CHAPTER III

SYNTHETIC APERTURE RADAR THEORY

Among the remote sensing tools now available, radar is unique. It is an "active" sensor and emits its own beam of energy, which reflects off the earth and returns to the sensor. Thus radar collects data independent of solar illumination and because of its comparatively long wavelength, weather has minimal affect (Ulaby et al., 1981). Within the electromagnetic spectrum (Figure 3.1) radar is in the microwave range of \sim 1 cm to \sim 1 m.

When radar was first being developed by the military, the microwave spectrum was divided into bands (Table 3.1), with illogical designators to help conceal their applications (Campbell, 1996). Common terminology uses "microwave" as passive and "radar" is usually reserved for active microwave. Radar also refers to the sensor itself including: the transmitter, the antenna, the receiver, and the data handling equipment. Radar has been used since the early 1960s to image the surface (and near surface) of sea ice and glaciers (Hall, 1998). Airborne radars frequently use the L, C, K, and X-bands, satellite radars have used the C and L-band frequencies (Campbell, 1996). These

longer wavelengths are used in satellites because they are least sensitive to atmospheric attenuation by clouds, rain, and snow.

Band	Wavelength (cm)
Ka	0.75-1.18
Κ	1.18-1.67
Ku	1.67-2.40
Х	2.40-3.75
С	3.75-7.50
S	7.50-15.0
L	15.0-30.0
UHF	30.0-100.0
Р	77.0-107.0

Table 3.1: Radar Frequency Designations.

Because the microwave range is well removed from the visible spectrum, it interacts quite differently with surfaces compared to visible light. Although radar images look very similar to a black and white aerial photograph, they defy many of the intuitive interpretation we unconsciously apply to visible light images. The scattering properties of surfaces in the microwave range are affected by the electrical properties of the surface, its orientation, and its porosity. These factors will be discussed later. The short radar wavelengths yield higher resolutions but lower penetration of the atmosphere due to moisture. The long wavelengths readily penetrate atmospheric moisture, but yield lower resolutions and higher surface penetration (Campbell, 1996).

Synthetic Aperture Radar Principles.

Side looking, fixed-antenna-length airborne radar was developed by the military to image areas behind enemy lines while flying over safe territory

(Figure 3.2) (Avery and Berlin, 1992). For fixed-length antennas, resolution depends on antenna length and decreases with increasing distance from platform to target (Avery and Berlin, 1992). Thus satellite application of radar was largely precluded. To overcome the limitation of antenna size "Synthetic Aperture Radar" (SAR) was developed (Ulaby et al., 1981). In the same way that a wide photographic aperture allows more light to reach the film in a camera, a long antenna receives more radar waves. Antenna *length* is analogous to a camera aperture. A larger antenna (aperture) is synthetically produced by using the forward motion of the platform to carry a relatively small antenna to a new location (Figure 3.3) (Lillesand and Kiefer, 1994). Because of the beam shape, some areas are imaged multiple times (Figure 3.2); the successive portions are treated electronically as though each one were an individual element of the same antenna (Avery and Berlin, 1992). The concatenation of the signal modulations of the multiple returns for each target is what increases the resolution in a SAR image (Raney, 1998). For example, the European Remote Sensing (ERS)-2 SAR synthesizes the equivalent of a 4 kilometer-long antenna (Alaska SAR Facility website, 2000).

Radar measures the round-trip travel time of the emitted and reflected microwaves (i.e. time domain) as well as the signal strength (Avery and Berlin, 1992). Imaging radars transmit about 1500 pulses per second, each pulse lasting for 10-50 microseconds (Ulaby et al., 1981). Once the pulse reaches the Earth's surface, it is scattered and some of the scattered energy is directed back towards the antenna. The signal is converted to digital format and then either temporarily stored using the satellite's on-board tape or immediately transmitted to a ground receiving station (Jet Propulsion Lab website, 2000).

On current satellite platforms, the radar beam is like-polarized. It is emitted vertically (V) or horizontally (H) and only the same polarization signals are accepted back into the SAR (called VV or HH) (Campbell, 1996). The space shuttle and various aircraft SARs can operate in multi-polarizations. They may be transmitting and receiving like *and/or* unlike polarizations.

Object range is calculated by using the time delay between emitted and reflected radar pulses (Avery and Berlin, 1992; Ulaby et al., 1981). Because the signal data is sorted by time delay, radars image to the side, rather than downward to remove ambiguities between the right or left return signals. Each pulse is coded so that the SAR knows *which* pulse is coming back: the first signal returning is from the near-range and the later signals are from progressively longer ranges until the last bit of information from the far-range is received (Avery and Berlin, 1992). The pulse length (how long the radar is emitting the pulse times the speed of light) determines range resolution (shorter the pulse, the higher the resolution) (Figure 3.4) (Campbell, 1996).

Azimuth, relative to the satellite, is calculated by measuring the doppler shift of the returning pulse relative to emitted pulse (Avery and Berlin, 1992). Doppler shift in the electromagnetic spectrum is analogous to the doppler shift of a whistle on a passing train: as it approaches, the whistle's tone is doppler shifted negatively (compressing incident wavelengths and producing a higher-pitched whistle), and as it moves away, it is doppler shifted positively (producing longer apparent wavelengths, and a lowerpitched whistle). In the same manner SAR measures the doppler shift, except the platform is moving and the target is stationary. The area of the earth that is illuminated by the SAR sensor is a series of teardrop-shaped footprints. Surface features enter the illumination area, and in each successive pulse, move through it and exit with the features further from the sensor being illuminated more times (*ibid*). Using multi-look signal processing, the signal modulations (signatures of the returns for a specific target) are matched at each point in the SAR scene (Raney, 1998). This signal processing, called SAR processing, is done on ground-based computer systems. Since the satellite is moving relative to the Earth, this processing requires very precise data on the relative motion between the imaging platform and the target (Avery and Berlin, 1992). The achievable azimuth resolution of a SAR is approximately equal to one-half the length of the actual (real) antenna and does not depend on platform altitude (distance) (Raney, 1998; Ulaby et al., 1981).

The final SAR image is composed of many small squares. These squares, or pixels (*pic*ture *ele*ments), represent the averaged intensity of radar signal returning to the sensor, or backscatter, for an area on the ground. SAR image pixel size is controlled by the length of the actual (real) antenna (controlling azimuth resolution), radar pulse which determines range resolution, signal coherence which controls signal quality or "noise", and the accuracy that the processor is able to match the signal modulations (Raney, 1998).

Radar Distortions and Terrain Corrections.

Initially, SAR distance is in slant range, or the inclined plane from the platform to the earth's surface (Figure 3.5). Maps, however, are made using planview ground distances. Using slant-to-ground range correction software, the satellite data are projected into ground distance. Each pixel represents a specific area on the ground and is re-projected into a standard grid (UTM, polar stereographic, etc). The pixels are then "geocoded" with evenly spaced in longitude and each row is assigned a specific latitude. Topographic distortions do occur because the radar data are originally collected in a time domain. They are foreshortening, layover, and shadowing.

Foreshortening occurs in mountainous terrain where the top of a mountain is close to the same distance from the platform as the bottom (Figure 3.6). Radar reflections returning from the base of the mountain arrive at very nearly the same time as those returning from the peak. The uncorrected image looks like the mountain's slope is much steeper than in reality. Layover is an extreme form of foreshortening and occurs when returns from a steep mountaintop arrives *before* its base (Figure 3.6). It is impossible to decorrelate the reflections to determine which is from the base or the top of the mountain and the image in this region has no recognizable features. Shadowing occurs in mountainous regions in the same way the sunlight casts shadows. Where the radar cannot illuminate some of the ground because a mountain blocks the radar beam, no returns are collected and become "no data" areas (Figure 3.6). These distortions are related to look angle from the platform

and surface topography (Lillesand and Kiefer, 1994). Look angle can vary not only from orbit to orbit, but also varies within a scene because the near-range has a smaller look angle than the far-range (*ibid*). For this reason, shadowing increases towards the far-range and foreshortening decreases (*ibid*). These terrain distortions (foreshortening, layover, and shadowing) can be minimized by employing known elevation data of the imaged area. This *terrain correction* will be discussed in detail in Chapter VI.

Radar Backscatter.

Bright pixels in a SAR image represent areas where a comparatively large fraction of the radar energy was reflected back, and dark pixels signify those areas from which little energy was returned. There are four types of radar scattering: diffuse, specular, volume and corner reflection (Figure 3.7). Diffuse scattering sends the incident energy in all directions (like light reflecting off a sheet of white paper). Specular reflection directs the incident radiation in a single direction (like light reflecting off a mirror). Volume reflection scatters the incident energy in all directions (like the dark, rich blue seen in a deep, clear lake, is a volume reflection of the visible blue light from varying depths in the lake). The fourth type of scattering is corner reflection, which occurs when a beam specular reflects two or more times, reversing the energy directly back towards the source. This type of reflection is used in land surveying methods for laser range finding. In SAR images, it commonly occurs in urban areas where buildings provide an abundance of highly reflective structures presenting right angles to incident radar (*ibid*). Naturally occurring corner reflectors include cliffs, fault lines, and tree trunks.

A variety of factors influence backscatter strength including: satellite groundtrack, incidence angle, radar polarization, surface roughness, and the dielectric properties of the surface (Campbell, 1996). A satellite ground-track (the path on the earth directly below the satellite) that is parallel to a linear feature (e.g., a fault line, row of crops, or ocean waves) will produce a higher backscatter than a perpendicular ground-track. Similarly, variations in the incidence angle of the radar beam with respect to the earth's surface, low incidence angles yield a high backscatter; high incidence angles yield low backscatter (causing more specular reflection). Because of this, slopes facing the radar beam will have a higher backscatter than slopes facing away. As mentioned before discussing satellite look angle, on a geoid the far range will have a higher incidence angle causing more specular reflection than the near range which will have lower incidence angles.

Backscatter will also vary depending on the use of different polarization. VV polarization is most sensitive to vertically oriented features such as plant stalks and tree trunks (Avery and Berlin, 1992). HH polarization is more sensitive to horizontal oriented surfaces like roads, riverbeds, and faults.

Roughness relative to the radar wave is determined by three factors: size of the surface variation, wavelength of the radar signal, and incidence angle of the radar beam (Avery and Berlin, 1992). Objects that are as large as or larger than the wavelength of the radar beam reflect the radar energy and thus are "rough," appearing bright. Objects smaller than the wavelength do not reflect much energy and appear dark (smooth) (Campbell, 1996). Roughness varies with wavelength: shortwavelength radar can discern smaller variations of roughness than long-wavelength radar. Incidence angle becomes less important in rough surfaces because the surface will be diffusely reflected (Figure 3.7) (Campbell, 1996).

Radar reflectivity also varies with an electrical property of the reflecting material called the *complex permittivity* ε_{c_i} often called the *dielectric constant*. It is the measure of a medium's response to the presence of an electric field (Raney, 1998). Specifically it is:

$$\varepsilon_c = \varepsilon' + i\varepsilon'' \tag{3-1}$$

where the first term on the right hand side, ε' , is the dielectric constant of the material, and the second term is the imaginary part, where *i* is the square root of -1, and ε'' is the "lossy" part of the dielectric constant. The dielectric constant of the material (ε ') is an absolute measure of the medium's response to an electrical field. When an electric field is applied to the medium, the molecules realign to the lowest energy state to fit their polarity to the electric field. Because the molecules are in a crystalline structure, they cannot completely align to the applied field. Different substances align with varying completeness and the success of the alignment is what the dielectric constant describes. The lossy part (or dielectric loss factor) of the dielectric constant (ε ") describes the lag time between the application of the electric field and response of the molecules in the medium. This lossy part is associated with the absorption of the electromagnetic radiation. As the dielectric of a material increases, the reflectivity also increases (Table 3.2). Liquid water, because of its high dielectric, has a pronounced effect on a material's dielectric constant (Avery and Berlin, 1992). For example, as a dry porous medium (soil, sand, snow) increases wetness; its dielectric constant increases, causing its reflectivity to radar waves to increase. Incident radar waves specular reflect away from the platform resulting in a dark pixel. Conversely, a dry medium, having a low dielectric, allows the radar wave to penetrate and volume reflect, producing a much brighter return at the sensor (Figure 3.7d).

Material	Dielectric constant of the material (ε ')			
Sea water	81	(Raney, 1998).		
Fresh water	81	(ibid).		
Wet earth	10-35	(Ulaby et al., 1981).		
Dry earth	3-5	(ibid).		
Dry snow	1_3	(ibid)		

Table 3.2: Dielectric values of some materials.

Radar Penetration.

Penetration of SAR energy into dry granular materials (e.g. sand or dry snow) has been documented for over a decade (Short and Blair, 1986). Radar penetrated 2 m of dry alluvium revealing buried igneous dikes in the Mojave Desert (Blom et al., 1984). Radar also penetrated "up to several meters" through dry sand in the Selma Sand Sheet in Sudan, exposing paleodrainage systems and buried geologic structures (Short and Blair, 1986; McCauley et al., 1982). For a single wavelength, the degree of penetration is related to the dielectric constant of the material (lower the constant, the higher the penetration) and its density (lower the density, the deeper the penetration). Longer radar wavelengths are able to penetrate deeper than shorter wavelengths (Shi and Dozier, 1993).

SAR Platforms.

Orbiting SAR sensors include Shuttle Imaging Radar–C/X (SIR-C/X), Radarsat satellite (Canadian Space Agency), and European Remote Sensing –2 satellite (ERS-2, European Space Agency). SIR-C/X first operated 1994, is occasionally carried aboard the space shuttle and consists of three individual antennas: L-band (23.5 cm), C-band (5.8 cm), and X-band (3 cm). The L-band and C-band antennas can measure both horizontal and vertical polarizations. Because of the different polarizations, SIR-C/X aids in understanding the interaction of microwaves with surfaces in more ways than a single polarization SAR can.

Radarsat carries a single frequency C-band antenna, with a unique ability to steer its radar beam over a 500-kilometer range (Table 3.3) (Jezek et al., 1993). A wide variety of beam selections are available: the swath width can be adjusted from 45 to 500 kilometers, with resolutions from 8 to 100 meters, and incidence angles from 10° to 60°. Repeat coverage is available daily in the high latitudes, and in equatorial latitudes every six days (Canadian Space Agency website, 2000). The orbital period is 100.7 minutes and the polarization is HH. The European Remote Sensing satellite (ERS-2), launched in 1995, carries a C-band SAR, with VV polarization (Table 3.3). It images a 100 km swath of the Earth's surface. Repeat coverage is available every three days, and has a resolution of 25 m.

	Radarsat	ERS-2
Frequency/Band	5.3 GHz/C-band	5.3 GHz/C-band
Wavelength	5.66 cm	5.66 cm
Polarization	HH	VV
Accessible swath	50-500 km	100 km
Look angle(s)	20-59°	23°
Resolution	8-100 m	25 m
Launch date	1995	1995

Table 3.3. Radar instrument specifications for Radarsat, and ERS-2 (Campbell, 1996).

Application of SAR to Snow and Ice.

Radar scattering from snow is dependent on its dielectric constant, which varies due to changes in water content. The snow's dielectric value influences whether the beam will reflect and/or penetrate the snowpack (Avery and Berlin, 1992). The imaginary part of the complex permittivity (ε ") is extremely sensitive to liquid water in the snow mixture, the greatest change of ε " occurs over wetnesses of only 0-0.5%. So only a small amount of liquid water in the snowpack will begin to absorb the radar and lessen volume scattering. The radar penetrates dry snow and the energy scatters from the dielectric discontinuity between ice crystals and air (Hall, 1998; Ulaby et al., 1981). The scattering occurs at varying depths of the snow pack, sending the signal in all directions, yielding a bright return at the sensor (Hall, 1998; Jezek et al., 1993; Mätzler, 1987). As the snow pack increases wetness the dielectric constant increases, penetration decreases and specular reflection increases (Avery and Berlin, 1992). Larger incidence angles also increase penetration resulting in deeper near-range penetration and shallower penetration at the far-range (Shi and Dozier, 1993).

Penetration in dry snow-packs is dominated by surface roughness, scattering by snow grains, and internal density contrasts (Hall, 1998; Rott and Mätzler, 1987; Shi and Dozier, 1993). As snow ages, grain size increases (Patterson, 1994), and changes the scattering properties, increasing reflectivity. Compared to new snow, firn (snow that survived the ablation season ~1 year old), with larger grain structure, yields a brighter reflection (Hall, 1998). Sublimation at depth creates large ice crystals in the shape of prisms, pyramids, or hollow hexagonal cups called depth hoar (Patterson, 1994). Depth hoar is highly porous and its density is low (100 to 300 kg m⁻³) with its large grain structure yields a bright SAR reflection.

At C-band frequencies, scattering losses in homogeneous dry snow are small and penetration depth can be calculated solely on the effective dielectric constant (ε) (Achammer and Denoth, 1994; Rott et al., 1993; Rott and Davis, 1993). The value of ε can be calculated by volumetrically weighted average of the dielectric constants of the bulk material, air and ice (Rott et al., 1993; Rott and Davis, 1993). Using these relations Rott and Mätzler (1987) calculated penetration depths of 21.7 m at a wavelength of 4.9 cm (C-band) and 8.1 m at a wavelength of 3.1 cm (X-band) for dry, homogeneous, firn.

Band	Χ	С	С	L
Frequency (GHz)	10.3	5.3	5.2	1.25
٤'		2.95	1.87	3.23
٤''	.00021	0.571	0.0001	0.170
Depth of estimated	8.1	0.027	21.7	0.404
penetration (m)				

Table 3.4. Snow dielectric properties and penetration depth for wet, 6% liquid water, density 500 kg m⁻³ (Rott and Davis, 1993) and dry, 440 kg m⁻³ (Rott et al., 1993) snow. Dry snow figures in **bold**.

Equation 3-1 contains two parts for determining the dielectric or complex permittivity. The first term ε' , or dielectric constant of the material, relates to the snow. The second term ε'' , or the imaginary part, relates to the amount of moisture of the snow. The absorption of the electromagnetic field by moisture in the snow is described by this second term. The dielectric constant (ε) for dry snow, is calculated by adding the real part (ε') and the imaginary part (ε'') of for the frequency (*f*) using Mätzler's (1987) mixing formula:

$$\varepsilon = \varepsilon' + i\varepsilon'' = \varepsilon_d + \frac{23W}{1 - i\left(\frac{f}{f_0}\right)} \quad (3-2)$$

where ε_d is the dielectric constant for dry snow, W is the liquid water content (expressed as a volume fraction), and f_0 is the relaxation frequency of wet snow. The penetration depth was obtained by:

$$d = \frac{\lambda_0 \sqrt{\varepsilon'}}{2\pi\varepsilon''} \qquad (3-3)$$

where λ_0 is wavelength of the SAR, and ϵ' and ϵ'' are obtained from the above formula

(Rott and Davis, 1993).

Penetration depth for wet snow with water content of 2-4% is typically one wavelength (Rott and Mätzler, 1987). Any surface melt on a snow surface results in almost complete specular reflection and lower backscattering values (Jezek et al., 1993; Rott and Mätzler, 1987). Therefore SAR return in wet snow is more dependent on the surface roughness; a smooth melting snow surface yields a dark backscatter (Bindschadler et al., 1987; Bindschadler, 1998; Fahnestock et al., 1993; Forster et al., 1991; Jezek et al., 1993) and a rough wet snow surface is brighter (Smith et al., 1997).

Ice, whether dry or wet, is uniform in its backscatter, specularly reflecting the radar energy away from the sensor (Bindschadler et al., 1987; Bindschadler, 1998; Fahnestock et al., 1993; Forster et al., 1996; Jezek et al., 1993; Partington, 1998; Smith et al., 1997). Only if the surface is very rough, can the beam reflect and yield a bright return (Bindschadler et al., 1987; Bindschadler, 1998; Fahnestock et al., 1993; Forster et al., 1987; Bindschadler, 1998; Forster et al., 1993; Forster et al., 1987; Bindschadler, 1998; Fahnestock et al., 1993;

Radar Zones.

Carl S. Benson developed a theory of glacier zones during his traverses across the Greenland Ice Sheet 1952-1955 (Benson, 1962). At about the same time Fritz Müller was also developing a similar theory (Müller, 1962). Because of the parallel development, the glacier zone model is known as the "Benson-Müller" facies model. The model treats glaciers and ice sheets as a monomineralic formation, primarily metamorphic, but with a sedimentary veneer of snow and firn. With this hypothetical model, the lithological term "facies" is used to differentiate zones on ice sheets and glaciers.

The four Benson-Müller facies are: ablation, soaked, percolation, and dry-snow (Figure 3.8). The ablation facies begins at the terminus of the glacier and ascends to the firn line approximately equal to the ELA. The firn line is the highest elevation to which the annual snow cover recedes at the end of the summer. It is an ice surface and is in temperate zones wet in the summer. The soaked facies is firn, which at the end of the melting season is wet throughout. The facie begins at the firm line and rise up glacier to the saturation line. The saturation line is the highest altitude that the 0° isotherm penetrates to the snow surface of the previous summer. The percolation facies is characterized by melting, and percolation of the water into the snow-pack, without becoming wet throughout. The melted water freezes inside the snow-pack forming lenses (lens-shaped inclusions parallel to firn strata), glands (pipe-like vertical ice masses), and ice layers (flat-shaped sheets extending over large areas parallel to the firm strata). This facie begins at the saturation line and terminates at the dry-snow line. The dry-snow facies includes the entire glacier above the dry-snow line in which negligible melting occurs.

The backscatter of radar energy appears to correspond with locations of the Benson-Müller facies (Table 3.5) (Partington, 1998; Fahnestock et al., 1993). An additional radar zone beyond the Benson-Müller facies model is included and called the crevassed zone. Because of the bright returns from crevasses, highly crevassed areas appear distinctly different.

re described rel	alive to facle.		
	Partington, 1998	Fahnestock et al., 1993	Smith et al., 1997
Location	Greenland & Mt. Wrangell, AK	Greenland	Stikine Icefeilds, B.C.
Type glacier	Polar/winter temperate	Polar	Temperate
Platform	ERS-1	ERS-1	ERS-1
Dry Snow	Very dark-grain size small (<5 mm).	Dark—small grain size and low density.	Bright return -cold winter snow, with no liquid water.
Percolation	Bright—ice pipes and lenses.	Bright—frozen pipes and lenses.	Dark-liquid water present (the 0° C isotherm).
Soaked	Dark.	Dark.	Bright—rough melting snow.
Ablation	Dark—specular reflection from super- imposed ice.	Dark—rough surface texture contributing to reflectance.	Dark—specular reflection from ice.
Crevassed		Bright—heavily crevassed ice providing linear reflectors.	

Table 3.5: The five glacier radar zones. SAR brightness and surface characteristics are described relative to facie.

Consensus on radar signatures of each zone (except for "soaked") is clear in polar glaciers. The temperate glacier in the Smith et al. (1997) study was conducted in winter when the upper part of the glacier was continuously below freezing. Smith's dry snow zone melts in the summer and likely contains ice pipes, lenses, and ice layers; which would be more like the percolation zone of the polar glaciers. Smith's percolation zone may more closely correspond to a soaked facie and the soaked zone of "rough melting snow" a local melt phenomena. If Smith's zones are indeed displaced and a melt feature of "rough melting snow" is disregarded, the glacier zones theory appears to agree across the studies.

Clearly different melt processes on the glacier control much of the tonal

patterns in C-band radar (Jezek et al., 1993). The ELA corresponds roughly to the boundary between the dark bare ice zone and the brighter snow areas on the SAR image (Bindschadler et al., 1987; Bindschadler, 1998; Jezek et al., 1993; Partington, 1998; Smith et al., 1997). However, "dark" and "light" in a SAR image, are a perception of the 0-255 brightness scale (8-bit) by the viewer. It is difficult to be exact as to where "dark" and "light" lie in this scale because it varies from viewer and image, but in general "dark" refers to 0 to 170, and light is 200 to 255 (Smith et al., 1997).