11. RADAR REMOTE SENSING

11.1 A bit of history

RADAR was initially an acronym standing for RA dio D etection A nd R anging\(^1\). Radio waves were first demonstrated by Heinrich Hertz in the late 19th century (Fig. 11.1), and a patent for a rudimentary radar was proposed by Christian Hülsmeyer in 1904, but at the time no practical means existed for generating shorter wavelength (< 50 cm) radio waves with sufficient power to be useful for radar. Rudimentary, radar systems were developed in the 1930's in England and the U.S. designed to detect approaching ships and aircraft. Development of radar was rapid during World War II, particularly after the invention of the cavity magnetron – a high-power, pulsed oscillator that operated at 10 cm wavelengths – by Sir Robert Watson-Watt, John Randall and Henry Boot in 1940. The radar systems developed rapidly from simple sets of dipole antennas – one for transmitting and a set of four for receiving – to scanning systems that used a single antenna for both transmitting and receiving. Use of higher frequencies (and therefore smaller antennas) also made it possible to mount radar on ships and aircraft.

The 1950's saw development of the first imaging radar systems, both real-aperture radars (RAR) and synthetic aperture radars (SAR), but imaging radar (primarily RAR) did not become available for civilian use until 1965 when images from the airborne Westinghouse AN/APQ-97 K-band multipolarized RAR became available to the civilian community. These images had a remarkable resolution of 7.5 m across-track (range resolution) and 1.1R m along-track (azimuth resolution), where \(R\) is the range (distance in kilometers) from radar to target.\(^2\) Except for the short-lived SeaSat SAR in 1979, radar data was very limited until the 1990's with the launch of satellite SAR systems on RadarSat, ERS-1 and JERS-1.

The most recent major development in radar for earth resources is the introduction of imaging interferometric SAR. By recording backscattered signals at two slightly separated SAR antennae it is possible to calculate the local slope of the terrain, thus bringing the third dimension into SAR imaging. The interferometric technique was first applied to SAR in 1974, using two slightly displaced antennas mounted on an aircraft to form an interferometric beam. The same effect can be achieved with a single antenna used at two locations – a two-pass system presently used with satellite systems – but more accurate results are obtained by having two physical antennae on the same platform, presently only available on aircraft systems.

One of the legacies of the years of military development is the naming convention for radar bands. The original letter-naming convention (which, with some modification, is still in use) was explicitly chosen to maintain secrecy. Thus, there was no apparent order to the letter sequence and bands would be referred to only by their letter name\(^3\). This led to a certain amount of confusion, which persists to this day, confounded by overlapping naming conventions internationally. A quick search of radar references may well produce different frequency ranges for the same band name. The naming convention presented in TABLE 11.1 is that published by the IEEE and by the International Telecommunications Union.

\(^1\) The word is now in such common usage that radar is correctly used as a proper noun.


\(^3\) There may have been some logic to the naming. See http://en.wikipedia.org/wiki/Radio_spectrum#IEEE_US
11.2 Basic radar concepts

Radar is based on the deceptively simple concept of locating objects by tracking the time of flight of a short pulse of microwave radiation to and from a target. Typically the same antenna is used as both source and receiver. The radar antenna alternately transmits and receives pulses at particular microwave wavelengths (in the range 1 cm to 1 m, which corresponds to a frequency range of about 300 MHz to 30 GHz) and polarizations (waves polarized in a single vertical or horizontal plane). The pulse normally covers a small band of frequencies, centered on the frequency selected for the radar.

Fig. 11.1: Key developments in the history of radar.

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>1886</td>
<td>Heinrich HERTZ (Germany) demonstrates radiowave reflections from various objects.</td>
</tr>
<tr>
<td>1904</td>
<td>Christian HÜLSMEYER (Germany) patented a radio echo device for locating objects at sea.</td>
</tr>
<tr>
<td>1935</td>
<td>Sir Robert WATSON-WATT and Arnold WILSON (U.K.) proposed in February 1935 using pulsed radio beams to detect aircraft. The concept was demonstrated experimentally that same month.</td>
</tr>
<tr>
<td>1939</td>
<td>A chain of radar stations was established along the south and east coasts of Britain to detect approaching ships and aircraft.</td>
</tr>
<tr>
<td>1940</td>
<td>Watson-Watt, together with John Randall and Henry Boot, invented the cavity magnetron, an efficient, high-power (10-kilowatt) pulsed oscillator that operated at 10 centimeter wavelengths.</td>
</tr>
<tr>
<td>1940's</td>
<td>Rapid development of (classified) RADAR for aircraft and ship detection.</td>
</tr>
<tr>
<td>1950's</td>
<td>Development of real aperture SLAR for military reconnaissance; optical image processing.</td>
</tr>
<tr>
<td>1960's</td>
<td>De-classification of SLAR and, later, SAR in the US; immediate civilian use for terrain analysis and natural resource surveys during 1960's and 1970's</td>
</tr>
<tr>
<td></td>
<td>Images from the airborne Westinghouse AN/APQ-97 K-band multipolarized Real Aperture Radar (RAR) became available to the civilian community</td>
</tr>
<tr>
<td></td>
<td>Spaceborne radar initially used as an aid for space rendezvous on the Gemini spacecraft and then turned toward use in earth imaging.</td>
</tr>
<tr>
<td>1970's</td>
<td>Development of multi-channel airborne SAR systems at ERIM and JPL for research purposes; increased knowledge of radar capabilities; digital image processing</td>
</tr>
<tr>
<td>1974</td>
<td>The interferometric technique was first applied to SAR by L.C. GRAHAM who used two slightly displaced antennas mounted on an aircraft to form an interferometric beam</td>
</tr>
<tr>
<td>1978</td>
<td>SEASAT (USA) deployment of first spaceborne SAR</td>
</tr>
<tr>
<td>1983</td>
<td>COSMOS (USSR) for experimental applications in oceanography.</td>
</tr>
<tr>
<td>1980's</td>
<td>Development of spaceborne SARs in the US, Canada, Europe and Japan for operational use.</td>
</tr>
</tbody>
</table>

**TABLE 11.1**

IEEE Standard for letter names assigned to radar frequency/wavelength bans. Alternate names are also included in a separate column.
At the Earth's surface, the energy in the radar pulse is scattered in all directions, with some reflected back toward the antenna. This backscatter returns to the radar as a weaker radar echo and is received by the antenna in a specific polarization (horizontal or vertical, not necessarily the same as the transmitted pulse). These echoes are converted to digital data and passed to a data recorder for later processing and display as an image. Given that the radar pulse travels at the speed of light, it is relatively straightforward to use the measured time for the roundtrip of a particular pulse to calculate the distance or range to the reflecting object. The chosen pulse bandwidth determines the resolution in the range (cross-track) direction. Higher bandwidth means finer resolution in this dimension.

### 11.3 Information sensed by radar

Since radar is an **active system** and supplies its own radiation, it is able to collect information that is similar to that collected with passive systems (signal strength, angle to an object) as well as information that is unique to active systems (range, or distance to the object and the relative velocity of the object sensed). In this section we consider the system and target characteristics that affect each of these types of information.

#### 11.3.1 Signal Strength

A radar system transmits pulses of microwave energy into a small range of angles and records the strength of the signal scattered or reflected from objects within the system's field of view. Consider, which illustrates an antenna transmitting microwave radiation toward a surface.
at a distance, $R_t$, and a second antenna receiving a portion of the radiation scattered from the surface at a distance, $R_r$. 

Fig. 11.2: Schematic of bistatic radar geometry

A microwave source that approximates a point source radiating a pulse of peak power, $P_t$, in all directions will produce a power density (irradiance) on a sphere of radius $R$ centered on the point source of:

$$\frac{P_t}{4\pi R^2} \ (11.1)$$

Most real antennas are directive, i.e., they emit radiation into a fixed solid angle. This focusing of radiation may be expressed as the gain of the transmitting antenna, $G_t$. Thus the energy density reaching a point at a distance $R_t$ from the antenna is:

$$\frac{P_t G_t}{4\pi R_t^2} \ (11.2)$$

If the radiation intercepts the surface at an angle of $\theta_t$ to the surface normal, then the irradiance at the surface is:

$$E_s = \frac{P_t G_t}{4\pi R_t^2} \cos \theta_t \ (11.3)$$

The target re-radiates (reflects, scatters) power in all directions ($4\pi$ steradians – the target is modeled here as a perfect point radiator). A portion of radiated power reaches the receiving antenna at distance $R_r$. The efficiency with which the target scatters energy in the direction of a receiving antenna is expressed as the radar cross-section, $\sigma$. Thus, the radiance scattered from the surface in the direction $\theta_r$ per unit solid angle is:

$$L = \frac{P_t G_t \cos \theta_t}{4\pi R_t^2} \frac{\sigma}{4\pi R_r^2 \cos \theta_r} \ (11.4)$$

The concept of cross-section, as its name suggests, is that of the effective area of the scattering target. An object that is 1 m$^2$ and scatters the same amount of energy as a perfectly diffuse
scattering sphere with a cross-sectional area of only 0.1 m$^2$ has a scattering cross-section of 0.1 m$^2$. The units of $\sigma$ are then area units, usually square meters\(^4\).

Assuming that the transmitting and receiving antennae are collocated, then $R = R_t = R_r$, $\theta_t = \theta_r$, and the power density (irradiance), $E_r$, at the radar is then:

$$E_r = \frac{P_t G_t}{4\pi R^2} \left| \frac{\sigma}{4\pi} \right| \left| \frac{1}{R^2} \right| = \frac{P_t G_t \sigma}{(4\pi R^2)^2}$$  \hspace{1cm} (11.5)

\(^4\) The scattering cross-section is sometimes expressed as the ratio of the received backscatter to that from an equivalent isotropic scatterer of the same size. It is then called $\sigma_0$ ("sigma zero" or "sigma naught"), a dimensionless quantity that is typically expressed in decibels (db).
The antenna, with effective receiving area $A_r$, focuses the incoming radiation, and the power received at the antenna is given by the **Radar Equation**:  

$$P_r = \frac{P_t G_t \sigma}{(4\pi R^2)^2} A_r \quad . \quad (11.6)$$

Antenna theory gives a relationship between antenna gain and effective area, $A$, of the antenna given by:

$$G_t = \frac{4\pi A_t}{\lambda^2} \quad . \quad (11.7)$$

If the same antenna is used both for transmitting and receiving, then $G_t = G_r = G$, and $A_t = A_r$, and the radar equation may then be expressed either in terms of the antenna area of the antenna:

$$P_r = \frac{P_t A^2 \sigma}{4\pi \lambda^2 R^4} \quad (11.8)$$

or, alternatively, in terms of the area of the antenna:

$$P_r = \frac{P_t G^2 \lambda^2}{(4\pi)^3} \cdot \frac{\sigma}{R^4} \quad (11.9)$$

Unfortunately, there is also substantial noise contaminating the signal. Some of the noise is external (atmosphere, earth, power facilities, other radars, etc.), and some of the noise is generated in the transmission of the radar pulse and reception of the return signal. The maximum radar range, $R_{\text{max}}$, is the distance beyond which the target cannot be detected. It is reached when the received signal, $P_r$ is just equal to the minimum detectable signal, $S_{\text{min}}$, above the noise level.

From Equation 11.9 it is clear that the power will drop off as the $4^{th}$ power of the distance, and that one may increase the received power by increasing the size of the antenna, $A$, or using shorter wavelengths, $\lambda$. This is balance by the fact that the atmosphere limits the usable wavelengths and large antennas are more than merely inconvenient on aircraft and satellites.

The radar cross-section is the factor that relates to the scattering surface. This is roughly analogous to reflectance in the optical range. The radar cross-section, $\sigma$, incorporates the slope, roughness, area, dielectric properties, and angular response of the target into a single factor. Issues of specular, diffuse and volume reflectance/scattering apply here much as they do in the visible domain. The major differences are that the scale of roughness is much different and that, instead of the index of refraction, we are concerned with the dielectric of the scattering surface. Note that $\sigma$ will vary with the viewing angle and polarization of the detector, as well as the surface roughness of the emitting material. We will consider each of these issues in the following sections.

**11.3.2 Dielectric properties**

The inherent capacity of a material to scatter radar radiation is characterized by the dielectric properties of the material. For natural materials, these relate to the inherent conductivity, water content, and salinity of the material. The dielectric constant, $\varepsilon'$, (introduced in
Sec. 10.2) is a measure of a material’s ability to transmit (or “permit”) an electric field, and consists of a real (scattering) component, $\varepsilon'$, and an imaginary (absorption) component, $\varepsilon''$.  

$$\varepsilon_r = \varepsilon'_{\text{scattering}} + i\varepsilon''_{\text{absorption}} \quad (11.10)$$

The real part of the dielectric constant, $\varepsilon'$, is a measure of the ability of a material to store (e.g. be polarized by) a charge from an applied electromagnetic field and then transmit (scatter) that radiation. The absorption quantifies the efficiency with which the electromagnetic energy is converted to heat (absorbed).

The dielectric is really only a constant at zero frequency and can be quite frequency dependent. For non-polar materials (i.e., most natural and non-metallic man-made materials) the value of $\varepsilon'$ is quite low and does not vary strongly with frequency. The absorption of most materials in the microwave is also quite low. Water is a polar molecule and, in liquid form, also absorbs microwave radiation very effectively. Water is of particular concern because of its prevalence on the earth and because of its frequency-dependent dielectric properties (Fig. 11.3). At zero frequency, the real part of the dielectric constant, $\varepsilon'$, of water is ~80 while the imaginary part is near zero. At typical radar wavelengths, $\varepsilon'$ is decreasing and is matched by the imaginary part in the K-band region.

The dielectric constant of many naturally occurring materials in a dry state varies little, usually between 3 and 8. Adding only a small amount of water will increase the dielectric of the material making water content an important consideration in evaluating radar return. For example, wet soil scatters more efficiently than dry soil (Fig. 11.4). The reflectivity of snow and ice are also sensitive to the liquid water content. Water content affects the penetration depth of radar into the soil (or snow or ice). In very dry soils, radar may penetrate and record returns from several meters below the soil surface. In saturated soils the penetration depth may be little more than a centimeter.

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5 The dielectric constant of a material at zero frequency is also known as its static relative permittivity. Or sometimes the static dielectric constant. In modern common usage, the frequency dependent version is still called the dielectric constant. A more strictly correct term would be relative permittivity. In any case, this "constant" varies with frequency.
11.3.3 Surface Roughness

Radar system use wavelengths that are on the order of centimeters to meters. Distinguishing between surfaces that will reflect/scatter specularly versus surfaces that will reflect/scatter diffusely requires that we understand the nature of roughness at these wavelengths. Surfaces that are smooth at these wavelengths are vastly different from surfaces that are smooth at optical wavelengths. The criterion for a smooth surface is that a surface may be considered smooth (specular) if:
where \( \Delta h \) is the root-mean-square variation in the surface height, \( \lambda \) is the wavelength of the radar pulse and \( \theta_0 \) is the incidence angle. There are various ways of defining the value for the constant \( A \). For the Rayleigh Criterion, \( A = 8 \). For the Fraunhoffer criterion, \( A = 32 \). One may also use Equation 11.11 to define rough or moderately rough surfaces. One commonly used states that:

If \( \Delta h < \frac{\lambda}{25 \cos \theta_0} \) the surface is smooth and

if \( \Delta h < \frac{\lambda}{4.4 \cos \theta_0} \) the surface is rough.

The categories of rough, smooth an intermediate surfaces for various satellite radar systems is shown in Error! Reference source not found.. A schematic drawing of the relationship between the radar cross-section and the incidence angle for surfaces in the different roughness ranges is shown in Error! Reference source not found..

### TABLE 11.2

<table>
<thead>
<tr>
<th>Roughness scales for various satellite radar systems.</th>
<th>Frequency</th>
<th>Wavelength</th>
<th>Dep. Angle</th>
<th>Smooth</th>
<th>Intermediate</th>
<th>Rough</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ka 0.75 - 1.10 cm</td>
<td>35.0 GHz</td>
<td>0.86 cm</td>
<td>40.0 deg</td>
<td>&lt; 0.05 cm</td>
<td>0.05 cm - 0.3 cm</td>
<td>&gt; 0.3 cm</td>
</tr>
<tr>
<td>K  1.10 - 1.67 cm</td>
<td>20.0 GHz</td>
<td>1.5 cm</td>
<td>40.0 deg</td>
<td>&lt; 0.09 cm</td>
<td>0.09 cm - 0.53 cm</td>
<td>&gt; 0.53 cm</td>
</tr>
<tr>
<td>Ku 1.67 - 2.40 cm</td>
<td>15.0 GHz</td>
<td>2.0 cm</td>
<td>40.0 deg</td>
<td>&lt; 0.12 cm</td>
<td>0.12 cm - 0.71 cm</td>
<td>&gt; 0.71 cm</td>
</tr>
<tr>
<td>X 2.40 - 3.75 cm</td>
<td>10.0 GHz</td>
<td>3.0 cm</td>
<td>50.0 deg</td>
<td>&lt; 0.16 cm</td>
<td>0.16 cm - 0.89 cm</td>
<td>&gt; 0.89 cm</td>
</tr>
<tr>
<td>C 3.75 - 7.5 cm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radarsat-1,2</td>
<td>5.36 GHz</td>
<td>5.6 cm</td>
<td>20.0 deg</td>
<td>&lt; 0.65 cm</td>
<td>0.65 cm - 3.72 cm</td>
<td>&gt; 3.72 cm</td>
</tr>
<tr>
<td>ERS-1,2</td>
<td>5.30 GHz</td>
<td>5.7 cm</td>
<td>68.0 deg</td>
<td>&lt; 0.24 cm</td>
<td>0.24 cm - 1.39 cm</td>
<td>&gt; 1.39 cm</td>
</tr>
<tr>
<td>SIR-C</td>
<td>5.20 GHz</td>
<td>5.8 cm</td>
<td>50.0 deg</td>
<td>&lt; 0.30 cm</td>
<td>0.3 cm - 1.71 cm</td>
<td>&gt; 1.71 cm</td>
</tr>
<tr>
<td>S  7.5 - 15 cm</td>
<td>3.00 GHz</td>
<td>10.0 cm</td>
<td>68.0 deg</td>
<td>&lt; 0.43 cm</td>
<td>0.43 cm - 2.45 cm</td>
<td>&gt; 2.45 cm</td>
</tr>
<tr>
<td>L  15 - 30 cm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SIR-A,C</td>
<td>1.28 GHz</td>
<td>23.5 cm</td>
<td>68.0 deg</td>
<td>&lt; 1.02 cm</td>
<td>1.02 cm - 5.77 cm</td>
<td>&gt; 5.77 cm</td>
</tr>
<tr>
<td>Seasat</td>
<td>1.28 GHz</td>
<td>23.5 cm</td>
<td>68.0 deg</td>
<td>&lt; 1.02 cm</td>
<td>1.02 cm - 5.77 cm</td>
<td>&gt; 5.77 cm</td>
</tr>
<tr>
<td>JERS-1</td>
<td>1.28 GHz</td>
<td>23.5 cm</td>
<td>68.0 deg</td>
<td>&lt; 1.02 cm</td>
<td>1.02 cm - 5.77 cm</td>
<td>&gt; 5.77 cm</td>
</tr>
<tr>
<td>P 30 - 100 cm</td>
<td>0.50 GHz</td>
<td>60.0 cm</td>
<td>68.0 deg</td>
<td>&lt; 2.59 cm</td>
<td>2.59 cm - 14.7 cm</td>
<td>&gt; 14.7 cm</td>
</tr>
</tbody>
</table>

A striking example of the effect of roughness is shown in Error! Reference source not found.. Water scatters (reflects) microwave radiation very effectively. When the water surface is smooth it behaves as a specular reflecting surface, directing the microwave radiation away from the source and water appears black. When the water surface is roughened by waves on the order of the radar wavelength (e.g., capillary waves), there is significant return, often making larger scale waves (gravity waves) visible because of the uneven distribution of capillary waves riding atop the gravity waves. The oil on the water from the Deepwater Horizon oil spill (Error! Reference source not found.)
Reference source not found.) has flattened the water surface resulting in specular reflection of the radar radiation, and contrasting the area of the spill with the surrounding uncontaminated water.

Fig. 11.5: Variation in the radar cross-section with incidence angle and surface roughness.

Fig. 11.6: Image of the Deepwater Horizon oil spill acquired by RADARSAT-2 in ScanSAR Narrow B Beam on April 28, 2010 at 11:51:29 UTC. a) New Orleans, Louisiana; b) Delta of the Mississippi River; c) Oil slick; d) Close-up of ships and equipment at the spill site. http://www.asc-csa.gc.ca/eng/satellites/radarsat2/
11.3.4 Angle to Target and Surface Orientation

The strength of the radar return is very dependent on the angle of incidence of the radar beam on the surface. Basically, the more nearly perpendicular the surface is to the direction of the radar beam, the stronger the return. Most materials scatter radiation in all directions, but differentially (recall the BRDF in the discussion of reflectance in the optical range). At microwave frequencies, the power returned from a given material is greatest when the surface is perpendicular to the illuminating beam, and falls off as the angle of incidence increases. Since the radar beam spans an array of angles, the same material at different ranges, will reflect/scatter the radiation differently even for a flat surface with uniform texture. The orientation of the target surface relative to the look angle affects the signal strength as well. We will revisit this issue when discussing imaging radar in Section 11.6.4.

11.3.5 Range to Target

Ranging—measuring the distance from the radar to a target—is at the heart of most radar systems. Range is determined by measuring the time of travel of the microwave pulse to the target and back. The intensity of the radar return is often quite low—recall that the intensity falls off as $1/r^4$—and the detected signal will likely be corrupted by extraneous noise. Since each pulse typically has a duration (pulse width) of 10-50 microseconds, rather than looking for the echo directly in the received signal, the echo is sought in the correlation between a reference signal (a copy of the original transmitted signal) and the received signal. This cross-correlation will be large at the lag time associated with the time duration of the signal to the reflecting object and its return, and the random noise in the signal will be small when averaged over a time appropriate for the correlation.

If the radar transmits a very short pulse which is reflected (scattered) by an object at distance $R$ from radar, total distance traveled by the pulse is $2R$; the time, $t$, required for the "round trip" is then found from the relation: $2R = c \times t$, where $c$ is the velocity of light. Thus the range of the target is given by:

$$R = \frac{c \times t}{2}$$  \hspace{1cm} (11.12)

11.3.6 Relative Velocity

Relative velocity is determined by observation of the difference in frequency (Doppler shift) between the transmitted and return radiation. This is the basis for police radar units. This topic will be covered in detail in the following section on Synthetic Aperture Radar (SAR).

11.4 Types of Radar

There are a wide variety of radar systems that exist. We will consider only those used for remote sensing of the earth and atmosphere and concentrate on those systems that are airborne or orbiting. In general these systems fall into two general categories of imaging and non-imaging systems. TABLE 11.3 lists the general categories that we will consider here.

Within these general classes the radar systems may be categorized according to the type of information they collect predominantly—power (scatterometer), range (altimeter), frequency (Doppler). However, the types of observation are often mixed. For example, Doppler weather radar is responsive to both the magnitude and the relative motion of the water droplets in the atmosphere.

TABLE 11.3:
11.5 Non-Imaging Radar

11.5.1 Ranging radar
There are basically two non-imaging instruments that rely on ranging and direction finding: the Surveillance Radar—one of the earliest forms of radar—and the radar altimeter.

11.5.1.1 Radar altimeter (To be expanded: TOPEX, Poseidon, etc.)
A radar altimeter measures the distance to the ground immediately below an aircraft or spacecraft. This is in contrast to a barometric altimeter which estimates the distance above a predetermined datum, usually sea level. [http://www.altimetry.info/html/alti/welcome_en.html](http://www.altimetry.info/html/alti/welcome_en.html)

11.5.1.2 Surveillance radar
This is primarily a ground-based radar that uses a continually rotating antenna to transmit microwave pulses that reflect, or backscatter, from the targets within its range. The radar system measures the time required for a radar echo to return and the direction of the signal. From this, the system then determines the distance and the azimuth of the target relative to the antenna. Probably the most familiar example of surveillance radar is the air traffic control radar used to detect the position of aircraft in the vicinity of the airport (Fig. 11.7a). Surveillance radar is also commonly used to monitor ship traffic at ports, on ships to detect the presence and direction of other ships or above-water obstacles, and has been adapted to detect movement of ground level targets in sensitive areas. Systems have also been developed for use aboard aircraft, the Airborne Warning and Control System (AWACS).

Information from the surveillance radar is typically displayed on a Plan Position Indicator (PPI). The distances of the echoes from the center of the screen indicate the ranges of targets, and the angular position of each echo indicates the bearing in azimuth of the target (Fig. 11.7b).
11.5.2 Scatterometer (non-imaging system)

A scatterometer is a microwave radar sensor used to measure the reflection or scattering effect produced while scanning the surface of the earth from an aircraft or a satellite.

11.5.2.1 Wind Scatterometry

Scatterometry derived from attempts to understand the noise in early radar systems. Early radar measurements over oceans were corrupted by sea clutter (noise). When it became apparent that the noise was simply the radar response to wind blowing over the oceans and that the magnitude of the noise was related to wind speed, measuring the "noise" became a method for measuring wind speed. The first scatterometer flew as part of the Skylab missions in 1973 and 1974, and demonstrated that spaceborne scatterometers were feasible.

The principle of wind scatterometry is that the magnitude of the radar pulse return is proportional to the roughness of the surface and the roughness of the surface is proportional to the wind speed. A difficulty with the measurement is that the magnitude of the return is also sensitive to the wave direction. Water waves traveling in the same direction as the viewing direction of the scatterometer will produce stronger returns than those traveling perpendicular to the radar beam. However, the wave motion relative to the look direction of the radar will also induce changes in frequency (Doppler shift). By observing the same piece of water from several different angles, both wind speed and direction can be measured.

An example of a scatterometer designed for measuring surface wind speed and direction over the ocean is the Wind Scatterometer that flew on the European Space Agency's Remote Sensing Satellite-1 (ERS-1) mission. This scatterometer used three sideways-looking antennae illuminating a swath 500 km wide, giving three independent backscatter measurements in three different directions, separated by a very short delay, from which the surface wind vector can be calculated (Fig. 11.8). Wind speed and direction are computed based on the magnitudes and frequency shifts of three observations for a single parcel of water.
Scatterometer wind measurements are particularly useful for monitoring hurricanes, but have also been used to measure winds over sand and snow dunes from space.

![Diagram of the ERS-1 wind scatterometer geometry. The three Wind Scatterometer antennae generate radar beams at 90° and ±45° from the satellite track across a 500 km swath.](http://ceos.cnes.fr:8100/cdrom-97/ceos1/satellit/ers/ers134.htm)

**11.5.2.2 Terrestrial Scatterometry**

For scatterometers that have been designed to operate over land, the information of interest is the change in the radar backscatter of the terrain as a function of the incidence angle. In this context scatterometers are particularly effective for characterizing the surface roughness of materials. This type of system is most commonly used now for discriminating among types of sea ice.

Since ground motion is not typically a factor in the observation, the direction observations serve to define the angular variation in the scattering properties of the surface. A schematic of such a system is illustrated in Fig. 11.9. This is a range-angle system in which the scatterometer beam is directed along the flight path. In this case, return from any one segment of the land surface arrives at the antenna from a different angle and at a different time.


Scatterometers have been applied to the study of vegetation, soil moisture, polar ice, and global change. Non-terrestrial applications include study of Solar System moons using space probes. This is especially the case with the NASA/ESA Cassini mission to Saturn and its moons.
11.5.3 Doppler Radar

Although important for many purposes from speed traps to weather radar, for our purposes the Doppler effect is important primarily in its use in synthetic aperture radar and will be considered for that application in Section 11.6.5.

11.6 Imaging Radar

Imaging radars provide map-like coverage of a scene but, since the radar provides its own illumination, the imaging process is very different from an optical, thermal or passive microwave scanning system. There are two major categories for imaging radar: Real Aperture Radar (RAR) and Synthetic Aperture Radar (SAR). Both RAR and SAR are side-looking systems with an illumination direction usually perpendicular to the flight line. The primary difference between the two from the user point of view is the along track, or azimuthal, resolution, with the SAR being much superior to RAR. However we will begin with a discussion of real aperture systems since they are conceptually simpler and will provide a good introduction into the radar imaging process.

11.6.1 Real Aperture Radar (RAR)

An illustration of the geometry of a RAR scan is shown in Fig. 11.10. A short pulse of microwave radiation is emitted by the antenna on the aircraft directed perpendicular to the line of flight. The gray arcs in Fig. 11.10 represent the leading edge and trailing edge of the pulse. The antenna is focused in the horizontal (or azimuthal) direction and is effectively unfocussed in the vertical direction. Thus the lowest portion of the pulse (the portion at the largest depression angle) arrives at the ground first and generates the first return. As the pulse progresses, the depression angle decreases and the range increases.

11.6.2 Range Resolution

Slant range, \( R_s \), is simply the distance from the radar antenna to the ground target. The slant-range resolution of the radar, \( \rho_s \), designates the smallest distance between two targets that can be discriminated, and is limited by the pulse width, \( \tau \). From Equation 11.12, the time of travel to targets at ranges \( R_s \) and \( R_s + \Delta R_s \) are:

\[
t_1 = 2 \frac{R_s}{c} ; \quad t_2 = 2 \frac{(R_s + \Delta R_s)}{c}
\]  

(11.13)

The difference between these two times is:

\[
\Delta t = t_2 - t_1 = \frac{2(R_s + \Delta R_s)}{c} - \frac{2R_s}{c} = \frac{2\Delta R_s}{c} > \tau = \text{pulse width}
\]  

(11.14)

Thus, to be resolvable, the difference in return time \( \Delta t \) must be greater than or equal to the pulse width, \( \tau \): \( \Delta t \geq \tau \). For non-overlapping returns, the range resolution is then:

\[
\rho_s \approx \frac{c\tau}{2}
\]  

(11.15)

---

6 The terms Side-Looking Radar (SLR) or Side-Looking Airborne Radar (SLAR) usually refer to real aperture systems, but are sometimes used as synonyms for either RAR or SAR.
By simple geometry, the corresponding ground distance over flat terrain is:

\[
\rho_g = \rho_s \sec(\varphi) = \frac{ct}{2 \cos(\varphi)}
\]  

(11.16)

Fig. 11.10: Illustration of the range resolution of a real aperture radar. The radar beam is directed perpendicular to the flight path. The gray arcs represent the leading and trailing edges of the radar pulses.

A pulse width of 10 µs – typical of radar – would then correspond to a range resolution of 3 km. This is clearly not acceptable. To achieve a range resolution on the order of meters, the pulse width would have to be on the order of nanoseconds (ns), which physically difficult to achieve. The solution is to employ pulse compression, which involves modulating the carrier frequency and using a receiver that matches this modulation in order to achieve a synthetic pulse width on the order of several nanoseconds.

**Note that the range resolution is independent of range!**

### 11.6.3 Azimuthal Resolution

For real aperture systems, "Angular," Azimuthal," or "along track" resolution is defined by the beamwidth, \( \beta \), and slant range, \( \rho_s \). With radar, all radiation is transmitted and received over the same angular interval, \( \beta \). As discussed in the section on passive microwave sensing, the beamwidth is determined by the size of the antenna; the larger the antenna the more directed the beam will be and the better the angular resolution. In general, the beamwidth can be expressed:

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

(11.17)

where \( \lambda \) is the operating wavelength and \( D \) is the length of the antenna (\( \beta \) measured in radians). If \( \beta \) is small enough to meet the small-angle criterion, then a swath on the ground spanned by \( \beta \) at a slant range \( R_s \) is simply \( \beta R_s \). This is sufficient to define the limit of the azimuthal resolution, \( \rho_\beta \), as:

\[
\rho_\beta \approx \beta R_s \approx \frac{\lambda R_s}{D}
\]  

(11.18)
Thus, for $\lambda = 1$ cm, $D = 3$ m and $R = 15$ km, $\rho_\beta = 50$ m. As is illustrated in Fig. 11.11, azimuthal resolution degrades with range. Points that are resolvable in the near range may appear as a single bright target in the far range. In general, for real aperture (brute force) systems, higher resolution is achieved with longer antennas (increase $D$) or shorter $\lambda$ (i.e., decrease $\beta$).

![Fig. 11.11: Azimuthal resolution is directly proportional to the slant range. Points that are resolvable in the near range are not resolvable in the far range.](image)

**11.6.4 Radar interaction with the surface**

Consider the example illustrated in Fig. 11.12 showing a single material with surfaces of various orientations viewed from several different viewing. At angle 1, surface A is tilted toward the viewing direction and yields the brightest return, surface B is hidden, blocked from view by surface A so that there is no return during the time it takes the radar pulse to traverse that distance, and surface C is at a very oblique angle and is therefore relatively dark. At this very shallow viewing angle, the length (in time) of the radar return is very close to the horizontal length of the surface. For look angle 2, surface A is nearly perpendicular to the radar look direction yielding a very strong return over a very short time.

![Fig. 11.12: The brightness and relative size of features are dependent on the viewing angle. The horizontal lines in the figure at the right indicate equal time intervals for the radar return.](image)

For look angle 3, surfaces B and C are tilted by roughly the same amount from the radar look direction. Since the surfaces are the same material, there is no differentiation in the radar return and the two tilted surfaces appear as one. Surface C is tilted slightly more toward look direction 3 and appears slightly brighter. The overall time for the return from look direction 3 is shorter because it is closer to the normal for the combined surface. Finally, in look direction 4, surface B is the brightest since it is tilted in toward the look direction and surface C is relatively dark while surface A is now hidden from the radar view and produces no return.
When two surfaces are at right angles to one another and are facing toward the radar, they form a **corner reflector**. As illustrated in Fig. 11.13, the orientation of the surfaces at right angles causes most of the radar energy to be reflected directly back to the antenna due to the double reflection. Corner reflectors are common in urban environments (e.g. buildings and streets, bridges, other man-made structures). Naturally occurring corner reflectors may include cliff faces or upright vegetation standing in water, or a forested shore at the edge of a lake. In all cases, corner reflectors show up as particularly bright targets in an image.

![Fig. 11.13: Corner reflector](image)

Thus far we have treated the radar return as if it were strictly a matter of surface scatter. While that is a major consideration, there can be very significant penetration of the microwave radiation into the volume of the material. This is obviously the case for weather radar, but is also an important consideration for terrestrial observations. The simplest version of volume scattering would be multiple scattering at a complex surface. There can be multiple bounces and reflections from different components within the volume. For example, in a forest, scattering can occur within the canopy from the leaves and branches, from the tree trunks and ground. The degree of scattering is highly frequency dependent as illustrated in Fig. 11.14 for a stand of trees. In this illustration, X-band radiation is responding to the canopy, whereas the longer wavelength P-band radiation is largely insensitive to the canopy structure, but is responding to the combination of ground and tree trunk serving as corner reflectors.

![Fig. 11.14: Frequency dependence of volume scattering.](image)

http://forsys.cfr.washington.edu/JFSP06/radar_overview.htm

Microwave radiation also penetrates the earth's surface, sometimes appreciably. This is particularly true in dry soils, ice and dry snow. As illustrated in Fig. 11.15, there is some surface...
return, as well as volume scattering and, if the scattering layer is shallow enough, return from the a layer through which the radar does not penetrate (bedrock, water table, etc.).

![Diagram](image)

**Fig. 11.15:** Radar penetration into dry surfaces (unknown source for figures).

**To be continued:** Topics: Volume scattering, Bragg scattering, Polarization

**Sources:**
- [http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20080044842_2008044254.pdf](http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20080044842_2008044254.pdf)

### 11.6.5 Synthetic Aperture Radar (SAR)

Real aperture radar can be very effective from aircraft, but from satellite altitudes, the limits on the azimuthal resolution imposed by Equation 11.18 are formidable. At polar orbiting altitudes (~800 km), and using a 3 cm wavelength, an azimuthal resolution of 3 km would require an 8 m antenna. To produce a more usable 300 m azimuthal resolution, an 80 m antenna would be required.

Synthetic aperture radar overcomes the range dependence of the azimuthal resolution by using the frequency shift (Doppler shift) of return from the return from targets at different azimuthal positions in the radar beam. Due to the motion of the aircraft or satellite platform relative to the earth, a signal returned from a point ahead of the platform will have a higher frequency than the original signal. Conversely, a signal returned from a point behind the platform will have a lower frequency than the original. For electromagnetic radiation, the Doppler-shifted frequency of the radiation reaching the target, $f_t$, as described by the relativity theory is:

$$
\text{frequency at the target} = f_t = f_0 \sqrt{\frac{1 + v/c}{1 - v/c}}
$$

(11.19)
where \( v \) is the velocity of approach (or separation). Multiplying the numerator and denominator of the expression in the radical by \( 1 + v/c \) yields:

\[
ft = f_0 \left( \frac{(1 + v/c)^2}{1 - (v/c)^2} \right)^{1/2}
\]  

(11.20)

When \( v \ll c \), as is the case for the aircraft or satellite velocities, then \((v/c)^2\) is negligible, and Eq. 11.20 reduces to:

\[
ft = f_0 (1 + v/c) \]  

(11.21)

The frequency shift at the target is then:

\[
f_t - f_0 = (v/c)f_0 \]  

(11.22)

Since two-way propagation doubles the phase shift, the Doppler shift, \( \Delta f_r \), observed at the radar, is:

\[
\Delta f_r = f_r - f_0 = \frac{2v}{c}f_0 = 2v/\lambda
\]  

(11.23)

Where \( \lambda \) is the transmitted wavelength.

![Fig. 11.16: Return from targets ahead of the platform will have a higher frequency than the transmitted frequency, \( f_0 \). Return from targets parallel to the platform in a direction perpendicular to the flight path will be at the transmitted frequency. Using the frequency differences to assemble the multiple views from a radar antenna with physical size, \( D \), results in a synthetic aperture of size, \( L \), defined by the beamwidth, \( \beta \), of the antenna. The relative velocity, \( v \), shifts continuously from the edge of the beam forward of the platform to the edge of the beam aft of the platform. Thus, the returns from within the beam in the azimuthal direction may be sorted by frequency. Also, a target within the beam is viewed multiple times as the platform progresses along the flight line (Fig. 11.16). SAR processing consists of compensating for the Doppler shift associated with the motion of a single source relative to the aircraft/satellite. The final image is assembled from multiple looks at the same object from different angles, sorted by frequency. The result is essentially the same as having a synthetic antenna with the effective size of the beamwidth. Consider Fig. 11.16. A target, \( T \), is illuminated by the radar during the time it takes for the radar to move through the distance \( L \). If \( \beta \) meets the small angle criterion \((\beta < 5^\circ)\) then:

\[
L \approx \beta R_s
\]  

(11.24)
At any one instant the physical antenna is, in effect, a single element of a phased array. The Doppler-shift processing is then analogous to the correction applied to each element of a phased array, resulting in an effective aperture of length $L$. The synthetic aperture beamwidth is:

$$\beta \approx \frac{\lambda}{L}$$  \hspace{1cm} (11.25)

and, using Equation 11.18, the effective angular resolution is then:

$$\rho_\beta \approx \frac{\beta R_s}{\lambda R_s/L} \approx \frac{\lambda}{\beta} \approx L$$  \hspace{1cm} (11.26)

Referring again to Fig. 11.16, point A (far range) is within the beam longer than point C (near range). In other words, the length of the synthetic antenna increases with range, counteracting the degradation in azimuthal resolution with range for the physical antenna.

### 11.6.5.1 Focused and Unfocused SAR

The previous argument for the increase in resolution provided by the Doppler-shift correction is only really applicable for the case of a beamwidth that meets the small angle approximation. In that case the arc of the beam on the ground can be approximated with a straight line. Applying the Doppler correction to larger beamwidths will result in errors unless the curvature of the wave front is taken into account. If the system has a large beamwidth and there is no correction for the curvature of the wave front, then the processing must be limited to a subset of the beamwidth. This is called the **unfocused mode**. If the processing compensates for the curvature of the wavefront, a larger beamwidth can be accommodated resulting in a higher azimuthal resolution. This is the **focused mode**.

### 11.6.5.2 Speckle

All radar images appear with some degree of what is called radar speckle. Speckle appears as a grainy "salt and pepper" texture in an image. This is caused by random constructive and destructive interference from the multiple scattering returns that will occur within each resolution cell. Speckle is essentially a form of noise which degrades the quality of an image and may make interpretation (visual or digital) more difficult. Thus, it is generally desirable to reduce speckle prior to interpretation and analysis. Speckle reduction can be achieved in two ways: a) multi-look processing, or b) spatial filtering.

**Multi-look processing** refers to the division of the radar beam (A) into several narrower sub-beams (1 to 5 in Fig. 11.17). Each sub-beam provides an independent "look" at the illuminated scene, as the name suggests. Each of these "looks" will also be subject to speckle, but by summing and averaging them together to form the final output image, the amount of speckle will be reduced. Note that multi-look processing decreases the effective beam width for each "look" thereby reducing the azimuthal resolution.

**Speckle reduction filtering** is generally simply convolution operation with a smoothing filter. This consists of moving a small window of a few pixels in dimension (e.g. 3x3 or 5x5) over each pixel of an image, applying a mathematical calculation using the pixel values under that window (e.g. calculating the average), and replacing the central pixel with the new value. The window is moved along in both the row and column dimensions one pixel at a time, until the entire image has been covered. By calculating the average of a small window around each pixel, a smoothing effect is achieved and the visual appearance of the speckle is reduced. (The original image is used as a reference and a new, smoothed image is created in this process.)
Fig. 11.17: A beam is divided into 5 sub-beams with smaller beamwidths. Each sub-beam provides an independent "look" at the illuminated area. Averaging of the "looks" results in a reduction of speckle.

11.6.6 Interferometric SAR

A complete description of the received radar signal includes three components: amplitude, frequency and phase. The amplitude information is what is recorded in a radar image of the Earth. The frequency information is used in SAR processing to improve the azimuthal resolution. The phase information is used in interferometry to retrieve subtle information on about differences in range to produce precise topographic maps or to measure changes in the surface (landslides, earthquakes, etc.) on the order of a fraction of the wavelength.

Each pixel of a radar image contains information on the phase of the radar signal. As there are many discrete scatterers in each pixel and pixels are large compared to the wavelength, it is reasonable to assume that phases from randomly distributed scatterers are uniformly distributed. The distribution of the phase differences is what gives rise to phase speckle.

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7 The presentation in this section is derived from several sources, particularly from _Physical Principles of Remote Sensing, 2nd Edition_, by W.G. Rees (Cambridge University Press) and from a presentation by Dr. Francisco Gomez, developed while he was a Postdoc at Cornell University.
d) Interferogram overlaid on amplitude

Fig. 11.18: Each pixel in an image contains amplitude and phase information. The phase information contains information about difference. The interferogram (fringe pattern) is the difference between the phase values of two registered images of the same area.

Although the phase is randomly distributed over a pixel, it is causally connected to physical features. Hence, the phase of a given area should be the same if viewed from the same position at different times as long as there has been no change in the imaged surface. If two images are collected of the same scene at different locations, taking the difference in phase of two scenes yields an interference pattern representing topography (Fig. 11.19). Similarly, if the topography is known, the difference of two images taken before and after a change in the surface (e.g., landslides earthquake, etc.) can be used to develop an interference pattern that represents the time-dependent change in topography.

Fig. 11.19: The basic geometry of interferometric sensing.

The basic geometry underlying the use of a pair of images to create an interferogram is illustrated in Fig. 11.19. We assume that images are acquired from points M and S. The "master" and "slave" images are separated by a distance B, the baseline. Both images include backscatter from point A. As measured from M, point A will lie somewhere along a small section of arc, c, since the slant range, $r_m$, is the same for all points on the arc. Similarly, the slant range to A from S, $r_s$, will lie somewhere along arc d. Since the arcs cross at only one point, we will refine the location of point A by considering the difference between $r_m$ and $r_s$.

This slant range difference is determined by comparing the phases of the signal in the two images. Specifying the amplitude, frequency and phase of an electromagnetic wave requires
the use of complex number notation. For example we may write an equation for the observed amplitude represented by a pixel in image M as:

$$a_m = a_1 \exp(i\varphi_1) \exp(2ikr_m)$$  \hspace{1cm} (11.27)

where $a_1$ and $\varphi_1$ are real numbers denoting the backscattered amplitude, and $k$ is the wavenumber of the radiation. The same pixel observed in the slave image has amplitude:

$$a_s = a_2 \exp(i\varphi_2) \exp(2ikr_s)$$  \hspace{1cm} (11.28)

If the baseline, $B$, is small, then the geometry for the two observations and the backscattering properties of the target at M and S will be nearly identical, that is:

$$a_1 \approx a_2 \quad \text{and} \quad \varphi_1 \approx \varphi_2$$

which means that if we multiply one image by the complex conjugate of the other we will obtain:

$$a_m a_s^* = |a_1|^2 \exp(2ik[r_m-r_s])$$ \hspace{1cm} (11.29)

This expression corresponds to an intensity image with interference fringes superimposed. The fringes contain the information about how $r_m - r_s$ changes between the two images with one complete fringe corresponding to a change of half a wavelength. Since the wavelength of a SAR system is typically on the order of several centimeters, the technique has potential to achieve extremely high resolution. Note, however, that a phase shift of $\theta$ is the same as a phase shift of $\theta + \pi$, meaning that there is an ambiguity in the phase information. The ambiguity can be resolved by using one image as a topographic reference.

![Diagram](image)

Fig. 11.20: In the flat-earth approximation, the ambiguity distance, $e$, is defined such that $(SB-MB)$ differs from $(SA-MA)$ by $\lambda/2$, where $\lambda$ is the wavelength of the radar.

The resolution of the interferometric SAR result is critically dependent on the geometry of the system relative to the imaged area. A convenient way of characterizing the potential offered by a particular imaging geometry for the generation of interference fringes is to calculate the "ambiguity distance", $e$, shown in Fig. 11.20. This is defined by the point B, which has the same distance from M as the reference point A, but for which the difference between the distance to M and S has changed by half a wavelength. Since this changes the difference in the round-trip distances by one wavelength, it means that one cannot distinguish between the positions A and B by interferometry alone.
Using simple flat-earth geometry for illustration (Fig. 11.20) the ambiguity distance may be expressed as:

\[
e = \frac{r_m^2 \lambda}{2(Hd - hr_g)}
\]  

(11.30)

For example, with \(H = 800\) km, \(r_g = 350\) km (\(r_s = 873.2\) km), \(h = 0\), and \(d = 1\) km for a SAR with \(\lambda = 6\) cm, we obtain \(e \approx 30\) m. The ambiguity height, \(e \tan \theta_i\), is about 11 m in this case, which means that if the signal-to-noise ratio in the complex image is high enough to detect, say, one tenth of an interference fringe, altitudes can be determined from the interferogram with an accuracy of about 1 m.

According to Equation (11.20), if \(Hd = hr_g\), the ambiguity distance \(e\) is infinite. This would occur when the master and slave positions are identical. Precision increases as \(e\) decreases, however values of \(e\) that are too small pose a problem since if \(e\) is much smaller than the slant-range resolution of the SAR system, a single pixel will contain many fringes and it will be impossible to count the number of fringes. Since small values of \(e\) arise from large values of the baseline between the master and slave, it is clear that the baseline must not be too large. For typical spaceborne SAR systems this maximum baseline is of the order of 1 km.

Interferometric phase depends on several parameters: a) the baseline, the distance between the positions of the imaging radar when the two images are collected, b) the topography of the imaged surface, c) temporal changes in the imaged surface, and d) atmospheric propagation delays.

11.6.6.1 Baseline

The baseline is the distance between two satellites. It can be represented by its length and orientation, or separated into two Cartesian components or expressed in polar form. (The term "temporal baseline" refers to the time interval between successive satellite observations.) To be readily useful, the two radar images used to produce the interferogram should be taken from similar positions. That is, the baseline – the separation distance between the two imaging positions – should be relatively small. The actual useful baseline length is dependent on the altitude and wavelength of the imaging system. For a C-band (wavelength = 5.6 cm) spaceborne system orbiting at an elevation \(h = \sim 700\) km range, a baseline may range from 0 to \(\sim 200\) m. Using image pairs with longer baselines leads to geometrical decorrelation due to the difference of lines of sight between the two images. This baseline length requirement scales linearly with the wavelength of the system. When the range is much larger than the baseline, the interferometric phase is given by

\[
\phi = \frac{4\pi}{\lambda}B \sin (\theta - \alpha), \quad \text{for } r_0 \gg B
\]  

(11.31)
The phase difference, \( \phi \), between the radar signal received by imaging systems using a wavelength, \( \lambda \), and located at \( S_1 \) and \( S_2 \), is given by:

\[
\phi = \frac{2\pi n}{\lambda} (S_1 - S_2)
\]

Retrieval of the interferometric phase is complicated by the \( n2\pi \) ambiguity in the solution, and is typically obtained by complex correlation of the first complex SAR image relative to the second image after precise co-registration. The interferometric phase may then be used to determine the precise look angle, \( \theta \), by first solving the cosine of the angle between the baseline vector and the look vector:

\[
\cos \left( \frac{\pi}{2} + \alpha - \theta \right) = \sin(\theta - \alpha) = \frac{\phi \lambda}{4\pi B}
\]

The altitude of the target is then given by:

\[
h = H - r_0 \cos \theta
\]

Sensitivity of the interferogram to topography depends upon the length of the baseline. Typical (usable) baselines for a C-band (wavelength = 5.6 cm) spaceborne system orbiting at an elevation \( h \approx 700 \) km range from 0 to \( \sim 200 \) m. Using image pairs with longer baselines leads to geometrical decorrelation due to the difference of lines of sight between the two images (Zebker and Villasenor, 1992). This baseline length requirement scales linearly with the wavelength of the system.

### 11.6.6.2 Topography

When two radar images are acquired from orbital positions separated by 100 to 300 meters in space and a short interval in time, the interference fringes that they produce run along topographic contours. We use these interferograms to map surface topography, creating Digital Elevation Models (DEMs). Usually, we use two radar images that are taken only a day apart, so that the effects of ground movement are small and the interference fringes result from surface topography alone.

### 11.6.6.3 Temporal changes

To be continued

### 11.6.6.4 Atmospheric propagation delays

To be continued

**Sources**
• **Shuttle Radar Topography Mission:**
  - [http://www2.jpl.nasa.gov/srtm/](http://www2.jpl.nasa.gov/srtm/)

• **TOPEX/Poseidon**
  - [http://topex.ucsd.edu/WWW_html/srtm30_plus.html](http://topex.ucsd.edu/WWW_html/srtm30_plus.html)