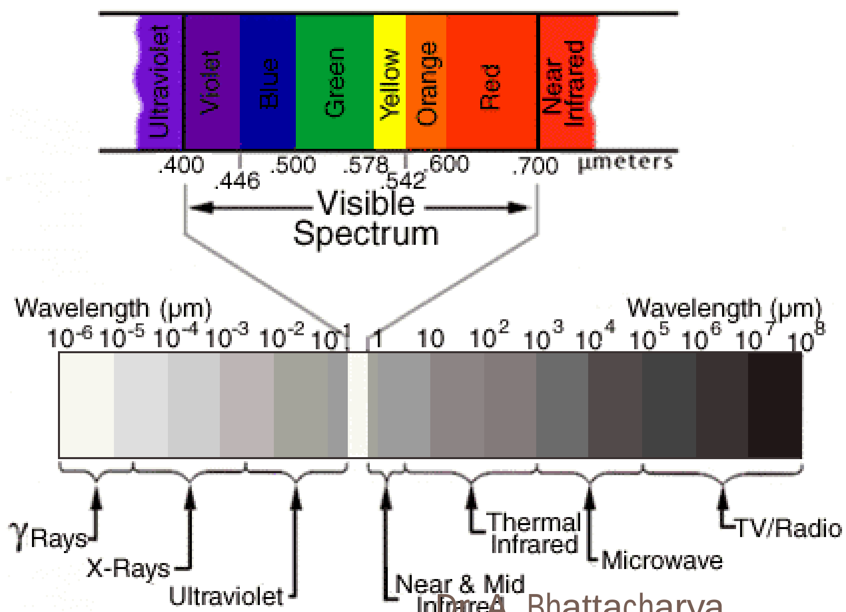
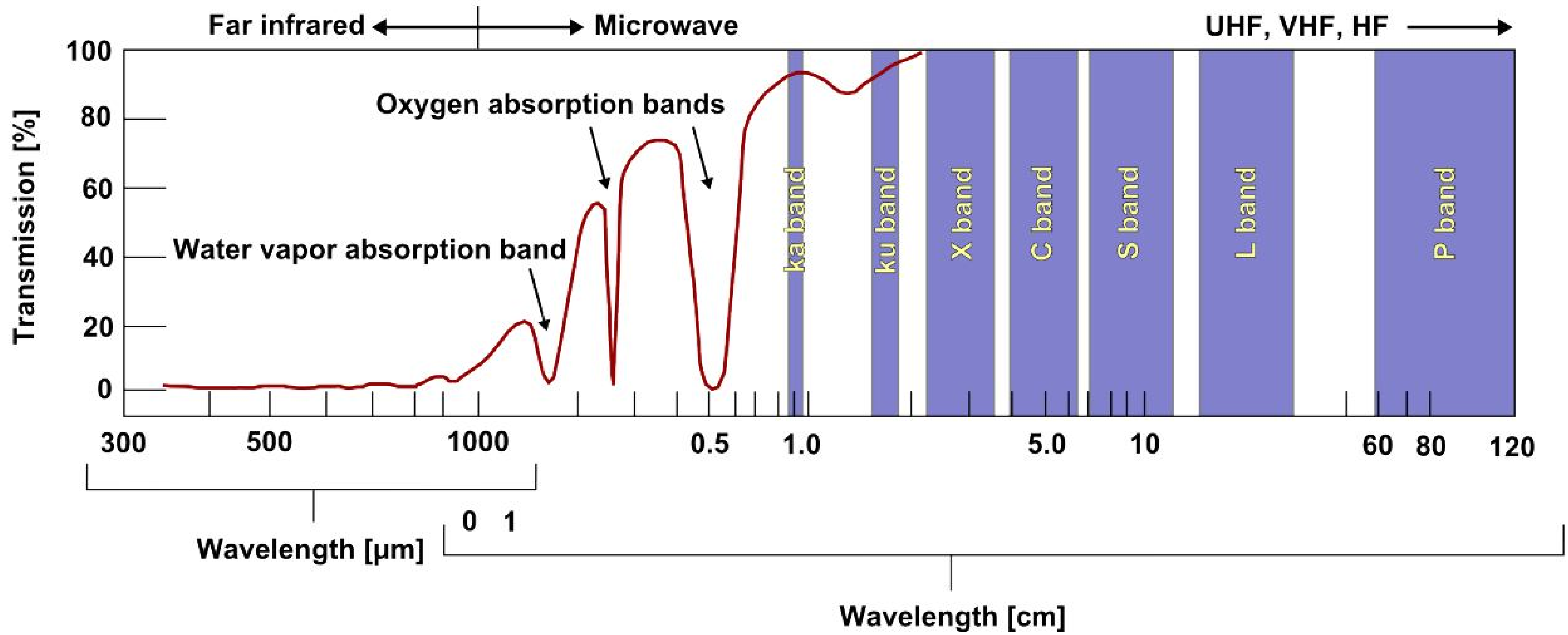
BASICS OF MICROWAVE REMOTE SENSING

Remote Sensing Fundamental

- **The entire range of EM radiation constitute the EM Spectrum**
- **Microwave sensors sense electromagnetic radiations in the microwave region of the EM Spectrum**

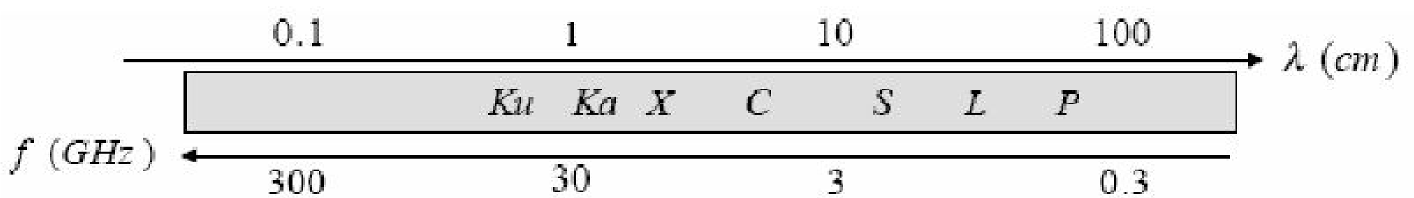


Radar wavelengths



Radar wavelengths

Frequency band	Wavelength (cm)	Frequency (GHz)
Ka	0.8-1.1	40 - 26.5
K	1.1-1.7	26.5 - 18
Ku	1.7-2.4	18 - 12.5
X	2.4-3.8	12.5 -8
C	3.8-7.5	8 - 4
S	7.5-15	4 - 2
L	15 -30	2 - 1
P	30 -100	1 - 0.3



f (in Hertz)=C/λ

C=3.10^8 m
λ =wavelength in m

RADAR

- Radar is an acronym for *<u>R</u>adio <u>D</u>etection <u>A</u>nd <u>R</u>anging.*
- A Radar system has three primary functions:
  - It transmits microwave (radio) signals towards a scene
  - It receives the portion of the transmitted energy backscattered from the scene
- It observes the strength (detection) and the time delay (ranging) of the return signals.
- Radar provides its own energy source and, therefore, can operate both day or night and through cloud cover. This type of system is known as an active remote sensing system.

Characteristics of radar remote sensing

- **Advantages compared to optical remote sensing**
  - **All weather capability (small sensitivity of clouds, light rain)**
  - **Day and night operation (independence of sun illumination)**
  - **No effects of atmospheric constituents (multitemporal analysis)**
  - **Sensitivity to dielectric properties (water content , biomass, ice)**
  - **Sensitivity to surface roughness (ocean wind speed)**
  - **Accurate measurements of distance (interferometry)**
  - **Sensitivity to man made objects**
  - **Sensitivity to target structure (use of polarimetry)**
  - **Subsurface penetration**

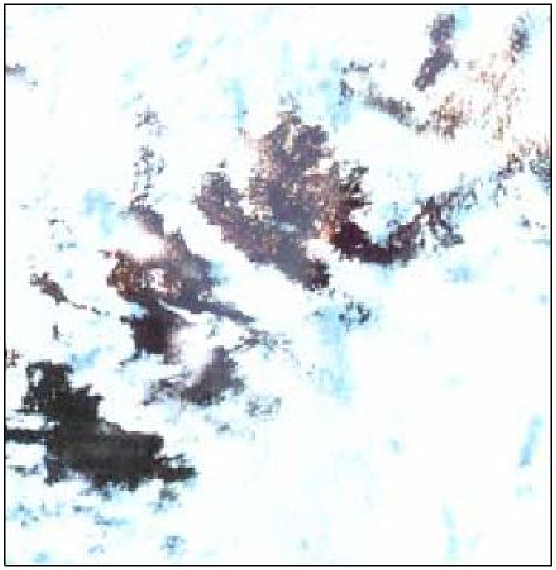
Characteristics of radar remote sensing

- **Inconvenients**

  - **Complex interactions (difficulty in understanding, complex processing)**
  - **Speckle effects (difficulty in visual interpretation)**
  - **Topographic effects**
  - **Effect of surface roughness**

All-weather system

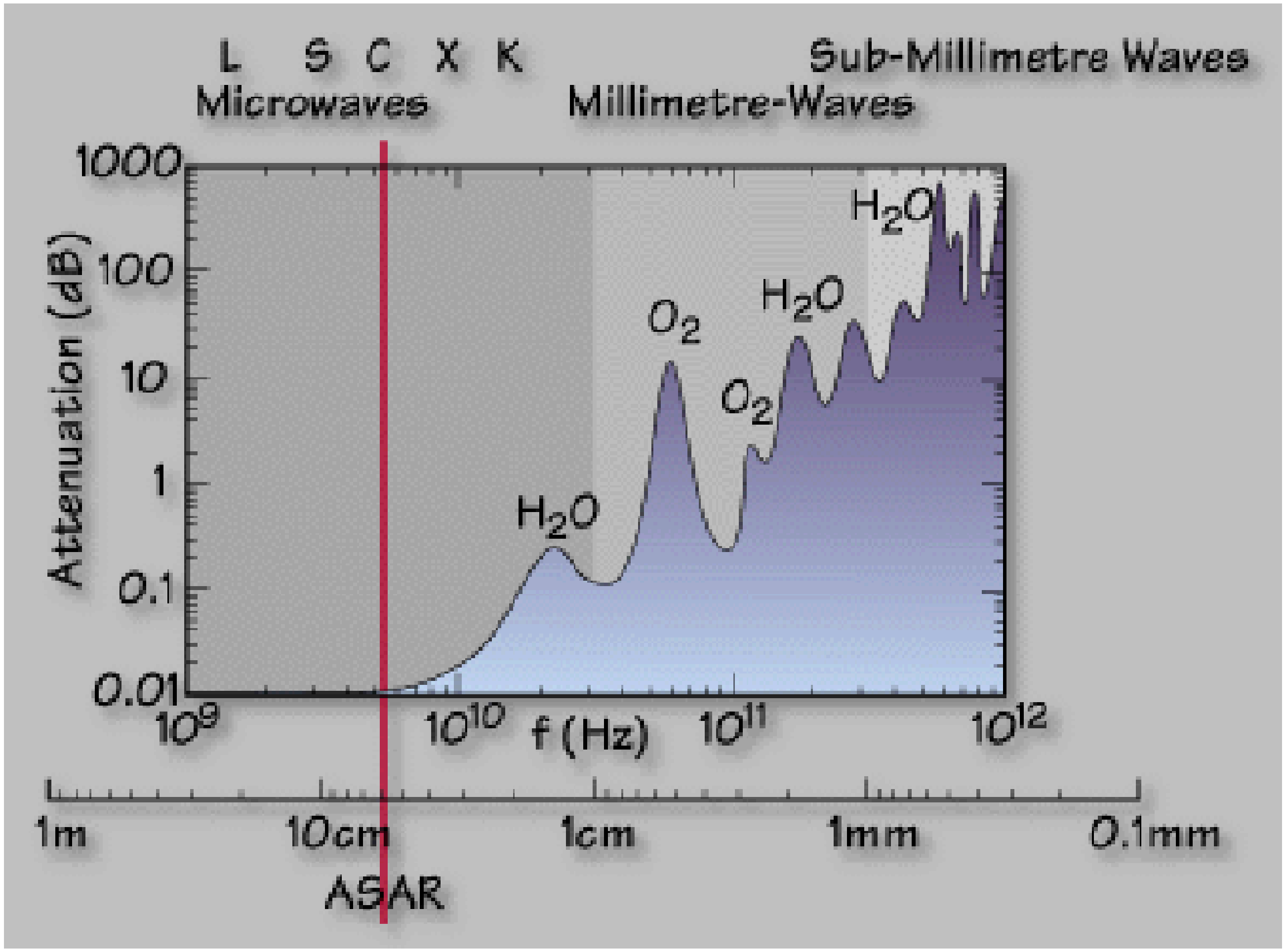
- An *' all-weather ' imaging system*
  - A microwaves system: cloud penetrating capabilities



ERS-1 SAR, 11.25 a.m. LANDSAT TM, 9.45 a.m.

Ireland, 09/08/1991

Marginal atmospheric effects



Effects of cloud and rain on microwave

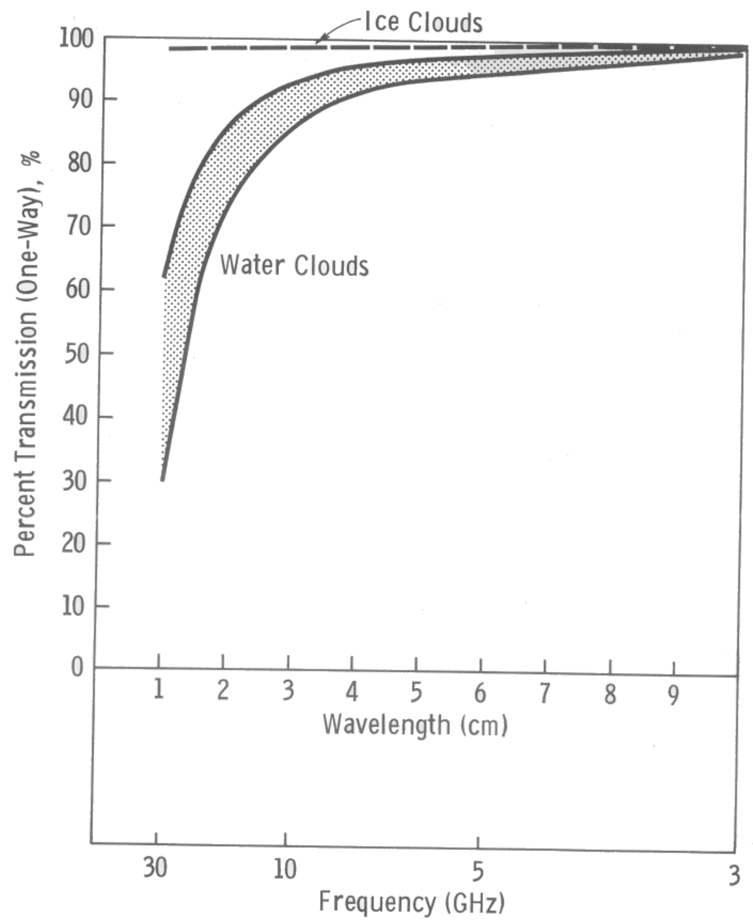
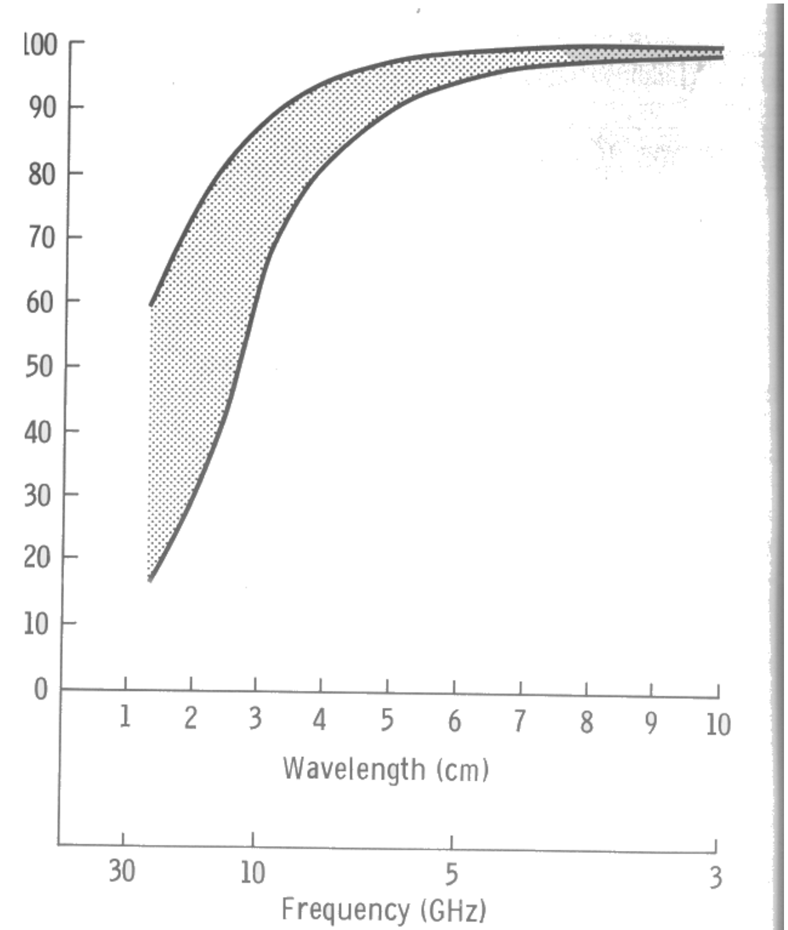


Fig. 1.1 Effect of cloud on radio transmission from space to ground.



Effect of rain on radio transmission from space to ground.

Effect of Rainfall on X-SAR images

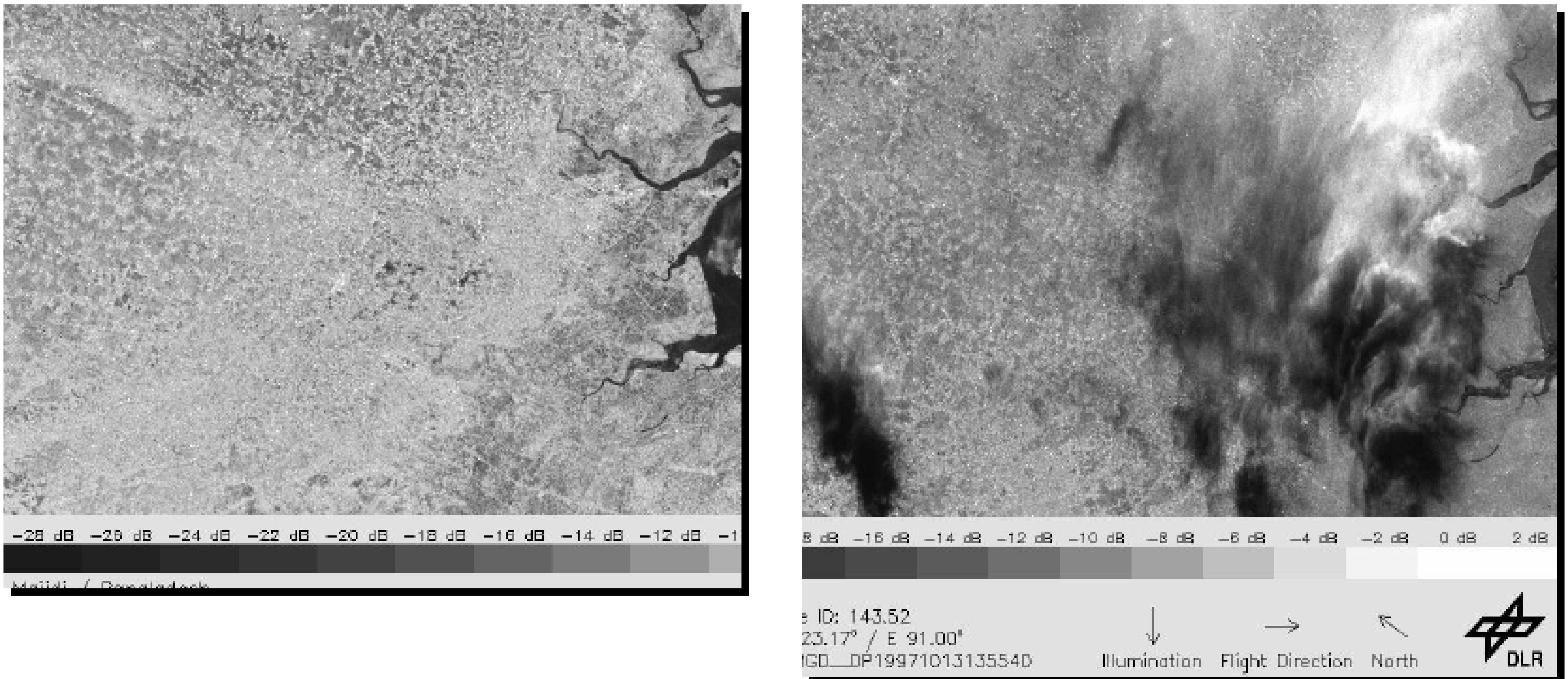


Fig. 1. Left: View around Noakhali, Bangladesh (22.8° N×91.2° E) on 7 October 1994 with no rain present. Right: Same scene on 18 April 1994. Note scattering by frozen hydrometeors in the upper right, scattering and attenuation by rain in middle-lower right, and absorption mainly by rain with little ice in the lower left. The maximum NRCS of the scattered signal is ∼−3 dB and the minimum NRCS value in the shaded area is ∼−30 dB.

Why Use Radar for Remote Sensing?

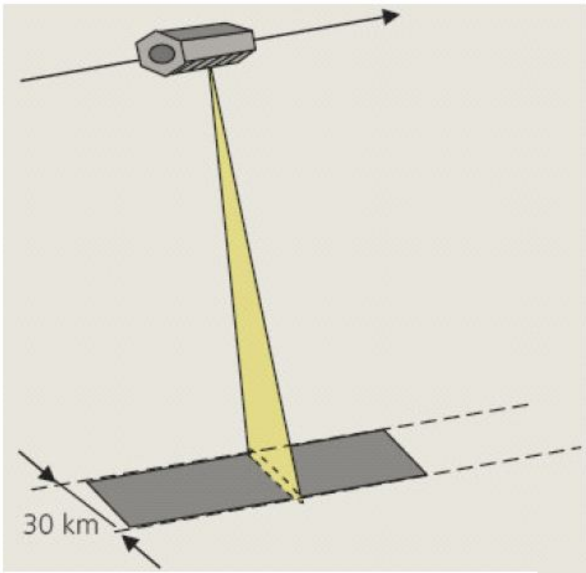
- Controllable source of illumination
  - sees through cloud and rain, and at night
- Images can be high resolution (3 - 10 m)
- Different features are portrayed or discriminated compared to visible sensors
- Some surface features can be seen better in radar images:
  - ice, ocean waves
  - soil moisture, vegetation mass
  - man-made objects, *e.g. buildings*
  - geological structures

Types of Microwave Remote Sensors

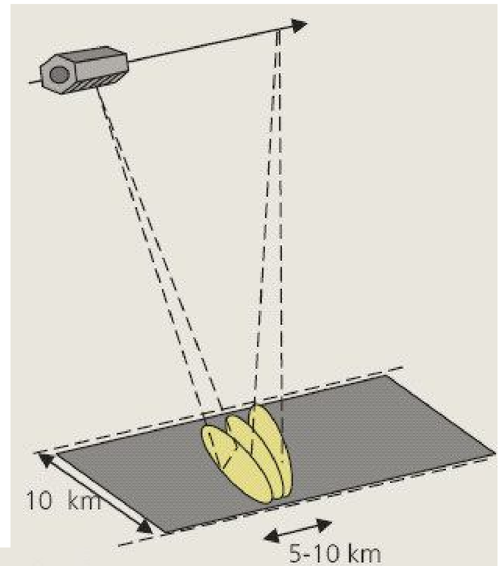
- **Microwave radiometers**
- **Measure the emittance of EM energy within the microwave region of the EM spectrum, just like thermal IR sensors**
- **– Non-imaging RADARs**
  - **1. Altimeters – measure the elevation of the earth's surface**
  - **2. Scatterometers – detect variations in microwave backscatter from a large area - measure variations in surface roughness, used to estimate ocean wind speed**
- **– Imaging RADARs**
  - **Synthetic Aperture Radars – map variations in microwave backscatter at fine spatial scales (10 to 50 m), used to create an image – measure variations in surface roughness and surface moisture**

Active Sensor Systems and System Parameters

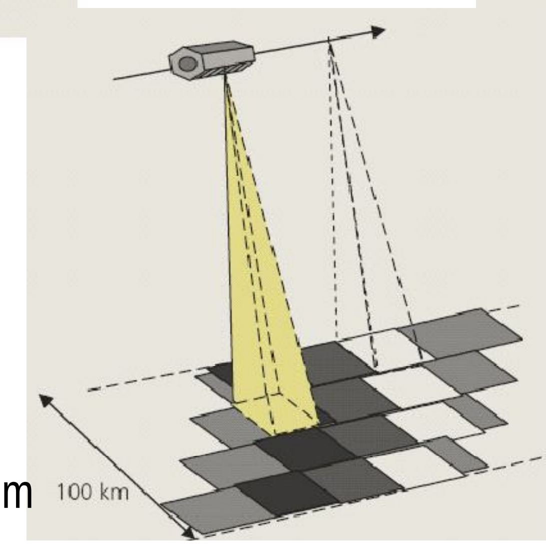
Various Imaging Modes



StripMode
Resolution: 3m

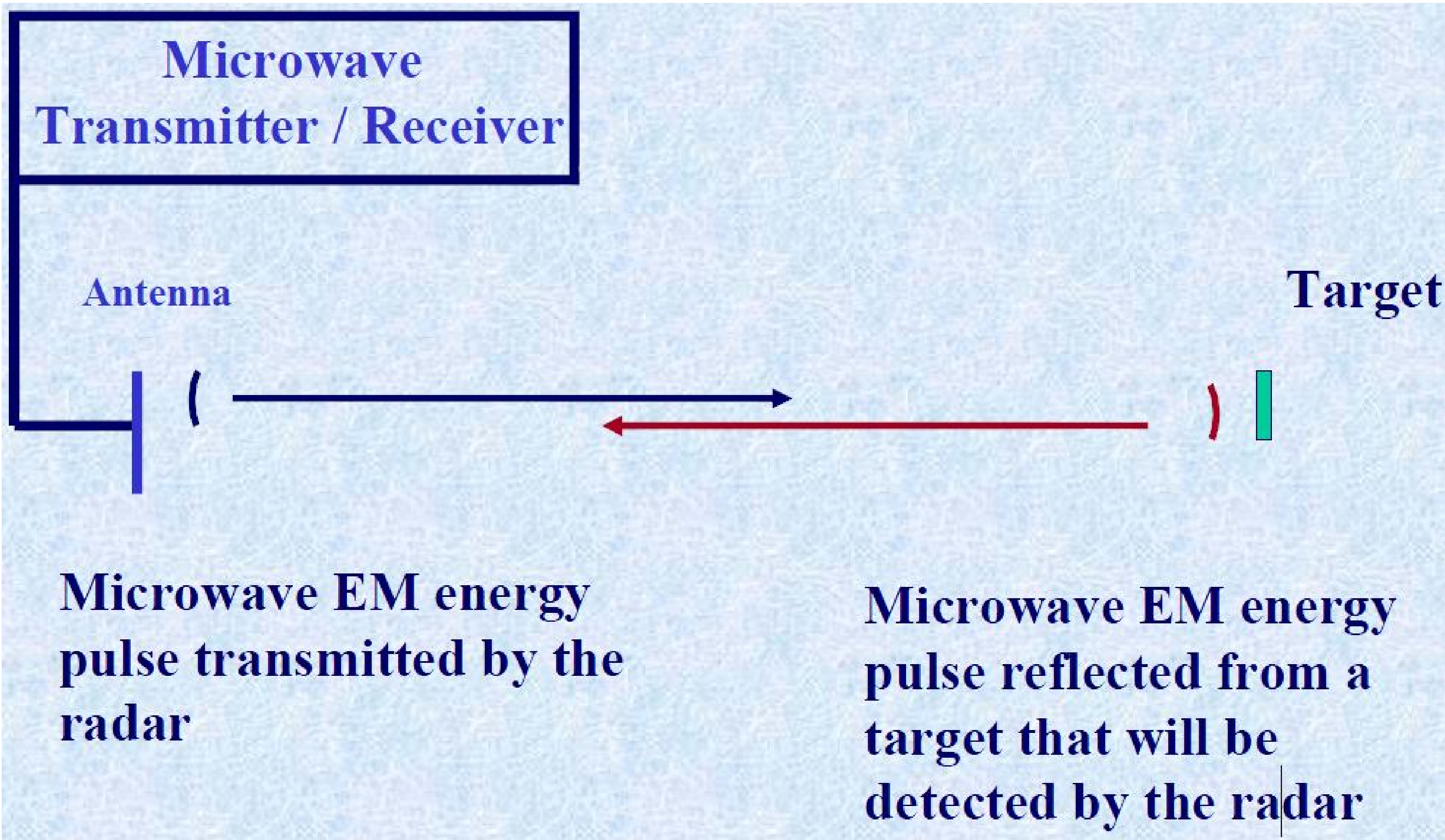


Spotlight
Resolution: 1 m

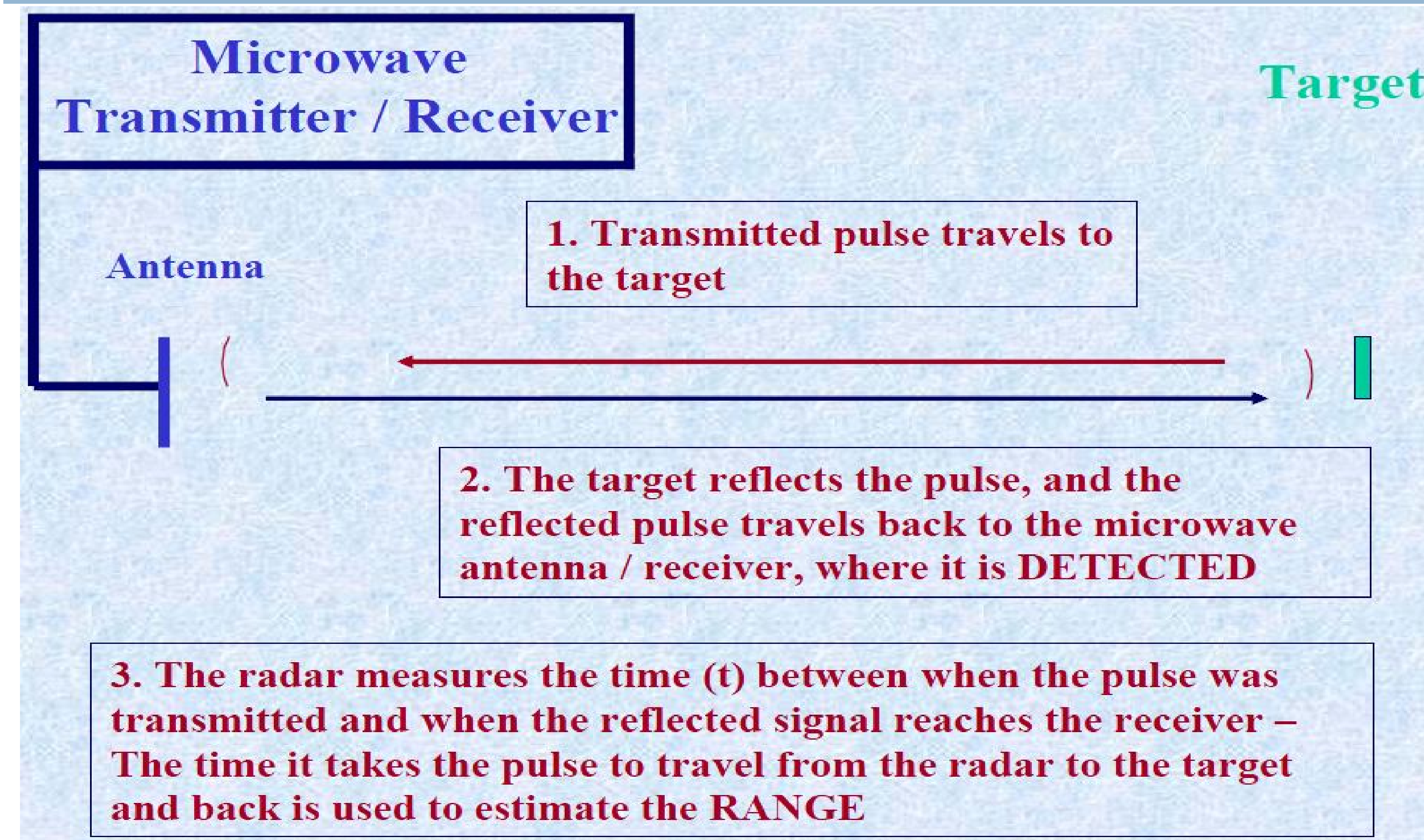


ScanSAR
Resolution: 16 m

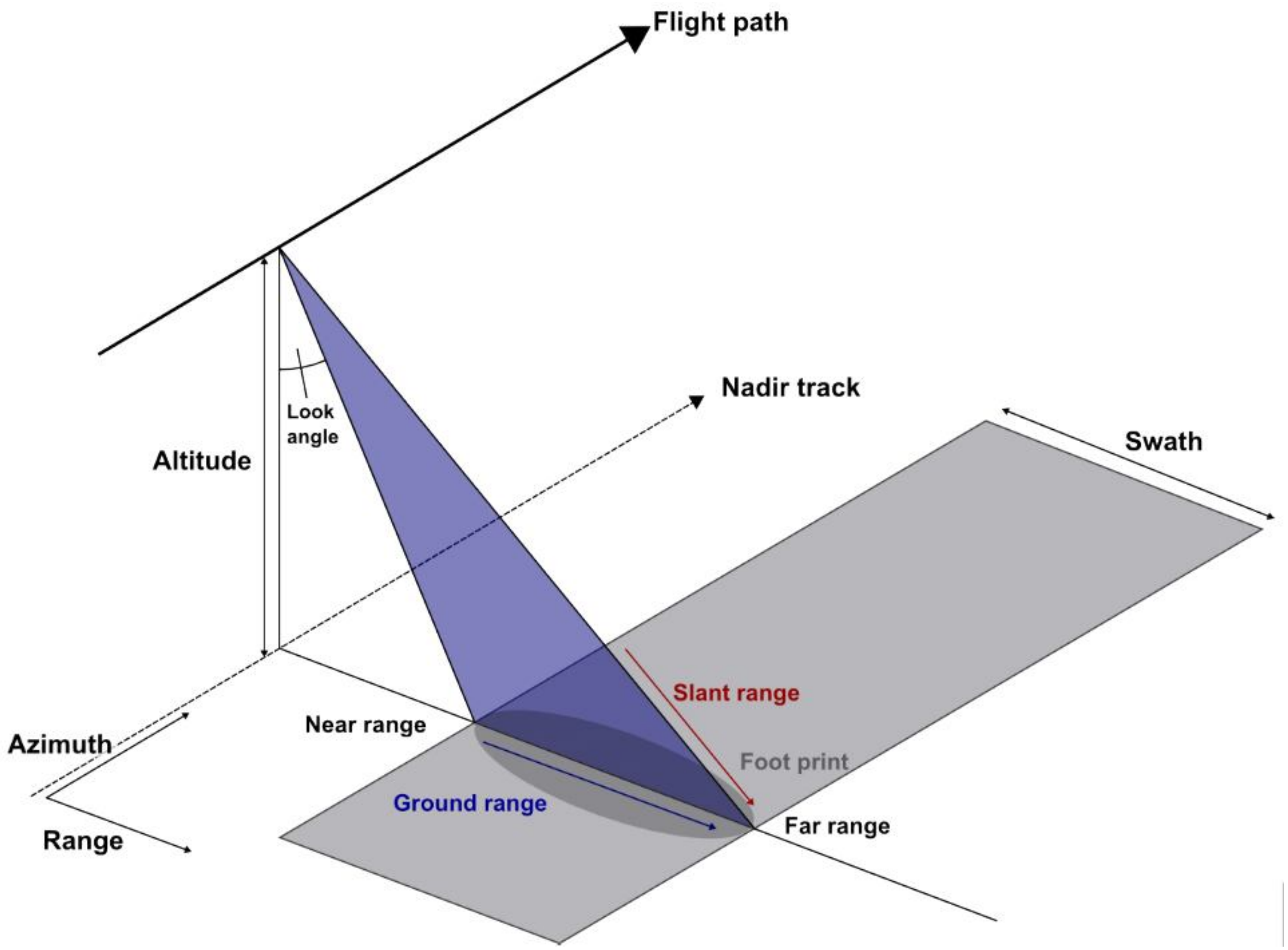
Microwave measurements



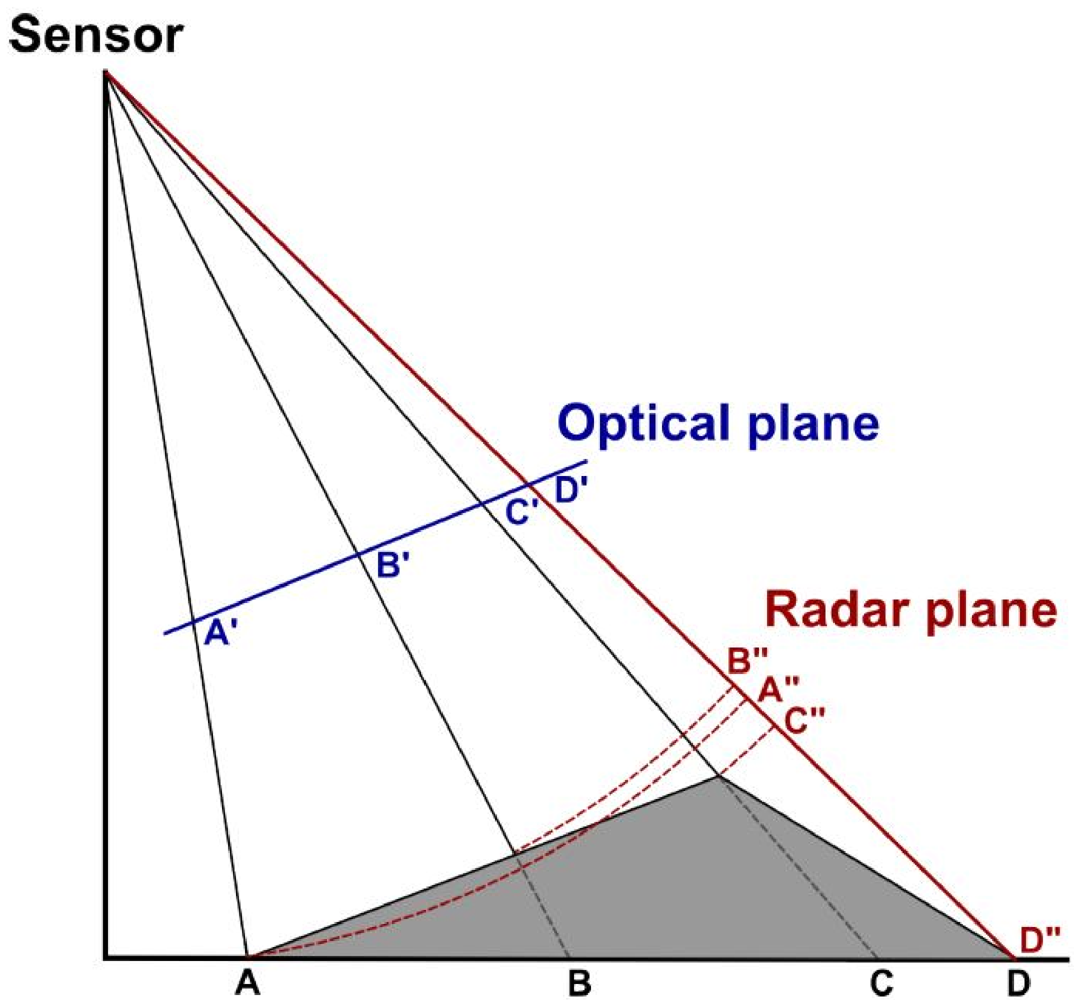
Microwave measurements



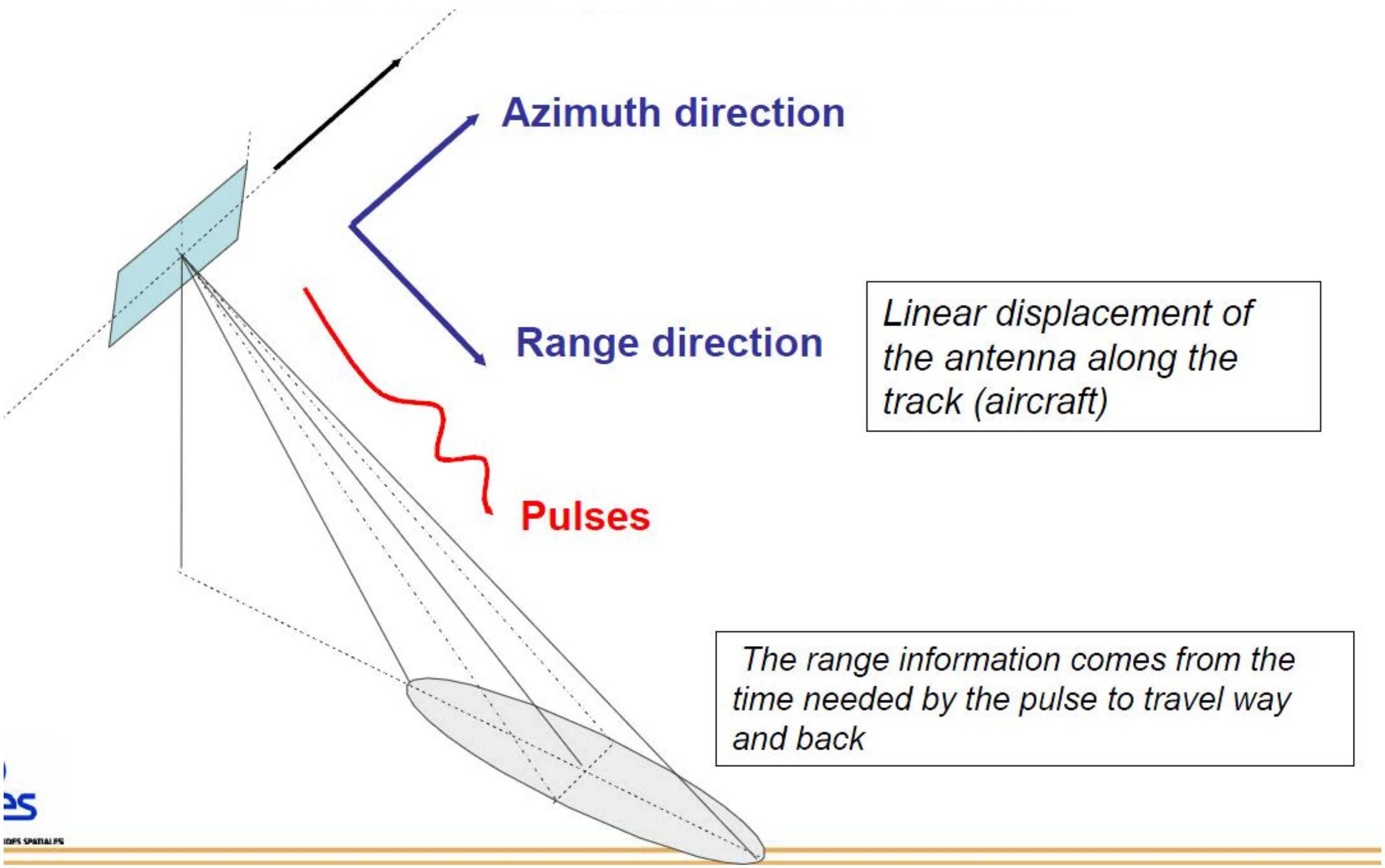
Radar geometry



Optical versus radar



Side-Looking Radar



Resolution

- Since SAR is an active system, the actual sensor resolution has two dimensions: range resolution and azimuth resolution. Resolution of a SAR sensor should not be confused with pixel spacing which results from sampling done by the SAR image processor.

- Range :
- Range resolution of a SAR is determined by built-in radar and processor constraints which act in the slant range domain. Range resolution is dependent on the length of the processed pulse; shorter pulses result in “higher” resolution. Radar data are created in the slant range domain, but usually are projected onto the ground range plane when processed into an image.

- Azimuth :
- For a real aperture radar, azimuth resolution is determined by the angular beamwidth of the terrain strip illuminated by the radar beam. For two objects to be resolved, they must be separated in the azimuth direction by a distance greater than the beam width on the ground. SAR gets its name from the azimuth processing and can achieve an azimuth resolution which may be hundreds of times smaller than the transmitted antenna beam width.

Range Resolution

The ability of the radar to distinguish two targets in the range direction.

$$\Delta R = c\tau/2 = PL/2$$

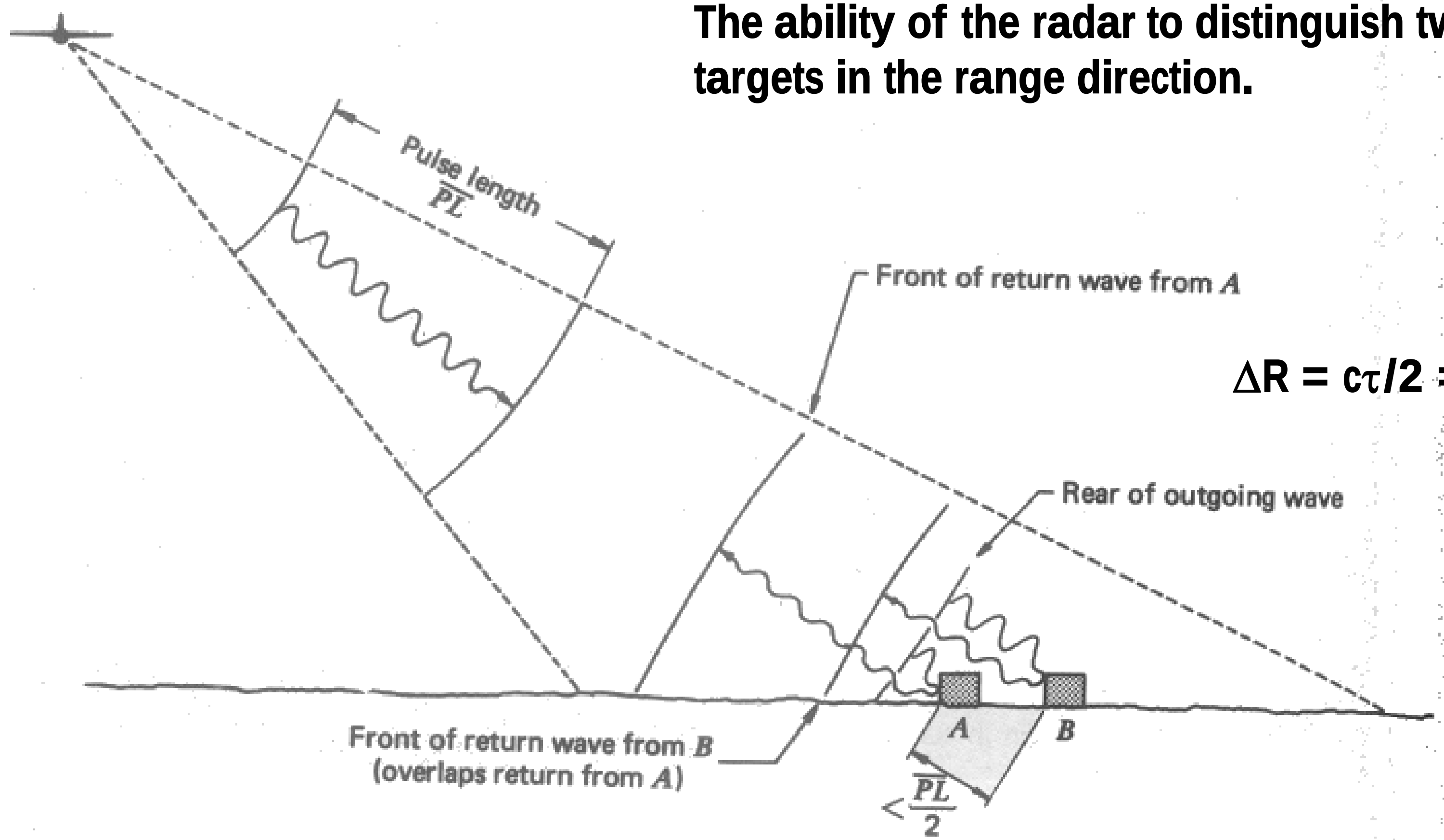
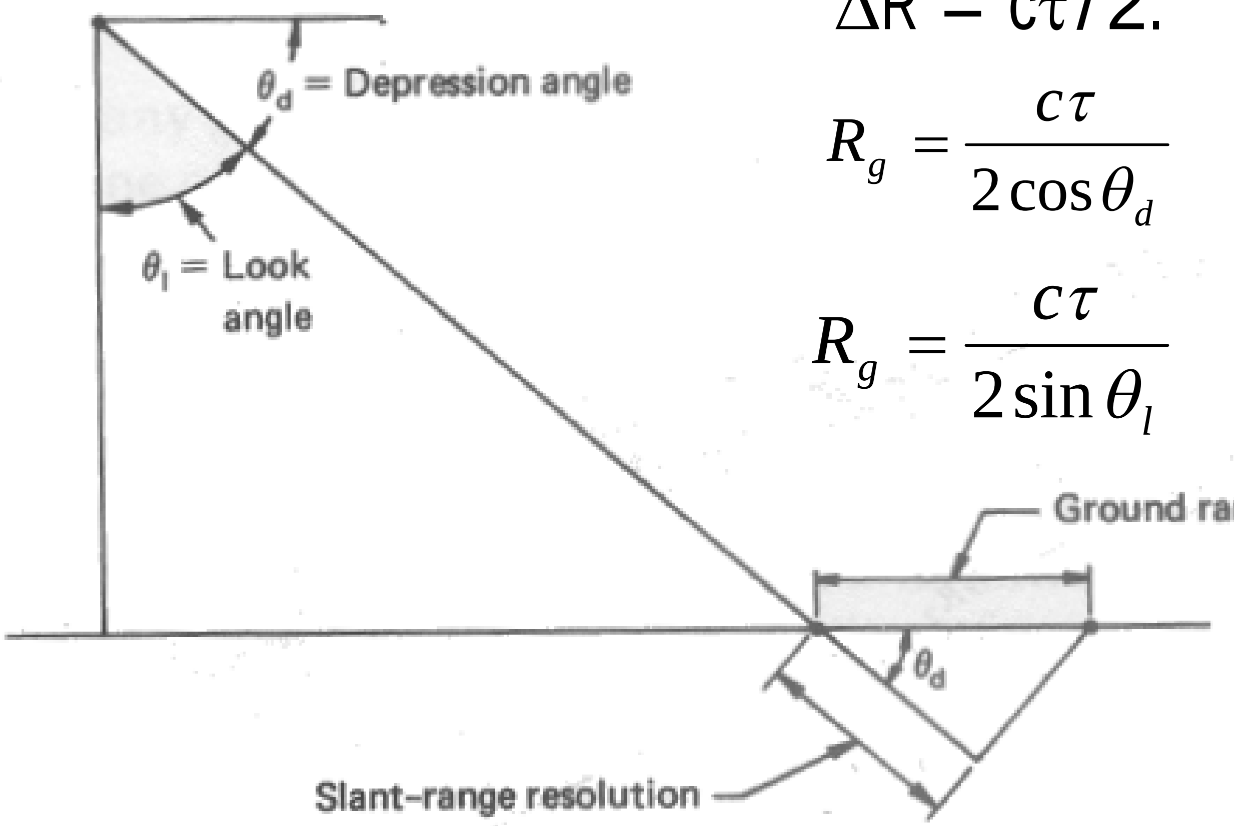


Figure 8.5 Dependence of range resolution on pulse length.

Range and Ground Resolutions

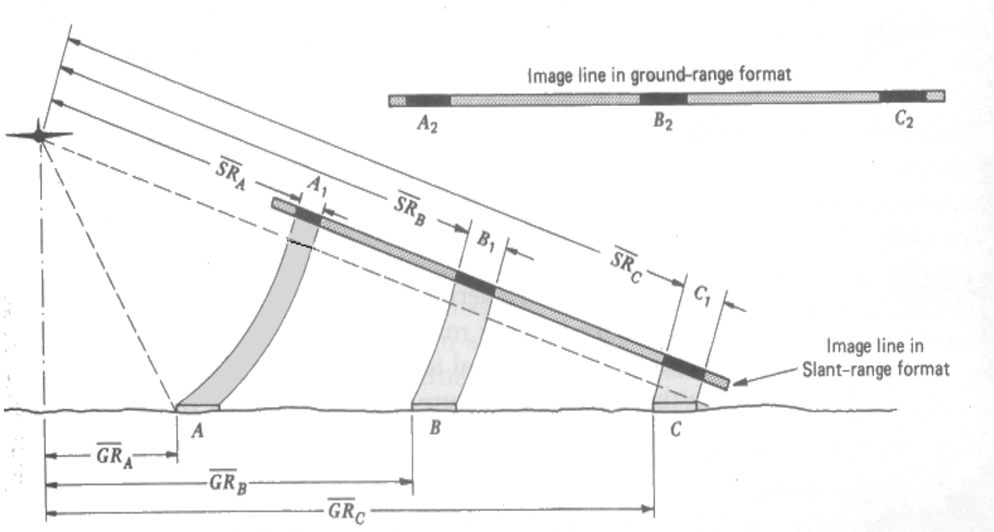


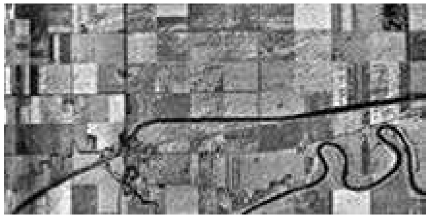
$$\Delta R = c\tau / 2.$$

$$R_g = \frac{c\tau}{2\cos\theta_d}$$

$$R_g = \frac{c\tau}{2\sin\theta_l}$$ Since $\theta_d = 90 - \theta_l$

Slant Range to Ground Range Conversion





Geometry of Radar Data collection

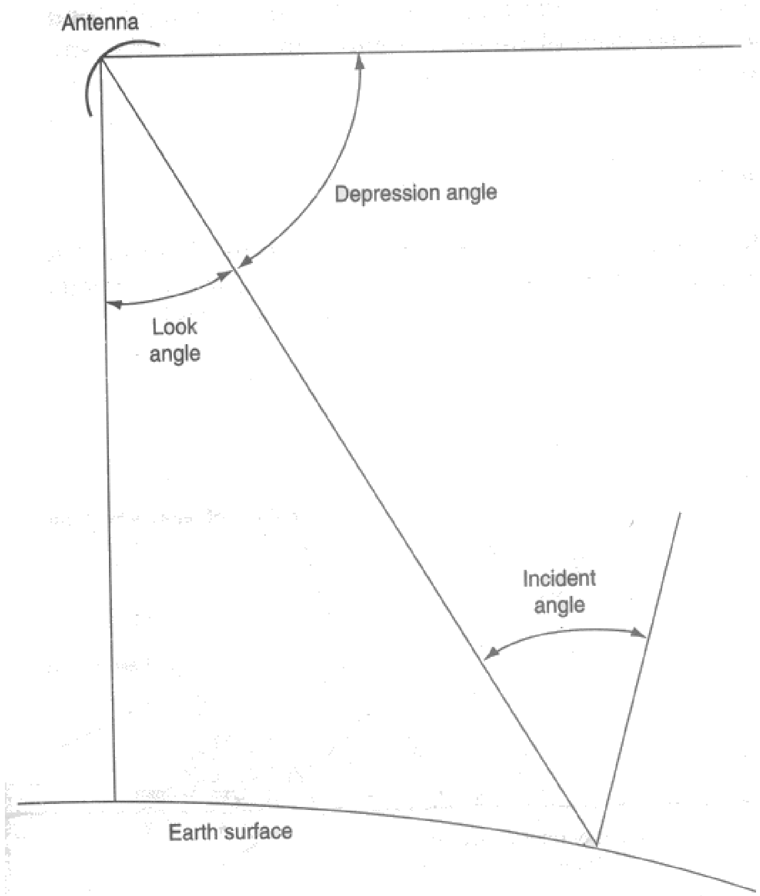
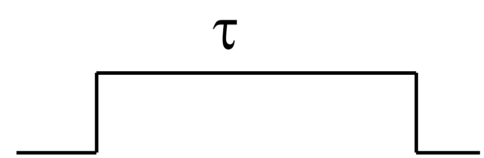


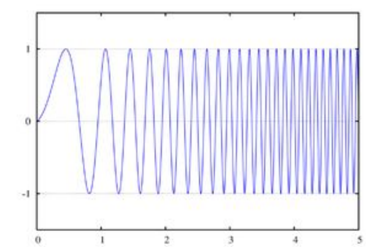
Figure 8.4 Nomenclature for the geometry of radar data collection.

Range Resolution (Examples)

- ERS-1 SAR Pulse length τ = 37.12 μs
- Range Resolution = $c\tau/2$ = $3.0 \times 10^8 \times 37.12 \times 10^{-6}/2$ = 5568 m = 5.568 km



- How to get high resolution ?
- Pulse Compression Techniques to improve Range Resolution
  - After pulse compression techniques the
  - Range Resolution = C/(2B) = $3.0 \times 10^8/(2. \times 15.5 \times 10^6)$ = 9.677 meters (Where $B=1/\tau$ is bandwidth)
  - Ground Range = C/[2.B.sin(23^0)] = 24.76 m
  - Compressed pulse length = 64 ns = 1/Bandwidth
  - Sampling frequency (fs)= 18.96 MHz. So range pixel size = C/(2*fs)=7.9 m



High resolution (Range)

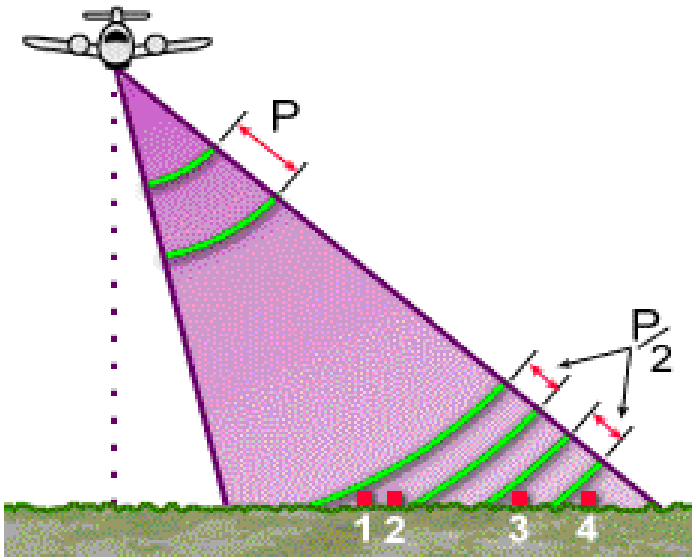
- **Pulse Length = 2 μs to 65 μs**
- **Bandwidth = 150 MHz nominal, 300 MHz high resolution**

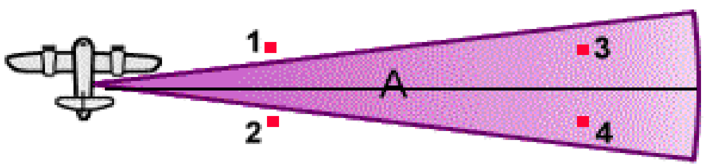
Range Resolution = C/(2B) = $3.0 \times 10^8 / (2 \times 150 \times 10^6)$

= 1 m (150 MHz)

and 0.5 m (300 MHz)

Azimuth Spatial Resolution





Range Resolution

SR= C*P/2

$R = C * P/(2 \sin \theta_i)$

Azimuth Resolution

$R_a = R * \beta$

β-Azimuth beam width.

Azimuth resolution

Elevation (θ_B) and Azimuth (Φ_B) Beam Widths

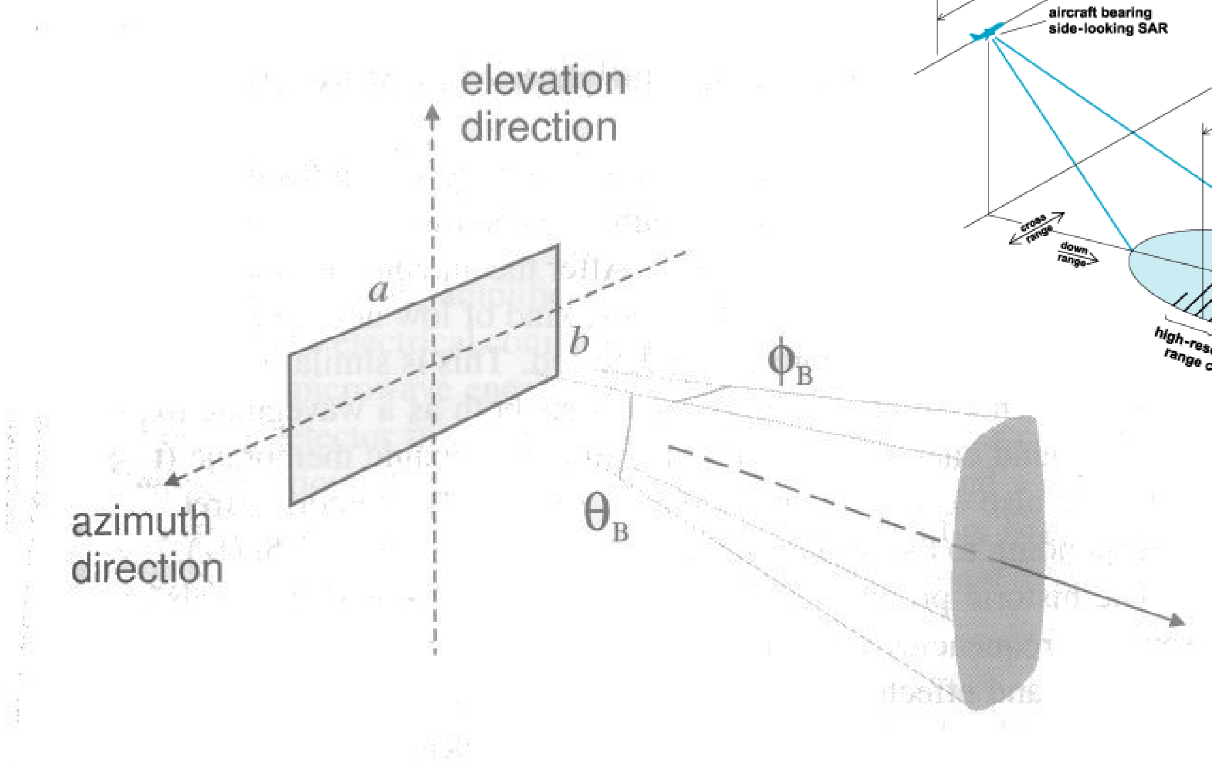
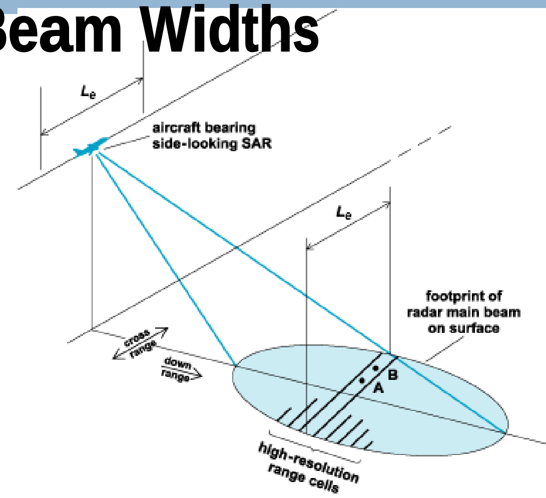
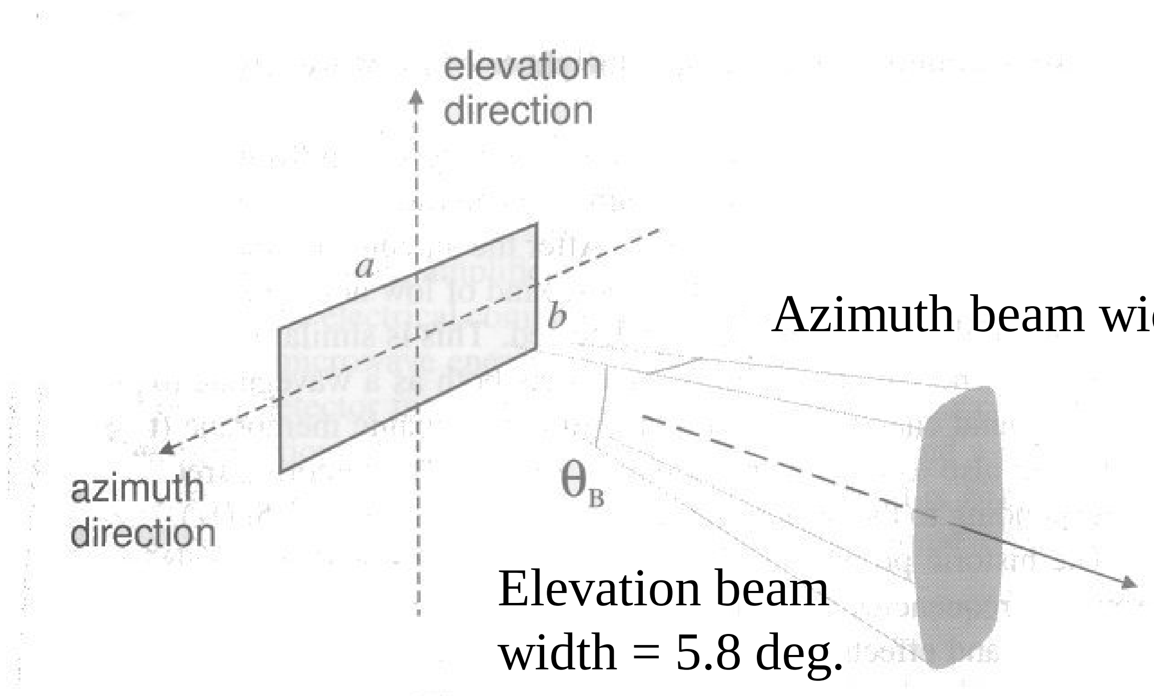


FIGURE 6.5 The definition of the angles within the beam of a rectangular antenna. Note that the thinner of the two angular beamwidths, ϕ_B, corresponds to the larger dimension of the antenna.



Azimuth resolution

Elevation (θ_B) and Azimuth (ϕ_B) Beam Widths



Azimuth beam width = 0.288 deg.

Elevation beam width = 5.8 deg.

FIGURE 6.5 The definition of the angles within the beam of a rectangular antenna. Note that the thinner of the two angular beamwidths, ϕ_B, corresponds to the larger dimension of the antenna.

Azimuth resolution

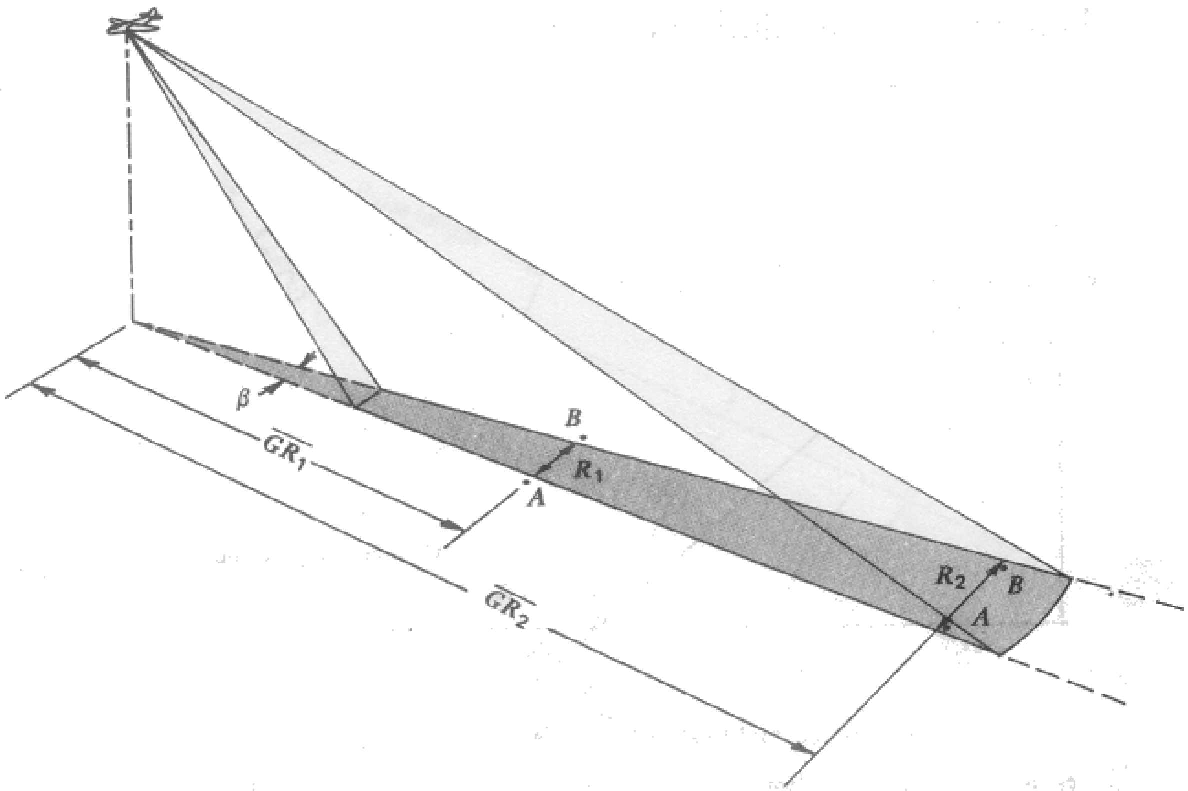


Figure 8.7 Dependence of azimuth resolution (R_a) on antenna beamwidth (β) and ground range ($\overline{GR}$).

$R_a = R.\beta$

$\beta = \lambda/L$

$R_a = R.\lambda/L$

Where L is length of antenna (10 m).

$R = H/\cos\theta_l$

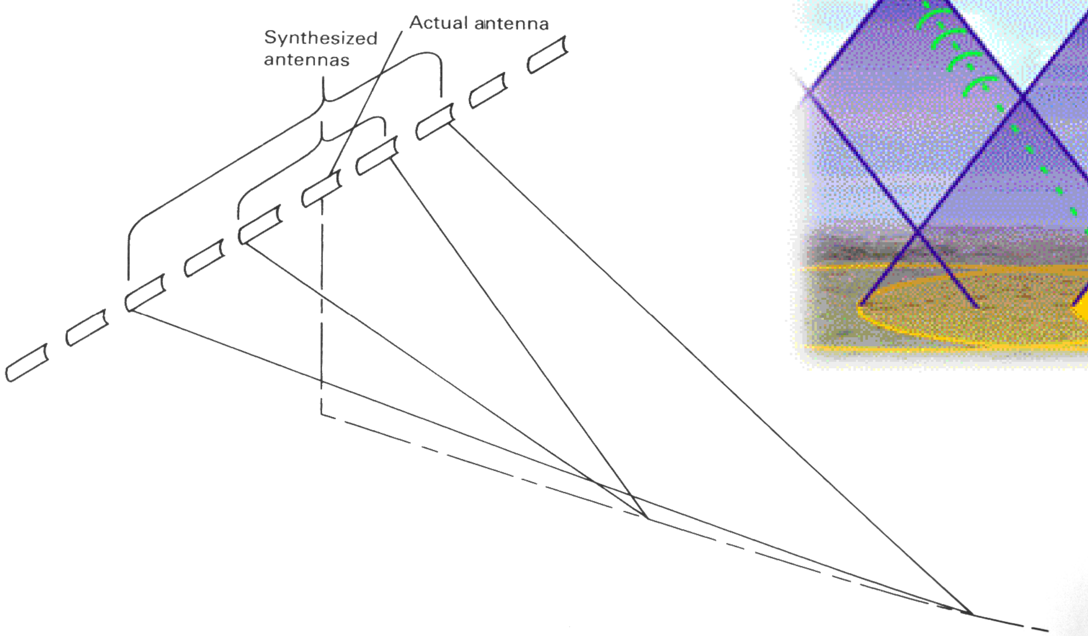
For H=10 km, $\theta_l = 23^0$, λ=5.66 cm

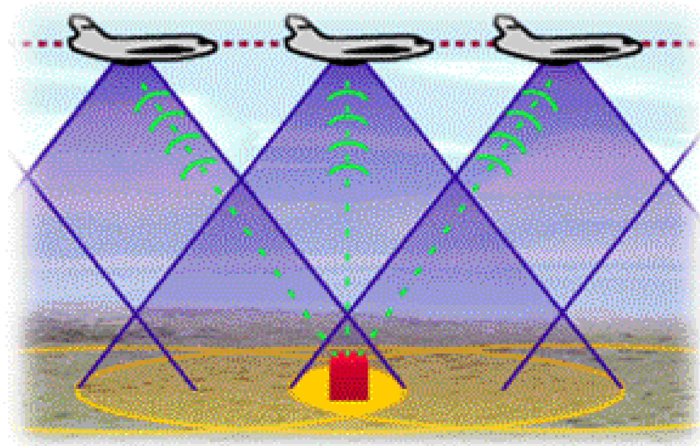
R_a= 60 meters

For H=765 km

R_a = 4.6978 km

Improvement in Azimuth Resolution !





Airborne or Spaceborne radar could collect data while flying over a large distance and then process the data as if it came from a physically long antenna. The distance the aircraft flies in synthesizing the antenna is known as the synthetic aperture.

What is Synthetic Aperture Radar (SAR)?

- A side-looking radar system which makes a high-resolution image of the Earth’s surface (for remote sensing applications)

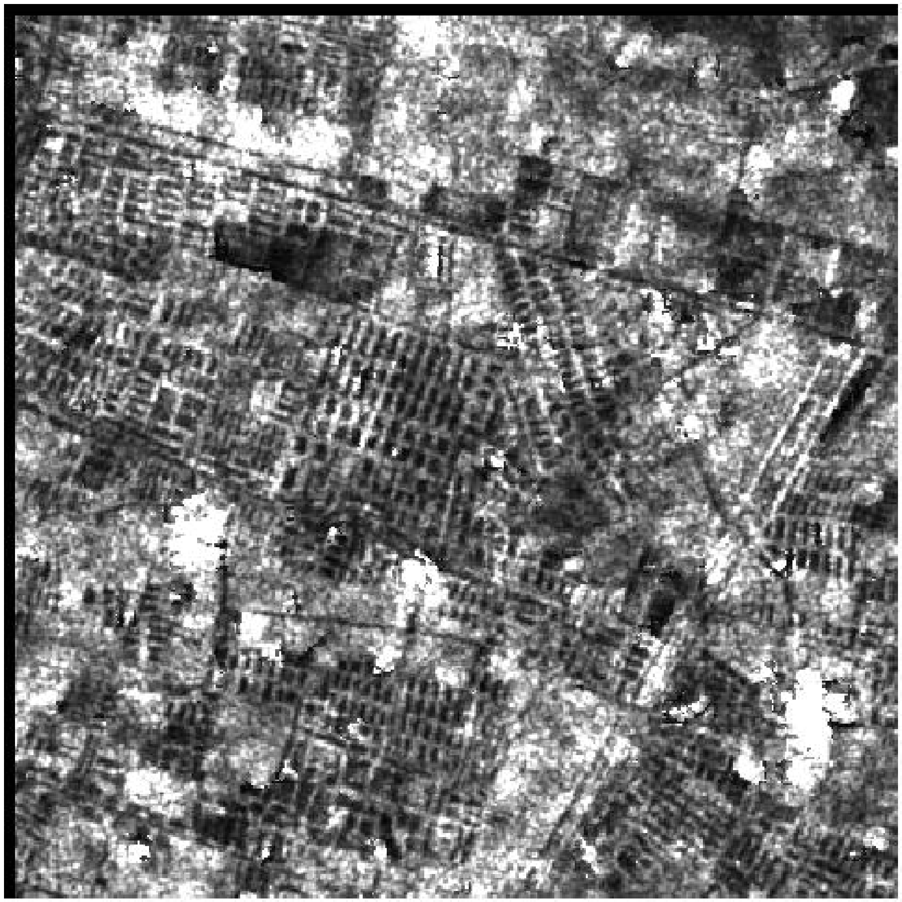
- As an imaging side-looking radar moves along its path, it accumulates data. In this way, continuous strips of the ground surface are “illuminated” parallel and to one side of the flight direction. From this record of signal data, processing is needed to produce radar images.

- The across-track dimension is referred to as “range”. Near range edge is closest to nadir (the points directly below the radar) and far range edge is farthest from the radar.

- The along-track dimension is referred to as “azimuth”.

- In a radar system, resolution is defined for both the range and azimuth directions.
- Digital signal processing is used to focus the image and obtain a higher resolution than achieved by conventional radar

What is a SAR image?



The image represents **physical processes**.

Pixels are **measurements**.

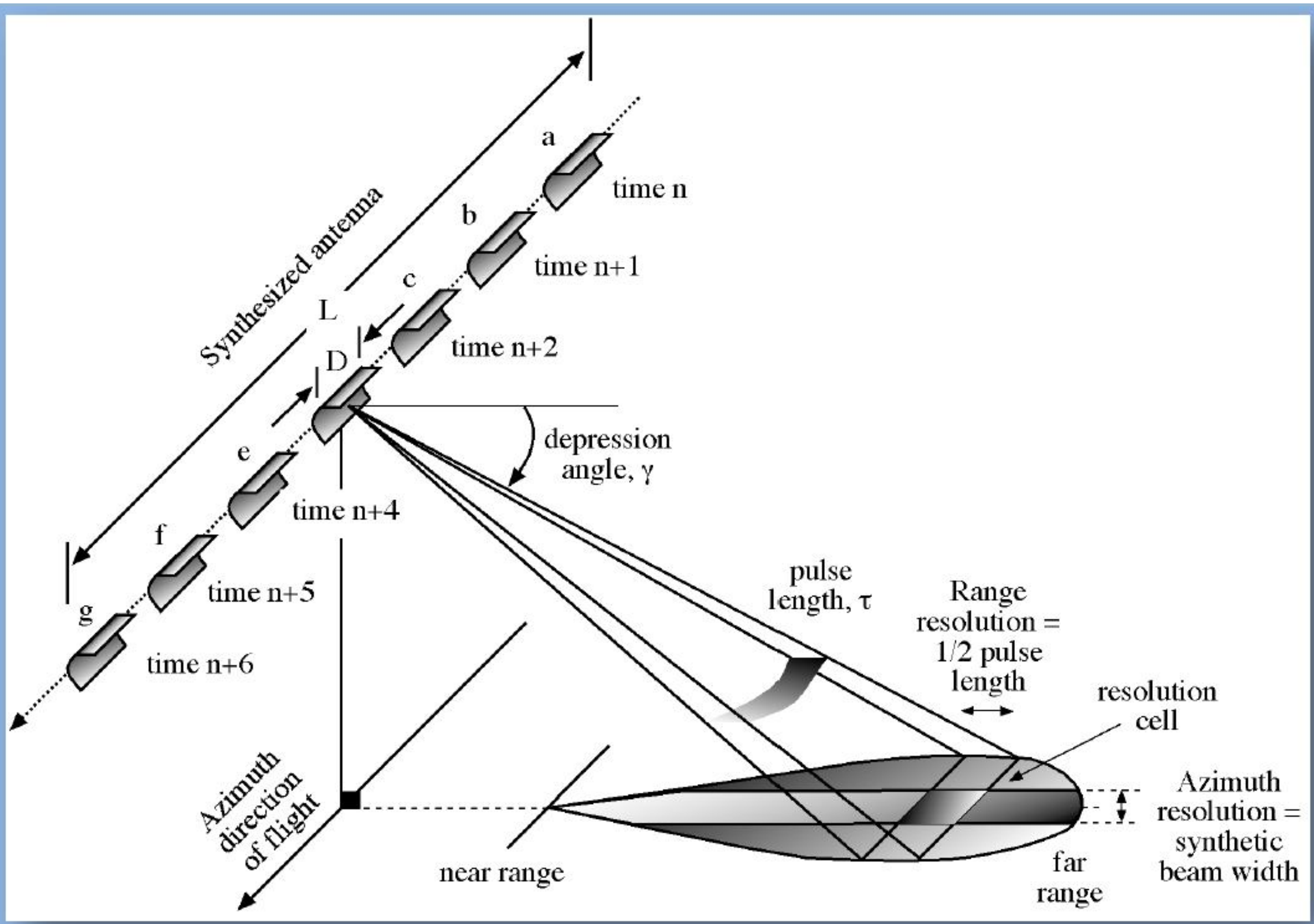
Image is interpretable based on understanding of the physical processes

Synthetic Aperture Radar (SAR) Systems

A major advance in radar remote sensing has been the improvement in azimuth resolution through the development of synthetic aperture radar (SAR) systems.

- **In a real aperture radar system that the azimuthal resolution inversely proportional to antenna length (L)**
- **Great improvement in azimuth resolution could be realized if a longer antenna were used.**
- **Engineers now synthesize a very long antenna electronically. The major difference is that a greater number of additional beams are sent toward the object.**
- **Large advantage: SAR technology allows high spatial resolution imaging**

Synthetic Aperture Radar (SAR) Systems

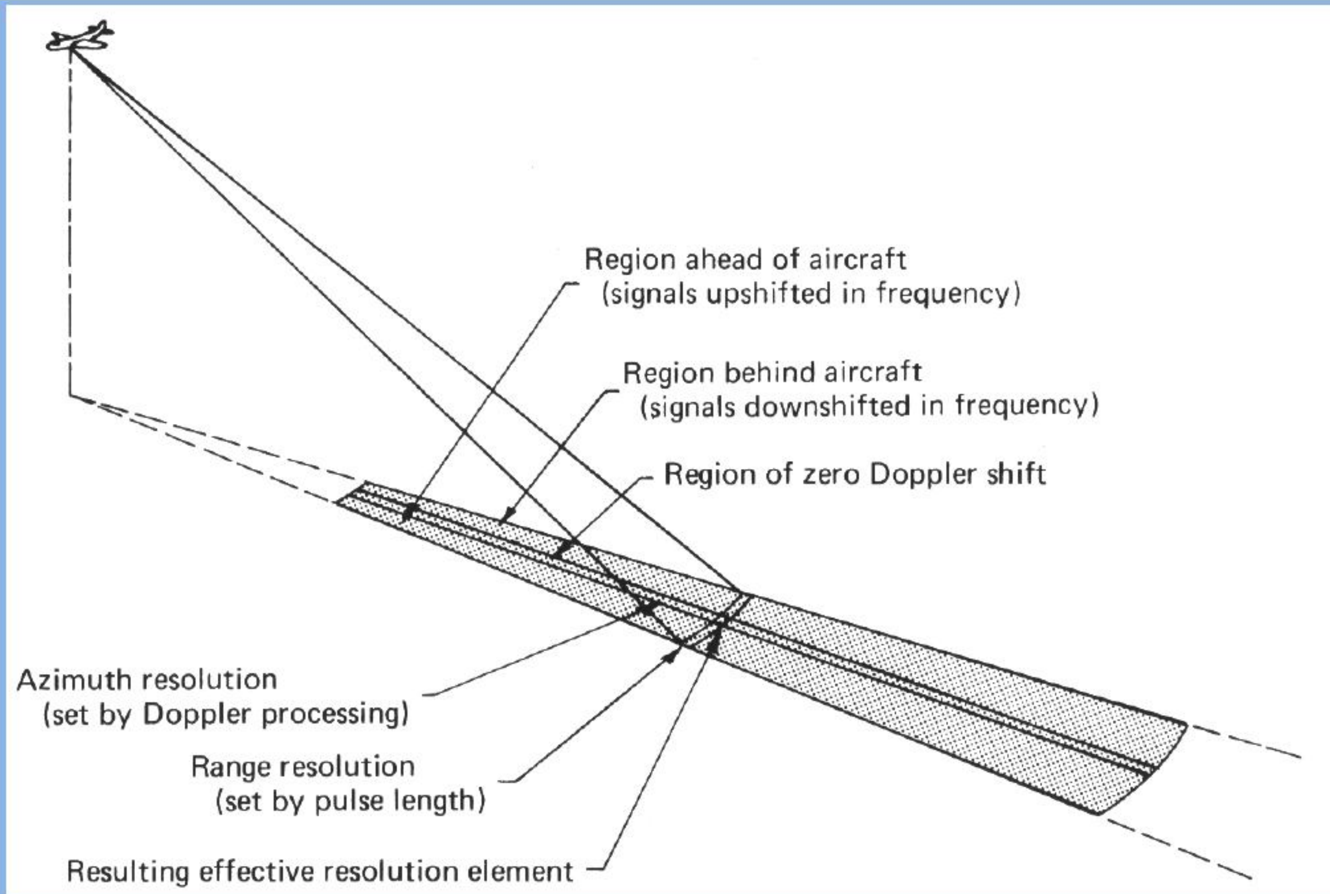


A longer antenna is "synthesized" electronically by using the same antenna but moving it. Recall that the azimuth resolution gets better with longer antennas in SLAR systems.

Synthetic Aperture Radar (SAR) Systems

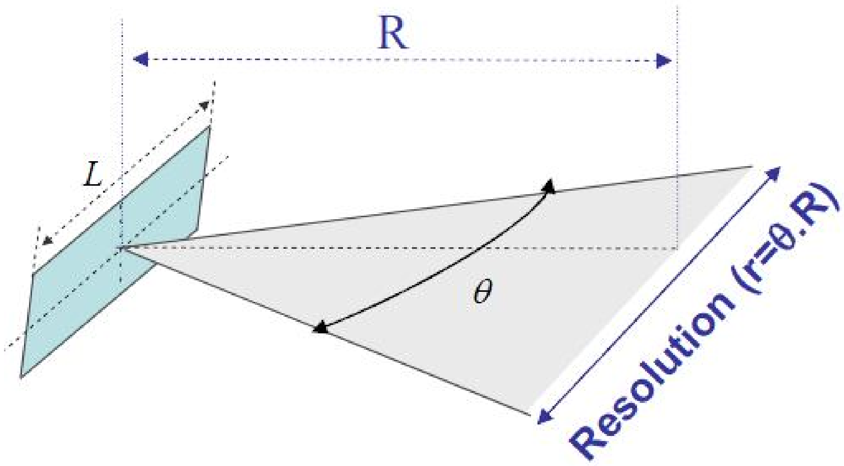
- The *Doppler principle states that the frequency (pitch) of a sound changes if the listener and/or source are in motion relative to one another.*
- •A doppler radar is a radar using the doppler effect of the returned echoes from targets to measure their radial velocity.
- •The microwave signal sent by the radar antenna's directional beam is reflected toward the radar and compared in frequency, up or down from the original signal, measuring the target velocity component in the direction of the beam.
- •*An approaching train whistle will have an increasingly higher frequency pitch as it approaches. This pitch will be highest when it is directly perpendicular to the listener (receiver). This is called the point of zero Doppler. As the train passes by, its pitch will decrease in frequency in proportion to the distance it is from the listener (receiver).*
- •This principle is applicable to all harmonic wave motion, including the microwaves used in radar systems.

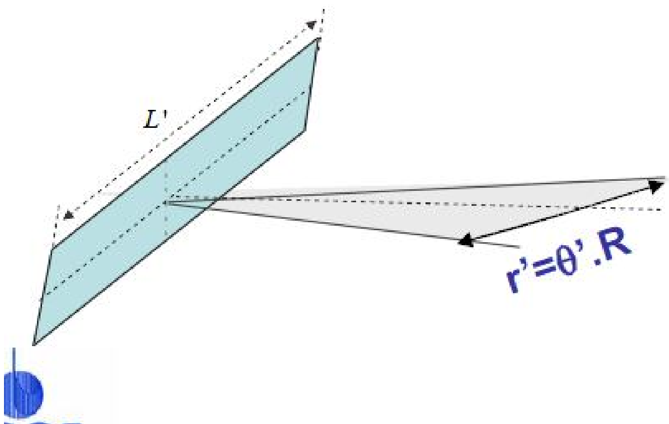
Synthetic Aperture Radar (SAR) Systems



If we include the ability to detect wavelengths, we can see the Doppler shift (lower frequency behind the sensor, higher ahead).

Antenna scattering





$$\theta = \frac{\lambda}{L}$$

Wavelength

Angular aperture (horizontal plane)

Antenna length (horizontal direction)

The larger the antenna, the narrower the aperture (finer resolution)

$$Ra = \frac{\lambda R}{L}$$

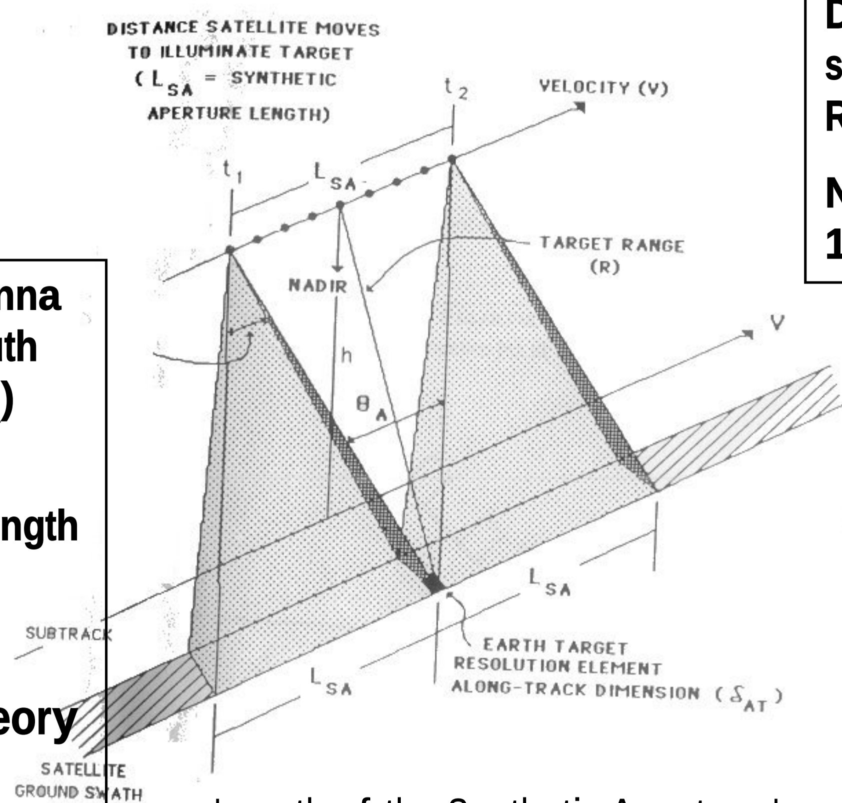
Numerical example:

L ≈ 10m, R ≈ 1000 km (spaceborne radar), λ ≈ 5 cm (C band) ➔ **resolution ≈ 5 km**

Improvement in Azimuth Resolution

Dwell or integration time
s = L_{SA}/V_{st}= $R\lambda/VL_a$=0.622sec

Number of pulses = PRF*S = 1679*0.622= 1045 pulses



Real SAR Antenna aperture azimuth beamwidth (θ_A)

Along track antenna real length = L_a

Through diffraction theory $\theta_a = \lambda/L_a$

Length of the Synthetic Aperture $L_{SA} = R\,\theta_A = R\,\lambda/L_a$

Azimuth Resolution with Synthetic Aperture

$$\delta_{AT} = \frac{R}{2}\frac{\lambda}{L_{SA}} = \frac{R\lambda}{2\frac{R\lambda}{L_a}} = \frac{L_a}{2}$$

Improvement in Azimuth Resolution

$$L_{SA} = R\,\theta_A = R\,\lambda / L_a$$

$$\delta_{AT} = \frac{\lambda}{L_{SA}}\left(\frac{R}{2}\right) = \frac{\lambda R}{2\dfrac{R\lambda}{L_a}} = \frac{L_a}{2}$$

ERS-1 SAR antenna length $L_a = 10$ m

So, Azimuth Resolution = 10/2 = 5 m

Azimuth Resolution is Independent of distance between object and sensor.

The lesser the antenna size, the better the resolution.

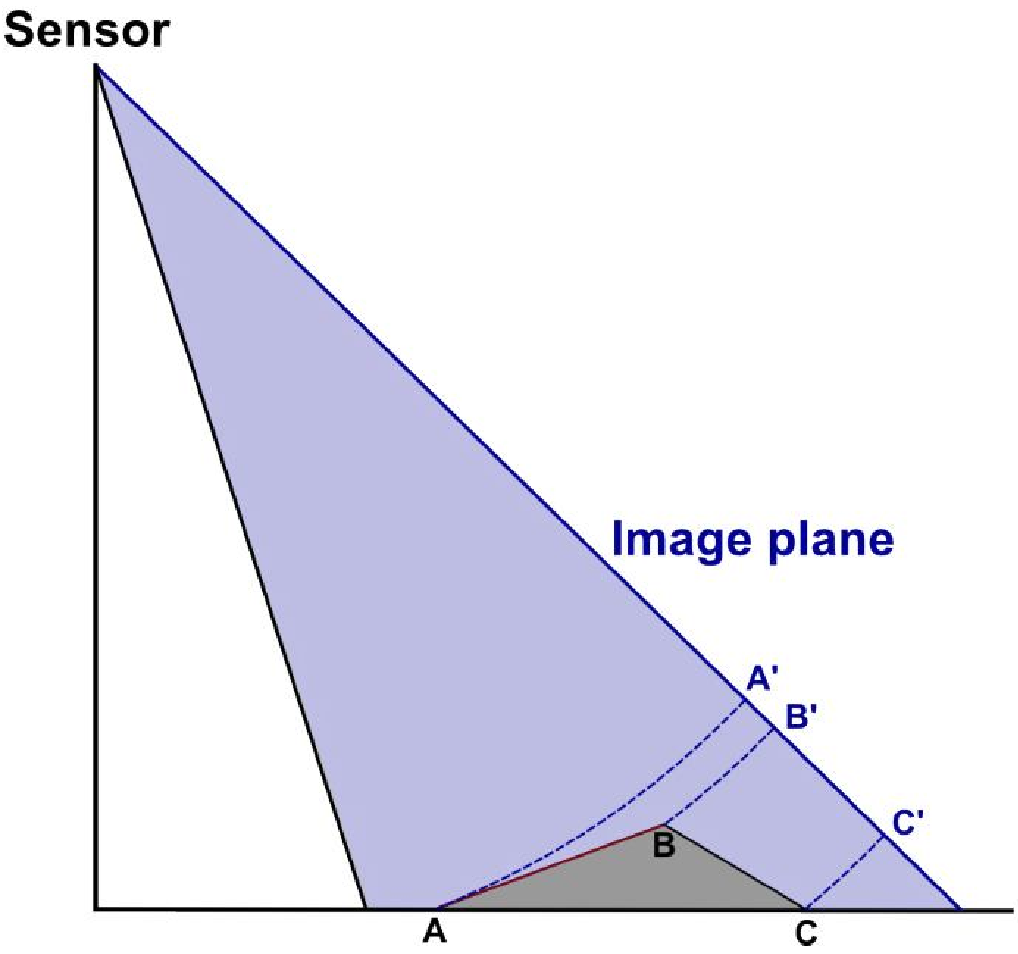
One cannot reduce the antenna size below the limit because the sensitivity of the radar diminishes due to low directivity.

Geometric distortions

- Geometric distortion caused by the side looking geometry of radar

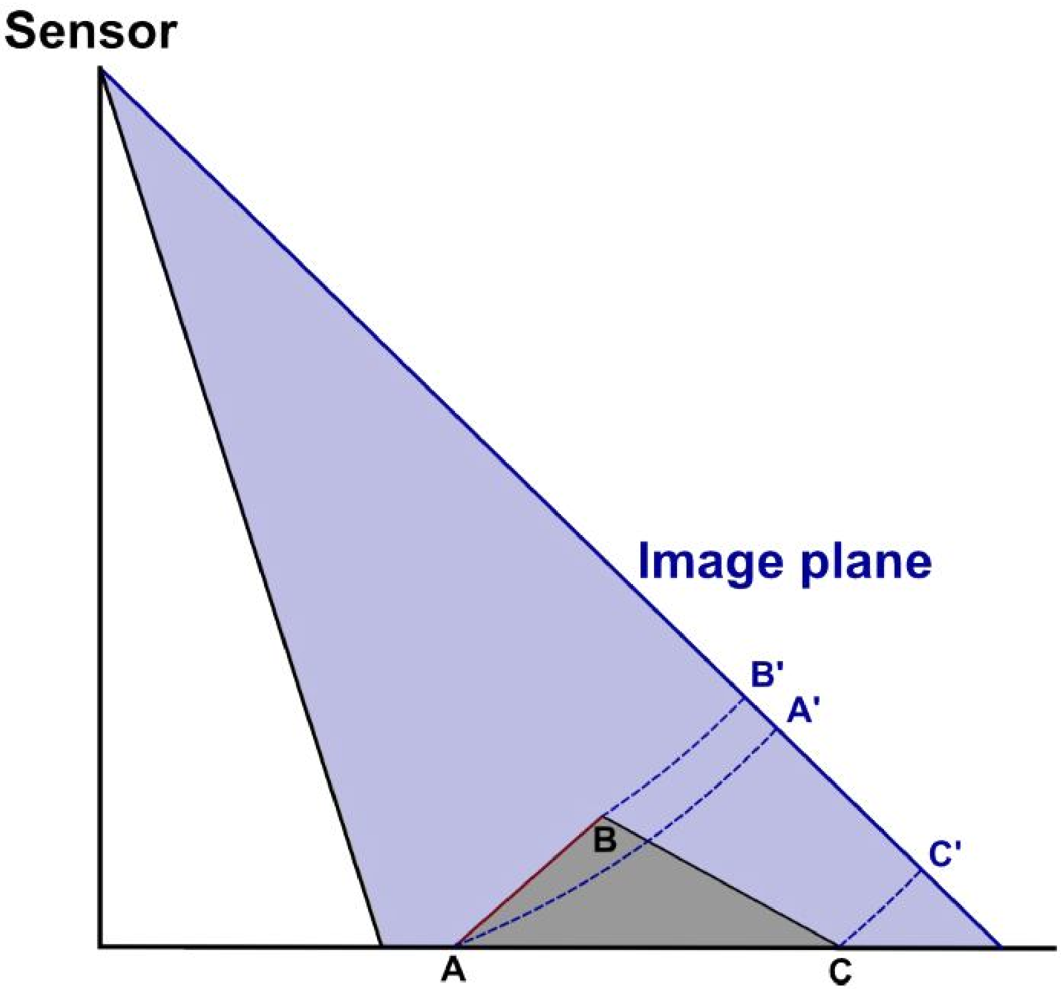
  - Foreshortening
  - Layover
  - Shadow

Foreshortening



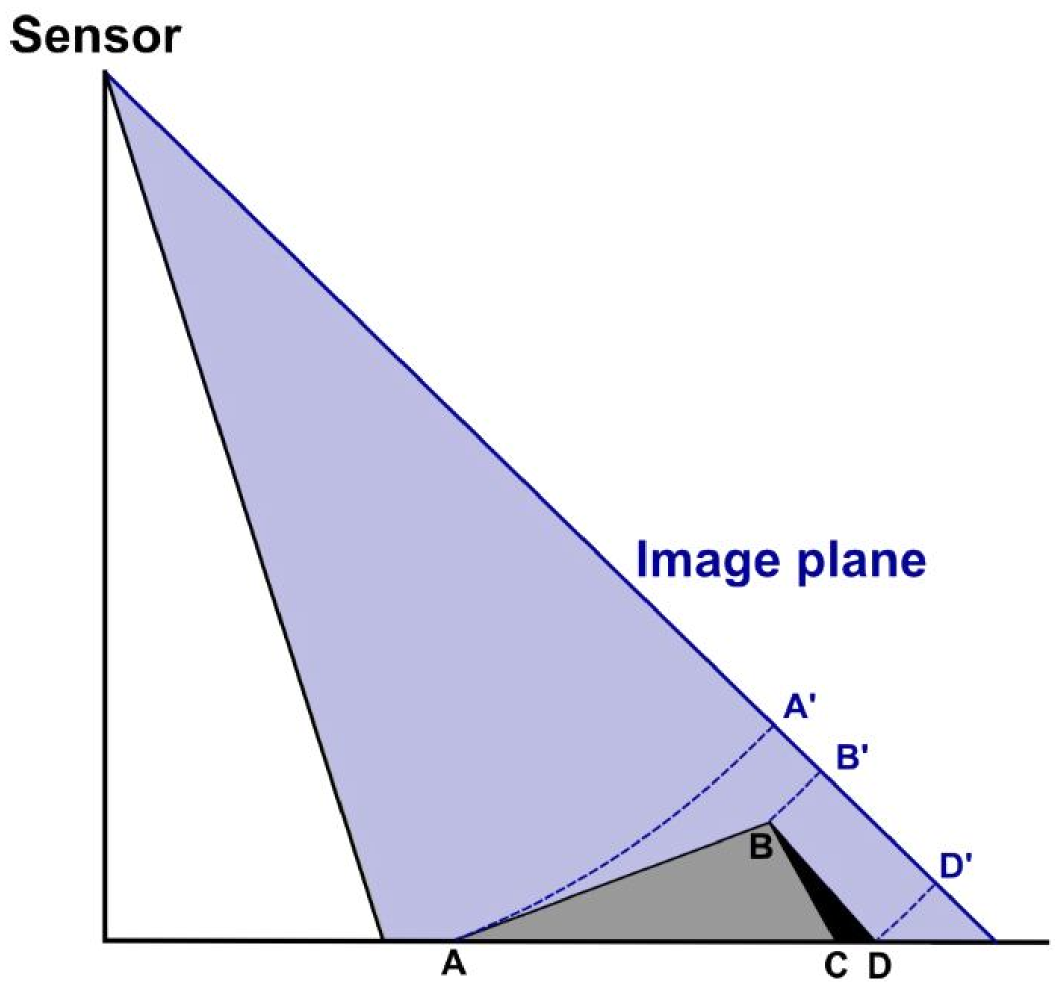
- distance A-B on the slope is shortened to A'-B' in the SAR image
- bright pixel values

Layover



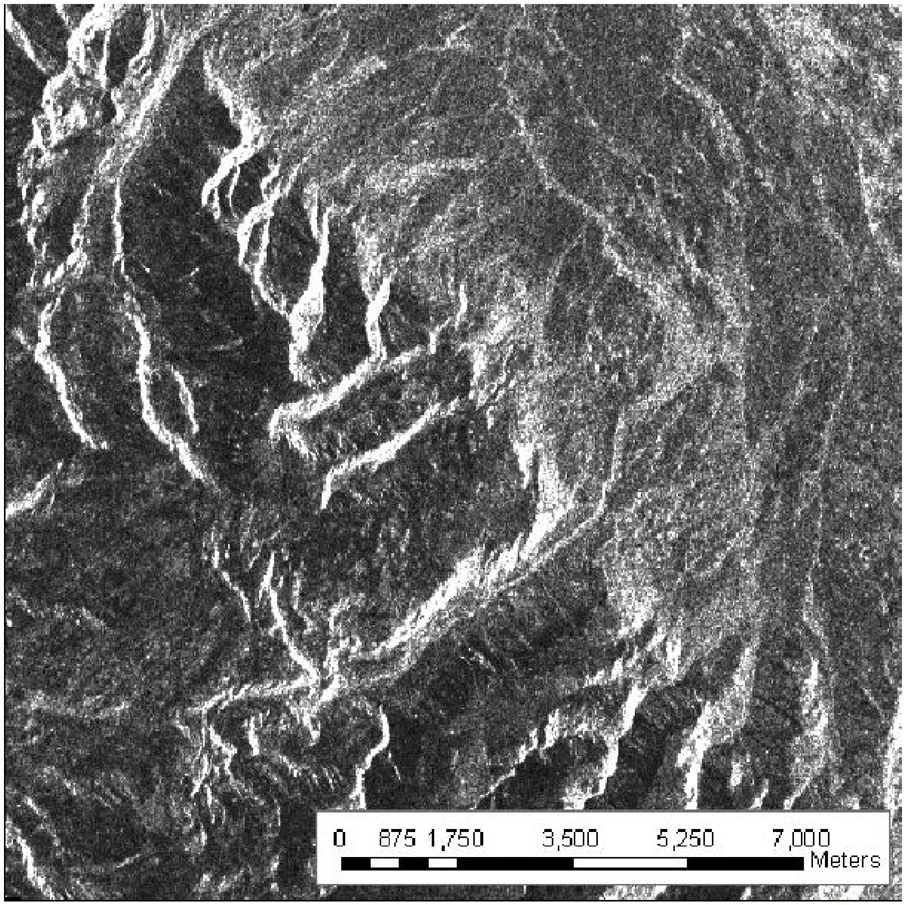
- distance A-B on the slope is shortened to A'-B' in the SAR image
- extreme case of foreshortening
- top of the mountain is closer to the sensor than the bottom
- bright pixel values

Shadow

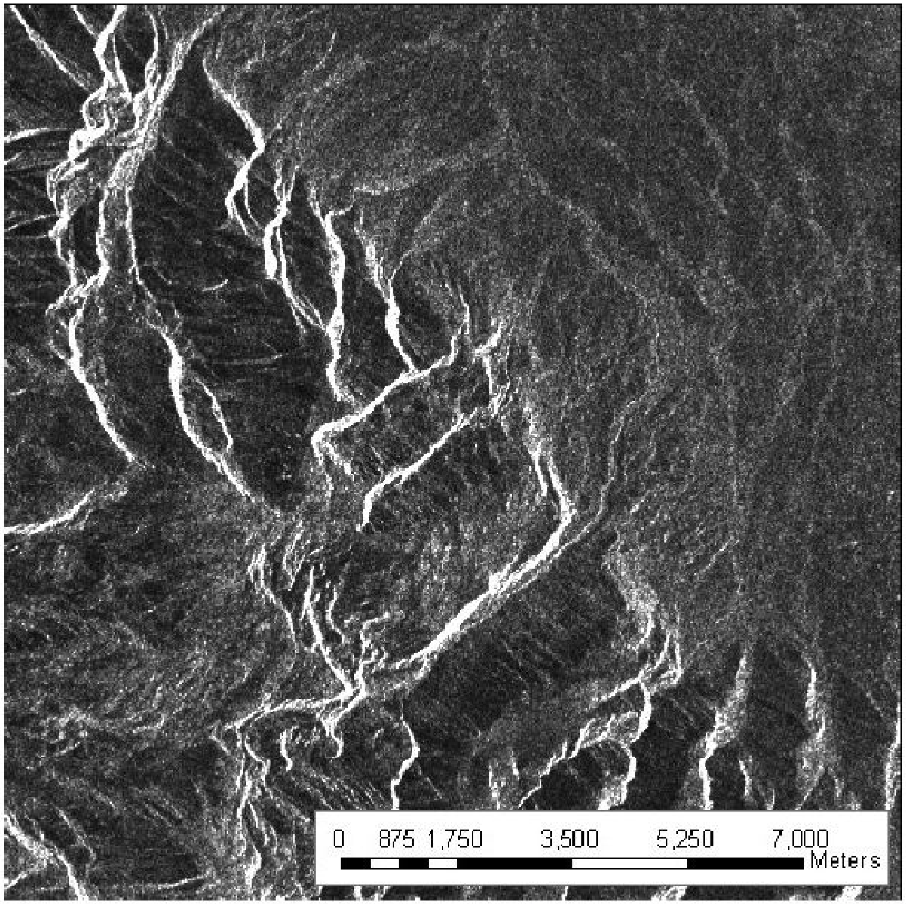


- distance B-C on the slope does not appear in the SAR image
- top of the mountain high enough so that backslope is completely in the shadow
- dark pixel values

Distortions: Foreshortening

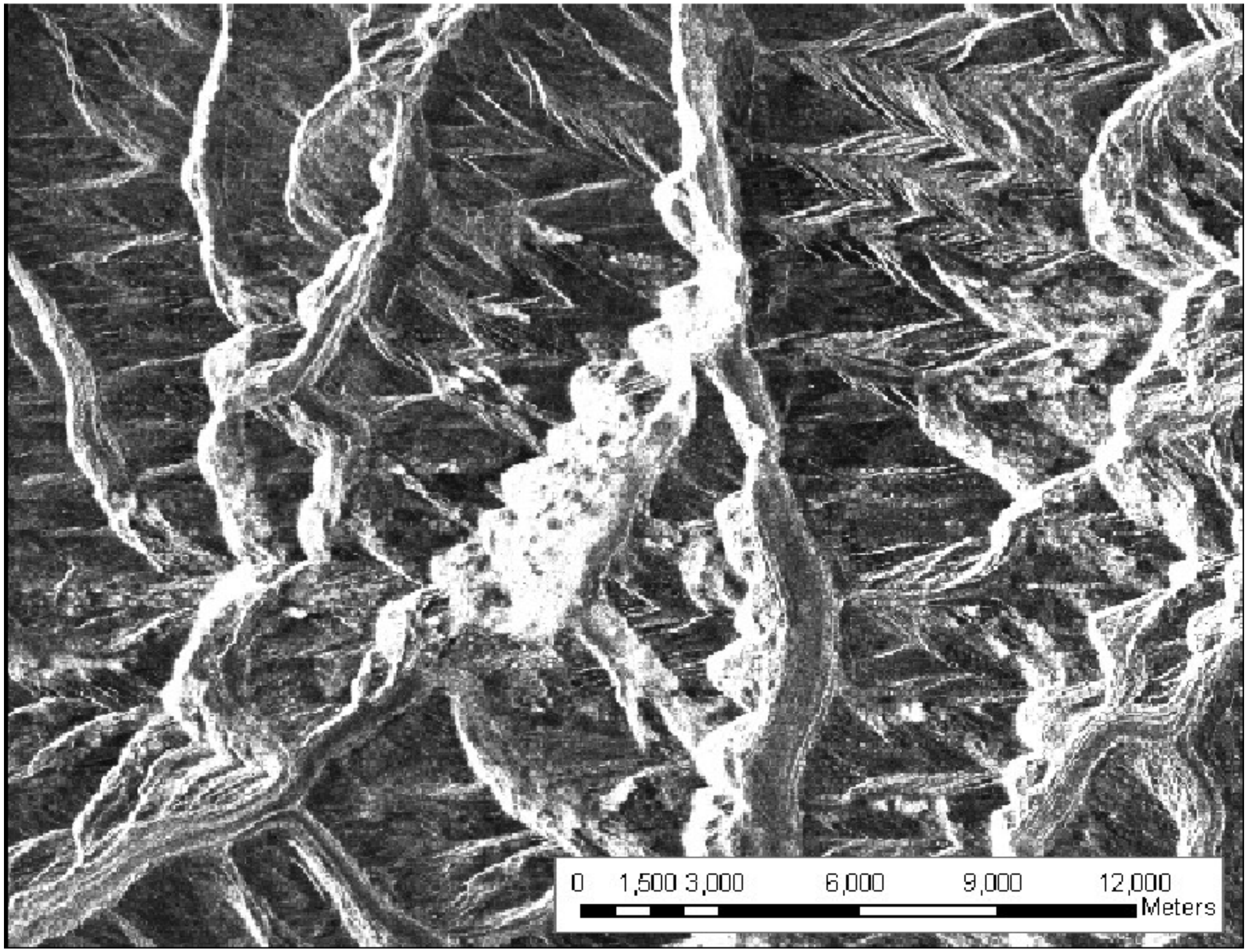


JERS-1 Credits: JAXA

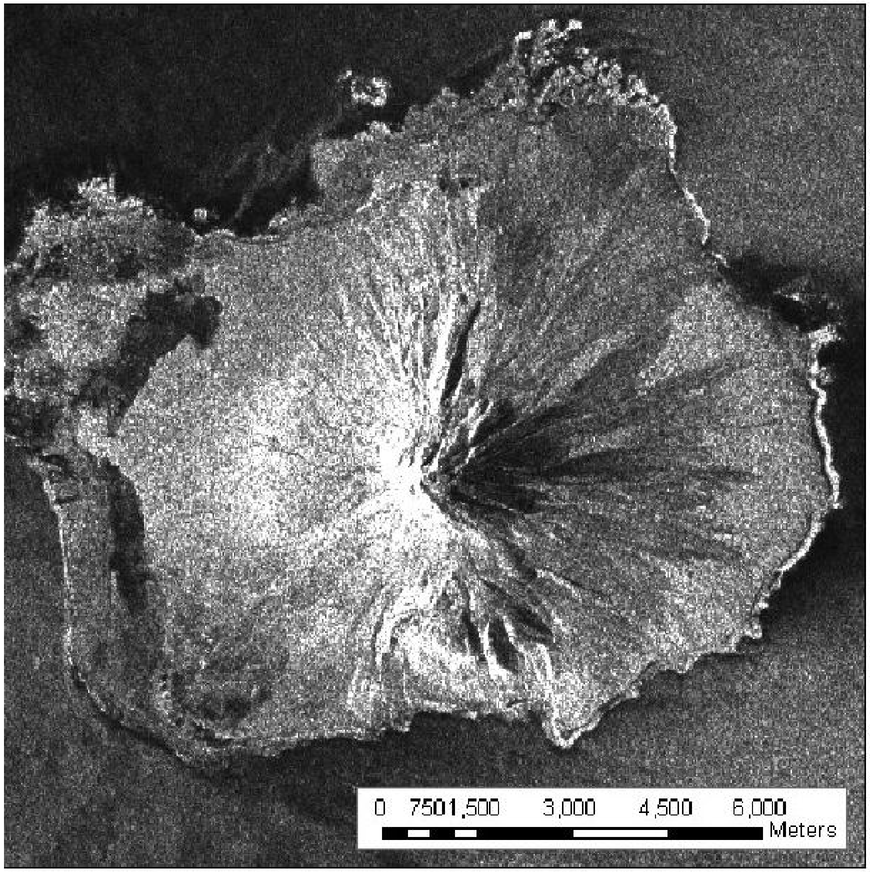


Radarsat-1 Credits: CSA

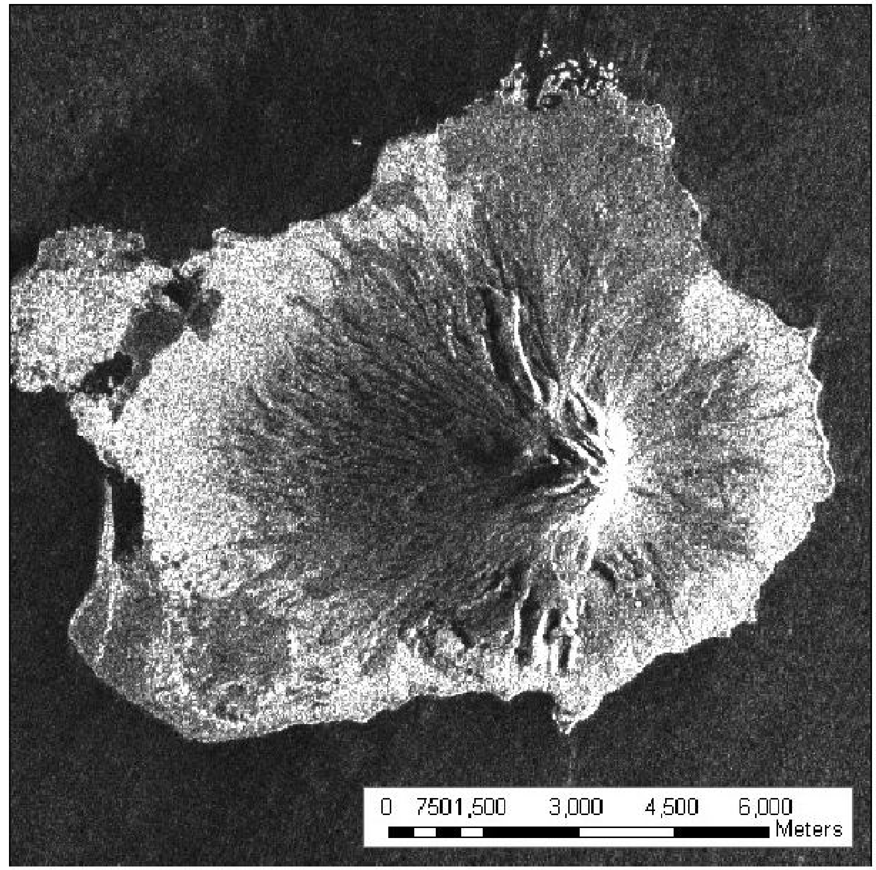
Distortions: Layover



Distortions: Shadow



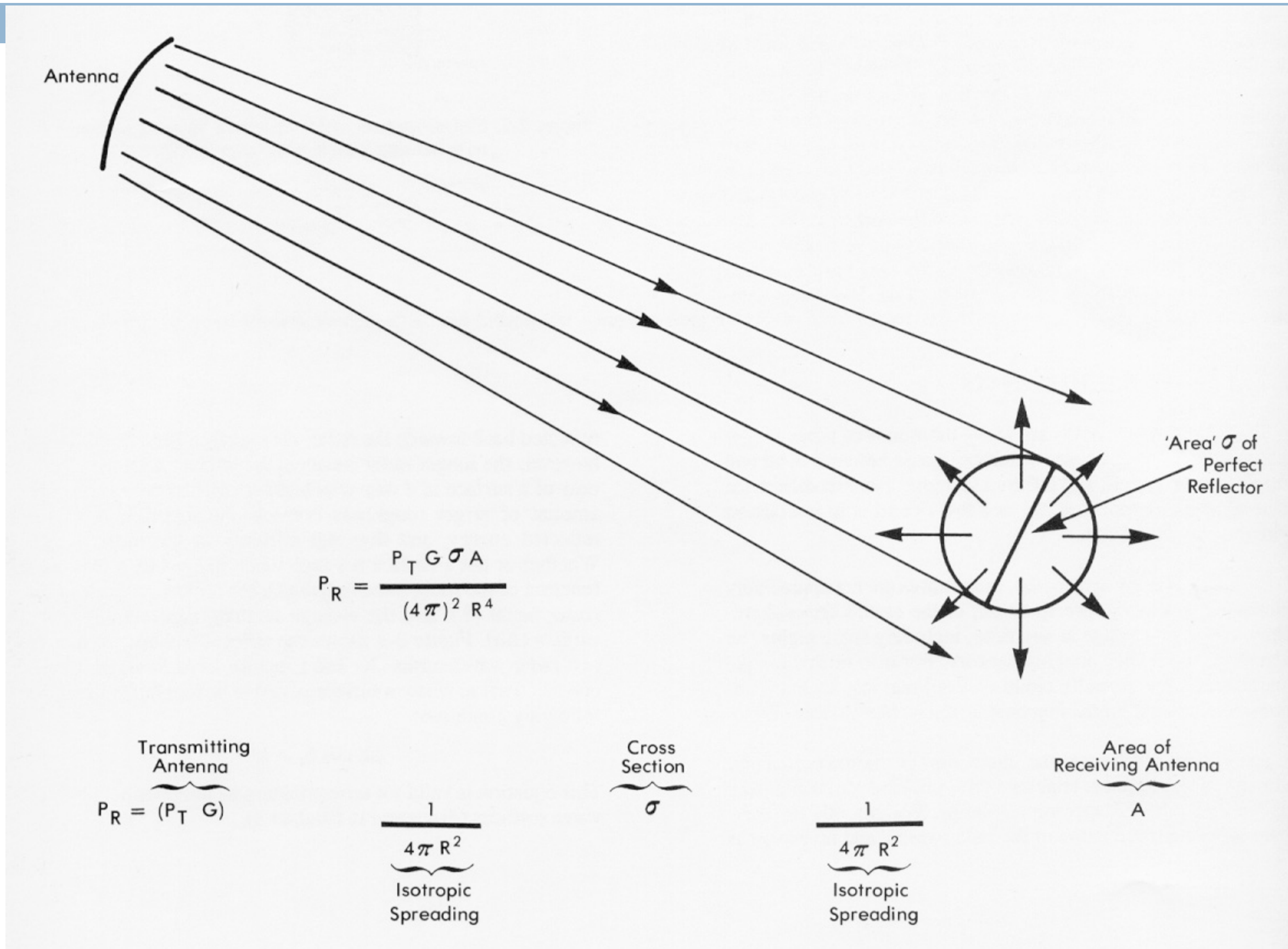
Ascending



Descending

Credits: CSA

The Radar Equation



Radar cross section

σ - is the radar surface backscatter coefficient

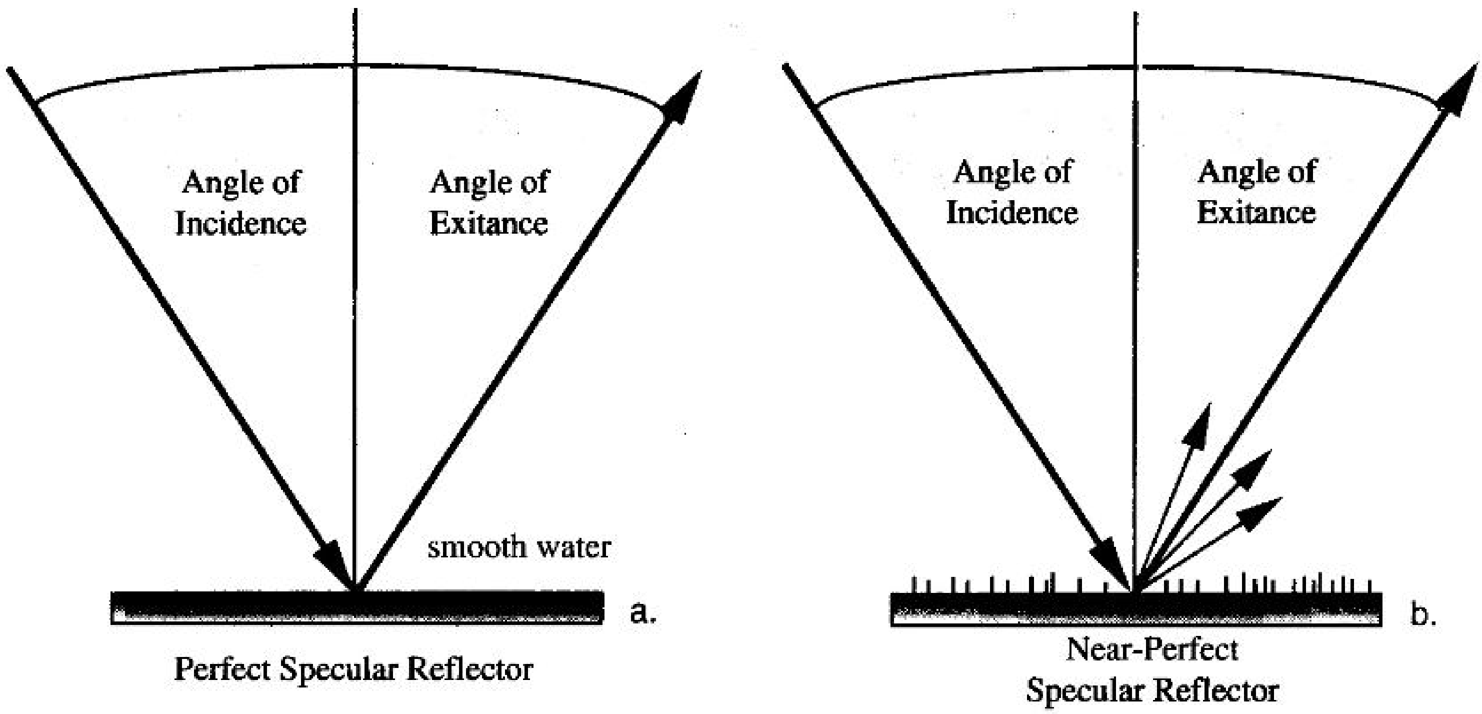
- **It represents the fraction of incoming EM radiation that is scattered from the surface in the direction of the transmitted energy (hence the term “backscatter)**
- **It is equivalent to the reflection coefficient in the visible/RIR region of the EM spectrum**

$$\sigma^0 = f(Roughness, Moisture, Geometry, Look\ angle, Polarization)$$

- **Factors controlling variations in σ**
  - **Surface roughness**
  - **Surface dielectric constant**

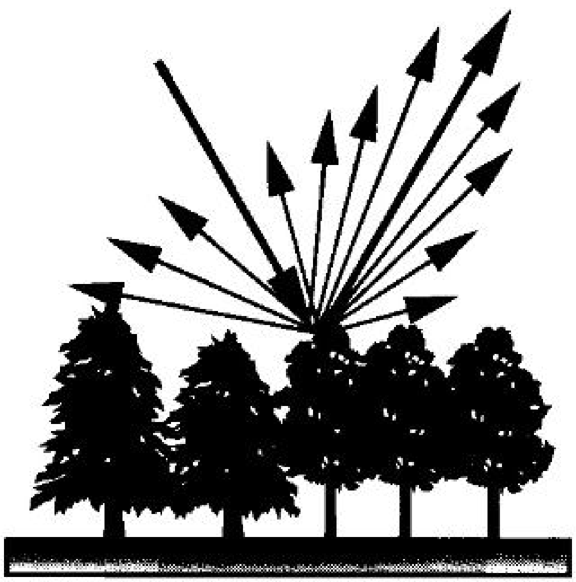
Specular Reflection or Scattering

- **Occurs from very smooth surfaces, where the height of features on the surface << wavelength of the incoming EM radiation**



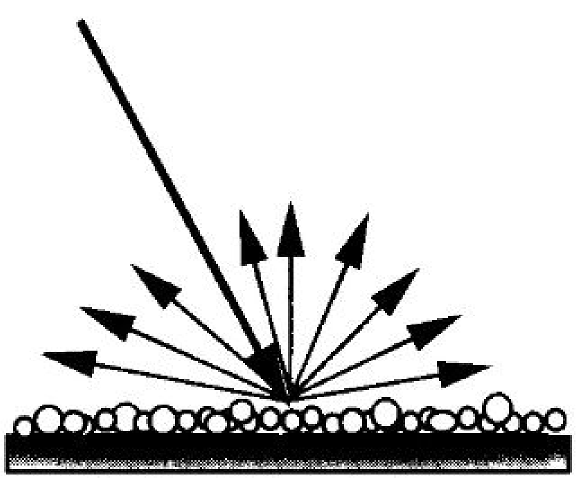
Diffuse Reflectors or Scatterers

- **Most surfaces are not smooth, and reflect incoming EM radiation in a variety of directions**
- **These are called diffuse reflectors or scatterers**



c.

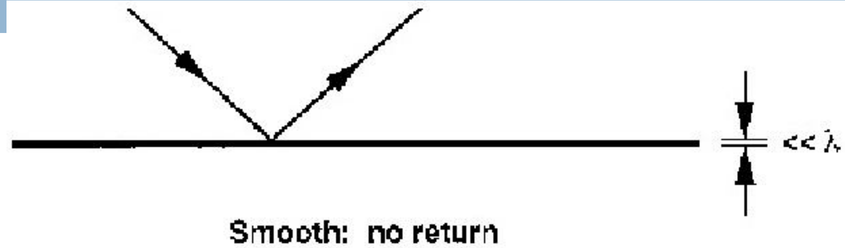
Near-Perfect
Diffuse Reflector



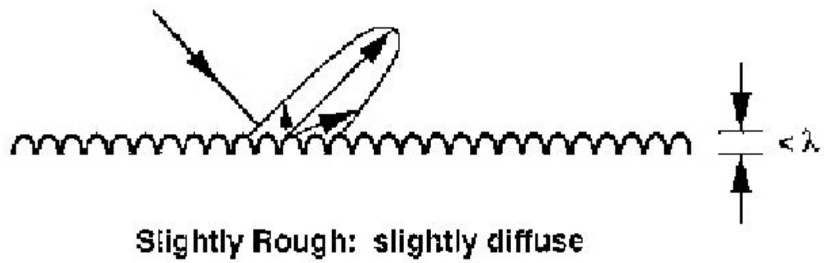
d.

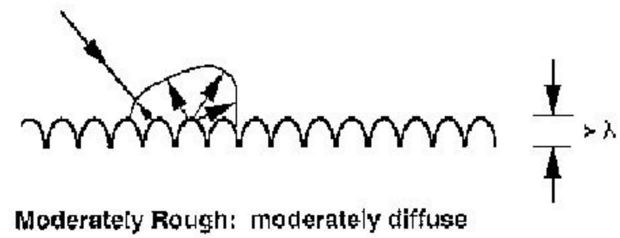
Perfect Diffuse Reflector
Lambertian Surface

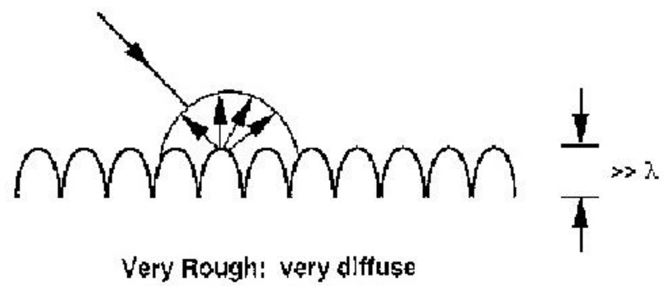
Surface scattering



Radar backscattering is dependent on the relative height or roughness of the surface

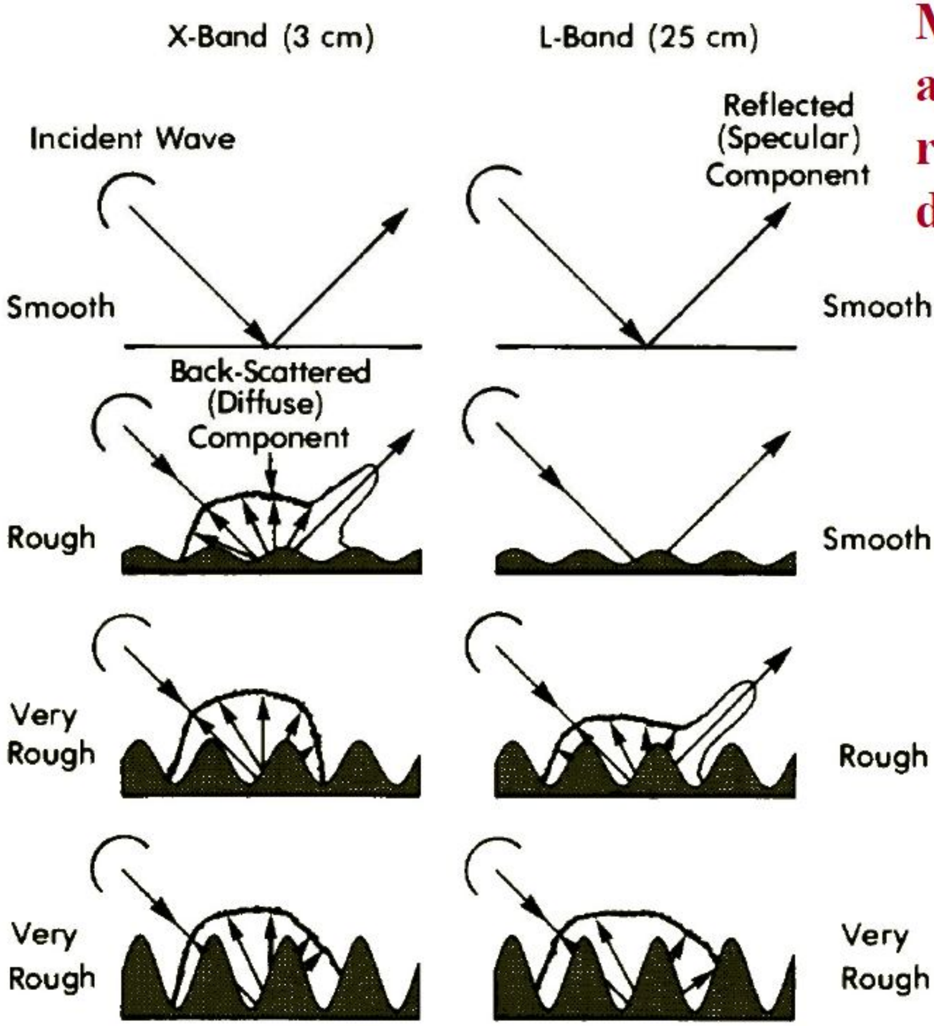






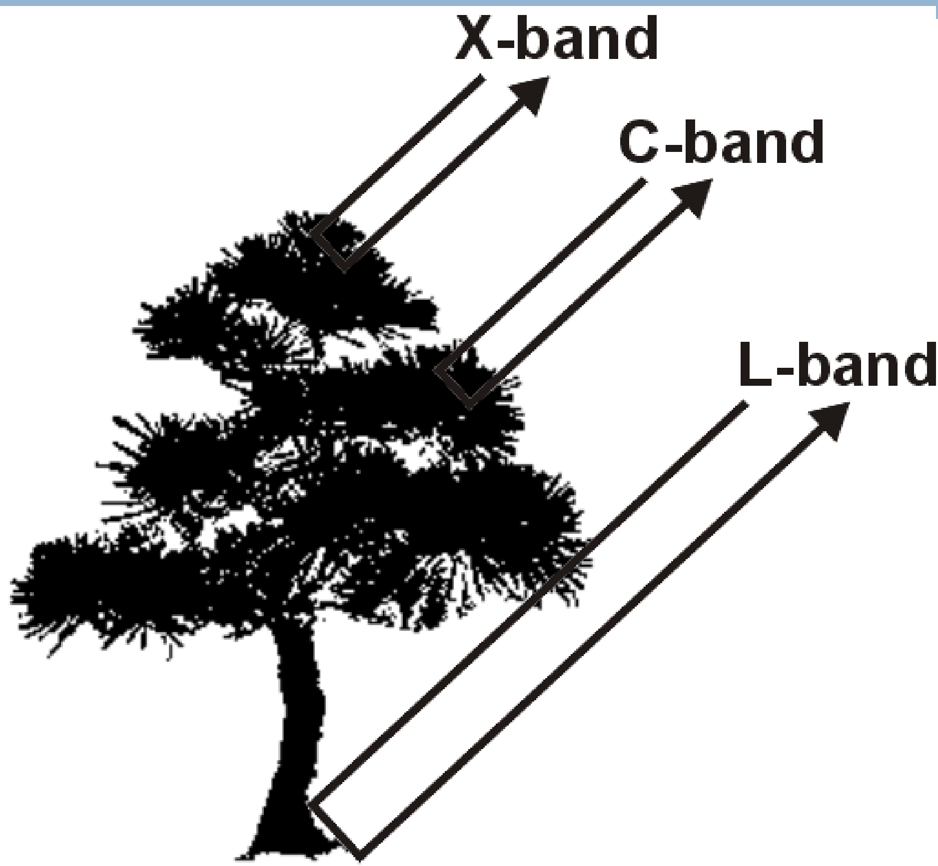
Figures from http://pds.jpl.nasa.gov/mgddf/chap5/f5-4f.gif

Scattering dependency on wavelength

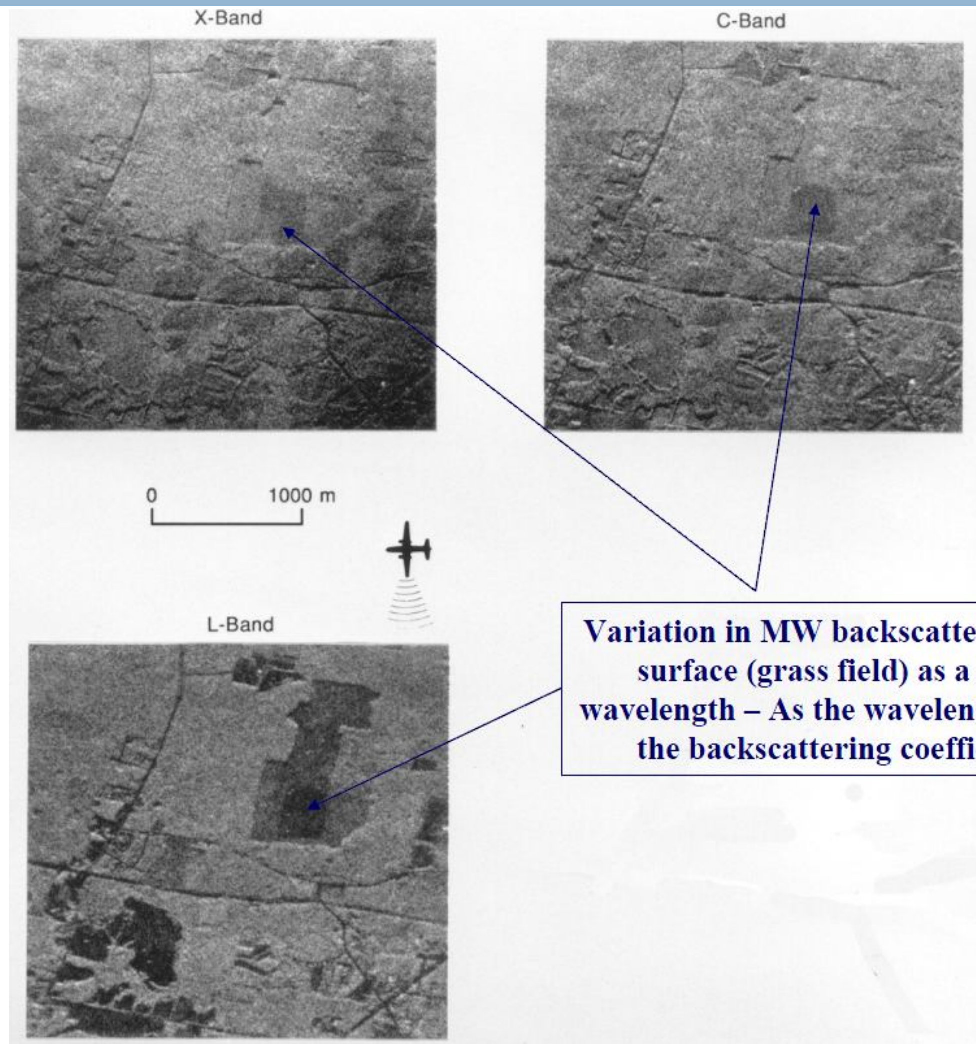


Microwave scattering as a function of surface roughness is wavelength dependent

Radar wavelengths

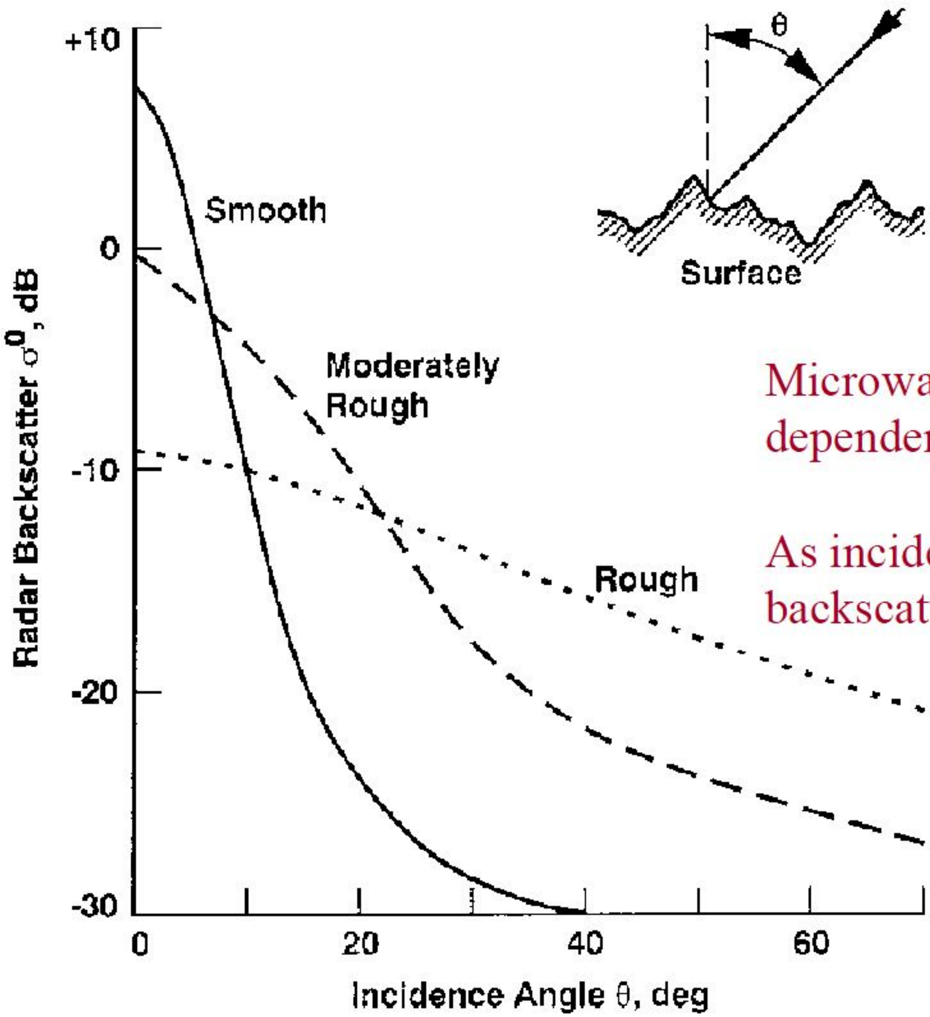


Scattering dependency on wavelength



Variation in MW backscatter from a rough surface (grass field) as a function of wavelength – As the wavelength gets longer, the backscattering coefficient drops

Scattering dependency on incidence angle

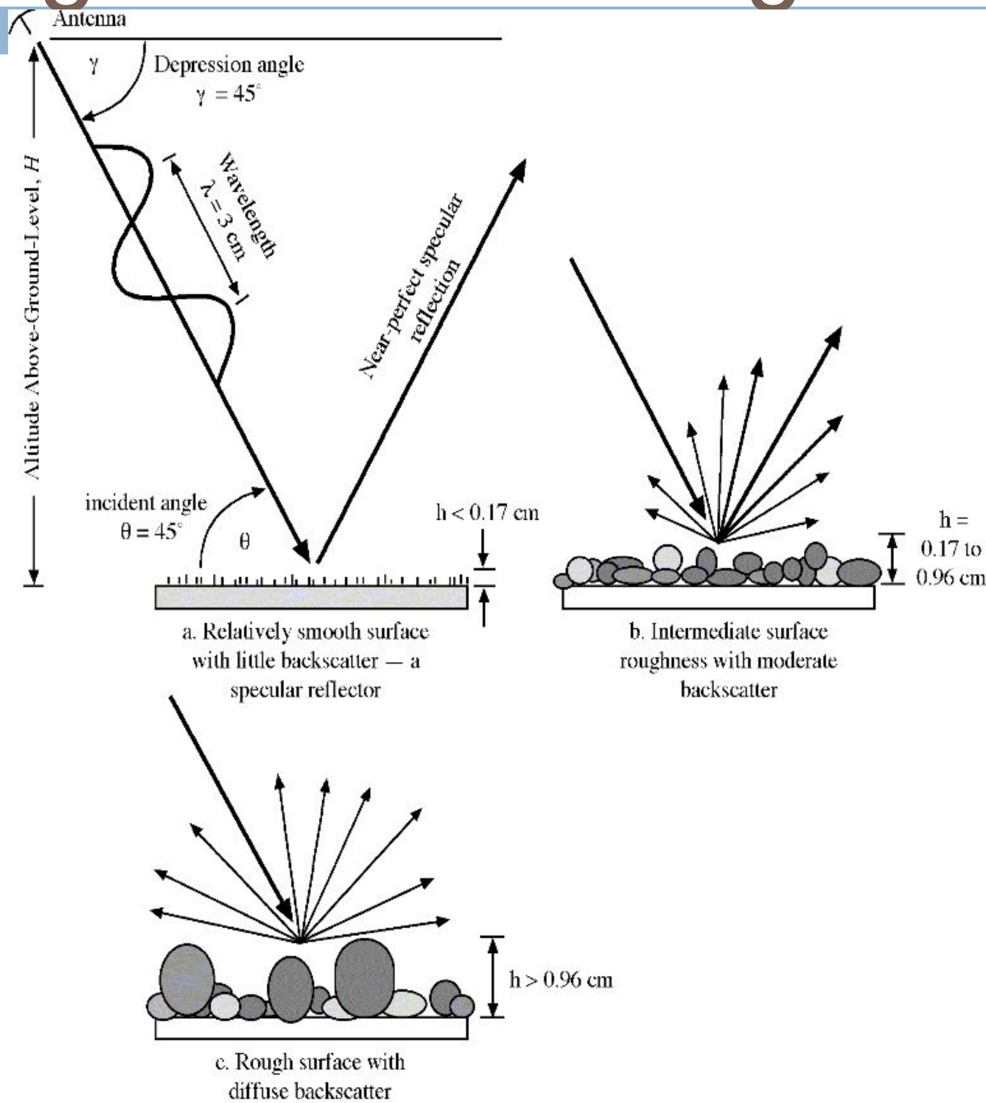


Microwave scattering is dependent on incidence angle

As incidence angle increases, backscattering decreases

Figure from http://pds.jpl.nasa.gov/mgddf/chap5/f5-4f.gif

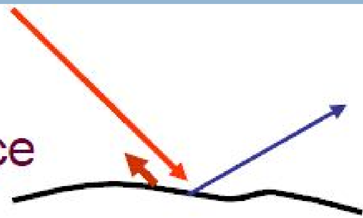
Scattering dependency on incidence angle and wavelength



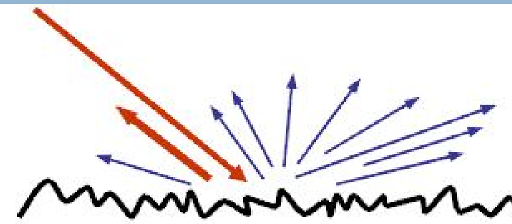
Expected surface roughness back-scatter from terrain illuminated with 3 cm wavelength microwave energy with a depression angle of 45˚.

Surface scattering

Smooth surface



ε_{r1}

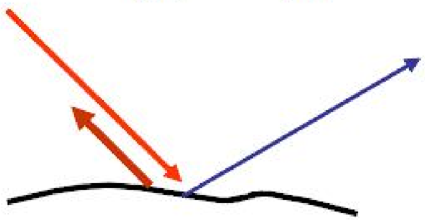


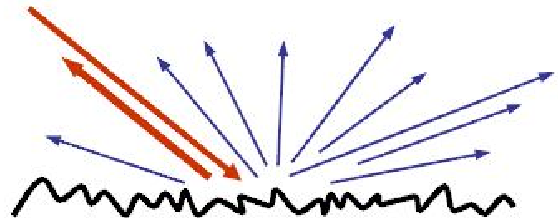
Rough surface

ε_{r1}

The roughness of the surface (wrt to the wavelength) governs the scattering pattern

$\varepsilon_{r2} > \varepsilon_{r1}$ medium 2 is wetter than medium 1





Wetter media

ε_{r2}

ε_{r2}

The dielectric constant (moisture content) of the medium governs the strength of the backscatter

Radar image interpretation I

…what does a radar return look like?

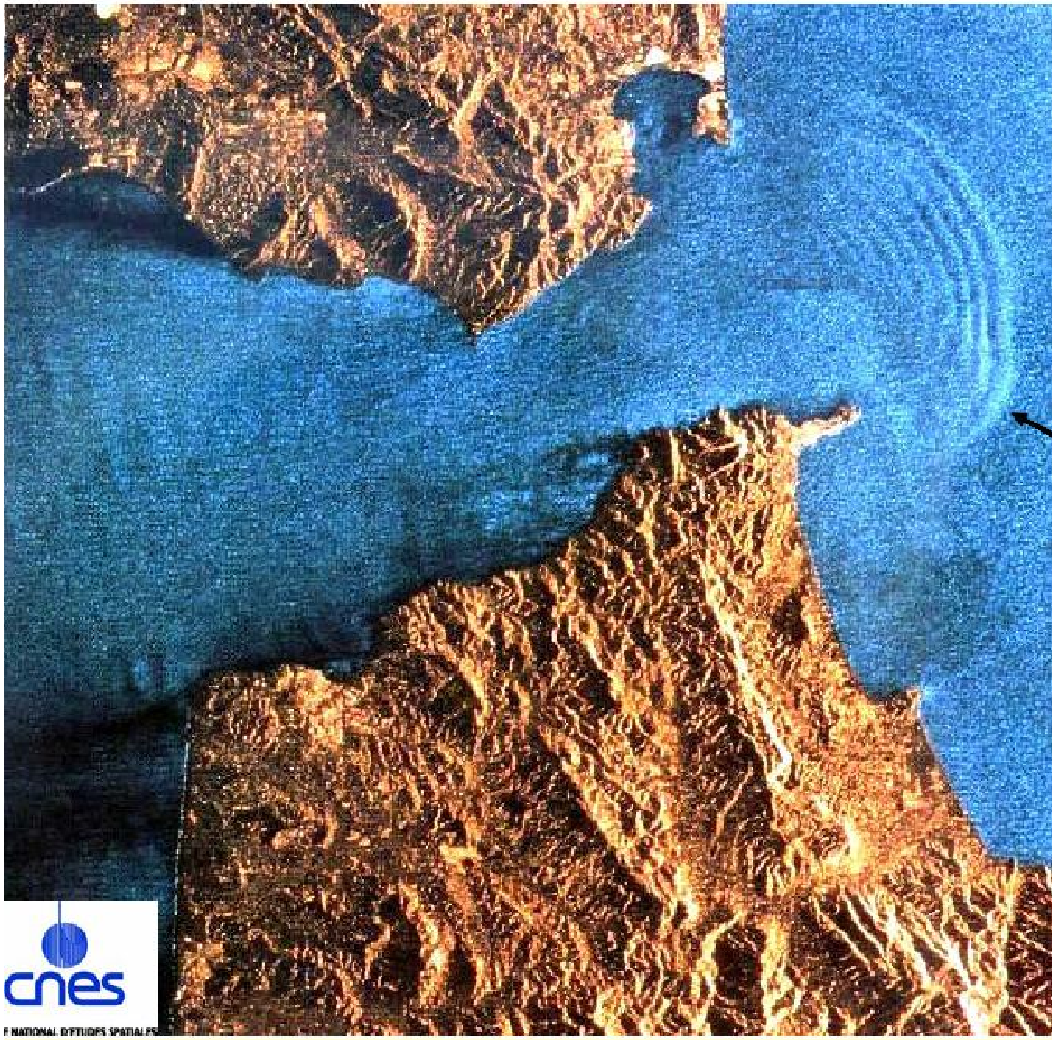
image signature	tone	terrain feature	cause of signature
highlights	bright	steep slopes, scarps *facing* antenna	much energy reflected back
shadows	very dark	steep slopes facing *away*	no energy reaches terrain; no return
diffuse surfaces	medium	vegetation	scatter in many directions (surface or volume scattering)

Radar image interpretation II

…what does a radar return look like?

image signature	tone	terrain feature	cause of signature
corner reflectors	very bright!	bridges, cities	intersecting surfaces reflect strongly (Cardinal effect)
specular surfaces	very dark	calm water, pavement, dry lake beds	smooth surfaces reflect energy away

Effect of surface roughness- Internal waves



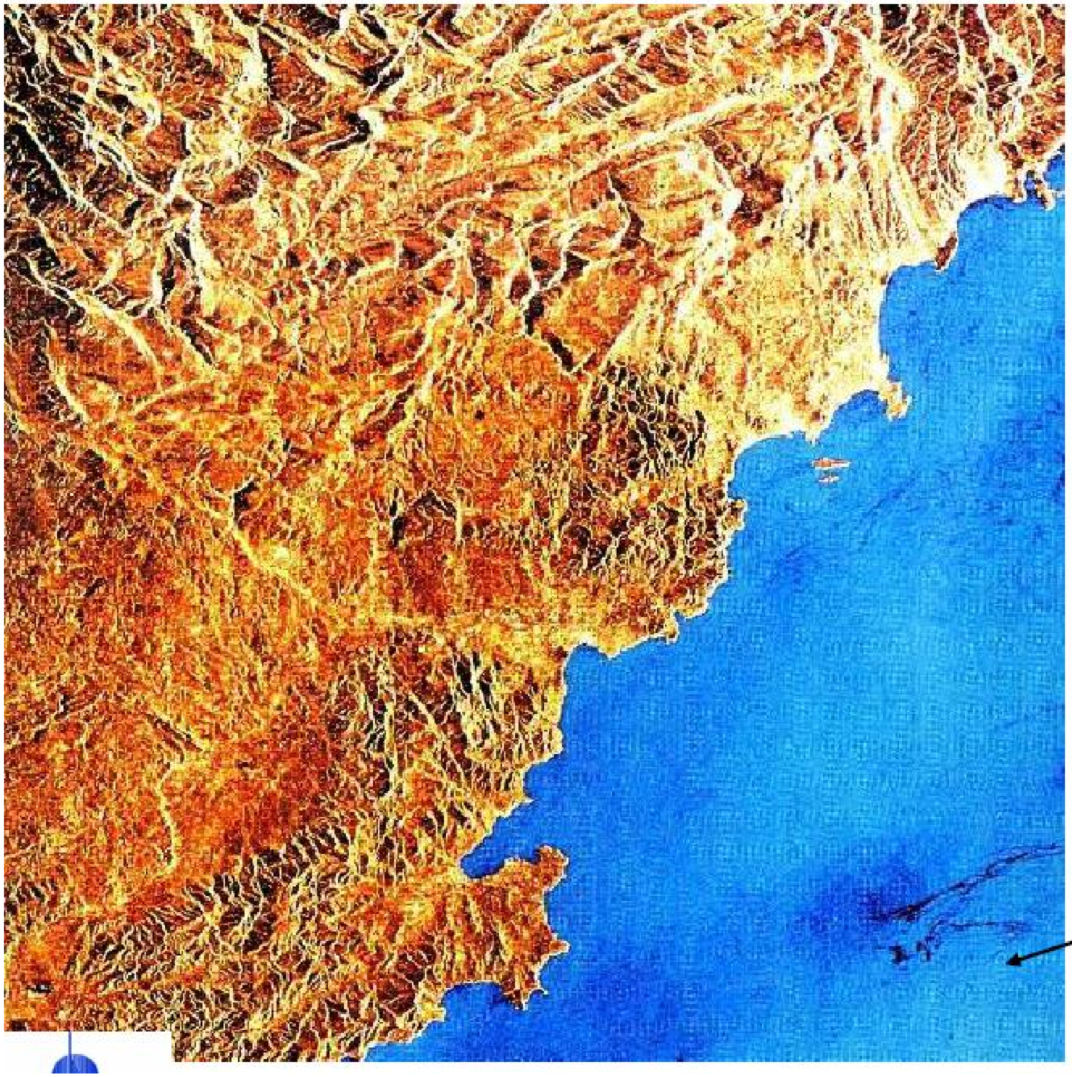
ERS Images (C band, 23°, VV) in false colors

Gibraltar strait
Image : **90 km x 100 km**

• Internal waves (l≈2 km)
Origin : difference of salinity between Atlantic Ocean and Mediterranean sea + tide effects

From 'ERS-1 : 500 days in orbit '. Published by the European Space Agency'

Effect of surface roughness- Oil sheet

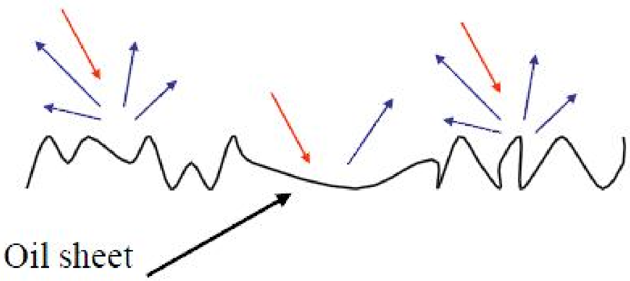


ERS Image (C band, 23°, VV)
in false colors.

France - Côte d 'Azur
90 km x 90 km, 19/09/91

• Decrease of the sea local roughness because of oil sheets:

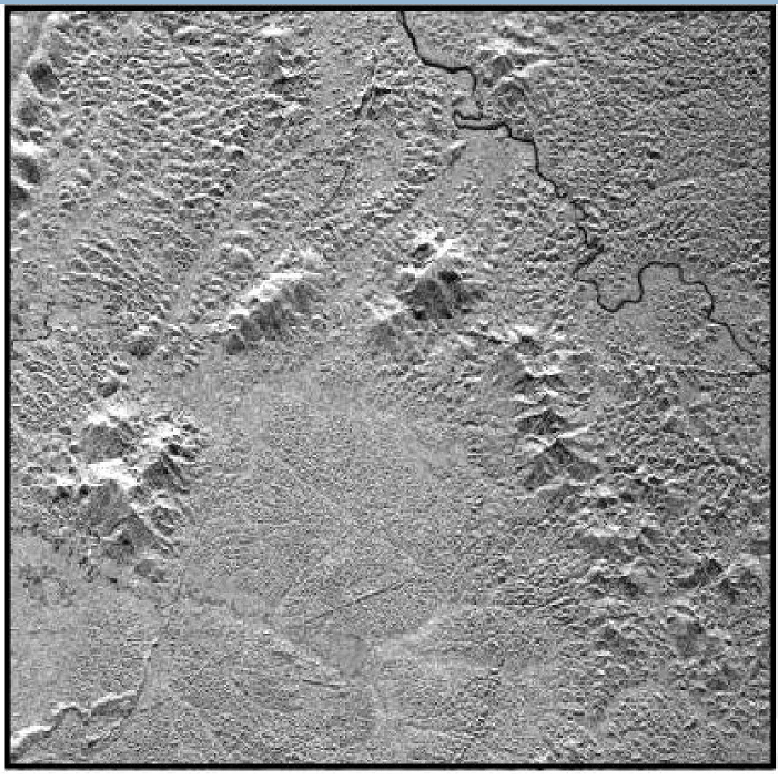
Application : detection of oil sheets, natural or illicit.



From 'ERS-1 : 500 days in orbit '. Published by the European Space Agency'

Topographic effects

Sedimentary basin (Kalimantan, Indonesia)
RADARSAT F4 (C band, ~ 45°, resolution : 8 m)



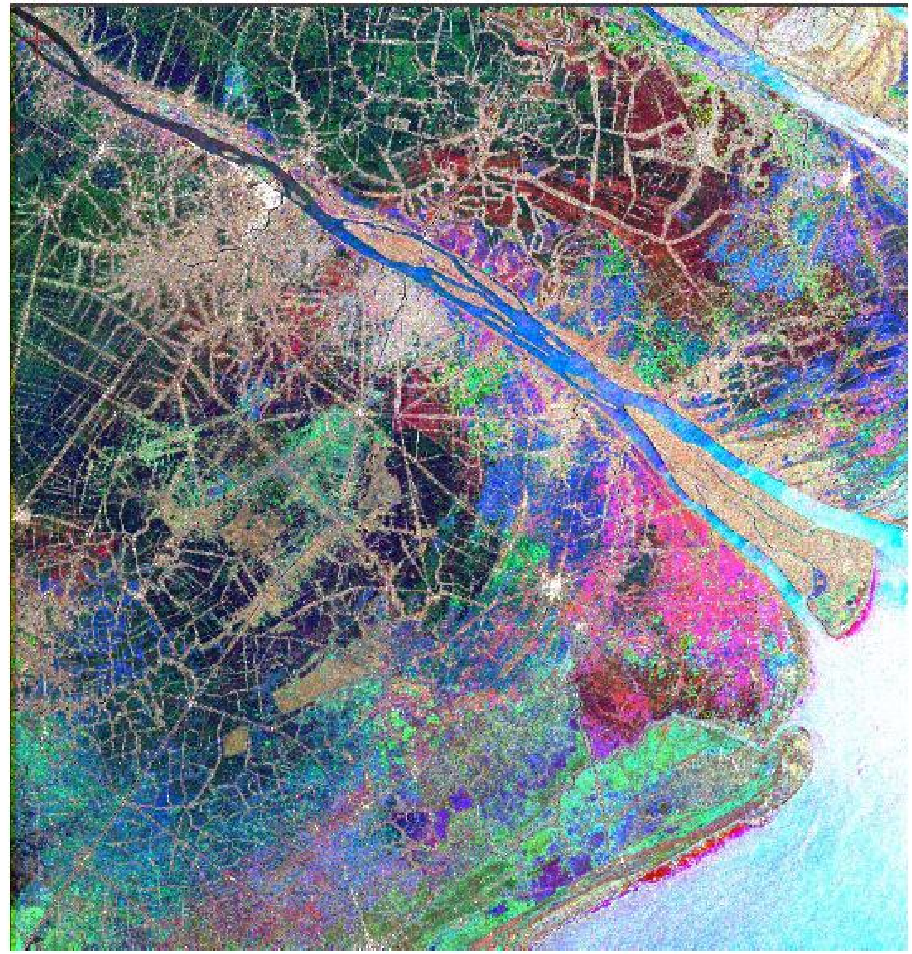
Tropical forest in French Guyana
ERS (C band, 23°, VV, resolution : 20 m)

cnes

- *The SAR side looking makes it extremely sensible to the relief, even under vegetation cover in tropical forests.*

Multitemporal analysis

Red: October 1997
Green: December 1997
Blue: January 1998



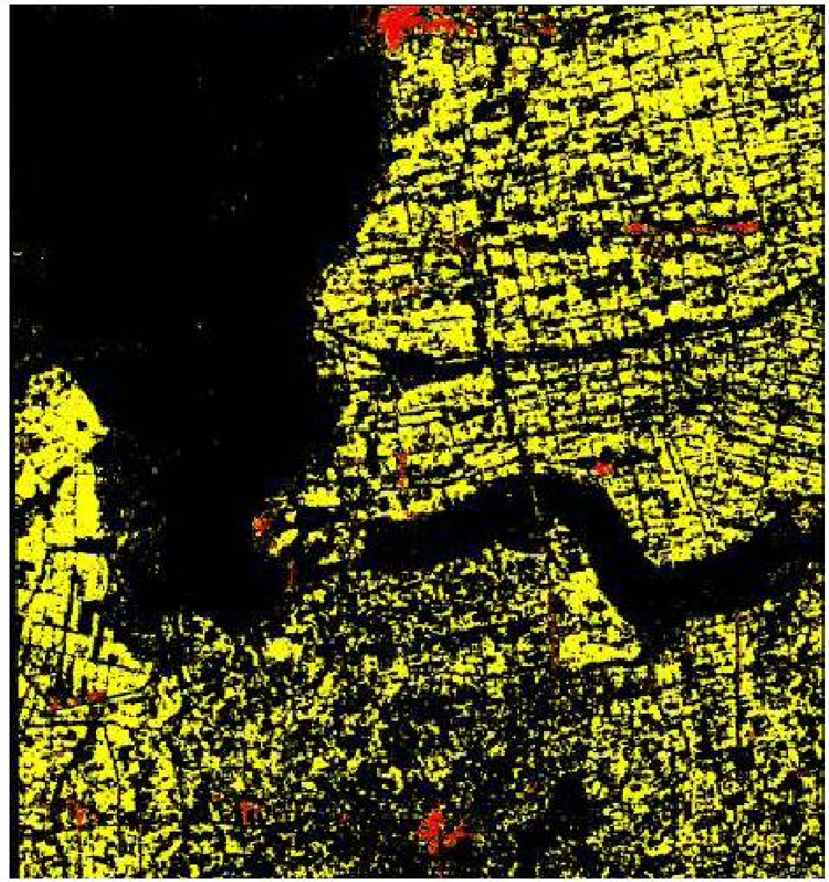
Multidate ERS data

Use of polarisation

Rice mapping using HH/VV at a single date

September 6th, 2004 **Hongze area**

Magenta=HH, Green=VV

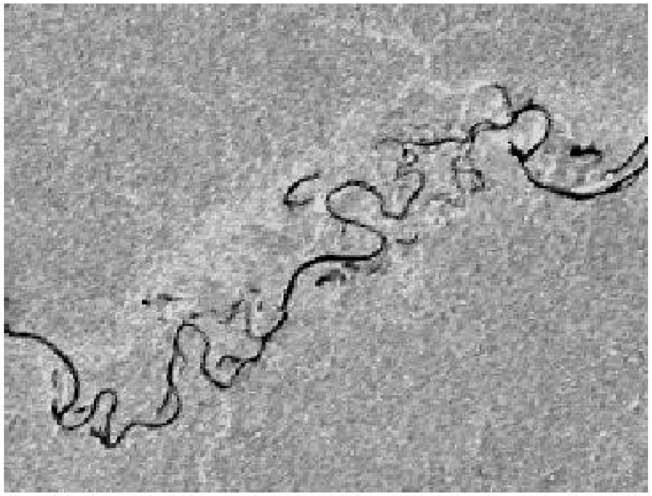


yellow=rice, red=urban, black=other

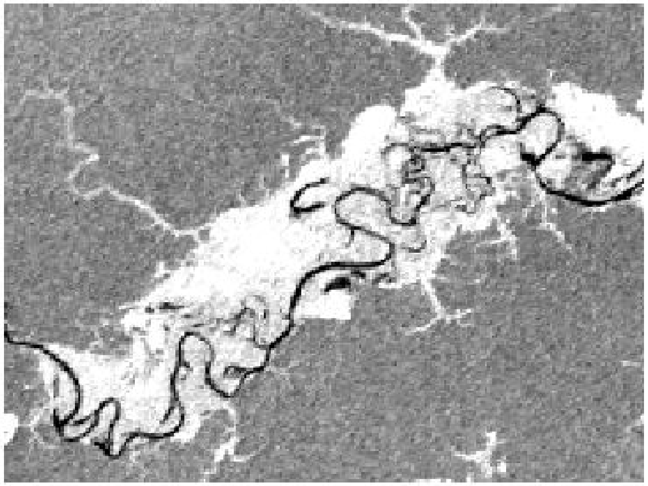
Sub-canopy penetration

Varzea Dry Season

Varzea Wet Season



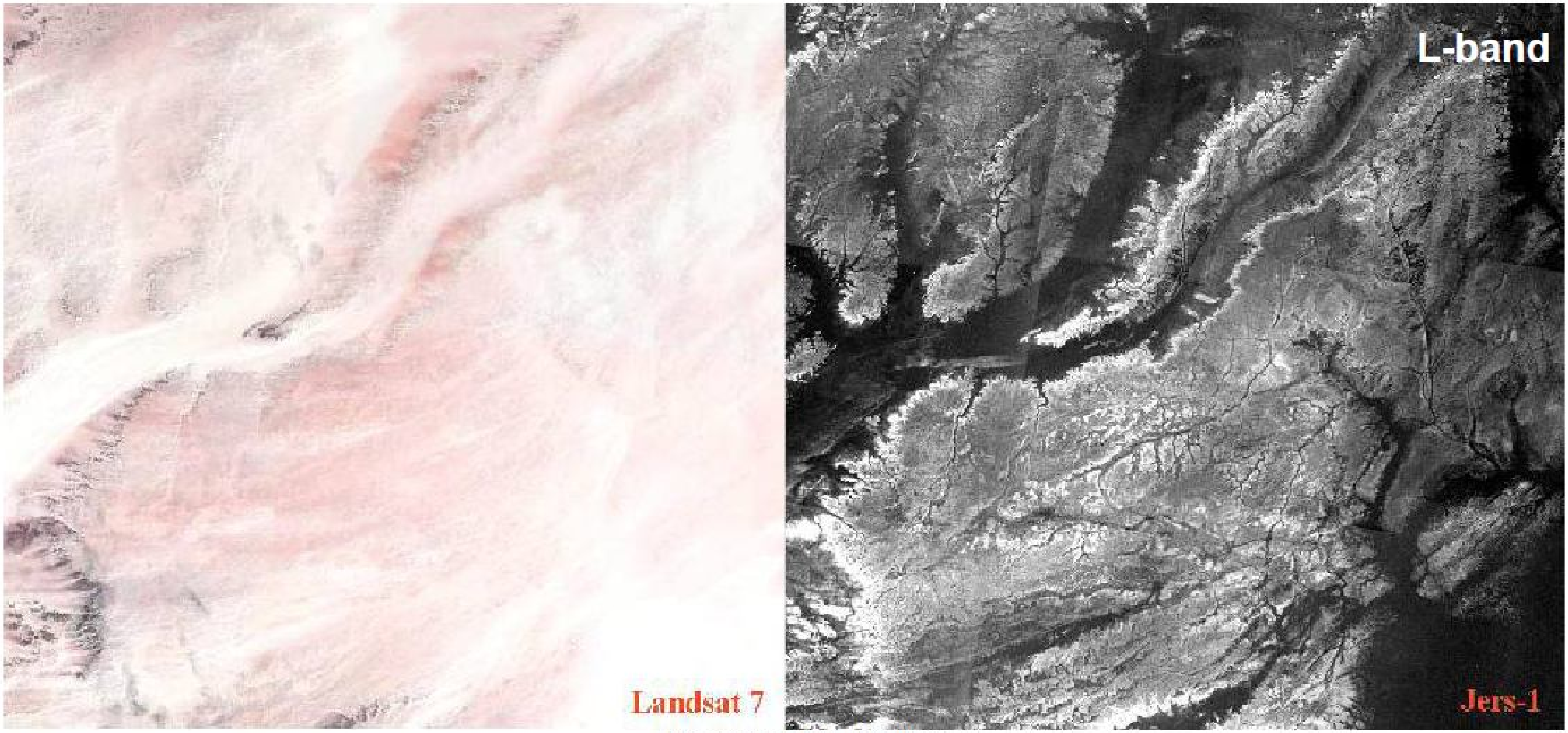
P-band image



P-band image

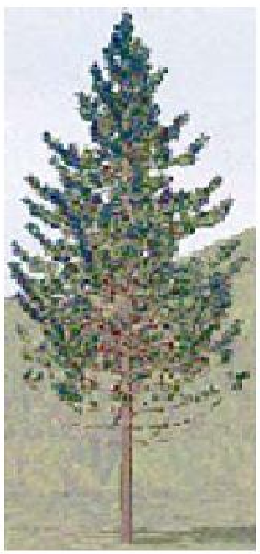
Document S.Saatchi, JPL

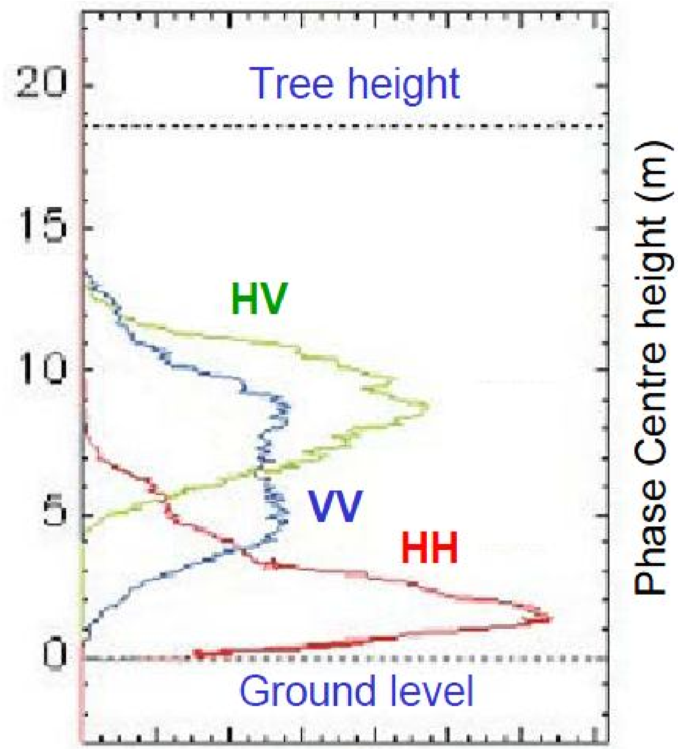
Subsurface penetration

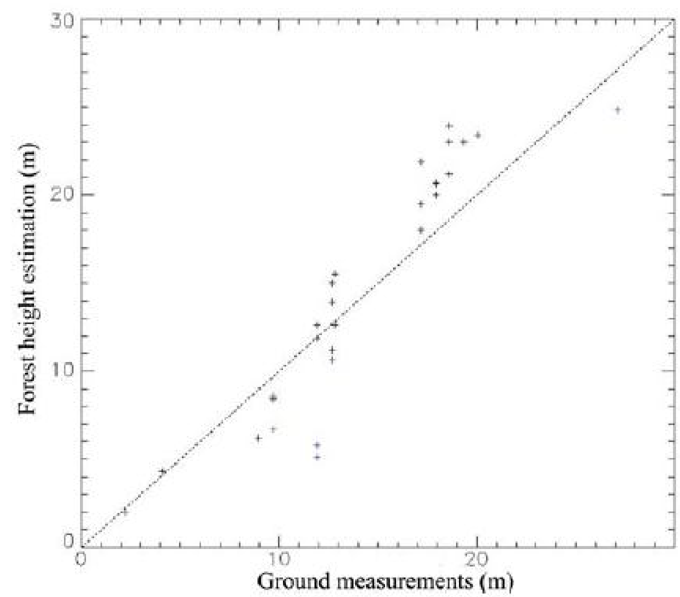


Document P. Paillou

Tree height inversion using Polarimetric Interferometry (PolinSAR)

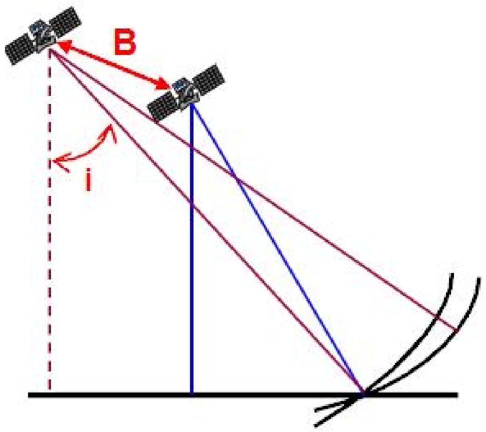


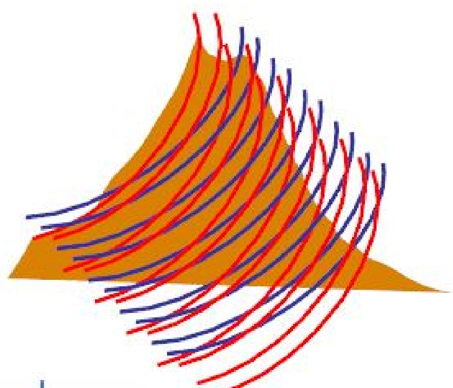




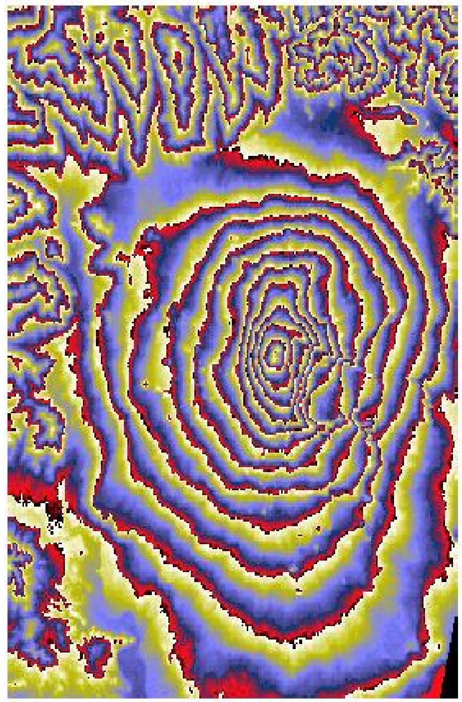
Garestier, 2006

Accurate range measurement
Radar Interferometry





Relief

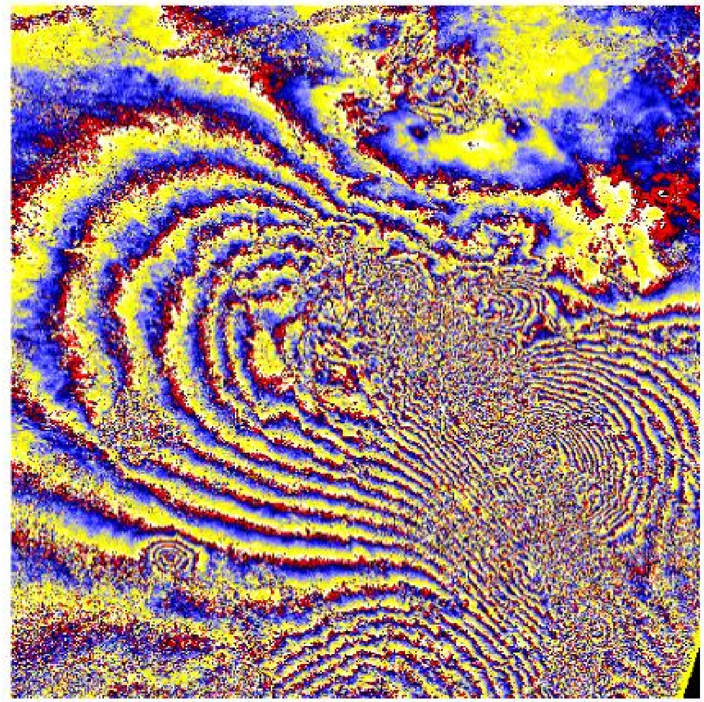


Etna

iso-altitude curves

Digital elevation models

Terrain displacement



Landers

iso-displacement curves

Cartography of terrain displacements