade-off between good stereo-viewing and geometric strength of Figure.

The geometry of a SAR image is related to the radial distance from the sensor (range) and the frequency shift of the coherent wave radar return due to relative target sensor motion (doppler shift). Imagery is produced by the SAR signal processors in either slant-range or ground-range format. Slant-range displays the image along a radial line from the sensor, ground-range presents the image along a line between the sensor NADIR and the point being imaged. Expressions for parallax and relief displacement have been derived for SAR images and math models for adjustment procedures are being implemented.

The errors found in a synthetic aperture image are usually related to the phase of the returned signal. Errors in the phase of the returned signal can be the result of many different causes. Uncorrected phase errors may lead to image blurring or image shift. Other errors and distortion can be introduced by Raleigh speckle, scintillation, and antenna pointing errors. Systematic errors identified prior to signal processing may be corrected during the processing operations.

The potential held by SAR for menuration purposes is high. Further investigation and quantification need to be done to identify potential errors found in SAR images. Evaluation of the math models to verify the assumptions made in their development will provide needed information for error analysis. In-depth investigation into the stereo-viewing problems and optimum flight-line configurations will make the extraction of information faster and easier for future radargrammetric applications.

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