**OVERVIEW**

The word “radar” is an acronym for Radio Detection and Ranging.

A radar measures the distance, or range, to an object by transmitting an electromagnetic signal to and receiving an echo reflected from the object.

Since electromagnetic waves propagate at the speed of light, one only has to measure the time it takes the radar signal to propagate to the object and back to calculate the range to the object.

The total distance traveled by the signal is twice the distance between the radar and the object, since the signal travels from the radar to the object and then back from the object to the radar after reflection. Therefore, once we measured the propagation time (t ), we can easily calculate the range ( R ) as

**Basic Principles of Radar Imaging**

* There are two different mechanisms by which radars can be used to produce images; the two types of radars are broadly classified as real aperture and synthetic aperture radars.
* These strips are often referred to as swaths or tracks.
* The cross-track direction, also known as the range direction in radar imaging, is the direction perpendicular to the direction in which the imaging platform is [moving.In](http://moving.In) this direction, radar echoes are separated using the time delay between the echoes that are back-scattered from the different surface elements
* The along-track direction, also known as the azimuth direction, is the direction parallel to the movement of the imaging platform.The angular size (in the case of the real aperture radar) or the Doppler history (in the case of the synthetic aperture radar) is used to separate surface pixels in the along-track dimension in the radar images
* Within the illumination beam, the radar sensor transmits a very short effective pulse of electromagnetic energy
* The brightness associated with each image pixel in the radar image is proportional to the echo power contained within the corresponding time bin.
* The first is the so-called slant range and refers to the range along the radar line-of-sight
* The second use of the term range is for the ground range, which refers to the range along a smooth surface (the ground) to the scatterer.
* The ground range is measured from the so-called nadir track, which represents the line described by the position directly underneath the radar imaging platform.

1. **Look Angle**:
   * Defined as the angle between the vertical direction and the radar beam at the radar platform.
2. **Incidence Angle**:
   * Defined as the angle between the vertical direction and the radar wave propagation vector at the surface.
3. **Flat Surface**:
   * When the surface is flat and surface curvature effects are neglected, the look angle equals the incidence angle.
4. **Space-Borne Systems**:
   * For space-borne radar systems, surface curvature must be considered.
   * This results in the incidence angle being larger than the look angle for flat surfaces.

**Radar Resolution**

* The resolution of an image is defined as that separation between the two closest features that can still be resolved in the final image.
* radar waves are usually not transmitted continuously; instead, a radar usually transmits shortbursts of energy known as radar pulses.
* For slopes facing the radar, the ground range resolution will be poorer than that for slopes facing away from the radar.
* effective pulse length is described in terms of the system bandwidth B
* modulated pulses, which have the property of a wide bandwidth even when the pulse is very long
* pulse-compression,a short effective pulse length is generated, increasing the resolution
* One way to modulate the pulse is to vary the radar signal frequency linearly while the pulse is being transmitted. This waveform is known as chirp
* In a chirp, the signal frequency within the pulse is linearly changed as a function of time. If the frequency is linearly changed from f0 to f0 + ∆f , the effective bandwidth would be equal to: $B = |(f0 +∆f)- f0| = |∆f|$
* **Range Resolution**: This refers to the ability of a radar system to distinguish between two targets that are close together in range. It's directly dependent on two factors:
  + **Pulse Duration**: The length of time a radar pulse is transmitted. Shorter pulses result in better range resolution because they help in distinguishing between targets that are close to each other.
  + **System Bandwidth**: The range of frequencies over which the radar system operates. A wider bandwidth allows for finer resolution, as it provides more detail about the range of targets.
* **Ground Range Resolution**: This is the resolution of targets on the ground (or another surface) as observed from the radar system. It is influenced by:
  + **Incident Angle**: The angle at which the radar beam strikes the ground. A steeper angle can sometimes improve resolution by reducing the size of the area illuminated by the radar.
  + **Pulse Length**: Longer pulses can result in poorer resolution, as they may cause overlapping of echoes from different targets. Shorter pulses improve the ability to distinguish between closely spaced targets.
* **Pulse Compression**: This technique improves resolution by using pulse shaping techniques. Specifically:
  + **Chirp Signals**: These are pulses whose frequency changes over time. By encoding more information in the pulse, chirp signals can help in achieving finer resolution.
  + **Matched Filtering**: This is a process where the received signal is correlated with a known reference signal to improve the detection of the pulse's features. It effectively compresses the pulse duration, leading to better resolution.
* **Bandwidth**: In Synthetic Aperture Radar (SAR) systems and other radar systems, bandwidth is crucial for achieving high resolution. A wider bandwidth allows for more precise determination of target distances because it increases the system's ability to differentiate between close targets. Higher bandwidth typically results in higher resolution images.

**Overview**

The resolution of a radar image is defined as the separation between the two closest features that can still be distinguished in the final image. Radar systems typically do not transmit waves continuously but rather transmit short bursts of energy known as radar pulses. The resolution of these pulses is influenced by various factors such as pulse length, bandwidth, incident angle, and modulation techniques.

**Range Resolution (Pages 6-7)**

**Fundamentals**:

* Range resolution is the ability of the radar to distinguish between two targets based on their distance from the radar.
* It is key to identifying objects that are close together in the radar's line of sight.

**Practical Consideration**:

* To differentiate two objects, the returned pulse from the second object must be received after the trailing edge of the pulse from the first object.

**Ground Range Resolution (Pages 7-8)**

**Incident Angle Impact**:

* Ground range resolution depends on the incident angle (\(\theta\)).
* The effective time length (\(\tau\)) of the pulse affects the resolution.

**Pulse Compression and Chirp Signals (Pages 8-9)**

**Pulse Compression**:

* Used to improve range resolution while maintaining high energy in pulses.
* Modulated pulses, which have wide bandwidth even when the pulse is very long, are utilized for this purpose.

**Matched Filtering**:

* A technique used to compress the returned signals, allowing for the resolution of targets closer than the physical pulse length.
* It combines the received signal with a replica of the transmitted signal.

**Impact of Bandwidth on Resolution (Page 10)**

**Bandwidth vs. Pulse Length**:

* The achievable range resolution depends on the bandwidth of the chirp, not the physical length of the pulse.
* Spaceborne systems often use physical pulse lengths of several tens of microseconds and bandwidths of several tens to hundreds of megahertz.

**Conclusion**

**Range Resolution**:

* Dependent on pulse duration and system bandwidth.

**Ground Range Resolution**:

* Affected by incident angle and pulse length.

**Pulse Compression**:

* Enhances resolution through chirp signals and matched filtering.

**Bandwidth**:

* Crucial for achieving high resolution, especially in SAR systems.

These concepts are fundamental for understanding radar imaging and its applications, particularly in spaceborne and airborne systems.

**Radar equation**

The radar equation is fundamental to understanding how radar systems operate and measure the power of returned signals from targets. It describes the relationship between the transmitted power, the properties of the target, and the received power.

The basic form of the radar equation is:

**Key Components of the Radar Equation**

1. **Transmitted Power (Pt)**: The power of the signal transmitted by the radar system.
2. **Antenna Gains (Gt and Gr)**: The gain of the antennas in the direction of the target. High gain antennas focus more power in a specific direction, enhancing the signal strength.
3. **Wavelength (λ)**: The wavelength of the radar signal. Shorter wavelengths (higher frequencies) provide better resolution.
4. **Radar Cross-Section (σ)**: A measure of how much of the radar signal is reflected back by the target. It depends on the size, shape, and material of the target.
5. **Range (R)**: The distance from the radar to the target. The received power decreases with the fourth power of the range, making it a critical factor in radar performance.
6. **Signal Strength**: The intensity of the reflected signal, which is captured to form the SAR image, depends on the transmitted power. [Stronger signals result in clearer and more detailed images3](https://www.geospatialworld.net/article/sar-imagery-and-quality-metrics/).
7. **Resolution**: The quality of SAR images is influenced by the power of the radar signal. [Higher power allows for better resolution, enabling the detection of finer details in the imaged area4](https://www.euspaceimaging.com/what-is-sar-imagery/).
8. [**Penetration**: In SAR, higher power can improve the penetration capability of the radar waves, allowing them to pass through obstacles like vegetation or soil to reveal underlying structures5](https://descanso.jpl.nasa.gov/SciTechBook/series2/02Chap1_110106_amf.pdf).
9. [**Noise Reduction**: Adequate power helps in reducing the noise in the received signal, leading to cleaner and more accurate images](https://www.earthdata.nasa.gov/learn/backgrounders/what-is-sar)

**Real Aperture Radar**

**1. Introduction**

Real Aperture Radar (RAR) is a radar imaging system that utilizes an antenna to illuminate the surface to one side of the flight track, forming images based on the reflected signals. The antenna typically emits a fan beam that illuminates a highly elongated elliptical area on the surface. The dimensions and characteristics of this illuminated area define the radar's imaging capabilities and resolution.

**2. Beam Formation and Swath Width**

The beam angular width in the range plane (across the flight track) is determined by the antenna width \( W \) and the radar wavelength \( \lambda \):

\[ \theta\_r \approx \frac{\lambda}{W} \]

The resulting surface footprint or swath \( S \) is calculated as:

\[ S \approx \frac{2h \lambda}{W \cos \theta} \]

where:

* \( h \) is the sensor height above the surface,
* \( \theta \) is the angle from the center of the illumination beam to the vertical.

This equation assumes a flat Earth and small beam angles. For spaceborne radars, the Earth's curvature must be considered, using the law of cosines to solve for the swath width if the antenna beam width is large.

**3. Along-Track Resolution**

RAR's resolution in the along-track direction (parallel to the flight track) depends on the antenna length \( L \) and the range to the scene \( R \). The antenna beam width in this direction is:

\[ \theta\_a \approx \frac{\lambda}{L} \]

The along-track resolution \( x\_a \) at a distance \( R \) is given by:

\[ x\_a \approx R \theta\_a \approx \frac{R \lambda}{L} \]

For example, with:

* \( h = 800 \) km,
* \( \lambda = 23 \) cm,
* \( L = 12 \) m,
* \( \theta = 20^\circ \),

the along-track resolution \( x\_a \) would be approximately 16 km. Even with a shorter wavelength of 2 cm and a lower altitude of 200 km, the resolution remains around 360 meters, which is considered poor for remote sensing purposes. Hence, RAR is rarely used for high-resolution imaging from space.

**4. Comparison with Passive Optical Systems**

RAR relies on the same imaging mechanism as passive optical systems for along-track resolution. However, due to the longer wavelength (typically about 1 μm for optical systems), passive systems can achieve higher resolutions with smaller apertures. For instance, from orbital altitudes, resolutions of a few meters can be achieved with an aperture size of only a few tens of centimeters. Aircraft altitudes can provide reasonable azimuth resolutions if higher frequencies (e.g., X-band) are used.

**5. Radar Equation for Real Aperture Radar**

The radar equation for a real aperture radar takes into account the area illuminated by the antenna in the along-track direction and the projection of the pulse on the ground in the cross-track direction. The along-track dimension of the antenna pattern is given by:

\[ x\_a \approx \frac{R \lambda}{L} \]

If the pulse has a length \( \tau\_p \) in time and the signal is incident on the ground at an angle \( \theta\_i \), the projected length of the pulse on the ground is:

\[ l\_p = c \tau\_p \sin \theta\_i \]

The radar equation becomes:

\[ P\_r = \frac{P\_t G\_t G\_r \lambda^2 \sigma}{(4\pi)^3 R^4 \sin \theta\_i L \tau\_p} \]

where:

* \( P\_r \) is the received power,
* \( P\_t \) is the transmitted power,
* \( G\_t \) and \( G\_r \) are the gains of the transmitting and receiving antennas,
* \( \sigma \) is the backscattering cross-section.

The normalized backscattering cross-section (\( \sigma^0 \)) is defined as:

\[ \sigma^0 = \lim\_{R \to \infty} \frac{4\pi R^2 \sigma}{A\_0} \]

where \( A\_0 \) is the illuminated surface area. The received power decreases as the range to the third power for extended area imaging, showing that received power increases with the square of the antenna width but only linearly with the antenna length. Increasing the antenna length improves along-track resolution but also decreases the swath width.

**6. Practical Considerations**

In practical applications, RAR is limited by its relatively poor resolution, especially for spaceborne remote sensing. Real aperture radars require long antennas to achieve better along-track resolution, which can be challenging to accommodate. As a result, RAR is not commonly used for high-resolution remote sensing but finds applications in scatterometers and altimeters that do not require high-resolution data.

**7. Summary**

RAR operates using a similar mechanism to passive imaging systems for along-track resolution but generally achieves poorer resolutions, making it less suitable for high-resolution remote sensing applications. Advances in technology and alternative radar systems, such as synthetic aperture radar (SAR), have largely superseded RAR for most remote sensing needs.

**SYNTHETIC APERTURE RADAR**

* Prior to the discovery of synthetic aperture radar, principle imaging radars operated using the realaperture principle and were known as side-looking aperture radars (SLAR).

**Doppler Frequency Analysis and the Birth of Synthetic Aperture Radar (SAR)**

**1. Introduction to Doppler Frequency Analysis**

Carl Wiley of the Goodyear Aircraft Corporation is generally credited with pioneering the use of Doppler frequency analysis for improving the along-track resolution of radar systems. This innovation marked a significant advancement in radar technology, particularly for moving coherent radars.

**2. Principle of Doppler Effect**

Wiley observed that two targets positioned differently along the track of an aircraft would be at different angles relative to the aircraft's velocity vector. As a result, these targets would exhibit different Doppler frequencies.

* **Doppler Effect:** As the radar moves, objects ahead of the radar appear to have a slightly higher frequency in the returned signal, while objects behind have a slightly lower frequency.

**3. Doppler Beam Sharpening**

Using the Doppler effect, targets could be distinguished in the along-track direction based on their varying Doppler frequencies. This capability allowed for much finer resolution than was possible with traditional radar techniques. Initially, this method was termed "Doppler beam sharpening."

* **Using Frequency Differences:** By analyzing these slight differences in frequency (Doppler shifts), the radar can distinguish between objects that are close together along the direction of flight. This helps in creating a sharper and more detailed image.

**4. Evolution to Synthetic Aperture Radar (SAR)**

The concept of Doppler beam sharpening eventually evolved into what is now known as synthetic aperture radar (SAR).

* coherent radar : The radar compares the phase of the returned signal with the phase of the transmitted signal. This comparison helps determine the exact position and velocity(speed) of the object.

1. **Coherent Integration**: This method involves adding the radar returns from multiple pulses while preserving the phase information. [This technique is highly effective in increasing the SNR because the signals are added in phase, but it requires the target to have a stable radar cross-section (RCS) over the integration period1](https://www.radartutorial.eu/10.processing/Pulse%20Integration.en.html).
2. **Non-Coherent Integration**: In this method, the phase information is discarded, and only the magnitudes of the radar returns are summed. [While this approach is less effective in improving the SNR compared to coherent integration, it is useful when the target’s RCS fluctuates2](https://www.mathworks.com/help/radar/ug/introduction-to-integration-and-fluctuation-losses-in-radar.html).

**5. Impact and Applications**

The development of SAR has had profound implications for various fields, including remote sensing, surveillance, and environmental monitoring. SAR's ability to provide high-resolution images regardless of weather conditions or lighting makes it an invaluable tool for both civilian and military applications.

**6. Summary**

Carl Wiley's insight into Doppler frequency analysis laid the groundwork for synthetic aperture radar, transforming radar imaging capabilities. By utilizing the Doppler effect to differentiate targets based on their relative motion, SAR technology has revolutionized our ability to capture detailed images of the Earth's surface.

imagine the radar is moving along a straight line. As it gets closer to the target, the distance between the radar and the target decreases until it reaches the closest point. After that, the distance starts increasing again as the radar moves away. This equation calculates that changing distance at any moment in time.

* The first equation calculates the exact distance between the radar and the target as the radar moves.
* The second equation is a simpler version that's easier to use, and it's still accurate enough when the radar is moving slowly compared to how far it is from the target.
* The nadir line is an imaginary line drawn directly downward from the radar platform to the ground. It represents the point on the ground directly below the radar at any given time

This formula calculates the phase of a signal after it undergoes range compression. Here's what the terms represent:

* ϕ(s): Represents the phase of the signal at a specific point in time (s).
* R(s): Represents the range (distance) of the target at time s.
* λ: Represents the wavelength of the signal.
* Ro: Represents a reference range (a fixed distance).
* ν: Represents the frequency of the signal.

The formula essentially states that the phase of the signal is related to the range of the target, the wavelength of the signal, and a reference range.

* f(s): Represents the instantaneous frequency of the signal at time s.
* ϕ(s): Represents the phase of the signal at time s, as calculated in the previous formula.
* ν: Represents the frequency of the signal.
* R0: Represents the reference range.
* λ: Represents the wavelength of the signal.

The formula essentially states that the instantaneous frequency of the signal is related to the rate of change of its phase.

1. **Equal to half the size of the physical antenna**: This means that the resolution in the azimuth direction is determined by the length of the radar antenna. Specifically, the resolution is half the length of the antenna. For example, if the antenna is 2 meters long, the azimuth resolution would be 1 meter.

**Radar Image Artifacts and Noise**

* range and azimuth ambiguities
* The leading edge of each echo corresponds to the near edge of the image scene; the tail end of the echo corresponds to the far edge of the scene
* The length of the echo is determined by the antenna beam width or the size of the data window used in the recording of the signal.
* If the timing of the pulses or the extent of the echoes is such that the leading edge of one echo overlaps with the tail end of the previous one, then the far edge of the scene is folded over the near edge of the scene. This is called range ambiguity.
* The **temporal extent of the echo** refers to the duration of time over which a radar pulse's echo is received after it has been transmitted and reflected off the surface being imaged. . The temporal extent of the echo is equal to:
* **PRF (Pulse Repetition Frequency):**
  + The number of radar pulses transmitted per second.
  + A higher PRF means pulses are transmitted more frequently.
* **c:**
  + The speed of light, which is approximately 3×108 meters per second.

3×1083 \times 10^8

* **W:**
  + The width of the radar antenna.
  + Affects the beam's footprint on the ground and thus the duration of the echo.
* **h:**
  + The height (altitude) of the radar platform above the surface being imaged.
* **λ:**
  + The wavelength of the radar signal.
* **θ:**
  + The angle between the radar beam and the vertical direction, often referred to as the **look angle**.
* side lobes of the point spread function
* The vast majority of these artifacts and ambiguities can be avoided with proper selection of the sensor and processor parameters

**Geometric Effects and Projections**

* In extremely rugged terrain, however, the nature of the radar image projection leads to distortions that sometimes cannot be corrected without knowledge of the terrain elevations.

**1. Foreshortening**

* **Definition**: Foreshortening occurs when areas that slope toward the radar sensor appear compressed or shorter in the radar image.
* **Cause**: This happens because the radar waves hit the slope at a steeper angle, causing the return signals to be received in a shorter time span.
* **Effect**: Objects or terrain features that slope toward the radar sensor will look shorter in the image compared to their actual size.

**2. Layover**

* **Definition**: Layover occurs when the slope of the terrain is steeper than the radar’s incidence angle, causing the top of the slope to appear closer to the radar than the base.
* **Cause**: When the slope angle exceeds the radar’s incidence angle, the radar waves hit the top of the slope before the base, making the top appear to be “laid over” the base in the image.
* **Effect**: This results in a distortion where the hill or slope looks as if it is projected over the area in front of it. Layover cannot be corrected and is best avoided by choosing an incidence angle larger than any expected surface slopes.

**3. Shadowing**

* **Definition**: Shadowing occurs when the radar waves do not illuminate the area on a slope facing away from the radar sensor, resulting in a dark or unilluminated area in the radar image.
* **Cause**: If the slope facing away from the radar is steep enough, the radar waves will not reach it, creating a shadow.
* **Effect**: The shadowed area will not be imaged, appearing as a dark region in the radar image. Unlike optical images, radar shadowing is always away from the sensor flight line and is not influenced by the time of day or the Sun’s angle

**Signal Fading and Speckle**

* A close examination of a synthetic-aperture radar image shows that the brightness variation is not smooth but, instead, has a granular texture that is called speckle.

• **Signal Standard Deviation (S\_N)**: The standard deviation of the signal (S\_N) is related to the mean signal power (P) by the equation This means that as you increase the number of looks (N), the standard deviation (variation) of the signal decreases, leading to a smoother image.

**Radar Signal Properties**

* **Noise-like Radar Signal**: The radar signal can be quite noisy, meaning it has a lot of random variations.
* **Statistical Properties**: The amplitude (strength) of the signal follows a Rayleigh distribution, and the power (intensity) of the signal follows an exponential distribution.

**Reducing Noise (Speckle)**

* **Incoherent Averaging**: By averaging the power values of successive signals or neighboring pixels, we can reduce the brightness fluctuations (speckle). This makes the image look smoother and more accurate, but it can reduce the image resolution.
* **Combining Images at Different Frequencies**: Another way to reduce speckle is to combine images taken at slightly different frequencies. This results in independent signals with the same statistical properties, and averaging them smooths out the image

**Smoothing in SAR Images**

* **Averaging Brightness**: In Synthetic Aperture Radar (SAR) images, smoothing is often done by averaging the brightness of neighboring pixels in the azimuth (along-track) or range (across-track) directions, or both.
* **Number of Looks (N)**: The number of independent pixels averaged is called the number of looks (N).