Introduction to Microwave Remote Sensing

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Introduction To Microwave Remote Sensing

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1.0 Introduction to Microwave Remote Sensing

1.1 Microwave Radiation

The optical wavelengths of the electromagnetic spectrum, which can be focused with lenses, cover the range from about 0.3 to 15 micrometers - the reflective and emissive portion of the spectrum. The microwave portion of the spectrum encompasses wavelengths from about 1 mm to 1.3 m (Figure 1). These non-optical wavelengths in the microwave portion of the spectrum must be focused with an antenna rather than a lens. The commonly used wavelength bands for active microwave (radar) remote sensing are given in Table 1.

1.2 Wavelength vs Frequency

Most radar engineers and technicians refer to the frequency which is transmitted and received by an imaging radar system. Most remote sensing application specialists, on the other hand, are more comfortable referring to the wavelength at which these work. As a result, the literature associated with microwave remote sensing contains both wavelength and frequency specifications and it is very useful for the end user to be able to easily convert from one to the other. Recall that according to Maxwell's Wave Theory,

\[ c = \lambda \times \nu \]

where
- \( c \) = speed of light, \( 3 \times 10^8 \) m s\(^{-1}\)
- \( \lambda \) = wavelength
- \( \nu \) = frequency.

A useful relationship between wavelength and frequency, called the "thirty rule", can be derived by expressing the speed of light in cm s\(^{-1}\), rather than the more common m s\(^{-1}\):

\[ c = 3 \times 10^8 \text{ m s}^{-1} = 30 \times 10^9 \text{ cm s}^{-1} \]

So, if \( \nu \) is expressed in Gigahertz (GHz = 10\(^9\) Hz), then

\[ \lambda_{(\text{cm})} = \frac{30}{\nu} \times \frac{10^9 \text{ cm s}^{-1}}{1 \text{ cycle s}^{-1}} \]

If \( \lambda \) is expressed in cm, then

\[ \nu_{(\text{GHz})} = \frac{30 \times 10^9 \text{ cm s}^{-1}}{\lambda \text{ cm cycle}^{-1}} \]
Electromagnetic Spectrum

Optical Wavelengths

Near IR
Shortwave IR
Thermal IR

Infrared (IR)

Microwave (radar)

Wavelength (micrometers, µm)

Table 1. Radar bands and designations

<table>
<thead>
<tr>
<th>Band Designation</th>
<th>Wavelength (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ka</td>
<td>0.75 - 1.10</td>
</tr>
<tr>
<td>K</td>
<td>1.10 - 1.67</td>
</tr>
<tr>
<td>Ku</td>
<td>1.67 - 2.40</td>
</tr>
<tr>
<td>X*</td>
<td>2.40 - 3.75</td>
</tr>
<tr>
<td>C*</td>
<td>3.75 - 7.50</td>
</tr>
<tr>
<td>S</td>
<td>7.50 - 15.0</td>
</tr>
<tr>
<td>L*</td>
<td>15.0 - 30.0</td>
</tr>
<tr>
<td>P</td>
<td>30.0 - 130</td>
</tr>
</tbody>
</table>

* most commonly used bands
1.3 Radar Operation

Imaging radar systems in typical use for remote sensing are **pulsed** - the energy that they transmit from their antenna is confined to a very short interval of time. This outgoing packet of energy eventually interacts with the landscape and some of it may be **backscattered** to return toward the antenna (Figure 2). In order to keep track of the outgoing and incoming energy packets, the system uses a **pulse repetition frequency** (the rate of recurrence of the transmitted pulses) which provides sufficient time for any backscatter from the far range portion of the scene to return to the antenna before the next transmitted pulse occurs (Figure 3).

The **pulse duration**, the time interval during which the antenna is energized during the transmit phase, controls the range-width of the outgoing energy packet and, as will be discussed later, is directly related to the range resolution of the system.

The heart of an imaging radar system is the **timing and frequency control module** (Figure 4). The **trigger** initiates the generation of the pulse which gets to the antenna through a one-way switching device. Most radars used for remote sensing are **monostatic** -- the transmit antenna and the receive antenna are essentially at the same location. The transmit / receive switch toggles the antenna between these two modes of operation, sending the transmitted pulse out and, during the quiet period between pulses, receiving backscattered energy which is sent to the **RF amplifier**.

The returned signal from the landscape is extremely weak and must be greatly amplified to be useful. As an example, the Seasat SAR produced an average radiated power of 50 watts - less than must light bulbs. The effective power received by the Seasat antenna from a typical object having a radar cross section of 10 m² was about $10^{-17}$ watts!

After RF amplification, the returned signal is sent to a demodulator where the envelope and phase of the return is separated from the carrier frequency. There are two output signals from this process: **in-phase (I)** and **quadrature (Q)**. These two signals are further amplified and then, in the A-to-D converter, quantized. These quantized signal data are then transferred to memory or transmitted to a ground receiving station for subsequent processing.
1.4 The Radar Equation

\[ P_R = P_T (\sigma^0 A) \left( \frac{G^2 \lambda^2}{(4 \pi)^3 R^4} \right) \]

where \( P_R \) = the power returned to the radar antenna from an areally extensive target

\( P_T \) = the power transmitted by the radar system

\( \sigma^0 \) = the radar scattering coefficient of the target

\( A \) = area of the resolution cell of the radar system

\( G \) = gain of the antenna

\( \lambda \) = wavelength of the radar system

\( R \) = range from antenna to target

So, the power returned from a target to the antenna on an imaging radar system is directly proportional to A) two system parameters: the transmitted power and the area of the resolution cell and B) one target property -- its radar scattering coefficient. Two other system factors, the antenna gain and wavelength, play a greater role in influencing the strength of \( P_R \) because returned power is directly proportional to the square of each of these system parameters. Finally, \( P_R \) is inversely related to the fourth power of range.

If all other factors are held constant, increasing the wavelength of an imaging radar system from 1 cm (K-band) to 3 cm (X-band) would increase the return power from a target by a factor of 3² or 9. Shifting from the K-band to the L-band (25 cm) would increase the return power from a target by a factor of 25² or 625!
1.5 Radar Angle Nomenclature

**Horizontal Surface**

- **Look Angle**: $\phi = 30^\circ$
- **Grazing Angle**: $\gamma = 80^\circ$
- **Depression Angle**: $\beta = 60^\circ$
- **Incident Angle**: $\theta = 30^\circ$

**Inclined Surface**

- **Look Angle**: $\phi = 30^\circ$
- **Grazing Angle**: $\gamma = 80^\circ$
- **Incident Angle**: $\theta = 10^\circ$
- **Slope**: $\alpha = 20^\circ$
1.6 Polarization

Recall that electromagnetic energy has two components - electrical and magnetic - which are planar fields of oscillation that are orthogonal to each other (Figure 5). Polarization refers to the spatial orientation of the electrical oscillation plane -- is it oriented vertically, horizontally, or at some other angle. Note that no matter what orientation the electrical field has, the magnetic field is always at right angles to it.

Because radar is an active remote sensing device, the orientation of the electromagnetic energy that is transmitted can be controlled. Although all angles are possible, only vertical or horizontal orientations are used. The orientation of the backscatter which will be received can also be controlled. This gives four possibilities for a radar system:

- **HH** horizontal transmit and receive
- **VV** vertical transmit and receive
- **HV** horizontal transmit, vertical receive
- **VH** vertical transmit, horizontal receive

### Wave Theory

\[ c = \lambda \nu \]

\[ c = 3 \times 10^8 \text{ m s}^{-1} \]

- **E** Electric field
- **M** Magnetic field
- **W** Plane-polarized, transverse wave
- **C** Velocity of light

\( \lambda = \text{Wavelength} \)  
\( \nu = \text{Frequency} \)  
\( \text{Distance between successive wave peaks} \)

\( \text{Number of cycles per second passing a fixed point} \)
- The electric field oscillations of the transmitted pulses are either in the VERTICAL or the HORIZONTAL plane (by design of the antenna elements).

- Most backscattered energy has the same polarization as the transmitted pulses.

<table>
<thead>
<tr>
<th>PARALLEL-POLARIZED or LIKE-POLARIZED systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>HH (horizontal transmit, horizontal receive)</td>
</tr>
<tr>
<td>VV (vertical transmit, vertical receive)</td>
</tr>
</tbody>
</table>

- Some backscattered energy is DEPOLARIZED.

- DEPOLARIZATION effects are STRONGER from VEGETATION than from bare ground (if horizontally transmitted radiation is used because of the dominantly vertical growth form of vegetation).

- Some radar systems have additional antenna elements in order to RECEIVE DEPOLARIZED backscatter oscillating at right angles to the plane of the transmitted pulse.

<table>
<thead>
<tr>
<th>CROSS-POLARIZED systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>HV (horizontal transmit, vertical receive)</td>
</tr>
<tr>
<td>VH (vertical transmit, horizontal receive)</td>
</tr>
</tbody>
</table>

- When four polarimetric channels are used, the radar is referred to as quadrature - polarimetric or "quad-pol" for short. This type of radar is different from, and more sophisticated than, the "polarization diversity" radars mentioned above. Quad-pol data may be analyzed over all polarization states to determine the reflectivity pattern of landcover types (their polarization signature). Zebker et al. (1991) reported that the reflectivity from the canopy of a tropical forest may be separated from the two-bounce reflectivity components from tree trunks in standing water.
1.7 A Brief History of Imaging Radar

The following brief history of imaging radar technology is based on the following two references:


1886 Heinrich Hertz experimentally tests Maxwell’s Theory of Electromagnetism. He discovers radio waves and showed that reflections could be received from metallic and nonmetallic objects.

1903 Christian Hulsmeyer demonstrates radar detection of ships at sea. He obtains the first patent for using radar as a ship detector.

1920 A.H. Taylor at the US Naval Research Laboratory develops a ground-based, pulsed radar system.

1930 The US Naval Research Laboratory team uses its ground-based radar system to detect and track ships and aircraft.

1937 Sir Watson-Watt (U.K.) develops the first practical radar system for aircraft detection.

1938 The first airborne radar images showing the reflections from ships at sea to a range of ten miles were made on 28 March.

1940s Independent and penecontemporaneous development of radar systems was conducted in secret during the period of WW II in Britain, France, Germany, Italy, Japan, Russia and the United States. This research perfected the plan position indicator (PPI) radar system.

1950s Real-aperture, side looking imaging radar systems (SLAR -- Side looking Airborne Radar) were developed to produce much better quality images (compared to PPI systems) for military reconnaissance. Optical image processing techniques were used to both create and analyze SLAR imagery.
Carl Wiley (USA) first observes that the azimuth resolution of a SLAR system can be significantly improved by using the Doppler shifts of the return signals. This observation gives birth to the current imaging radar technology -- synthetic aperture radar (SAR).

1952 The first operational SAR system was developed.

1953 The first airborne SAR image was acquired using a system operating at 930 MHz.

late 1950s Goodyear Corporation and The Ohio State University, among others, conduct research into the electromagnetic reflection properties of natural surfaces. Measurements of terrain backscattering from both static and airborne radars are made.

1960s Limited declassification of SLAR data in the early 1960s allows an open discussion of the geoscience potential of radar. SLAR surveys using real aperture systems become commercially available.

1962 The First Symposium on Remote Sensing of Environment was held at the University of Michigan.

1964 The first unclassified publications on geoscience radar reconnaissance appear in the *Proceedings of the Third Symposium on Remote Sensing of Environment* and in *Photogrammetric Engineering*.

late 1960s and early 1970s Extensive, unclassified SLAR coverage of the United States was acquired under a NASA radar program using the Westinghouse AN/APQ 97 system, $K_a$-band, multiple polarized, real-aperture imaging radar.

Goodyear/Aeroservice, Motorola, and Westinghouse collected SLAR imagery of the US and in Brazil, Indonesia, Panama, Nigeria and Venezuela using a variety of systems:

- Westinghouse AN/APQ 97  
  $K_a$-band, HH, RAR (Real Aperture Radar)

- Goodyear Electronic Mapping System (GEMS)  
  X-band, HH, SAR

- Motorola (MARS) Ltd.  
  X-band, HH, RAR with simultaneous dual look directions
The first major radar mapping project is conducted in the Darien Province of Panama using the Westinghouse AN/APQ 97 system. This project acquired the first complete image coverage (17,000 km²) of this area which is most often covered with clouds.

Multichannel, airborne SAR systems are developed at the Environmental Research Institute of Michigan (ERIM), the NASA Jet Propulsion Laboratory (JPL) and at the Canadian Center for Remote Sensing (CCRS).

RADAM (RADar of the AMazon)-Brazil was conducted. Initially, the mission acquired airborne SLAR imagery of the Amazon and Northeast, but eventually included imagery of all of Brazil -- in all, 8.5 million km² were imaged.

The first spaceborne SAR system, the Apollo Lunar Sounder Experiment radar, was flown around the Moon on Apollo-17.

RADAM-Colombia collected airborne SLAR imagery of the Colombian Amazon, mapping about 380,000 km².

Seasat, the first civilian satellite-based SAR was launched on 27 June. Flying at an altitude of 800 km, it provided L-band (23.5 cm), HH imagery with 25 m range and azimuth resolution across a 100 km swath. Seasat imaged over 126 million km² in its brief 3-month life-span.

Shuttle Imaging Radar-A (SIR-A) was flown for 2.5 days on the Space Shuttle Columbia (STS-2) at an altitude of 260 km. About 10 million km² of L-band (23.5 cm), HH imagery were acquired with 40 m range and azimuth resolution across a 50 km swath.

The Soviet Union experimented with its Kosmos real-aperture imaging radar system for oceanography applications. Their Verena-15 and -16 spaceprobes provided 2 - 4 km resolution radar imagery of Venus.

SIR-B was flown on the Space Shuttle Challenger. This was an L-band (23.5 cm), HH SAR which produced imagery with 25 m range resolution and 17 - 58 m azimuth resolution. SIR-B provided variable incident angles (15° - 64°); the swath width varied from 10 - 60 km.
The Soviet Union launched Kosmos 1870, an S-band (10 cm), HH SAR system. It provided variable incident angles (30° - 60°), producing image swath widths of 20 - 45 km. Resolution was approximately 30 x 30 m (range x azimuth).

The Magellan spaceprobe was launched from the Space Shuttle Atlantis on 4 May. Magellan entered its orbit around Venus on 10 August 1990. The radar mapping mission ran from 15 September 1990 to 15 May 1991. The Magellan radar was an S-band (12.6 cm), HH SAR. It produced imagery with 120 - 360 m range resolution and 120 - 150 m azimuth resolution.

The USSR/Russia launched Almaz on 31 March. This S-band (10 cm), HH SAR provided variable incident angles between (30° - 60°). Almaz imagery covered a swath which varied from 20 - 45 km at resolutions of 15 - 30 m in range and 15 m in azimuth.

The European Space Agency (ESA) launched its first earth-resources remote sensing satellite, ERS-1, in July. The SAR instrument on board is a C-band (5.7 cm), VV system operating at a fixed incident angle of 23°. Its 6-look imagery covers a 100 km swath and produced 26 m range resolution and 28 m azimuth resolution.

JERS-1, the Japanese Earth Resources Satellite, was launched in February. It carries an L-band (23.5 cm), HH SAR which provides 75 km-wide imagery having 18 m x 18 m resolution.

On 9 April, with the launch of the Space Shuttle Endeavor, a major milestone in spaceborne imaging radar began. This 11-day Shuttle mission carried the SIR-C/X SAR instrument into low (225 km) earth orbit. This system provided quadrature polarized, L-band (23.9 cm) and C-band (5.7 cm) data along with VV-polarized, X-band (3.1 cm) imagery. This mission included steerable incident angles, varying from (15° - 55°), which produced swath widths of 15 - 60 km. SIR-C/X SAR imagery has range resolutions of 10 - 30 m with an azimuth resolution of 30 m. SIR-C/X SAR flew a second time on STS-68 (Shuttle Endeavor) from 30 September to 11 October.

ESA launched ERS-2, the twin of ERS-1, on 21 April.

Canada launched its first earth-resources remote sensing satellite, Radarsat-1, on 4 November. This satellite carries a C-band (5.6 cm), HH SAR with a steerable antenna providing incident capture.
angles varying from (10° - 60°). This SAR system can be operated in several modes producing swath widths of 50 km, 75 km, 100 km, 150 km, 300 km and 500 km. The Fine Resolution Mode outputs imagery with a resolution of 11 m x 9 m (range x azimuth). Several other modes produce 25 m x 28 m data. The Narrow ScanSAR imagery has 50 m x 50 m resolution while the Wide ScanSAR produces 100 m x 100 m data.

Near Future

Several satellite SAR systems are planned for launch in the near future. Almaz II, a virtual twin of Almaz, is already built, but does not have a firm launch date. The Russian PRIRODA mission includes a SAR operating at both L-band and S-band frequencies. It is specified to provide VV or HH polarizations and a fixed incident angle of 35°. It will produce an 80 m image swath having 100 m range resolution and 50 m (L-band) or 150 m (S-band) azimuth resolution.

ESA plans to launch ENVISAT in November, 2000. The Advanced SAR (ASAR) instrument on ENVISAT will provide beam- elevation steerable, allowing the selection of different swaths within an operating swath over 400 km wide. In its alternating polarization mode, the transmit and receive polarization can be selected, allowing scenes to be imaged simultaneously in two polarizations.

Radarsat-2 is scheduled for launch in the first quarter of 2001. This system builds upon the basics of Radarsat-1, but provides several new capabilities including modes providing 3 m x 3 m resolution across either 20 km or 10 km swaths using one of four selectable polarizations (HH, VV, HV or VH) and fully polarimetric data sets at resolutions as fine as 11 m x 9 m.
2.0 Atmospheric Interactions

The atmosphere is virtually transparent to wavelengths in the microwave portion of the electromagnetic spectrum that are longer than about 7 mm (Figure 6). These radar wavelengths can penetrate all non-raining clouds and, as shown in Figure 7, wavelengths longer than about 3 cm can produce useful imagery (≥60% terrain signal) of the terrain beneath even moderate rain showers (<1.7 mm/hr).

3.0 Spatial Resolution

The spatial resolution of a radar system is controlled by several system parameters as listed in Table 2. As shown in Figure 8, the two-dimensional radar image is referenced by the range domain, orthogonal to the flight track, and the azimuth domain, parallel to the line of flight. The dimensions of the radar resolution cell are controlled by the pulse duration and the azimuth beamwidth. Since the azimuth beamwidth diverges with increasing range, so does the illuminated footprint. Pulse duration, on the other hand, is constant across the swath width. As discussed below, range resolution is either constant (slant-range resolution) or inversely dependent on range (ground-range resolution). Azimuth resolution is directly proportional to range for real-aperture radars and is constant for synthetic aperture systems (Figure 9).

3.1 Range Resolution

There are two aspects of the range domain. Slant range refers to the line-of-sight ray between the radar antenna and a position in the range domain. In slant-range terms, range resolution is constant and solely dependent on pulse duration. The shorter the pulse duration, the the narrower the transmitted energy packet (across the range axis) and the smaller (i.e. better) the slant-range resolution (Figure 10). In ground-range terms, range resolution is still a function of pulse duration, but is also inversely related to ground range. Ground-range resolution is poorest in the near-range portion of the scene and best in the far-range sector (Figure 9 and 10). The depression angle β is inversely related to ground range position -- a large β illuminates the near-range sector of the swath while small depression angles irradiate the far-range portion of the beam. From this relationship, we can associate depression angle with ground-range resolution:

\[
R_{GR} = \frac{\tau \cdot c}{2 \cos \beta}
\]

where \( \tau \) = pulse duration
\( c = 3 \times 10^8 \text{ m s}^{-1} \)
\( \beta \) = depression angle
Table 2

For imaging radars, the size of the *Ground Resolution Cell* is controlled by:

<table>
<thead>
<tr>
<th>PULSE DURATION</th>
<th>GROUND RANGE</th>
<th>BEAMWIDTH</th>
</tr>
</thead>
</table>

Pulse duration and ground range dictate the spatial resolution in the direction of energy propagation, referred to as the

*RANGE RESOLUTION*

Beamwidth determines the spatial resolution in the direction of flight, referred to as

*AZIMUTH RESOLUTION*
3.2 Azimuth Resolution

3.2.1 Azimuth Resolution for SAR  As given by Raney (1998), the equation for the maximum attainable, single-look azimuth resolution for a spaceborne SAR system is:

\[ R_a^{(SAR)} = \frac{V_B}{V_{sc}^2} \times \frac{D_A}{2} \]

where

- \( R_a^{(SAR)} \) = azimuth resolution
- \( V_B \) = rate of antenna footprint movement at the illuminated surface
- \( V_{sc} \) = velocity of the spaceborne SAR
- \( D_A \) = antenna size (length) in azimuth

For aircraft mounted SARs, this relationship becomes simply

\[ R_a^{(SAR)} = \frac{D_A}{2} \]

There are several important things to note about these relationships. First, SAR azimuth resolution is independent of range and is constant across the whole swath width. Second, shorter SAR antennas produce better azimuth resolutions -- the opposite of the case for real aperture radar. Third, since the \( V_B / V_{sc} \) ratio is always very small, the azimuth resolution of spaceborne SAR systems are notably better than the \( R_a \) of aircraft SAR systems!

3.2.2 Azimuth Resolution for RAR  For real aperture radars (RAR), which are no longer in use for environmental remote sensing, azimuth resolution degrades (i.e. becomes poorer) from near range to far range (Figures 8 and 9). This is due to the divergence of the physical beamwidth as a function of range as indicated by the relationship:

\[ R_a^{(RAR)} = \overline{GR} \times \beta \]

where \( \overline{GR} \) = ground-range distance

\[ \beta = \frac{\lambda}{D_A} \]

Beamwidth for a real aperture radar is directly proportional to the system wavelength and inversely related to the antenna length:
4.0 Synthetic Aperture Processing

A synthetic aperture radar is a coherent imaging system on a moving platform which looks obliquely at the landscape. The backscattered energy a SAR receives has a frequency spread in the azimuth domain. This Doppler spectrum of the system, as it is called, has a shape and bandwidth ($\beta_{DOP}$) which is established by the azimuth pattern of the antenna, the velocity of the platform and the transmitted wavelength. The Doppler shift ($f_D$) imposed on the backscatter from each target is determined by the component of apparent motion along the line-of-sight (LoS) between the SAR antenna and the target (Figure 11). The Doppler frequency shift is zero ($f_D=0$) when the LoS velocity between the antenna and the scatterer is zero. This occurs at the moment the LoS to the target is orthogonal to the line of flight.

During the time any target is illuminated in the fore-beam zone, its backscatter is upshifted ($f_D^+$) because the range between it and the antenna is constantly diminishing. After passing the zero Doppler shift line, the range to a target is constantly increasing and its backscattered signals are downshifted in frequency ($f_D^-$).

Any target in the scene can produce backscatter only during the time interval $T_A$ that it is irradiated by the SAR antenna. This azimuth integration time ($T_A$) for a given scatterer is proportional to the slant range. In combination with the platform velocity, $T_A$ determines the distance along the line of flight for which the target is illuminated (Figure 12). This distance $L_A$ is the length of the synthetic aperture.

As discussed previously, beamwidth is inversely proportional to antenna length. A large beamwidth results in a long illumination integration time $T_A$. Hence, for synthetic aperture radars, the azimuth resolution $R_{azSAR}$ is directly proportional to azimuth antenna length $D_A$. For SAR systems, shorter antennas produce improved azimuth resolution.

SAR systems have a large azimuth time-bandwidth product ($TBP_A = T_A \times \beta_{DOP}$) which describes the spatial complexity of the Doppler modulation across the real aperture. Most SARs have a $TBP_A > 10$ and spaceborne SAR systems often have a $TBP_A > 100$. The large $TBP_A$ property of SAR systems means that they can operate efficiently in a range-Doppler mode. The two-dimensional SAR image is built up by the processor's knowledge of the range to each scatterer and its Doppler phase (Figure 13). At any given range, a scatterer is mapped at its zero Doppler position.
**Introduction to Microwave Remote Sensing**

**Doppler Shift $f_D$**

At any given range, targets in the fore-beam area have upshifted $f_D$ while those in the back-beam area have downshifted $f_D$.

**Synthetic Aperture**

Target $T$ at range $R$ remains within $\beta_r$ for a distance $L_s = R \beta_r$ (the azimuth resolution $R_{a(RAR)}$ for a RAR).

\[ \beta_r = \frac{\lambda}{D_\lambda} \]

where $\beta_r$ = real beamwidth

\[ D_\lambda = \text{real antenna length in azimuth} \]

Synthetic beamwidth

\[ \beta_s = \frac{\lambda}{2L_s} = \frac{D_\lambda}{2R} \]

For airborne SAR, the synthetic azimuth resolution $R_{a(SAR)}$ at range $R$ is

\[ R_{a(SAR)} = R \frac{\beta_s}{\beta_r} = \frac{D_\lambda}{2} \]

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Range / Doppler Domain

Equi-Doppler lines

Equi-range lines

H
Line of flight

Range domain

f₀⁻
f₀⁺
f₀₀
5.0 Radar Image Geometry

5.1 Layover

A radar image in the range domain is a record of the time it took for the signals to interact with targets and return to the antenna. These times are converted to distances, but in the slant range geometry. As a result, tall objects will be displaced toward the flight line since the wave front will encounter the top of the object before it illuminates the bottom of the target. Radar layover is an extreme case of relief displacement. As shown in Figure 14 (A, B and C), radar layover is not dependent on absolute range but on the difference in range between the return from the top of an object and the return from its bottom section.

The amount of layover is a function of the depression angle, which controls the angle of the wave front, and the local incident angle. Layover is most extreme at large depression angles (near range portion of the scene) and diminishes as the depression angle becomes smaller out in the far range portion of the scene. Spaceborne SAR imagery is, therefore, prone to this type of distortion, whereas aircraft SAR imagery is less troubled by layover, except in the immediate near range.

From an image interpretation viewpoint, there are two important affects of layover. As can be observed at example A in Figure 14, in the near range where layover is severe, the landscape surface in front of the tall object is at the same slant range as the top of the object. As the wave front moves outward across the landscape, it produces simultaneous backscatter from places in the foreground terrain and along the radar-facing slope. In most cases, the radar-facing slope produces the stronger backscatter of the two and, as a result, information about the foreground landscape is obliterated. In high relief terrain with most of the landscape in slope, this can make the imagery virtually uninterpretable.

The second important aspect of layover for an image interpreter is that the length of the slope is distorted in proportion to the depression angle (i.e. position in the ground range) and the local slope angle. Since local slope angles may not be know a priori, estimating slope length and inclination becomes impossible.

A very instructive example of layover is presented in Figure 15. As seen in the side-view sketch, the center span of this bridge is an arched structure. The upper edge of the arch is closer to the radar antenna (in slant range) than the roadway section is. As a result, the bridge is imaged as if it were laying on its side in the river. Two other linear reflections can be observed to the right of
Radar Image Geometry

Radar Layover Example

Seasat SAR image of the bridge crossing the St. Lawrence Seaway at Trois Rivieres, Quebec, Canada
the arched return. The straight line in the middle of the three reflections is an example of dihedral corner reflection. It represents the double-bounce reflections from the river surface to the side of the bridge and back to the antenna and the reverse circumstance. Both of these dihedral paths have the same slant range and are additive. The slightly curved reflection across the river on the far right of the triplet represents a very interesting situation. This is the image of the bottom of the bridge roadway! In this case, these reflections result from a triple-bounce pathway: from the river surface up to the bottom of the roadway, back to the river surface and then back to the antenna. Since the bridge roadway is gently curved to reach its maximum height-above-water at mid-span, the triple bounce pathway is longest at mid-span and the reflection is also gently curved, but displaced down range from the antenna (Raney, 1998).

5.2 Foreshortening

At small depression angles, layover ceases and a new distortion, foreshortening, occurs (example E, Figure 14). Radar imagery shortens terrain slopes in all cases except where the local angle in incidence (see Section 1.5, page 8) is equal to 90°. Terrain slopes imaged at a 0° incident angle, as shown by the example D in Figure 14, are foreshortened to a bright line on the image.

5.3 Radar Shadows

Radar shadows are dependent on the relationship between the depression angle and the inclination of the terrain slope facing away from the radar antenna. If the angle of the backslope is less than the depression angle, the backslope will be fully illuminated (no shadow) The backslope is irradiated at an acute grazing angle, producing weak backscatter, when the depression angle and the backslope angle are nearly equal (examples A and B, Figure 14). If the backslope angle is greater than the depression angle, it is not illuminated at all due to terrain obscuration which produces a radar shadow (examples C, D and E, Figure 14). Radar shadows occur more frequently and are more areally extensive at small depression angles. Airborne SAR systems are prone to this problem (landscape obscuration due to radar shadows).
6.0 Controls of Radar Backscatter

6.1 Backscatter

- STRONGER returns produce BRIGHTER signatures

- Backscatter intensity is determined by:

  I. RADAR SYSTEM PARAMETERS
     
     Polarization
     * Depression Angle
     * Wavelength

  II. TARGET PROPERTIES

     Complex Dielectric Constant
     (moisture content)

     * Surface Roughness

     Local Geometry

     * = interrelated factors to be discussed together

- RADAR BACKSCATTER is a function of:

  I. SURFACE REFLECTIVITY

     - Dielectric Constant

  II. SURFACE GEOMETRY

     - micro (roughness)

     - macro (incident angle)
6.2 Dielectric Constant

- description of a medium's response to the presence of an electric field

- indication of REFLECTIVITY and CONDUCTIVITY

- difficult to measure

- few published values especially for landscape features rather than individual elements

- at radar wavelengths:

<table>
<thead>
<tr>
<th>object</th>
<th>dielectric constant</th>
</tr>
</thead>
<tbody>
<tr>
<td>dry rocks &amp; soils</td>
<td>3 - 8</td>
</tr>
<tr>
<td>liquid water</td>
<td>80</td>
</tr>
</tbody>
</table>

- Dielectric constant is DIRECTLY RELATED to MOISTURE CONTENT:

![Graph showing the relationship between dielectric constant and moisture content]
6.3 Surface Roughness

- As a function of wavelength
  
  + SMOOTH SURFACES (SPECULAR REFLECTORS)
    
    \[ h < \frac{\lambda}{25 \sin \gamma} \]
    
    \( h = \) surface micro-relief
    \( \lambda = \) radar wavelength
    \( \gamma = \) grazing angle between terrain and incidence vector
    
    **note:** \( h \) and \( \lambda \) must be in the same units (usually cm)

  + ROUGH SURFACES (DIFFUSE REFLECTORS)
    
    \[ h > \frac{\lambda}{4.4 \sin \gamma} \]

- Influence on backscatter in relation to depression angle

![Graph showing return intensity vs depression angle for smooth and rough surfaces.](image-url)
Models of surface roughness and return intensity for X-band radar ($\lambda = 3$ cm).

6.4 Penetration Depth

- **DIRECTLY RELATED to WAVELENGTH**
  (i.e. longer wavelengths penetrate more)

\[
D_{\text{pen}} \approx \frac{\lambda}{\pi \tan \theta}
\]

where \( \theta \) = incident angle

- **In lithologic materials**
  - INVERSELY RELATED to DIELECTRIC CONSTANT
  - INVERSELY RELATED to WATER CONTENT
  - As dielectric constant increases, SURFACE REFLECTIVITY increases
  - moist soils reflect more radar energy than dry soils

- **In vegetative canopies**
  - Function of the radar cross-section of the canopy (scattering element density vs wavelength)
6.5 Sigma Nought ($\sigma^0$)

Sigma nought is a fraction which describes the amount of average backscattered power compared to the power of the incident field. It represents the average reflectivity of a material normalized with respect to a unit area on the horizontal ground plane. It is sometimes referred to as the *scattering coefficient*. The magnitude of $\sigma^0$ is a function of the physical and electrical properties of the target, the wavelength and polarization of the SAR system, and the incident angle as modified by the local slope.
7.0 Radar Backscatter From Vegetation

- Dielectric constant of vegetation is DIRECTLY PROPORTIONAL to its *in vivo* MOISTURE CONTENT

- Backscatter strength from a canopy is a function of:
  - Scattering geometry (specular <-- diffuse)
  - Frequency distribution of scatterer sizes
  - Surface reflectivity beneath the canopy
  - Leaf area (density of scattering elements per unit volume)
  - Polarization of the radar energy (stronger *vertical* backscatter)
  - Row structure and orientation relative to the range domain of the radar
Types of Canopy Backscatter

A. Canopy Backscatter (volume scatter)
B. Direct Soil Backscatter
C. Canopy-Soil Multiple Scatter
D. Soil-Canopy Multiple Scatter

Leaf Dielectric Constant VS Moisture Content


7.1 Applying SAR Data To Tropical Forest Issues

7.1.1 Overview. Tropical rainforests present particularly difficult challenges for applying remote sensing for the following reasons:

- frequent, nearly ubiquitous cloud cover
- very high biomass densities (200 - 600 tons ha\(^{-1}\))
- complex vertical stratification of the forest canopy
- lack of seasonal variation in structural attributes


- The best discrimination of forest type with SAR imagery is achieved by visual interpretation:
  - backscatter intensity, texture and context
  - understanding of local ecology and cultural practices is essential
  - knowledge of topography is important to determine ecological niche and to account for the effects of different incident angles
  - drainage patterns also give important clues

- Results regarding SAR use from temperate and boreal forests cannot be applied to tropical forests:
  - tropical forests have much larger species diversity and much greater biomass density

- Forest mapping in the humid tropics consists of delineating general forest types and units which are often classified by their physiographic setting.

- Example forest units that have been mapped using airborne SAR:
  - primary and secondary forest
  - mangrove swamp
  - beach forest
  - high scrub forest
  - hill dipterocarp
- coastal plain forest
- eucalyptus

RADAM-Columbia (1973-1979) used X-band, HH SAR imagery to map the following classes:
- floodplain
- dry land terrace and low hills
  - with dense, homogeneous forest
  - with savanna and savanna-forest
- high hills and plains


- Satellite SAR data should be selected for the largest possible incident angle to maximize the contrast of forest clearings.
- Airborne SAR data should be acquired at incident angles greater that 60° to facilitate mapping forest clearings.


- Western Province, Papua New Guinea
  ERS-1 SAR C-VV; 100 m resolution (smoothed from original 30 m data); 23.5° incident angle.

- ERS-1 data can discriminate forest from nonforest (Kappa = 77.7%). Landsat TM over the same area produced a similarly accurate classification (Kappa = 73.4%).

- One-date data set provides successful results (Kappa = 84.7%) if it is acquired during the dry season.

- Multitemporal data analysis, using acquisitions from both the wet and dry seasons, yields the most accurate results (Kappa = 77.7% - 90.3%).

- The potential of ERS-1 SAR data for forest type discrimination is very low.

- Northeast of Jaru, Rondonia State, Brazil.

- SIR-C C- and L-band; HH and HV; 25 m resolution; 32° incident angle.

- Six-category classification scheme (Figure 16):
  - Primary forest
  - Secondary forest (Young and Old)
  - Pasture/Crops
  - Quebradao
  - Disturbed forest

- MAP classification of 4-channel SAR data (L-HH, L-HV, C-HH, C-HV) produced an overall average classification accuracy of 72% (Table 3).

<table>
<thead>
<tr>
<th>Truth Class</th>
<th>PF</th>
<th>SR</th>
<th>DF</th>
<th>QB</th>
<th>PS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary forest (PF)</td>
<td>84%</td>
<td>4%</td>
<td>11%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>Secondary regrowth (SR)</td>
<td>32%</td>
<td>62%</td>
<td>0%</td>
<td>6%</td>
<td>0%</td>
</tr>
<tr>
<td>Disturbed forest (DF)</td>
<td>16%</td>
<td>0%</td>
<td>77%</td>
<td>6%</td>
<td>0%</td>
</tr>
<tr>
<td>Quebradao (QB)</td>
<td>0%</td>
<td>8%</td>
<td>10%</td>
<td>69%</td>
<td>13%</td>
</tr>
<tr>
<td>Pasture / crops (PS)</td>
<td>0%</td>
<td>29%</td>
<td>0%</td>
<td>0%</td>
<td>71%</td>
</tr>
</tbody>
</table>

**Table 3**

SIR-C C-HH, C-HV, L-HH and L-HV channels
Confusion Matrix of Land Cover Types Derived from MAP Classifier

<table>
<thead>
<tr>
<th>Truth Class</th>
<th>Primary Forest</th>
<th>Regrowth/ Disturbed</th>
<th>Pasture/ Crops</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary forest (PF)</td>
<td>93%</td>
<td>7%</td>
<td>0%</td>
</tr>
<tr>
<td>Regrowth / Disturbed</td>
<td>18%</td>
<td>81%</td>
<td>1%</td>
</tr>
<tr>
<td>Pasture / crops (PS)</td>
<td>0%</td>
<td>13%</td>
<td>87%</td>
</tr>
</tbody>
</table>

The Regrowth/Disturbed class includes both young and old regrowth as well as forest disturbances. The Pasture/Crops class includes Quebradao, Pasture and Agricultural Fields.

SIR-C Data for Mapping Tropical Deforestation

1: Pasture/Crops
2: Primary Forest
3: Quebradão
4: Young Regrowth
5: Old Regrowth
6: Disturbed Forest

- Significant confusion existed between Primary and Secondary forests and between Secondary forests and Pasture/Crops. Disturbed forests were also confused with Primary forests, but less often (16%).

- C-HH and C-HV channels help delineate the low vegetative areas but add confusion to the distinction between forest types achieved by L-HH and L-HV.

- Using all four SAR channels, with a simplified three-category classification scheme (Primary forest, Regrowth/Disturbed forest and Pasture-Crops/Quebradao), the MAP classifier produced an overall accuracy of 87% with greater separability between the classes (Table 3).

- Using only the two L-band channels (L-hh and L-HV), with the three-category legend, the MAP classifier produced a classification with 92% overall accuracy.

- L-band SAR data in this study area and during the dry season appeared to saturate at less than 10 years forest regrowth (woody biomass < 100 tons / hectare) because the green biomass and canopy water content are high.

- L-band SAR data acquired during the wet season is not suitable for land cover classification (for example, Figure 17 shows the impact of a local rain shower on the backscatter from a forest canopy).

- Some areas of Secondary regrowth appear in Landsat TM imagery, but not in the SAR data. Other studies have shown the opposite -- that L-band SAR data have better sensitivity to Secondary regrowth than do the Landsat data.

- Some areas of disturbed forest do not appear clearly on Landsat TM imagery, but have distinctive backscatter characteristics in the L-band SAR data.
Enhanced Backscatter from Wet Forest Canopy

ERS-1 SAR

Local rain shower

© 1999 David P. Lusch, Ph.D., Center for Remote Sensing & GIS, Michigan State University

- 50 km southeast of Porto Velho, Rondonia State, Brazil.

- SIR-C C- and L-band, quad-polarized, incident angle ca. 37°.

- JERS-1 L-HH, incident angle ca. 39°.

- Land cover classes:
  - Open water
  - Flooded, dead forest
  - Clearings with no woody biomass
  - Initial regrowth (0-5 years old; 0-60 tons/ha)
  - Intermediate regrowth (5-8 years old; 60-120 t/ha)
  - Recent clearings with high woody biomass slash
  - Forest (292-436 t/ha)

- For tropical forests, volume scattering dominates both C- and L-band SAR data. The magnitude of the cross-polarized returns is controlled by the volume, structure and moisture content of the canopy.

- Volume scatter is larger for L-band than C-band. At C-band frequencies the canopy is dense enough to promote single-bounce scattering. At L-band wavelengths the signals penetrate deeper into the canopy promoting volume scatter.

- Flooded forest returns are dominated by double-bounce scatter.

- Single-bounce scatter is typical of old forest clearings.

- Recently cleared areas produce unique polarimetric returns: single-bounce, double-bounce and volume scattering contribute almost equally to total backscatter.

- Landsat TM data separate deforested areas from forest better than SIR-C data, primarily because SIR-C does not separate older regrowth well from the forest class.

- SIR-C data provide better information on the residual woody biomass of deforested areas than Landsat TM data.
- Single-date, C-band SAR data (e.g. ERS-1 and -2 or RADARSAT) have very limited potential for deforestation studies.

- JERS-1 SAR data acquired during the rainy season (February) underestimated deforestation by more than 100% because forest fallow and undisturbed forest had similar brightness values. JERS-1 data from the dry season (October) showed better contrast between forest and clearings, but most areas of regrowth were not well separated from intact forest.

- At least two polarizations are required at L-band (preferably HH and HV) to separate regrowth with good accuracy.

- Polarimetric information provides the highest regeneration mapping accuracy (overall 91%).

- The combined use of optical and radar imagery provides the most reliable form of landcover mapping, without requiring data from the same year (Table 4).
### Table 4

**Classification of Polarimetric C- and L-band SAR Data, with and without Landsat TM Imagery, to Map Deforestation and Secondary Regrowth**

**SIR-C L-band quad-pol and C-band quad-pol**

**MAP classifier**

(Combined Kappa Coefficient = 91)

<table>
<thead>
<tr>
<th>Truth Class</th>
<th>Classification Category</th>
<th>OW</th>
<th>FDF</th>
<th>CC</th>
<th>INIR</th>
<th>S</th>
<th>F</th>
<th>Kappa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open water (OW)</td>
<td></td>
<td>198</td>
<td>0</td>
<td>25</td>
<td>2</td>
<td>0</td>
<td>2</td>
<td>87</td>
</tr>
<tr>
<td>Flooded dead forest (FDF)</td>
<td></td>
<td>0</td>
<td>5525</td>
<td>0</td>
<td>54</td>
<td>160</td>
<td>15</td>
<td>95</td>
</tr>
<tr>
<td>Clearing (CC)</td>
<td></td>
<td>78</td>
<td>0</td>
<td>14648</td>
<td>138</td>
<td>13</td>
<td>80</td>
<td>97</td>
</tr>
<tr>
<td>[no woody biomass]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial regrowth (INIR)</td>
<td></td>
<td>0</td>
<td>0</td>
<td>17</td>
<td>6656</td>
<td>1</td>
<td>2480</td>
<td>68</td>
</tr>
<tr>
<td>Recent clearings (S)</td>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>111</td>
<td>3451</td>
<td>42</td>
<td>95</td>
</tr>
<tr>
<td>[with high woody biomass]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Primary forest (F)</td>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>11529</td>
<td>100</td>
</tr>
</tbody>
</table>

**SIR-C L-band quad-pol and C-band quad-pol (MAP classifier)**

**Combined Using Logical Operators With**

**Landsat TM** (ISODATA classifier)

(Combined Kappa Coefficient = 93)

<table>
<thead>
<tr>
<th>Truth Class</th>
<th>Classification Category</th>
<th>OW</th>
<th>FDF</th>
<th>CC</th>
<th>INIR</th>
<th>INTR</th>
<th>S</th>
<th>F</th>
<th>Kappa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open water (OW)</td>
<td></td>
<td>227</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>100</td>
</tr>
<tr>
<td>Flooded dead forest (FDF)</td>
<td></td>
<td>153</td>
<td>5525</td>
<td>0</td>
<td>30</td>
<td>2</td>
<td>34</td>
<td>12</td>
<td>95</td>
</tr>
<tr>
<td>Clearing (CC)</td>
<td></td>
<td>86</td>
<td>0</td>
<td>14640</td>
<td>138</td>
<td>17</td>
<td>30</td>
<td>46</td>
<td>97</td>
</tr>
<tr>
<td>[no woody biomass]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial regrowth (INIR)</td>
<td></td>
<td>1</td>
<td>0</td>
<td>17</td>
<td>6451</td>
<td>864</td>
<td>339</td>
<td>131</td>
<td>79</td>
</tr>
<tr>
<td>Intermediate regrowth (INTR)</td>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>205</td>
<td>922</td>
<td>28</td>
<td>196</td>
<td>67</td>
</tr>
<tr>
<td>Recent clearings (S)</td>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>111</td>
<td>0</td>
<td>3458</td>
<td>35</td>
<td>96</td>
</tr>
<tr>
<td>[with high woody biomass]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Primary forest (F)</td>
<td></td>
<td>5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>11524</td>
<td>100</td>
</tr>
</tbody>
</table>


- Acre State, Brazil; RADARSAT, Standard mode, C-HH calibrated in terms of $\gamma = \sigma^o / \cos \theta_{inc}$, incident angles 30°-49°, resampled to 10 m pixel spacing.

- There is no significant difference in backscatter between open forest with bamboo and closed forest. Closed-canopy forest presents a nearly invariant C-HH backscatter with time.

- The backscatter of non-forested areas is less than that of forested areas. Pasture and regenerating pasture exhibited the lowest backscatter, while overgrown pasture exhibited intermediate backscatter.

- C-HH backscatter is not a reliable indicator of degree of regeneration within the early stages of this process. Backscatter variation within a given pasture class is larger than the mean between-class differences. These variations are probably due to differences in surface and near-surface moisture contents.

- All cover types exhibited higher relative backscatter on days of precipitation due to a moist canopy (see Figure 17).

- Variations in the multitemporal backscatter from cleared areas are considerably larger than those from the forest class.

- Burned forest exhibits the largest temporal variation of any cover type.

- The multitemporal contrast between deforested areas and the primary forest was variable. The greatest contrast was observed on an afternoon overpass (no dew, which can increase the backscatter from pastures) at the end of the dry season when no rain was recorded in the previous 24 hours (hence, moisture variations were minimized).

- Multitemporal C-HH data can be reliably used to detect and map deforestation. The ideal two-date combination would be to obtain one image under very dry conditions and a second image following a recent rainfall.

- Kayapo Indigenous Area, Para State, Brazil; RADARSAT, Standard Beam at 25 m x 28 m resolution with incident angles 20°-49° and Fine Mode at 9-11 m x 9 m resolution with incident angles 37°-48°.

- This study sought to identify 1) small canopy openings from logging activities and 2) environmental gradients such as floodplain forest to upland forest or forest to cerrado.

- No evidence of logging roads or log-loading areas within mahogany groves was evident in the RADARSAT imagery. In this study area, tree crowns averaged about 10 m in diameter while the graded logging roads averaged 9.1 m wide and the skidder trails averaged only 4 m wide (Figure 18 provides an example (from Southeast Asia) of the fine-grain nature of these types of forest disturbances).

- Recent, large (i.e. tens of meters across) forest clearings were discernible, but older agricultural areas were not evident.

- The general consensus among those who have studied C-band SAR data of tropical forests is that it is off little use in distinguishing among vegetation types or biomass classes, with the exception of delineating bare ground or very recently cut areas.

- Small, natural cerrado "islands" were not discernible.

- At C-band, the confusion potential for biomass variation being confounded with topographic variation in the backscatter signal is great.

- They successfully distinguished floodplain forest from upland forest, in part based on differences in mean backscatter, but primarily on the basis of backscatter graininess (Figure 19).
Figure 18. STAR-1, airborne X-HH SAR imagery at 6 m resolution of a coastal swamp forest in Southeast Asia. Top image was acquired in 1989; the bottom image was acquired in 1991. Note the land use / cover changes: forest clearing for a plantation near the center of the imagery and selective logging activities in the lower left of the image. (Imagery from Intera Information Technologies, Ltd., Canada.

Forest Association Mapping Using Radarsat Backscatter Graininess


- Guyana and Colombia; 1992 South American Radar Experiment (SAREX-92) = CCRS SAR: C-band, HH and HV plus X-band, HH and HV with a spatial resolution of 4.8 m x 6.1 m; 1993 AIRSAR South American Deployment = AIRSAR: C-, L- and P-band, fully polarimetric with a spatial resolution of 6.7 m x 12.1 m; both SAR systems operated at incident angles of ca. 20° -65°.

- This study employed a fairly detailed, eight-class legend:
  - Mixed forest (645 t / ha)
  - Wallaba forest (460 t / ha)
  - Xeric mixed forest (240 t / ha)
  - Low swamp forest n/a
  - Mora forest (575 t / ha)
  - Logged-over forest --
  - Secondary forest (40 t / ha) [15 years old]
  - Nonforest --

- Texture, not backscatter magnitude, is the most important source of information for identifying tropical land cover types in high-frequency, high-resolution SAR imagery (Figure 20).

- L-band and P-band data have comparable capabilities to discriminate nonforest from forest classes. Based on a single L- or P-band combination, 65%-80% of the nonforest points were correctly classified. Nonforest is not generally confused with the other classes, except secondary forest.

- P-band VH and L-band VH are able to classify secondary forest with 90% accuracy.

- Overall, P-band is generally better than L-band for classifying forest types and P-TP and circular polarized P-band combinations yield better results than P-HH or P-HV.

- P-band combinations classified logged-over forest more accurately than did the L-band combinations. P-VH and P-LL yielded the best results (>= 83% correct).

- Primary forest types are the most difficult to classify.
Importance of SAR Texture For Tropical Forest Mapping

- NASA/JPL AIRSAR L-band VV
- CCRS SAR X-HH

- The best performing two-channel combination of C-RR and P-LL yielded an overall classification accuracy of 73%.

- The best performing three-channel combination of C-LL, P-VH and P-TP gave an overall classification accuracy of 88%.

- Combinations including linear, cross-polarized or circular like-polarized channels yielded better results than other combinations. This illustrates the importance of canopy architecture for forest type identification, since backscatter with such polarizations results from diffuse scattering in the canopy.

- Regardless of frequency band, the HH-HV phase difference (PPD) yields a poor classification result.

### 7.1.3 Relating SAR Data to Tropical Forest Biomass.

The problem of relating SAR data to tropical forest biomass is twofold. First, the biomass density of the Primary forest is so large that backscatter differences are nil beyond about 100 t / ha biomass densities. Secondly, with respect to mapping clearings in the forest and their regeneration, many regenerating pastures have large enough biomass densities to produce backscatter equivalent to that from the surrounding Primary forest. The biomass relationship between the Primary forest and abandoned pastures is shown in Figure 21. An example of the backscatter confusion from these types of land covers is given in Figure 22 which shows a SIR-A SAR image (L-HH, 40 m x 40 m resolution, incident angle = 50°). Several large cattle ranching areas within the tropical forest can be seen. Recent forest clearings or maintained pastures (i.e. little or no woody biomass) presents a very dark backscatter return in contrast to the medium-bright grey tone return from undisturbed forest. Note the enhanced, bright return from the closed forest canopy over the stream courses (double bounce). Also of interest are the various shades of grey (increasing backscatter) associated with regeneration vegetation in old clearings of differing age.


- 90 km north of Manaus, Para State, Brazil; SIR-C C- and L-band, HH, HV and VV with a spatial resolution of about 25 m x 25 m, incident angle ca. 26°.
Introduction to Microwave Remote Sensing - Center for Remote Sensing and GIS, Michigan State University

Forest and Pasture Plant Mass

- Total live and dead above-ground plant mass (t/ha)
- Stand 1
- Stand 2
- Forest
- Light use
- Moderate use
- Heavy use
- Abandoned pasture

Live Biomass
Prostrate Trunks
Standing Dead Trees
Litter


SIR-A SAR Image of Forest and Pasture Cover Types, Para, Brazil

© 1999 David P. Lusch, Ph.D.
- They found no significant relationship between SAR backscatter in the six channels and forest biomass which ranged from 64 to 141 tons / hectare.

- The various backscatter channel ratios increased the correlation strength with biomass. The strongest correlation observed was with the L-HV / L-HH ratio which produced an $r = 0.64$ at the 95% level of confidence.


- Tapajos National Forest, Para State, Brazil. SIR-C C- and L-band, HH and HV

- The sensitivity of microwave to biomass saturates after a certain level is reached.

- The biomass dependence of microwave backscatter varies as a function of radar wavelength and polarization.

- The saturation point is higher for longer wavelengths and the HV polarization is the most sensitive to biomass.

- This study used a seven-class regeneration mapping scheme:
  - Recent activities (bare soil and pasture)
  - 0 - 2 year old regeneration
  - 2 - 4 year old regeneration
  - 4 -6 year old regeneration
  - 6 - 8 year old regeneration
  - $>= 9$ year old regeneration
  - Primary forest

- Some discrimination between forest and nonforest areas is possible with L-HV and, to a lesser extent, with L-HH. C-band, regardless of polarization, is not useful for such discrimination.

- The variation between the global mean values of Primary forest and Bare soil/Pasture is about 5 dB for L-HV, 2 dB for L-HH and less than 0.5 dB for either polarization of C-band (Figure 23).

- There appears to be no mean backscatter difference between the 4 - 6 year old and the 6 - 8 year old regeneration age classes.

- For L-HV, there is a two-fold decrease in CV (a measure related to texture) between the Bare soil/Pasture class and the 4- 6 year old regrowth class. There are only slight differences in the CV associated with the 4 - 6 year old, 6 - 8 year old, >= 9 year old and Primary forest classes (Figure 23).


- Tapajos region, Para State, Brazil; ERS-1, JERS-1 and SIR-C.

- Backscatter at L-band shows a greater variation with vegetation type than at C-band.

- L-band HV backscatter responds slightly more to vegetation differences than L-band HH.

- C-band backscatter shows more variation with vegetation type during the dry season (December image) than during the wet season (July image).
Mean Backscatter & CV vs Regeneration Stage

- L-band is more appropriate than C-band because the longer wavelength penetrates farther into the vegetation canopy, better discriminating forest areas from those of lower biomass density.

- The apparent disappearance of pasture areas in the C-band imagery between the dry season (when it was detectable) and the wet season (not detectable) is probably due to the increased backscatter from the moist ground.

- C-band presents no useful relationship between biomass density and backscatter. The threshold of maximum retrievable biomass (90% of maximum) is only about 22 tons / hectare, making it responsive to only very young (less than five years?) forest regeneration (Figure 24).

- L-HH backscatter presented a useful relationship to biomass density up to about 60 tons / ha. L-HV backscatter saturated at about 50 tons / ha (Figure 24).


- Tapajos region, Para State and Manaus region, Amazonas State, Brazil; JERS-1.

- Mature tropical forest canopies present very stable backscattering properties, regardless of time or season [not including dew or rain events as variables].

- L-HH backscatter appears to saturate at about 60 tons / ha biomass, but the biomass retrieval limit, which is tolerant of both speckle and image texture, is only 31 tons / ha.

- A quantized biomass retrieval scheme was proposed which parsed the backscatter range into bins of limited ranges of biomass density. The size of the bins should be constant in the logarithmic (dB) scale and equal to the confidence interval calculated for the worst-case texture and speckle, based on 1 ha samples. Figure 25 and Table 5 present this approach.
\( \sigma^0 \) vs Above-ground Biomass

\[ \text{JERS-1 L-HH} \]
\[ \text{SIR-C L-HH} \]
\[ \text{SIR-C L-HV} \]

\[ \text{variance envelopes at 3x the standard error of the mean at each site} \]

\[ \text{ERS-1 C-VVV (dry season)} \]

\[ \text{variance envelope at 3x the standard error of the mean at each site} \]

---


---

JERS-1 \( \sigma^0 \) vs Biomass

\[ \text{JERS-1 L-HH} \]

\[ \text{1.2 dB interval} \]

\[ \text{Error bar at twice the standard error of the mean backscatter} \]

---


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### Table 5
Biomass Density and Backscatter Thresholds for the Quantized Retrieval Scheme

<table>
<thead>
<tr>
<th>Image Tone</th>
<th>Lower $\sigma^0$ Threshold</th>
<th>Upper $\sigma^0$ Threshold</th>
<th>Typical Land Cover</th>
<th>Biomass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black</td>
<td>Noise floor -11.9 dB</td>
<td>-10.7 dB</td>
<td>Inland water</td>
<td>n/a</td>
</tr>
<tr>
<td></td>
<td>-11.9 dB</td>
<td>-9.5 dB</td>
<td>Pasture and Crops</td>
<td>n/a</td>
</tr>
<tr>
<td></td>
<td>-10.7 dB</td>
<td>- 9.5 dB</td>
<td>Young regrowth</td>
<td>6-13 t/ha</td>
</tr>
<tr>
<td></td>
<td>- 9.5 dB</td>
<td>- 8.3 dB</td>
<td>Established regeneration</td>
<td>13-31 t/ha</td>
</tr>
<tr>
<td></td>
<td>- 8.3 dB</td>
<td>- 7.1 dB</td>
<td>Old regeneration to Primary Forest</td>
<td>&gt; 31 t/ha</td>
</tr>
<tr>
<td>White</td>
<td>7.1 dB</td>
<td>Maximum</td>
<td>Flooded forest and Urban Areas</td>
<td>n/a</td>
</tr>
</tbody>
</table>

Numerous investigators have commented on the enhanced backscatter from a forest canopy where it is above standing water or saturated soils (Figures 26 and 27). Figure 28 shows several good examples of this phenomenon. This SIR-B, L-HH image in southern Colombia shows a tropical forest canopy in the left portion of the image and a grassland on the right part of the scene. Note the double-bounce, enhanced backscatter from the forest canopy were it closes over rivers. The floodplains of all the rivers in the scene are forested and present strong backscatter which presents extreme contrast with the low backscatter from the grasslands (penetrated by the long wavelength L-band).
Enhanced Backscatter From Arboreal Canopy Over Water or Saturated Soil

Weaker Return

Stronger Return

Smaller Dielectric Constant

Larger Dielectric Constant


Enhanced Backscatter from Vegetation Over Water

L-HH SAR Image of Tropical Forest and Grassland
7.2 Agricultural Applications of Imaging Radar

7.2.1 Overview. The following brief summary is abstracted from the expansive review provided by:


- Lower SAR frequencies (i.e. longer wavelengths) tend to penetrate through most crops. At these wavelengths, soils properties are more influential in governing the backscatter from agricultural fields.

- Higher frequencies (i.e. shorter wavelengths) interact more with the vegetation and thus contain more information about canopy parameters.

- Crop type classification (up to 90% correct) has been demonstrated with multitemporal SAR data, but increased soil moisture usually diminishes the classification accuracy.

- Crop condition monitoring (i.e. vigor, stress, etc.) has not been successfully demonstrated, but crop growth monitoring has been.


- Montespertoli, Italy; AIRSAR, fully polarimetric P-, L- and C-band, 12.2 m x 6.6 m spatial resolution with incident angles from 35°-45°; SIR-C, fully polarimetric L- and C-band, 25 m x 20 m spatial resolution at incident angles of 35°-45°.

- Plant constituents (leaves, stems, trunks, etc.) affect backscatter in a different way according to both their dimensions and the observing wavelength. For each frequency, a main source of scattering can be identified (e.g. L-band backscatter is mostly influenced by the return from large leaves while C-band backscatter is significantly influenced by small leaves).
- For bare soil, $\sigma_{HV}^o$ is generally very low and $\sigma_{VV}^o$ is greater than $\sigma_{HH}^o$.

- On vegetation, $\sigma_{HV}^o$ is generally higher (due to the contribution of inclined and relatively large cylindrical scattering elements) and $\sigma_{VV}^o$ becomes very similar to $\sigma_{HH}^o$.

- If double-bounce occurs, originated by vertical structures (e.g. trunks at P-band or stalks in corn or sunflowers at L-band) over a relatively smooth soil, $\sigma_{HH}^o$ can be even greater than $\sigma_{VV}^o$.

- Herbaceous vegetation is essentially transparent at P-band.

- L-band SAR data are capable of identifying agricultural crops, like sunflower and corn, when they are well-developed and characterized by relatively large scattering elements (large leaves and stems).

- The best sensitivity to crop growth was noted at the L-band, using both $\sigma_{HH}^o / \sigma_{VV}^o$ and $\sigma_{HV}^o$.

- The strongest relationship ($r^2 = 0.74$) between backscatter and LAI was found at L-band for the broadleaf crops (e.g. corn, sunflower or sorghum). This relationship appears to be asymptotic, just as it is in the optical wavelengths.

- A useful parameter for investigating variations of $\sigma^o$ with increasing dimensions of leaves and stems is the Normalized Volumetric Leaf Area Index (NVLAI, in $m^3 m^{-3}$). NVLAI = (LAI) x (Leaf Thickness, in m) x (the wavenumber: $k = 2\pi / \lambda$, in $m^{-1}$).

- In a comparison between the NVLAI and the $\sigma_{HV}^o$ value at P-, L- and C-bands ($\theta = 35^\circ$), an $r^2 = 0.76$ was achieved (Figure 29).

- The SAR-computed NVLAI was compared with ground-measured NVLAI and generated a strong correlation $r^2 = 0.76$ (Figure 29).

7.2.3 Other Aspects of SAR Backscatter from Crops. Figures 30 through 36 present other aspects which can affect the backscatter from crops, such as canopy moisture content, SAR system polarization and the crop row direction with respect to the range domain of the SAR.
Backscatter vs NVLAI

NVLAI = (LAI in m$^2$ m$^{-2}$) * (leaf thickness in m) * (wave number [k= 2π / λ in m$^{-1}$])

Corn Canopy Backscatter vs Moisture Content


Size Distribution of Canopy Scattering Elements

Sorghum Canopy Backscatter VS Leaf Area Index (LAI)

Backscattering Coefficient $\sigma^2$ (dB)

-6 -8 -10 -12 -14

Leaf Area Index LAI (m$^2$ m$^{-2}$)

frequency: 13.0 GHz
VV polarization
$\theta = 50$ degrees

Corn Canopy Backscatter VS Leaf Area Index (LAI)

- Frequency: 13.0 GHz
- VV polarization
- $\theta = 50$ degrees

Wheat Canopy Backscatter VS LAI and Polarization

- LAI = 8
- LAI = 4


**Introduction to Microwave Remote Sensing** - Center for Remote Sensing and GIS, Michigan State University

---

**Canopy Backscatter VS Rectangular Row Direction**

- **Sorghum**
- **Wheat stubble**
- **Direction of Flight**
- **Radar Look Direction**
- **L-band, 10m x 10m VV - polarization**

---

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**Canopy Backscatter VS Circular Row Direction**

- **Azimuth angle near to rows (φ ≈ 0°)**
- **SEASAT L-band SAR 1.28 GHz (23.4 cm) HH-polarization 23° incidence angle**

---

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8.0 Radar Backscatter From Soils

- Dielectric constant of soils is DIRECTLY PROPORTIONAL to its MOISTURE CONTENT

- Backscatter strength from soils is DIRECTLY PROPORTIONAL to its MOISTURE CONTENT
  - The positive relationship between backscatter intensity and soil moisture content is present even with a vegetative cover. However, the presence of vegetation is a source of error for microwave soil water measurement, especially where both bare and vegetated fields occur intermixed in the imagery

- Backscatter strength from soils is a function of:
  - Surface scattering geometry (specular <-> diffuse)
  - Depression angle of radar since most soils are near-specular
  - Cultivation row structure and orientation relative to the range domain of the radar

- Penetration depth of soils by radar is a function of:
  - Moisture content (moist = limited depth; dry = greater depth)
  - Wavelength (longer λ penetrate more deeply)

- Variations in backscatter strength from regolith may be related to its ORIGIN or AGE
**Dielectric Constant of Soils**

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>Sand</th>
<th>Silt</th>
<th>Clay</th>
</tr>
</thead>
<tbody>
<tr>
<td>sandy loam</td>
<td>51.5</td>
<td>35.0</td>
<td>13.5</td>
</tr>
<tr>
<td>loam</td>
<td>42.0</td>
<td>49.5</td>
<td>8.5</td>
</tr>
<tr>
<td>silt loam</td>
<td>30.6</td>
<td>55.9</td>
<td>13.5</td>
</tr>
<tr>
<td>silt loam</td>
<td>17.2</td>
<td>63.8</td>
<td>19.0</td>
</tr>
<tr>
<td>silty clay</td>
<td>5.0</td>
<td>47.6</td>
<td>47.4</td>
</tr>
</tbody>
</table>

- **1.4 GHz**
- **18 GHz**

Volumetric Moisture $m_v$


---

**Backscatter vs Soil Moisture Content for Bare Soils**

- **1974**
- **1975**
- **1977**
- Multiple data points

11 fields with different soil types and surface roughnesses

freq. = 4.5 GHz
\[ \lambda = 6.7 \text{ cm} \]
HH polarization
\[ \theta = 10^7 \]

$r^2 = 0.85$

The bright returns from right half of image are due to increased soil moisture after a rain storm. The diagonal bright streaks are swaths of moist soil marking the ground tracks of several individual storm cells.
**Backscatter vs Soil Moisture Content for Vegetated Fields**

- **Corn**
- **Soybeans**
- **Milo**
- **Wheat**
- **Multiple data points**

freq. = 4.5 GHz
λ = 6.7 cm
HH polarization
θ = 10°


---

**Backscatter vs Soil Moisture Content for Bare vs Vegetated Soils**

- **Bare soils**
- **Vegetated soils**

freq. = 4.5 GHz
λ = 6.7 cm
HH polarization
θ = 10°

### Soil Moisture and Surface Roughness vs Scattering Coefficient for Bare Soils

![Graph showing the relationship between soil moisture content and scattering coefficient](image)

- **freq. = 1.5 GHz**
- **$\lambda = 20$ cm**
- **HH polarization**
- **angle of inc. = 20°**

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### Angle of Incidence vs Scattering Coefficient for Bare Soils

![Graph showing the relationship between angle of incidence and scattering coefficient](image)

- **Freq. = 1.1 GHz**
- **$\lambda = 27$ cm**

- **Freq. = 7.25 GHz**
- **$\lambda = 4$ cm**

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Radar Penetration Depth of Soil vs Moisture Content

Soil Type: LOAM

1.3 GHz
\[ \lambda = 23 \text{ cm} \]

4.0 GHz
\[ \lambda = 7.5 \text{ cm} \]

10.0 GHz
\[ \lambda = 3 \text{ cm} \]

Volumetric Moisture Content (g cm\(^{-3}\))

Penetration Depth (meters)


Fault Displacement Detection Using Multiparameter SAR

Age Discrimination of Lava Flows Using Multiparameter SAR

9.0 Radar Backscatter From Water

9.1 Dielectric Constant of Water

- Dielectric constant of water is very high compared to other earth-surface materials.

- Dielectric constant of water (Figure 47) is dependent on:
  - Temperature -- at wavelengths greater than 10-15 cm, the dielectric constant of both fresh and sea water is greater at 0°C than at 20°C.
  - Wavelength -- at wavelengths less than 10 cm, dielectric constant of both fresh and sea water decreases rapidly.
    \[
    \varepsilon' = \begin{cases} 76 - 79 & @ \lambda = 10 \text{ cm} \\ 15 - 25 & @ \lambda = 1 \text{ cm} \end{cases}
    \]
  - Salinity -- at wavelengths greater than 3-5 cm, fresh water has a greater dielectric constant than sea water.

9.2 Backscatter Response From Water Features

The following summary is taken verbatim from:


Radar imagery has been demonstrated to be potentially useful for the identification, mapping and measurement of hydrologic phenomena such as streams, lakes, runoff, extent of flood cover, water levels, coastal wetlands and snow field mapping. Analysis of these features makes it possible to derive information on water flow, water storage and changes in storage as basic inputs to understanding and predicting the behavior of hydrologic systems at a particular location.

Most surface water features are detectable on radar imagery because of the contrast in return between the smooth water surface and the rough land surface. This high contrast ratio is based on a low return from the water surface and high return
Dielectric Constant of Fresh Water and Sea Water

adapted from Paris, J.F. 1969. Microwave radiometry and its application to marine meteorology and oceanography. College Station, Texas: Texas A & M University, Department of Oceanography.
from the rougher land (vegetated). Obviously, target and system parameters that affect radar return will influence detection of surface water. Some influencing parameters are roughness characteristics of the land and water, changes in the dielectric constant, incident angle and wavelength. Surface roughness, and therefore the radar backscatter and the land / water tonal contrast are related to: 1) the actual roughness characteristic of the land and water; 2) the wavelength of the system; and 3) incident angle. Although the relationship of these and other parameters is complex, in general a decrease in the land / water contrast will occur with: 1) a decrease in surface roughness contrast; 2) an increase in incident angle; and 3) an increase in system wavelength.

The occurrence of low return areas (radar shadows, open sand dunes, bare ground and airport runways) adjacent to water bodies reduces detectability. The latter three low return areas are due primarily to surface roughness whereas radar shadowing depends on look angle, look direction and terrain backslope. Extensive radar shadowing is especially problematic in mountainous terrain and is aggravated by imaging at high look angles. Any object, aquatic or terrestrial, imaged within a radar shadow is undetectable because no information -- no radar backscatter -- is returned within the shadowed area. The occurrence of radar layover, an extreme case of relief displacement, is especially prominent in mountainous areas imaged at low look angles and may confuse feature recognition. This loss of information would be important in identifying narrow water bodies bounded by high banks or trees and oriented parallel to the flightline, such as canals.
### 10.0 Satellite SAR Systems

#### 10.1 ERS-1 and -2 and ENVISAT

<table>
<thead>
<tr>
<th></th>
<th>ERS-1, -2</th>
<th>ENVISAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Country</td>
<td>Europe</td>
<td>Europe</td>
</tr>
<tr>
<td>Agency</td>
<td>ESA</td>
<td>ESA</td>
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<tr>
<td>Spacecraft</td>
<td>ERS-1, ERS-2</td>
<td>ENVISAT</td>
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<tr>
<td>Launch date</td>
<td>Jul 91, Apr 95</td>
<td>Nov 00</td>
</tr>
<tr>
<td>Design life</td>
<td>2-3 yrs</td>
<td>5 yrs</td>
</tr>
<tr>
<td>Band</td>
<td>C</td>
<td>C</td>
</tr>
<tr>
<td>Wavelength</td>
<td>5.7 cm</td>
<td>5.7 cm</td>
</tr>
<tr>
<td>Frequency</td>
<td>5.3 GHz</td>
<td>5.3 GHz</td>
</tr>
<tr>
<td>Polarization</td>
<td>VV</td>
<td>VV + HH</td>
</tr>
<tr>
<td>Incident angle</td>
<td>23°</td>
<td>20° - 50°</td>
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<tr>
<td>Range resolution</td>
<td>26 m</td>
<td>~ 25 m</td>
</tr>
<tr>
<td>Azimuth resolution</td>
<td>28 m</td>
<td>~ 25 m</td>
</tr>
<tr>
<td>Looks</td>
<td>6</td>
<td>~ 4</td>
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<tr>
<td>Swath width</td>
<td>100 km</td>
<td>100 km (500 km)</td>
</tr>
<tr>
<td>Recorder</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Altitude</td>
<td>~ 780 km</td>
<td>~ 700 km</td>
</tr>
<tr>
<td>Repeat cycle</td>
<td>3 days</td>
<td>?</td>
</tr>
</tbody>
</table>

![ERS-1, -2](image1)

![ENVISAT](image2)
### 10.2 JERS-1

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<tr>
<th>Country</th>
<th>Japan</th>
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<tbody>
<tr>
<td>Agency</td>
<td>MITI / NASA</td>
</tr>
<tr>
<td>Spacecraft</td>
<td>JERS-1</td>
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<tr>
<td>Launch date</td>
<td>Feb 92</td>
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<td>2 yrs</td>
</tr>
<tr>
<td>Band</td>
<td>L</td>
</tr>
<tr>
<td>Wavelength</td>
<td>23.5 cm</td>
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<tr>
<td>Frequency</td>
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<tr>
<td>Polarization</td>
<td>HH</td>
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<tr>
<td>Incident angle</td>
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<tr>
<td>Range resolution</td>
<td>18 m</td>
</tr>
<tr>
<td>Azimuth resolution</td>
<td>18 m</td>
</tr>
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<td>Looks</td>
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<tr>
<td>Recorder</td>
<td>Yes</td>
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<td>Altitude</td>
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</tr>
<tr>
<td>Repeat cycle</td>
<td>44 days</td>
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</table>

![JERS-1 Image](image-url)
### 10.3 RADARSAT-1 and -2

<table>
<thead>
<tr>
<th></th>
<th>Radarsat-1</th>
<th>Radarsat-2</th>
</tr>
</thead>
<tbody>
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<td><strong>Country</strong></td>
<td>Canada</td>
<td>Canada</td>
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<tr>
<td><strong>Agency</strong></td>
<td>CSA</td>
<td>CSA / MDA</td>
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<td><strong>Spacecraft</strong></td>
<td>Radarsat-1</td>
<td>Radarsat-2</td>
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<td><strong>Launch date</strong></td>
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<td><strong>Design life</strong></td>
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<td>5 yrs</td>
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<tr>
<td><strong>Band</strong></td>
<td>C</td>
<td>C</td>
</tr>
<tr>
<td><strong>Wavelength</strong></td>
<td>5.7 cm</td>
<td>5.7 cm</td>
</tr>
<tr>
<td><strong>Frequency</strong></td>
<td>5.3 GHz</td>
<td>5.3 GHz</td>
</tr>
<tr>
<td><strong>Polarization</strong></td>
<td>HH</td>
<td>Fully polarimetric</td>
</tr>
<tr>
<td><strong>Incident angle</strong></td>
<td>&lt;20° - &gt;50°</td>
<td>&lt;20° - &gt;50°</td>
</tr>
<tr>
<td><strong>Range resolution</strong></td>
<td>10 - 100 m</td>
<td>3 - 100 m</td>
</tr>
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<td><strong>Azimuth resolution</strong></td>
<td>9 - 100 m</td>
<td>3 - 100 m</td>
</tr>
<tr>
<td><strong>Looks</strong></td>
<td>1 - 8</td>
<td>?</td>
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<tr>
<td><strong>Swath width</strong></td>
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<td>10 - 500 km</td>
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<td><strong>Recorder</strong></td>
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<tr>
<td><strong>Repeat cycle</strong></td>
<td>24 days</td>
<td>24 days</td>
</tr>
</tbody>
</table>

---

**Radarsat-1**

**Radarsat-2**
11.0 SIVAM Airborne SAR

11.1 SIVAM Remote Sensing Aircraft (RSA)

- Suite of three Embraer 145 aircraft
- Each aircraft includes:
  - A Synthetic Aperture Radar (SAR)
  - A Multispectral Sensor (MSS)
  - A Forward-Looking Infrared (FLIR) Sensor
  - Two Optical Cameras
- RSA will support flights from 900 m to 11,300 m

11.2 SIVAM RSA SAR

- X-band (9.60 GHz) and L-band (1.28 GHz)
- X-HH
  L-HH, L-VH, L-HV and L-VV
- Resolution:
  - StripSAR multilook mode
    - 3 m x 3 m at 4 looks
    - 6 m x 6 m at 8 looks
    - 18 m x 18m at 16 looks
  - StripSAR single look complex
    - L-band: 0.95 m x 6 m; 0.95 m x 18 m
    - X-band: 0.8 m x 3 m; 0.8 m x 6m; 0.8 m x 18 m
  - Interferometric mode (InSAR)
    - 0.8 m x 3 m; 5 m x 5 m
  - SpotSAR
    - 1.8 m x 1.8 m; 0.8 m x 1.8 m
  - Wide-Area Surveillance (WAS)
    - 6 m x 6 m; 18 m x 18 m