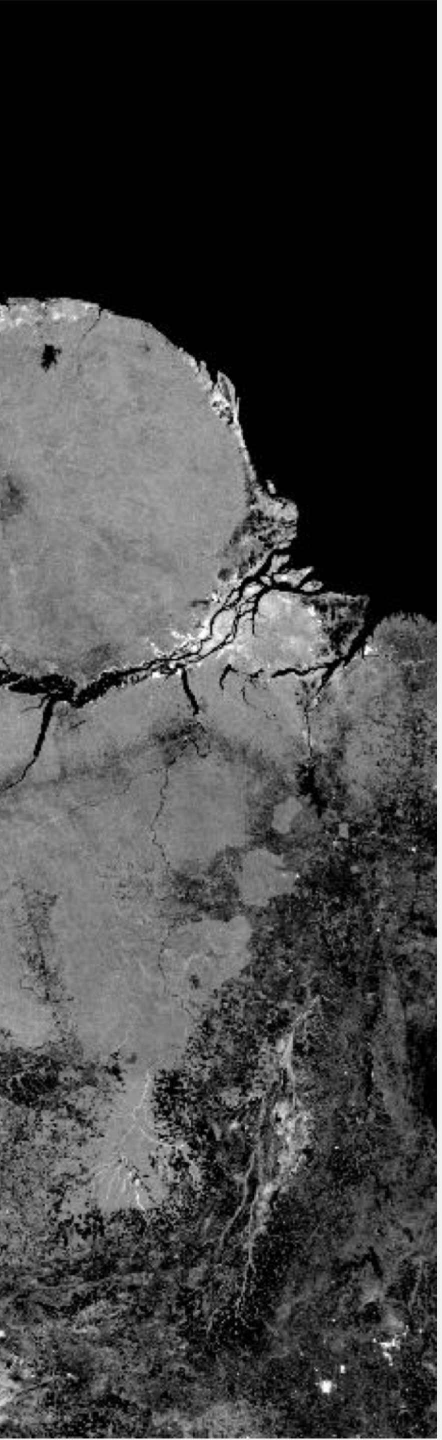


National Aeronautics and
Space Administration

ARSET

Applied Remote Sensing Training

http://arset.gsfc.nasa.gov

@NASAARSET

Basics of Synthetic Aperture Radar

Erika Podest

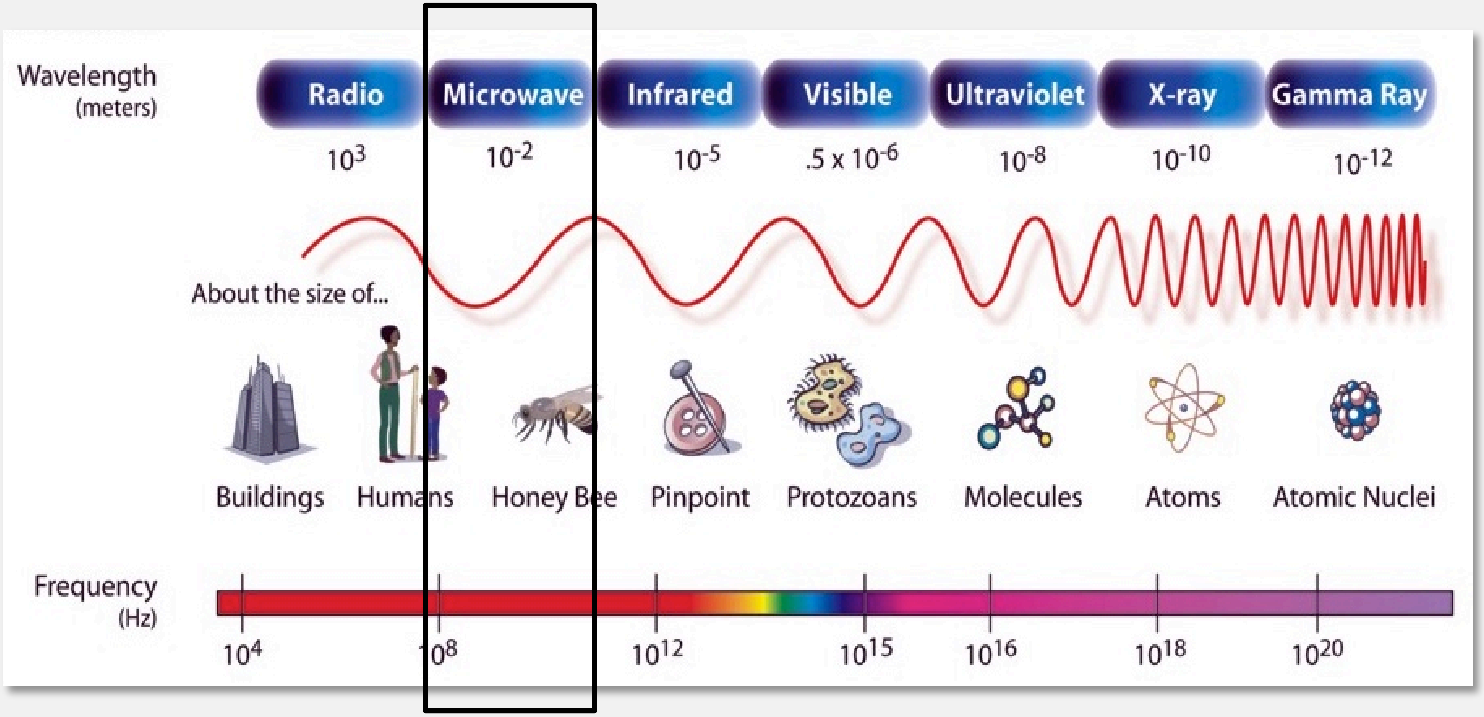
Learning Objectives

By the end of this presentation, you will be able to:

- Understand the physics of SAR image formation
- Describe the interaction of SAR with the land surface
- Describe the necessary data preprocessing
- Explain what information is available from SAR

The Electromagnetic Spectrum

- Optical sensors measure reflected solar light and only function in the daytime
- The surface of the Earth cannot be imaged with visible or infrared sensors when there are clouds
- Microwaves can penetrate through clouds and vegetation, and can operate in day or night conditions



Advantages and Disadvantages of Radar Remote Sensing Over Optical

Advantages

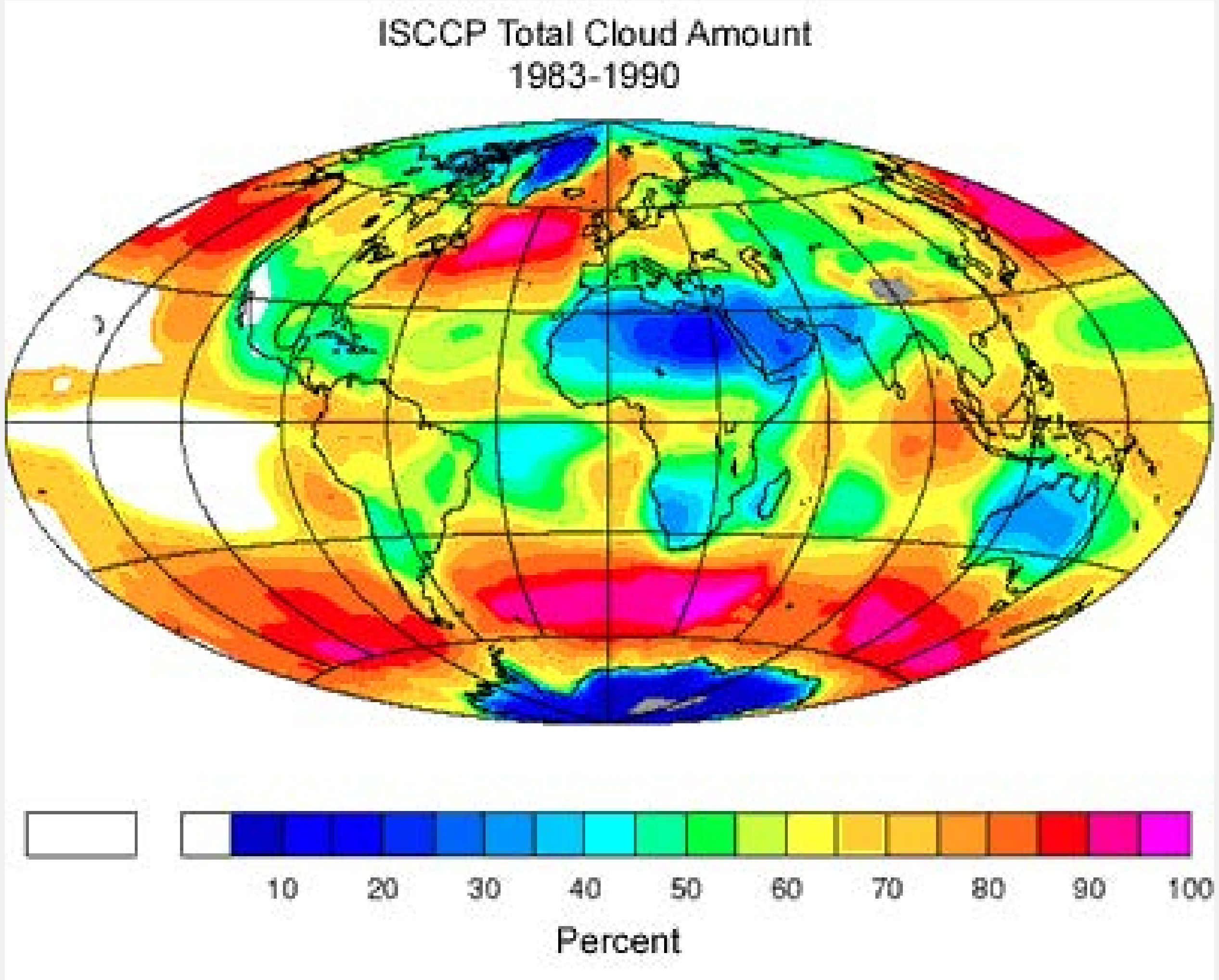
- Nearly all weather capability
- Day or night capability
- Penetration through the vegetation canopy
- Penetration through the soil
- Minimal atmospheric effects
- Sensitivity to dielectric properties (liquid vs. frozen water)
- Sensitivity to structure

Disadvantages

- Information content is different than optical and sometimes difficult to interpret
- Speckle effects (graininess in the image)
- Effects of topography

Global Cloud Coverage

- Total fractional cloud cover annual averaged from 1983-1990, compiled using data from the International Satellite Cloud Climatology Project (ISCCP)



Source: ISCCP, NASA Earth Observatory

Optical vs. Radar

Volcano in Kamchatka, Russia, Oct 5, 1994

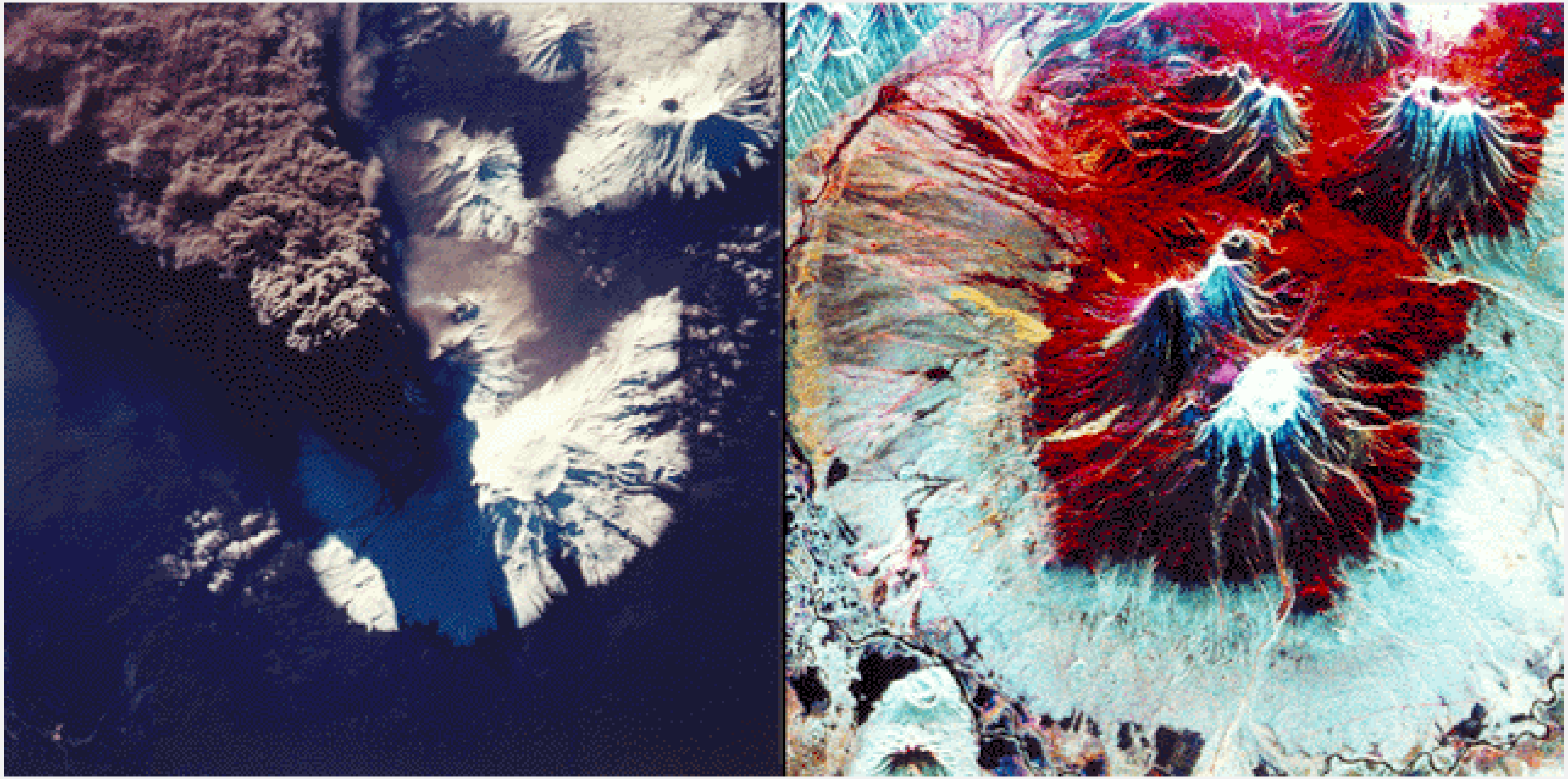
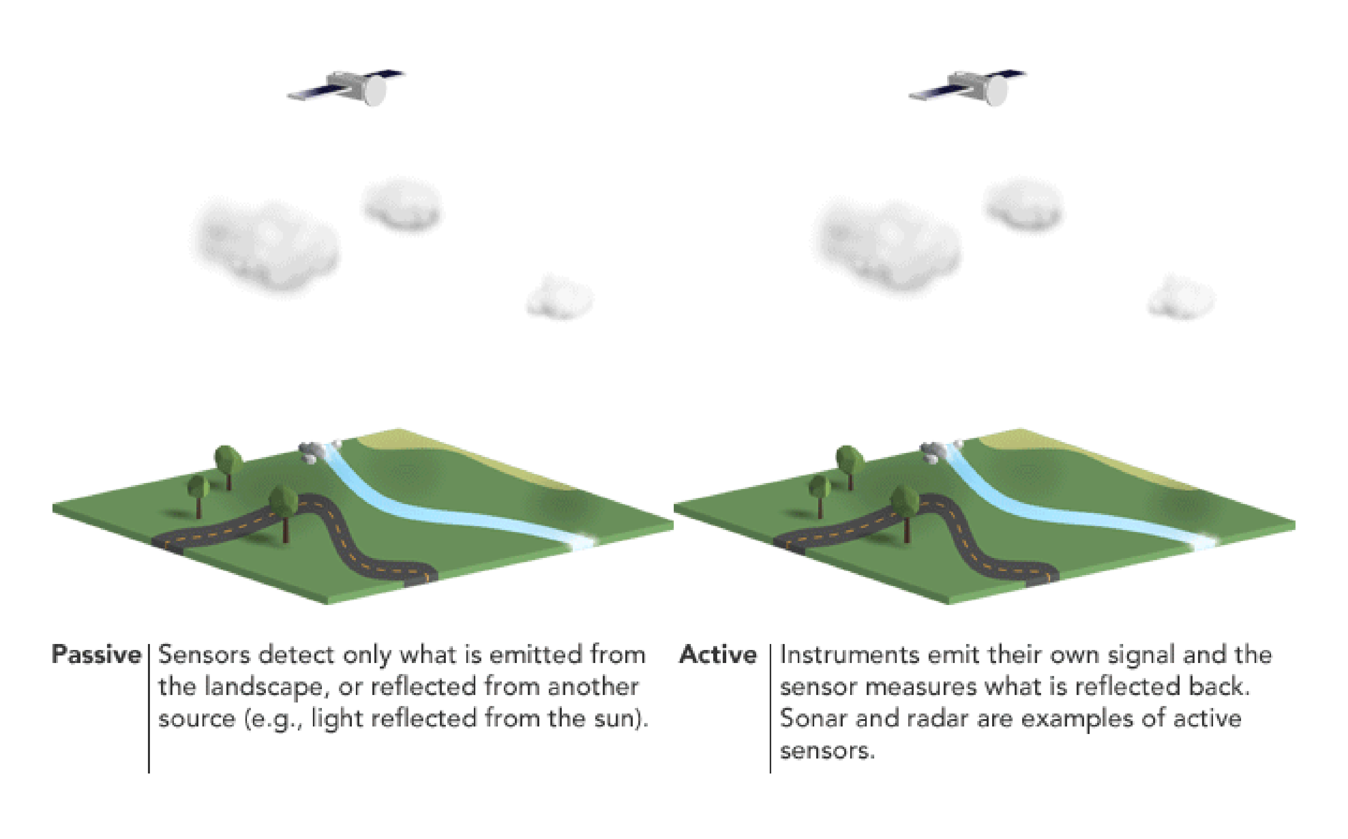


Image Credit: Michigan Tech Volcanology

Active and Passive Remote Sensing



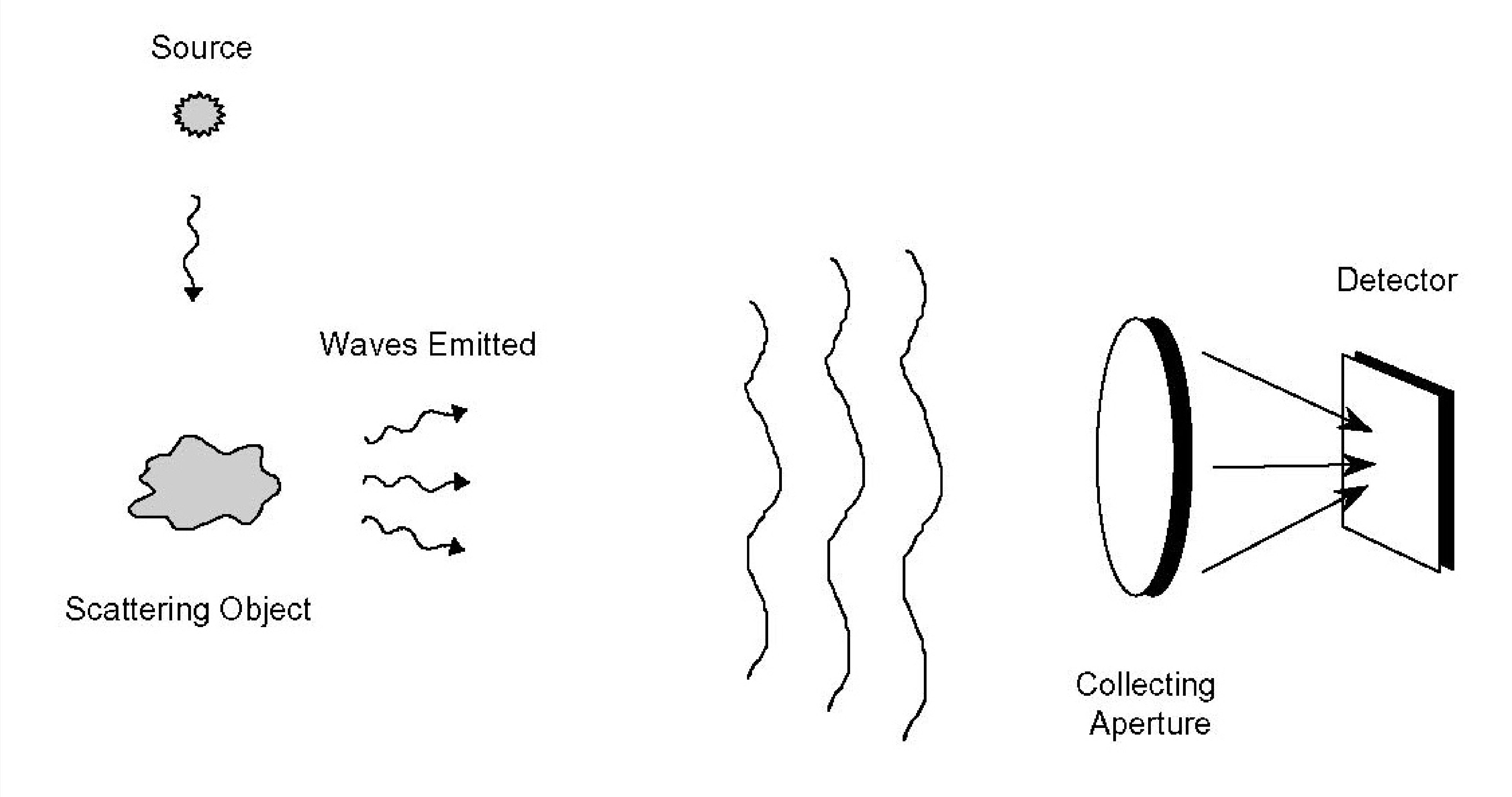
Passive Sensors:

- The source of radiant energy arises from natural sources
- e.g. the sun, Earth, other “hot” bodies

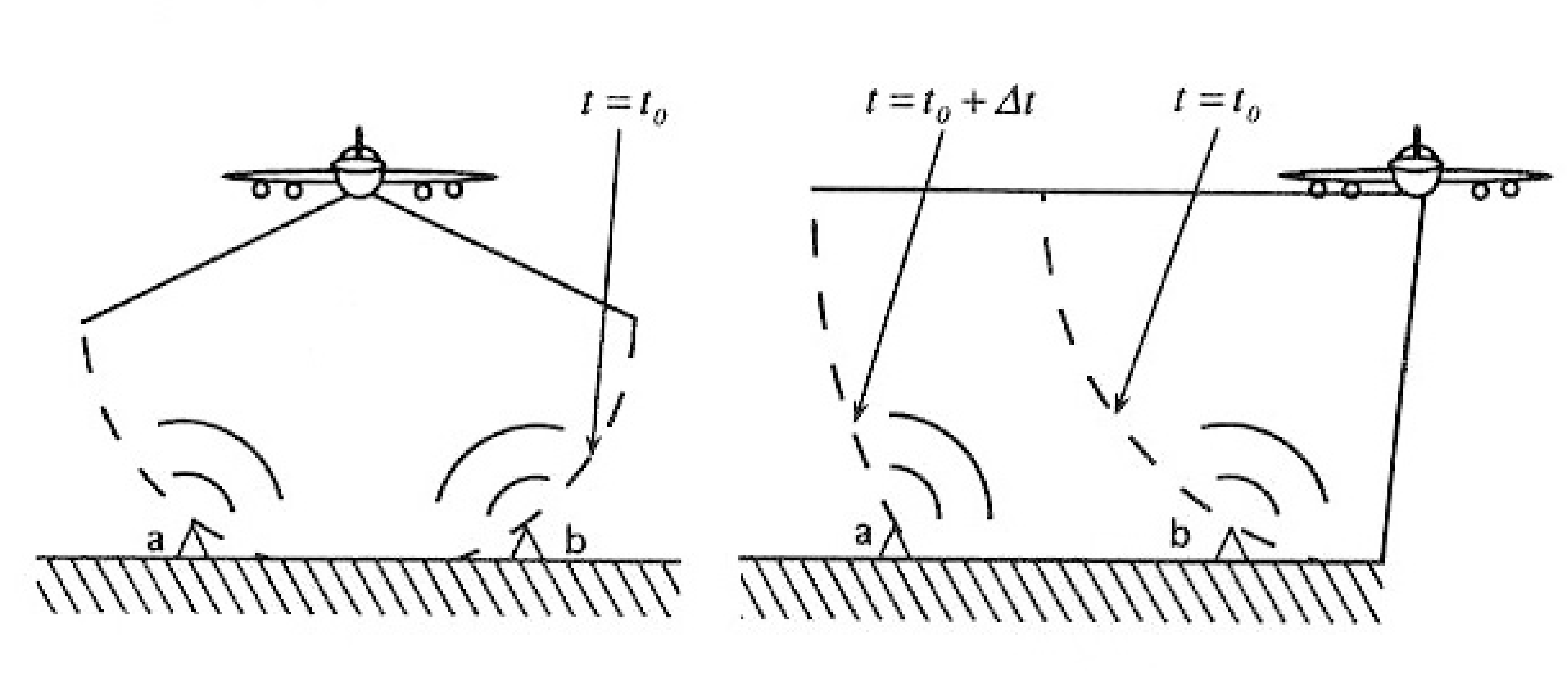
Active Sensors

- Provide their own artificial radiant energy source for illumination
- e.g. **radar, synthetic aperture radar (SAR)**, LIDAR

Basic Remote Sensing System

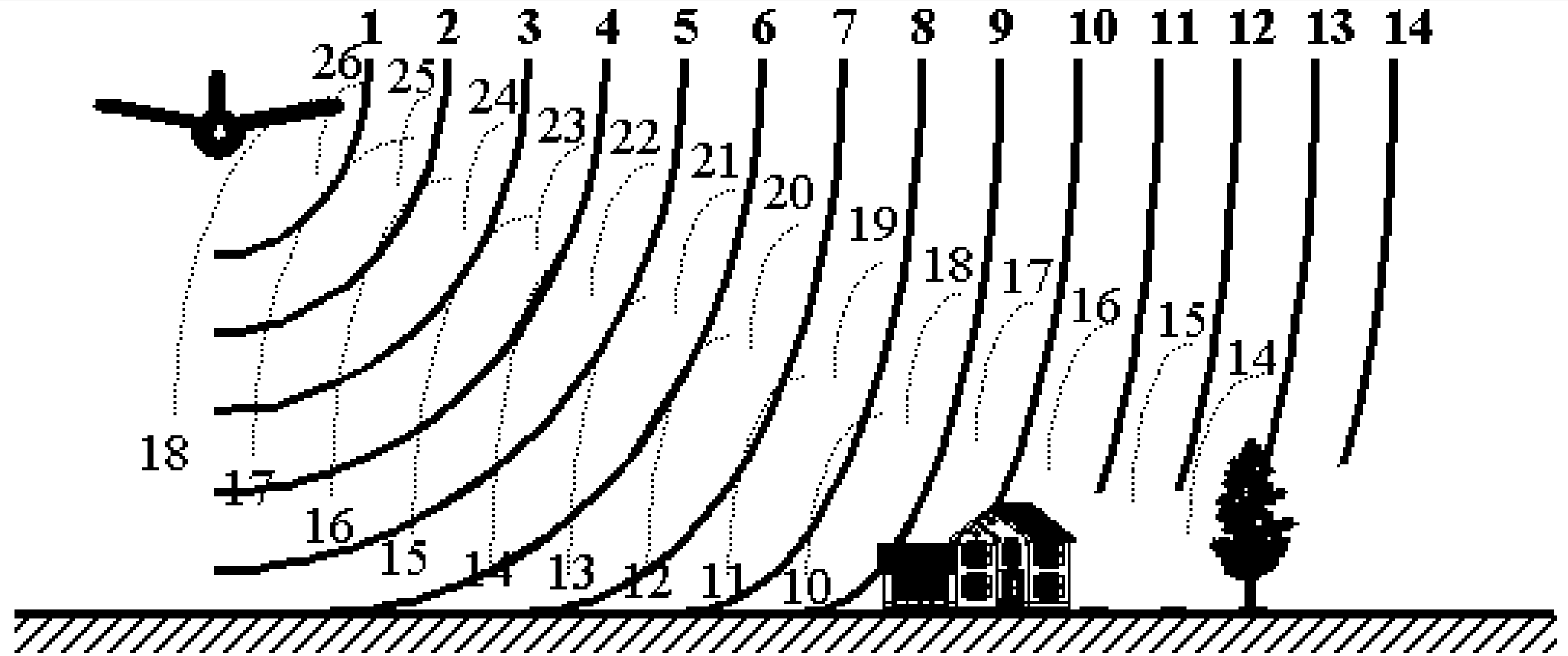


Basic Concepts: Down Looking vs. Side Looking Radar



Basic Concepts: Side Looking Radar

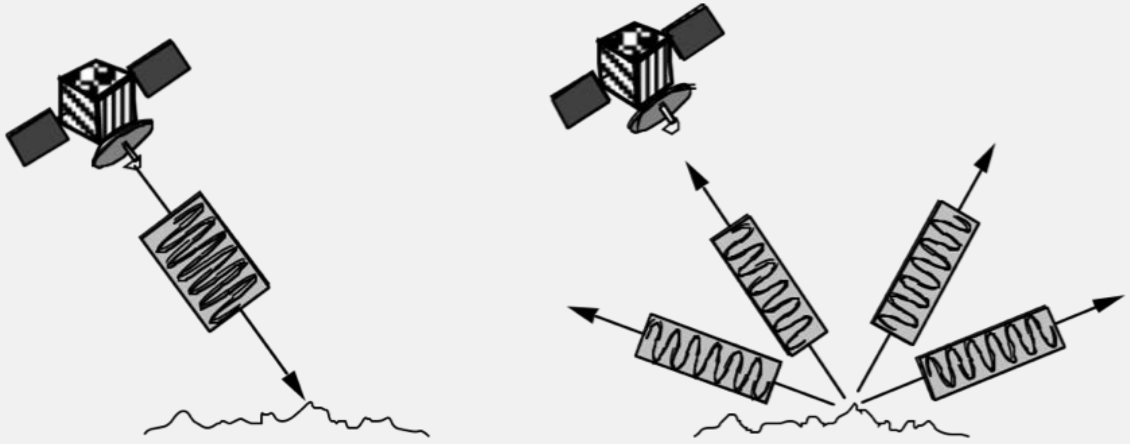
- Each pixel in the radar image represents a complex quantity of the energy that was reflected back to the satellite
- The magnitude of each pixel represents the intensity of the reflected echo



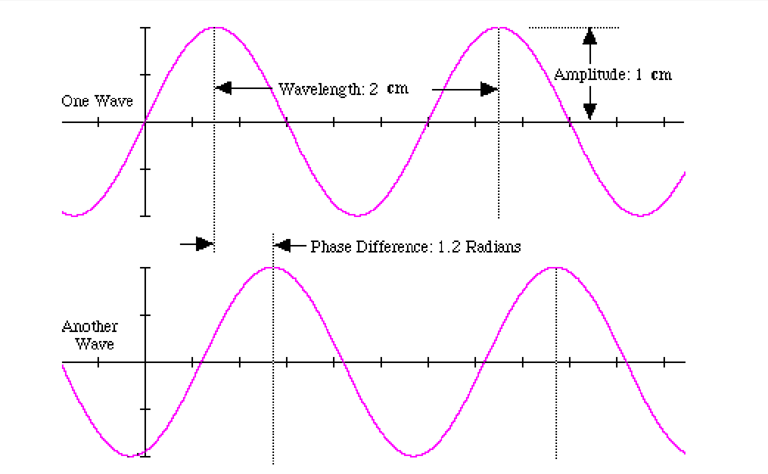
Credit: [Paul Messina, CUNY NY](), after Drury 1990, Lillesand and Kiefer, 1994

Review of Radar Image Formation

1. Radar can measure amplitude (the strength of the reflected echo) and phase (the position of a point in time on a waveform cycle)
2. Radar can only measure the part of the echo reflected back towards the antenna (backscatter)
3. Radar pulses travel at the speed of light



RADAR TRANSMITS A PULSE MEASURES REFLECTED ECHO (BACKSCATTER)



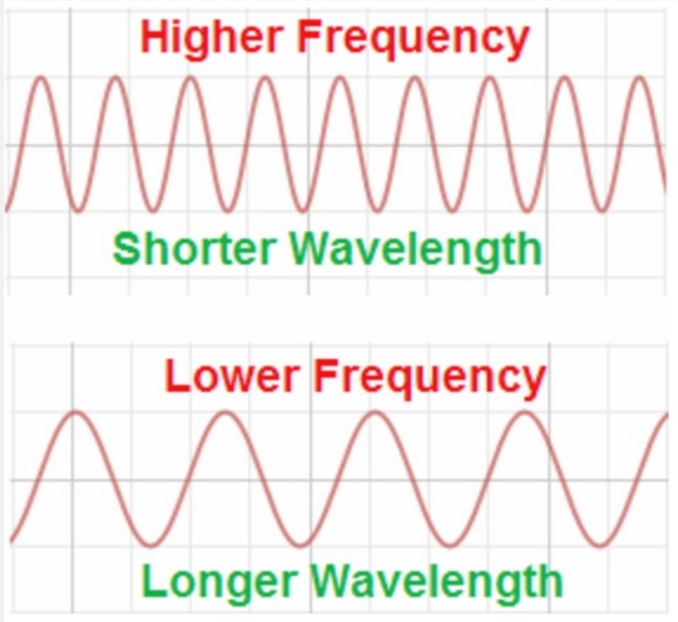
Source: ESA- ASAR Handbook

Radar Parameters to Consider for a Study

- Wavelength
- Polarization
- Incidence Angle

Radar Parameters: Wavelength

$$\text{Wavelength} = \frac{\text{Speed of light}}{\text{frequency}}$$



Band designation*	Wavelength (λ), cm	Frequency (ν), GHz (10^9 cycles · sec^{-1})
Ka (0.86 cm)	0.8 to 1.1	40.0 to 26.5
K	1.1 to 1.7	26.5 to 18.0
Ku	1.7 to 2.4	18.0 to 12.5
X (3.0 cm, 3.2 cm)	2.4 to 3.8	12.5 to 8.0
C (6.0)	3.8 to 7.5	8.0 to 4.0
S	7.5 to 15.0	4.0 to 2.0
L (23.5 cm, 25 cm)	15.0 to 30.0	2.0 to 1.0
P (68 cm)	30.0 to 100.0	1.0 to 0.3

* Wavelengths most frequently used in SAR are in parenthesis

Radar Parameters: Wavelength

- Penetration is the **primary factor** in wavelength selection
- Penetration through the forest canopy or into the soil is greater with longer wavelengths

Commonly Used Frequency Bands

Frequency band	*Frequency range*	*Application Example*
• VHF	300 KHz - 300 MHz	Foliage/Ground penetration, biomass
• P-Band	300 MHz - 1 GHz	biomass, soil moisture, penetration
• L-Band	1 GHz - 2 GHz	agriculture, forestry, soil moisture
• C-Band	4 GHz - 8 GHz	ocean, agriculture
• X-Band	8 GHz - 12 GHz	agriculture, ocean, high resolution radar
• Ku-Band	14 GHz - 18 GHz	glaciology (snow cover mapping)
• Ka-Band	27 GHz - 47 GHz	high resolution radars

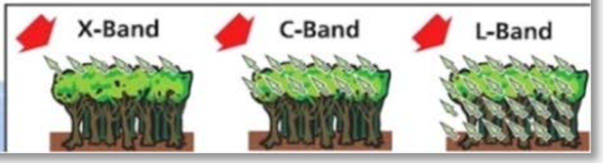
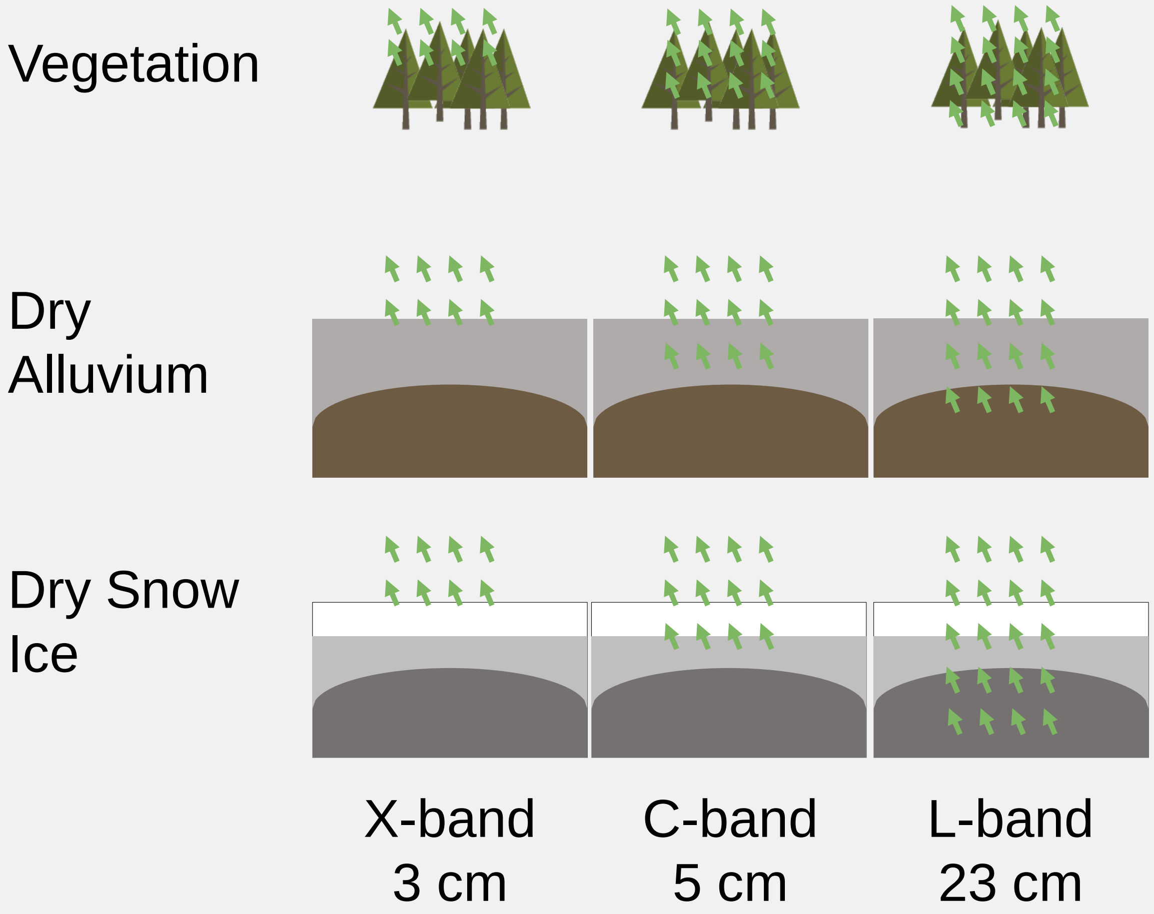


Image Credit: DLR

Penetration as a Function of Wavelength



- Waves can penetrate into vegetation and (in dry conditions) soil
- Generally, the longer the wavelength, the stronger the penetration into the target

Image based on ESA [Radar Course 2]

Example: Radar Signal Penetration into Dry Soils

- Different satellite images over southwest Libya
- The arrows indicate possible fluvial systems

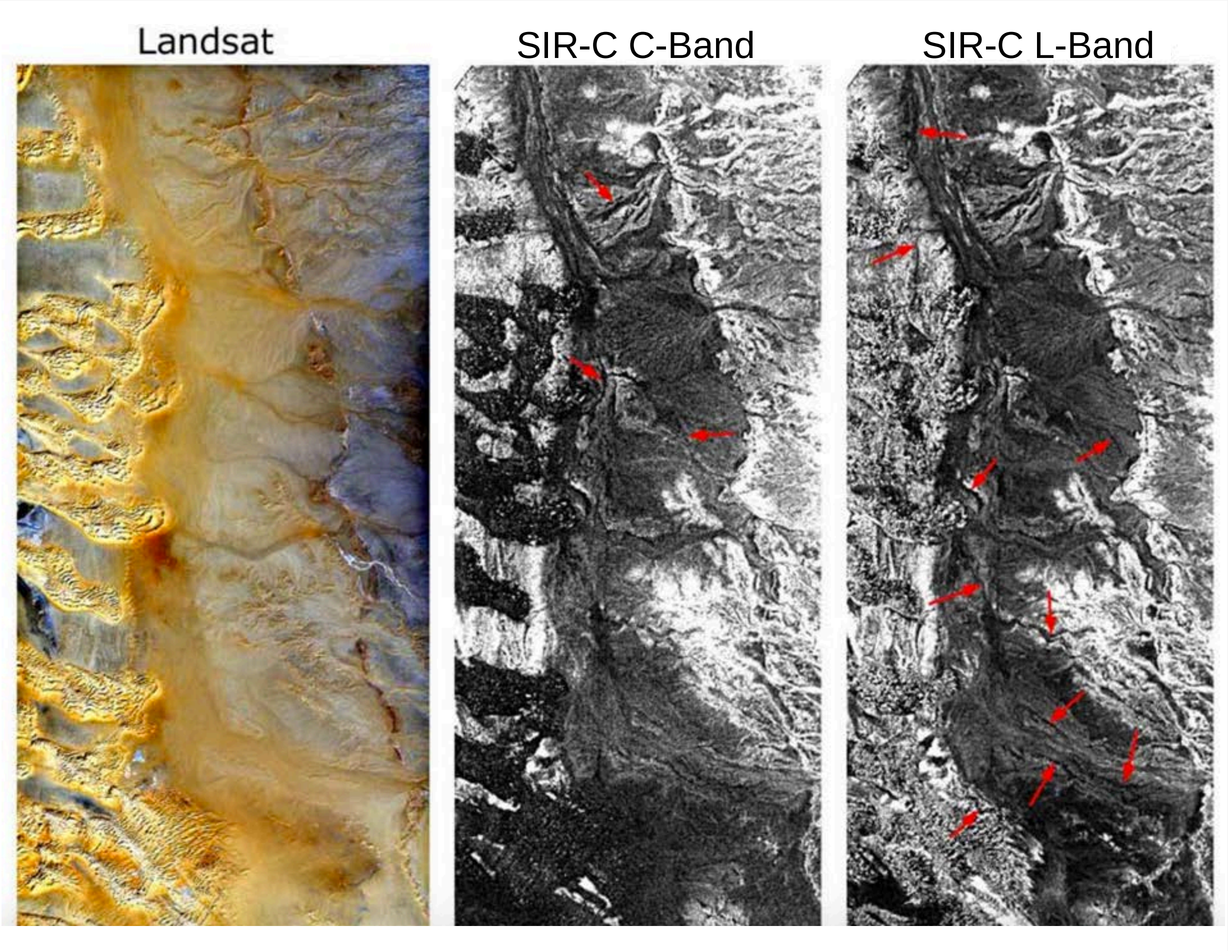
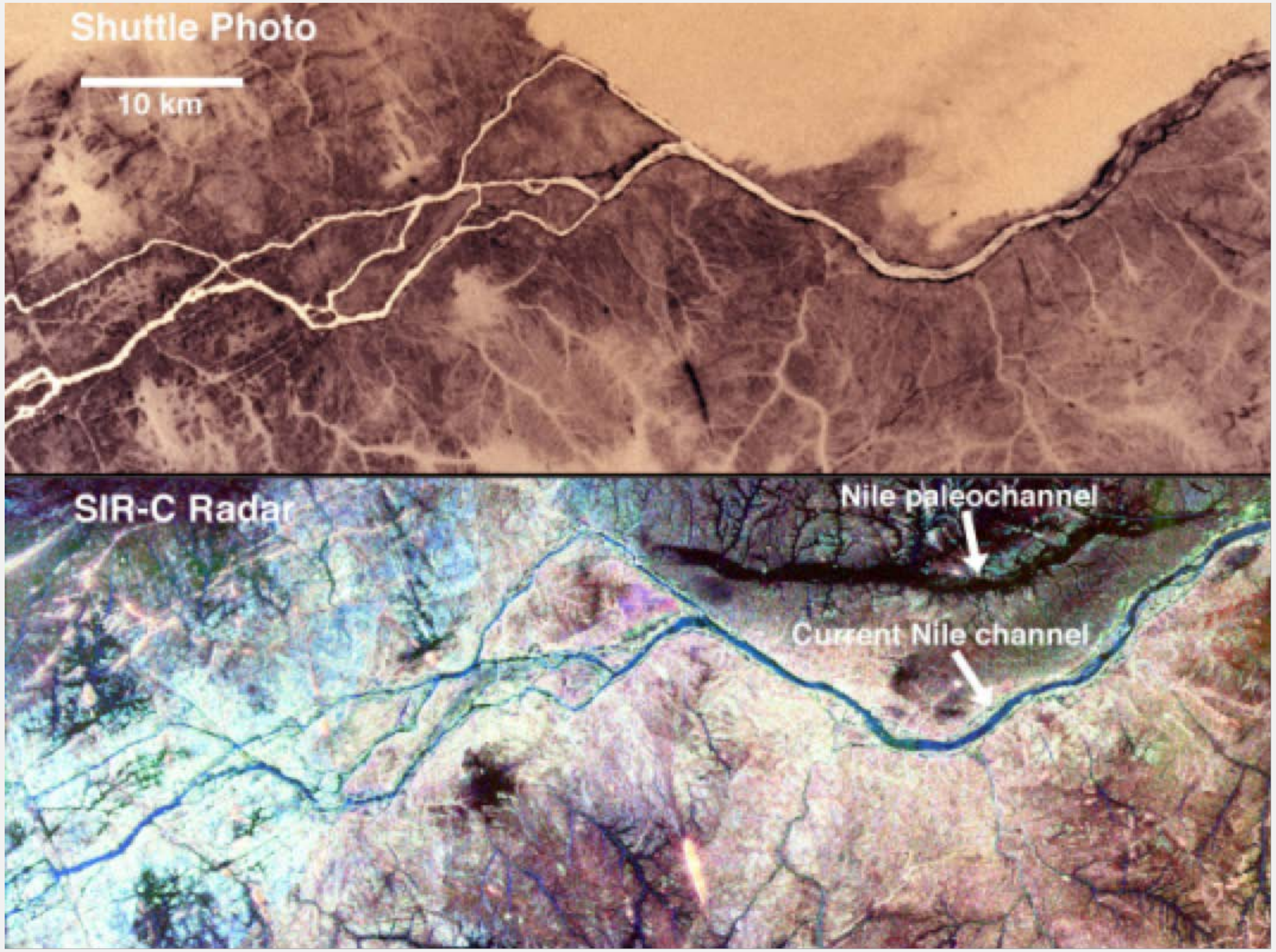
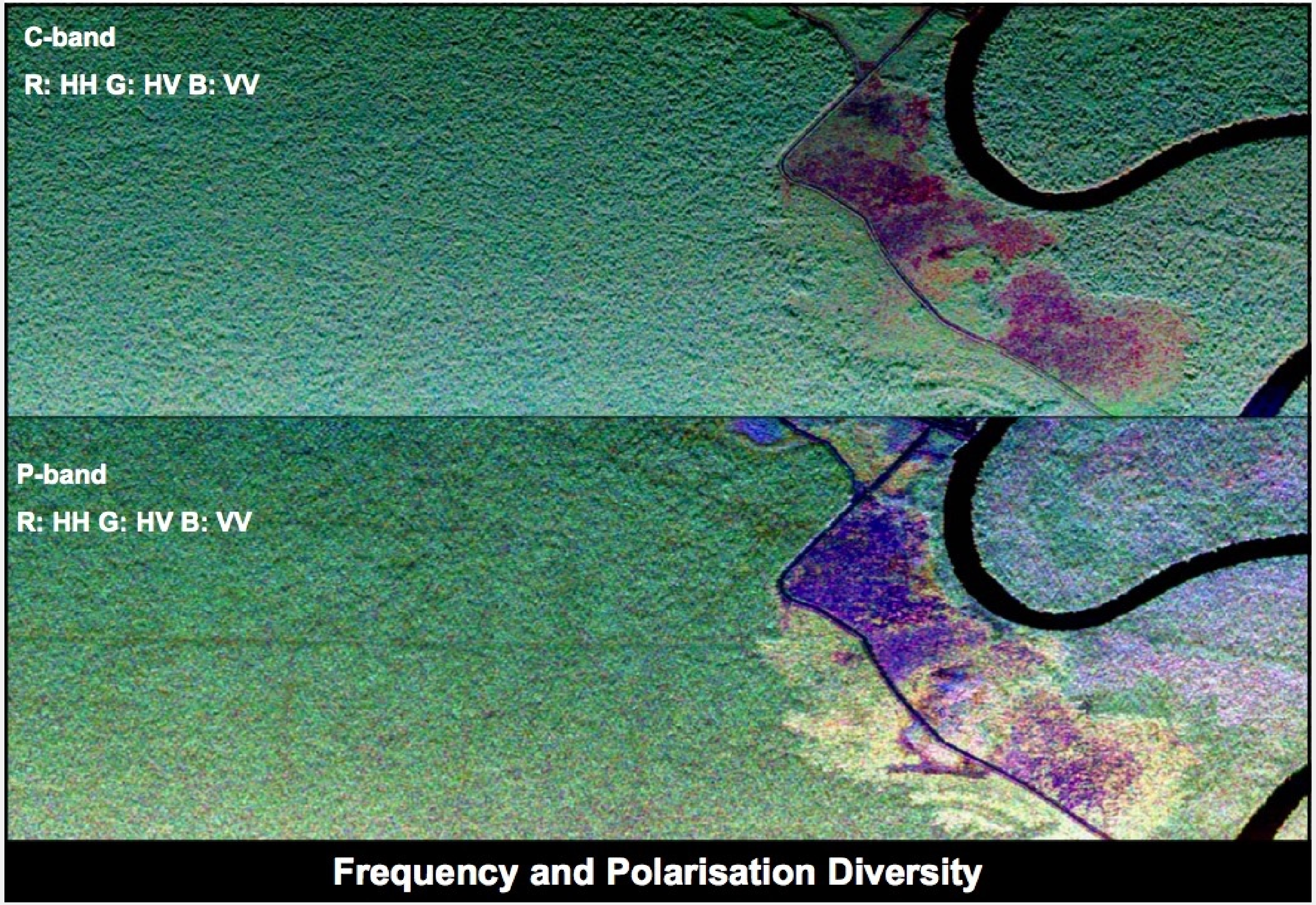


Image Credit: A Perego

Example: Radar Signal Penetration into Dry Soils



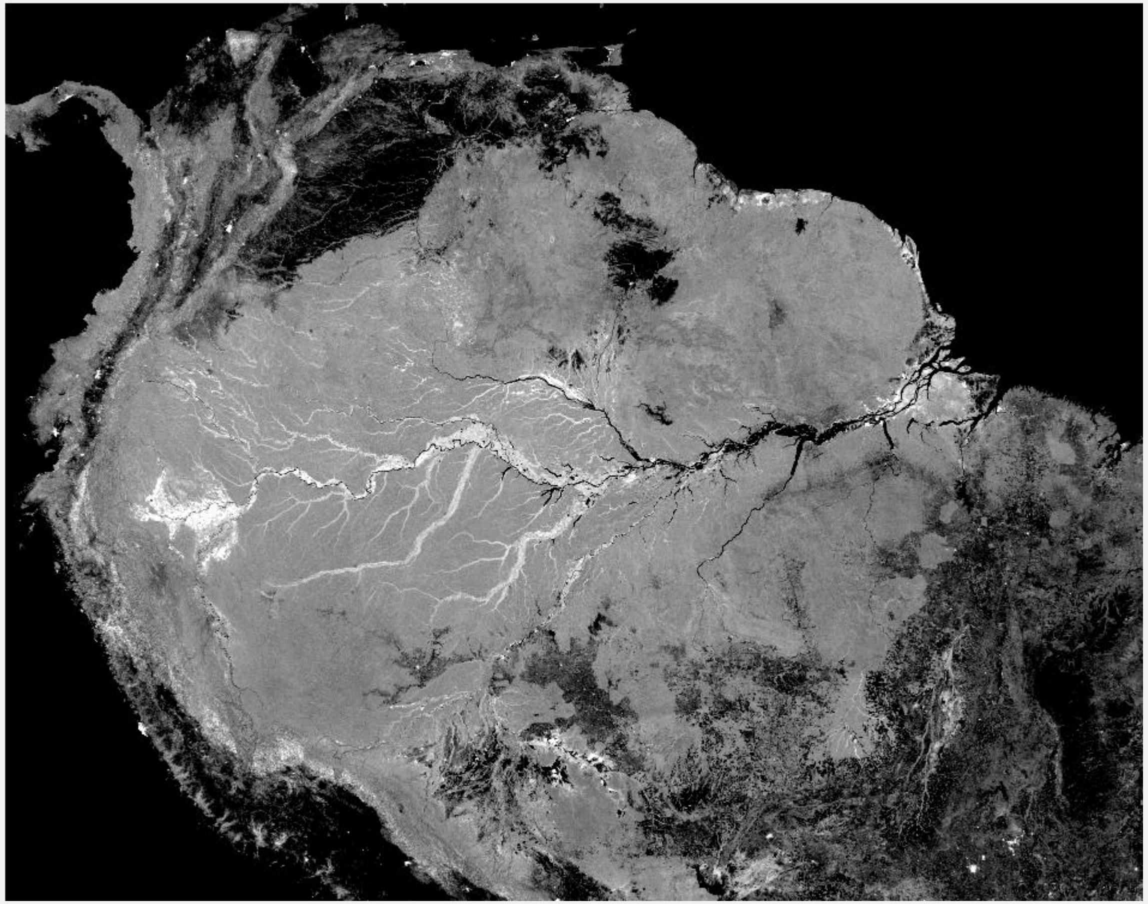
Example: Radar Signal Penetration into Vegetation



Example: Radar Signal Penetration into Wetlands

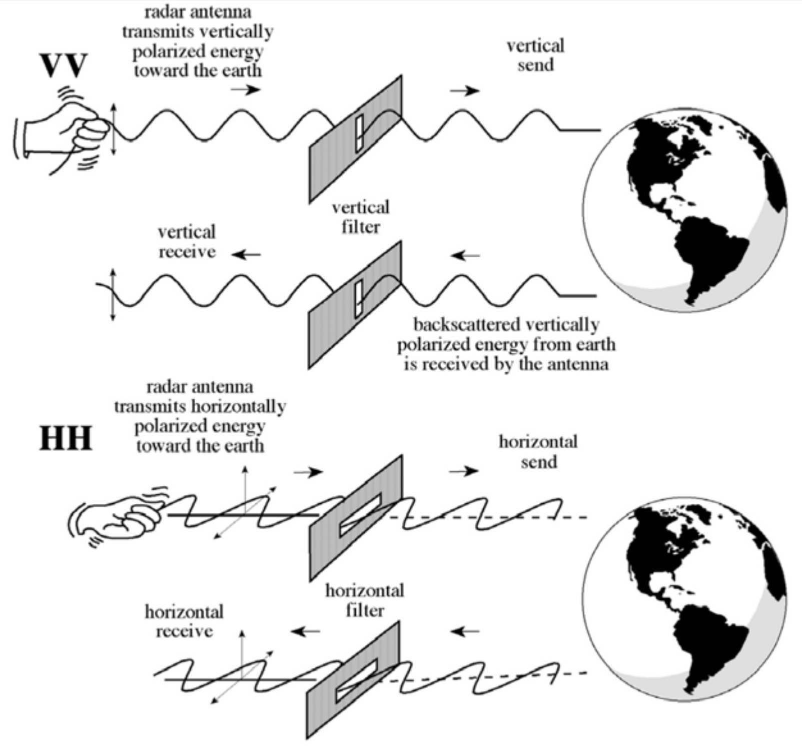
- L-band is ideal for the study of wetlands because the signal penetrates through the canopy and can sense if there is standing water underneath
- Inundated areas appear white in the image to the right

SMAP Radar Mosaic of the Amazon



Radar Parameters: Polarization

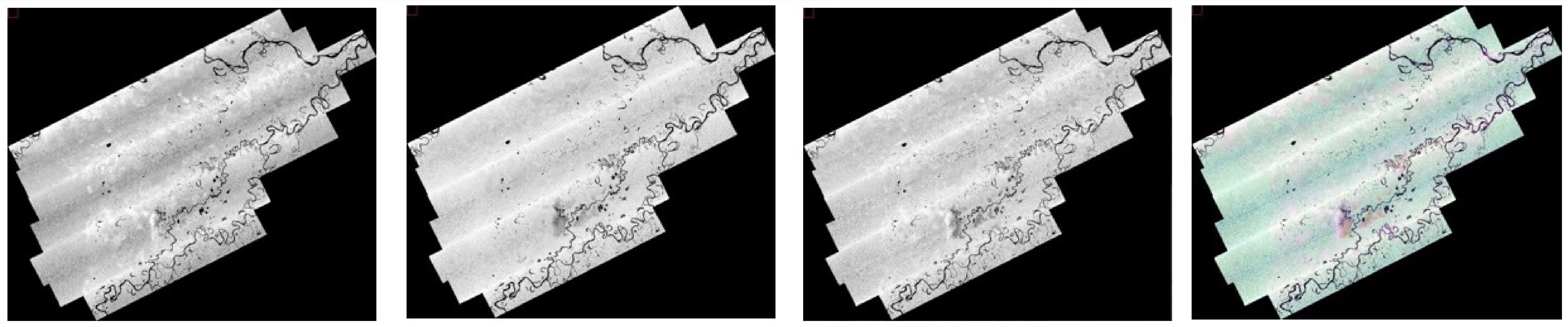
- The radar signal is polarized
- The polarizations are usually controlled between H and V:
  - HH: Horizontal Transmit, Horizontal Receive
  - HV: Horizontal Transmit, Vertical Receive
  - VH: Vertical Transmit, Horizontal Receive
  - VV: Vertical Transmit, Vertical Receive
- Quad-Pol Mode: when all four polarizations are measured
- Different polarizations can determine physical properties of the object observed



Example of Multiple Polarizations for Vegetation Studies

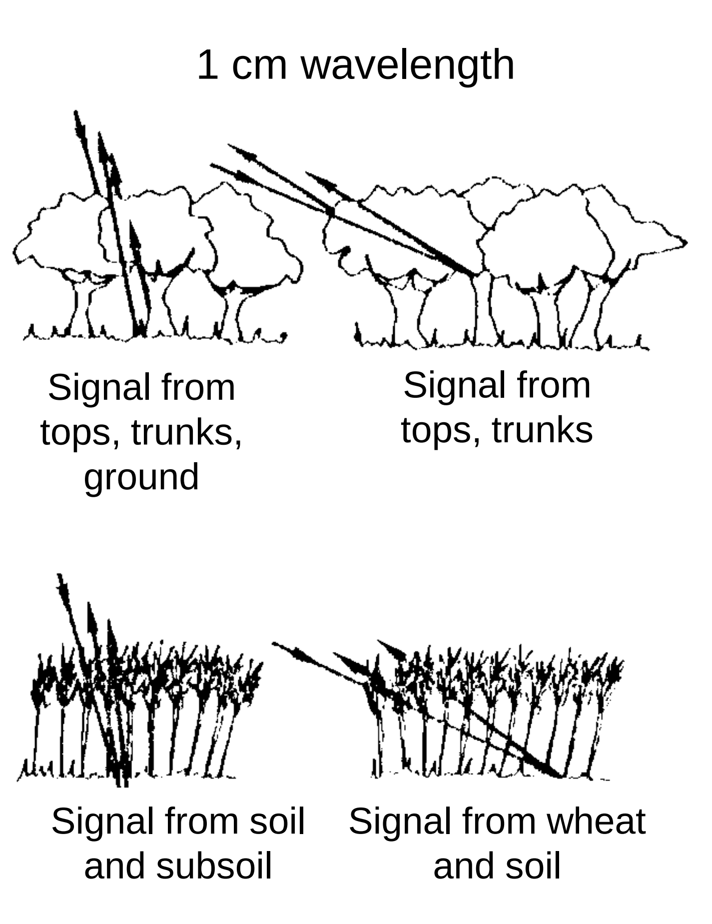
Pacaya-Samiria Forest Reserve in Peru

Images from UAVSAR (HH, HV, VV)



Radar Parameters: Incidence Angle

- The angle between the direction of illumination of the radar and the Earth's surface plane
- Depending on the height of the sensor, the incidence angle will change
- This is why the geometry of an image is different from point to point in the range direction
- Local Incidence Angle:
  - accounts for local inclination of the surface
  - influences image brightness



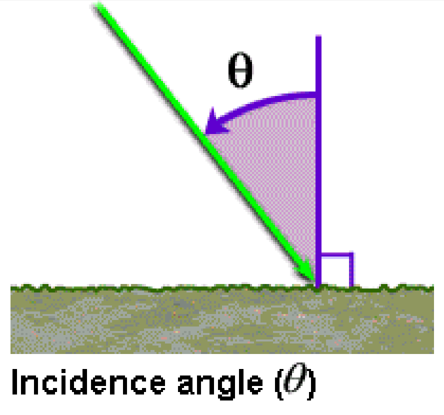


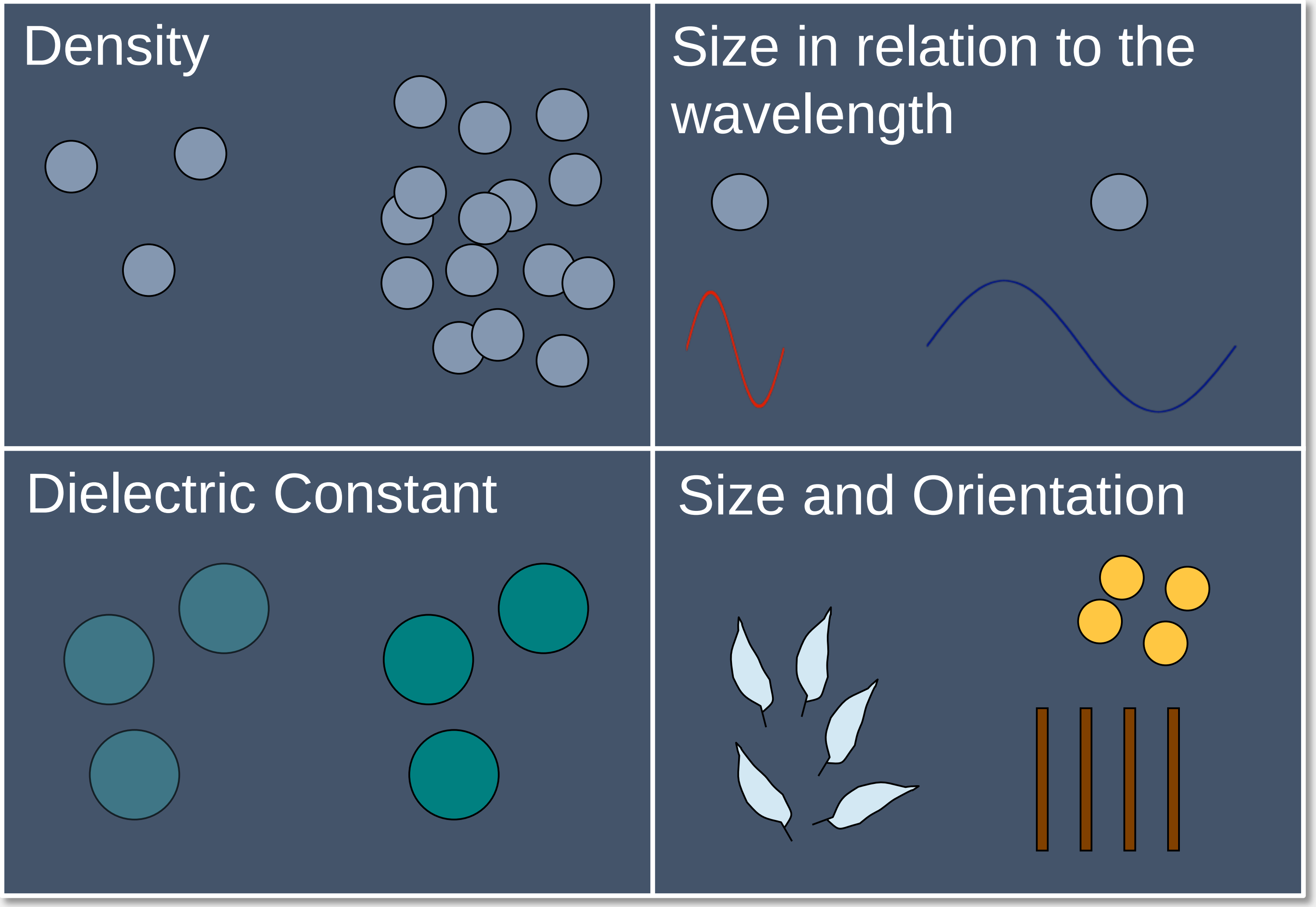
Image Credit: Left: Ulaby et al. (1981a), Right: ESA

Radar Backscatter

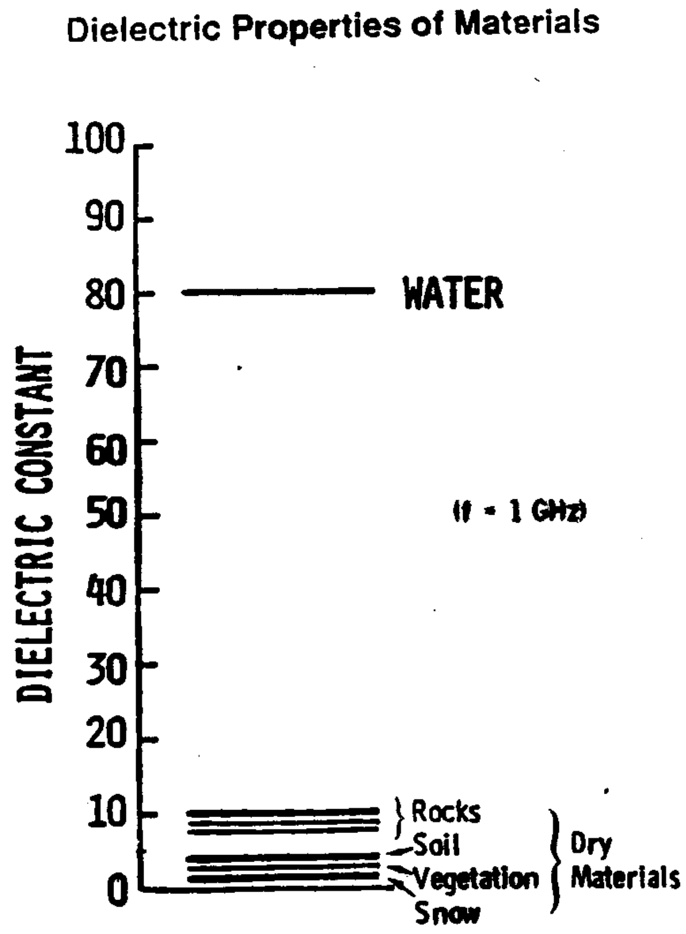
Radar Backscatter

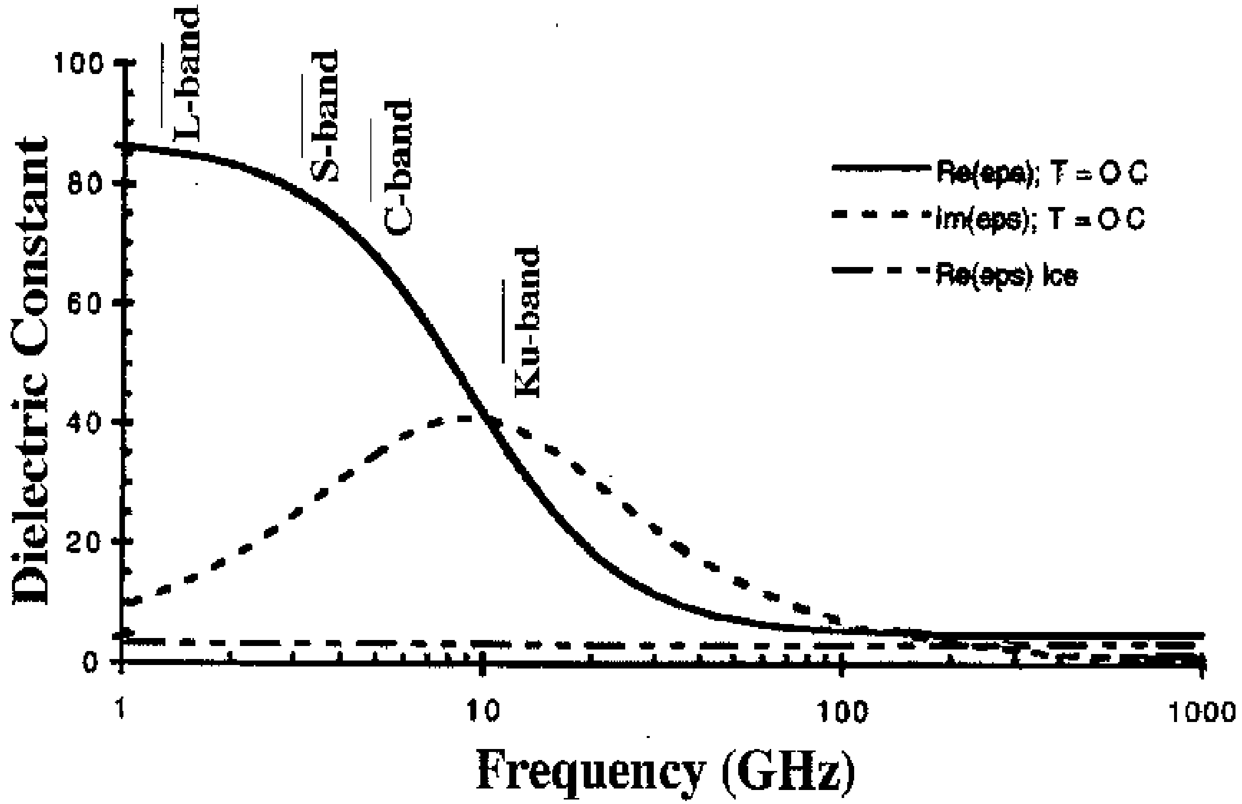
- The radar echo contains information about the Earth’s surface, which drives the reflection of the radar signal
- This reflection is driven by:
  - The frequency or wavelength: radar parameter
  - Polarization: radar parameter
  - Incidence angle: radar parameter
  - Dielectric constant: surface parameter
  - Surface roughness relative to the wavelength: surface parameter
  - Structure and orientation of objects on the surface: surface parameter

Backscattering Mechanisms



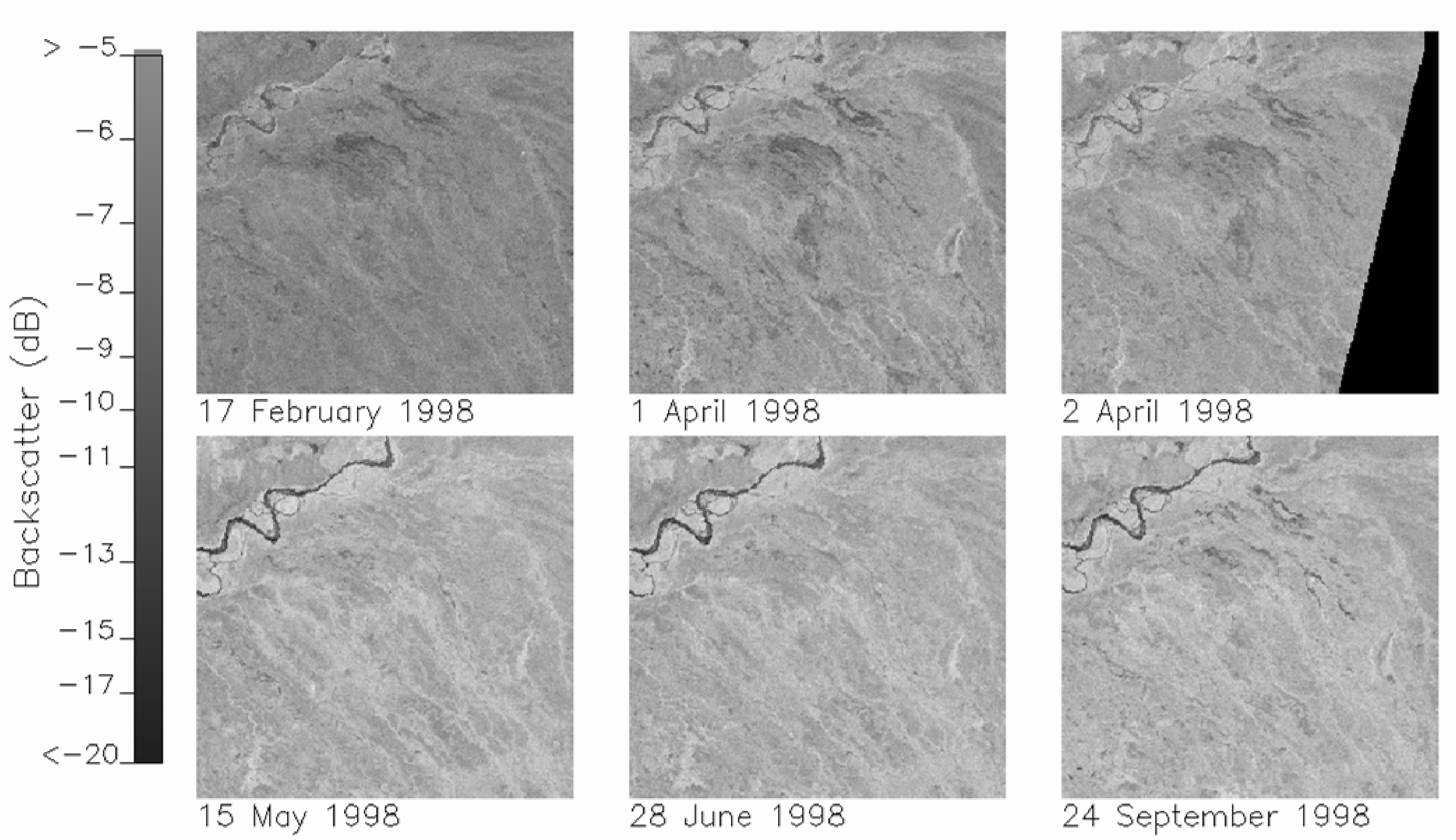
Surface Parameters: Dielectric Constant





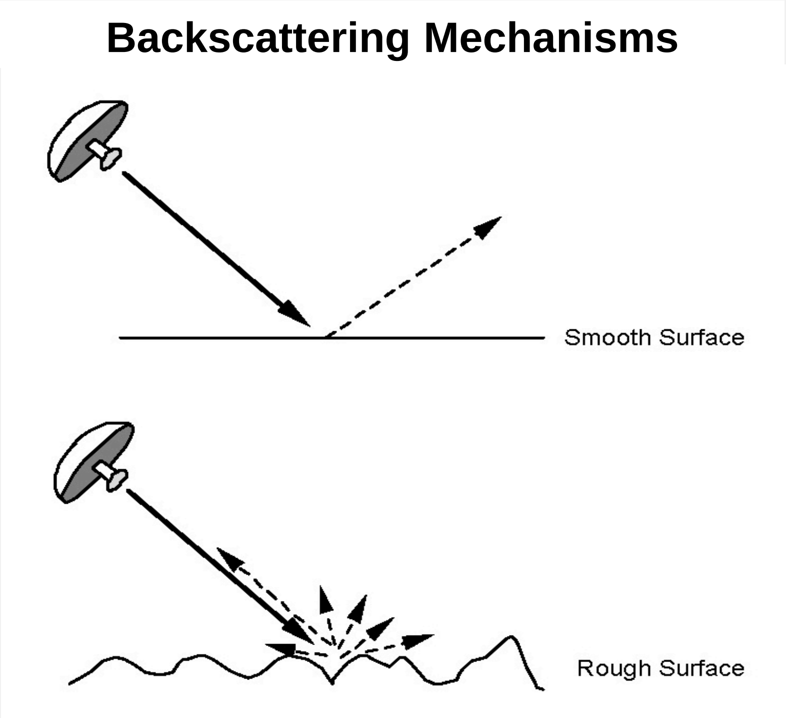
Dielectric Properties of the Surface and its Frozen or Thawed State

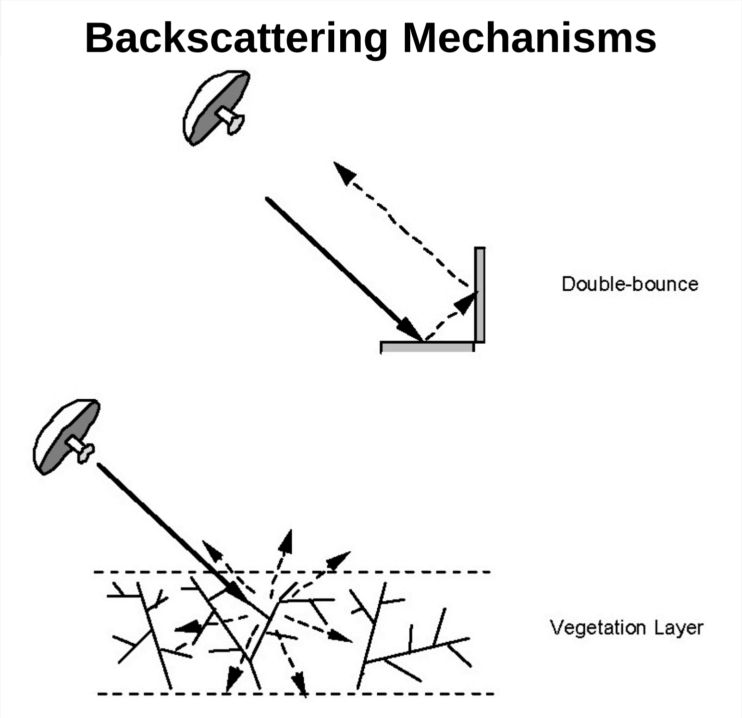
- During the land surface freeze/thaw transition there is a change in dielectric properties of the surface
- This causes a notable increase in backscatter



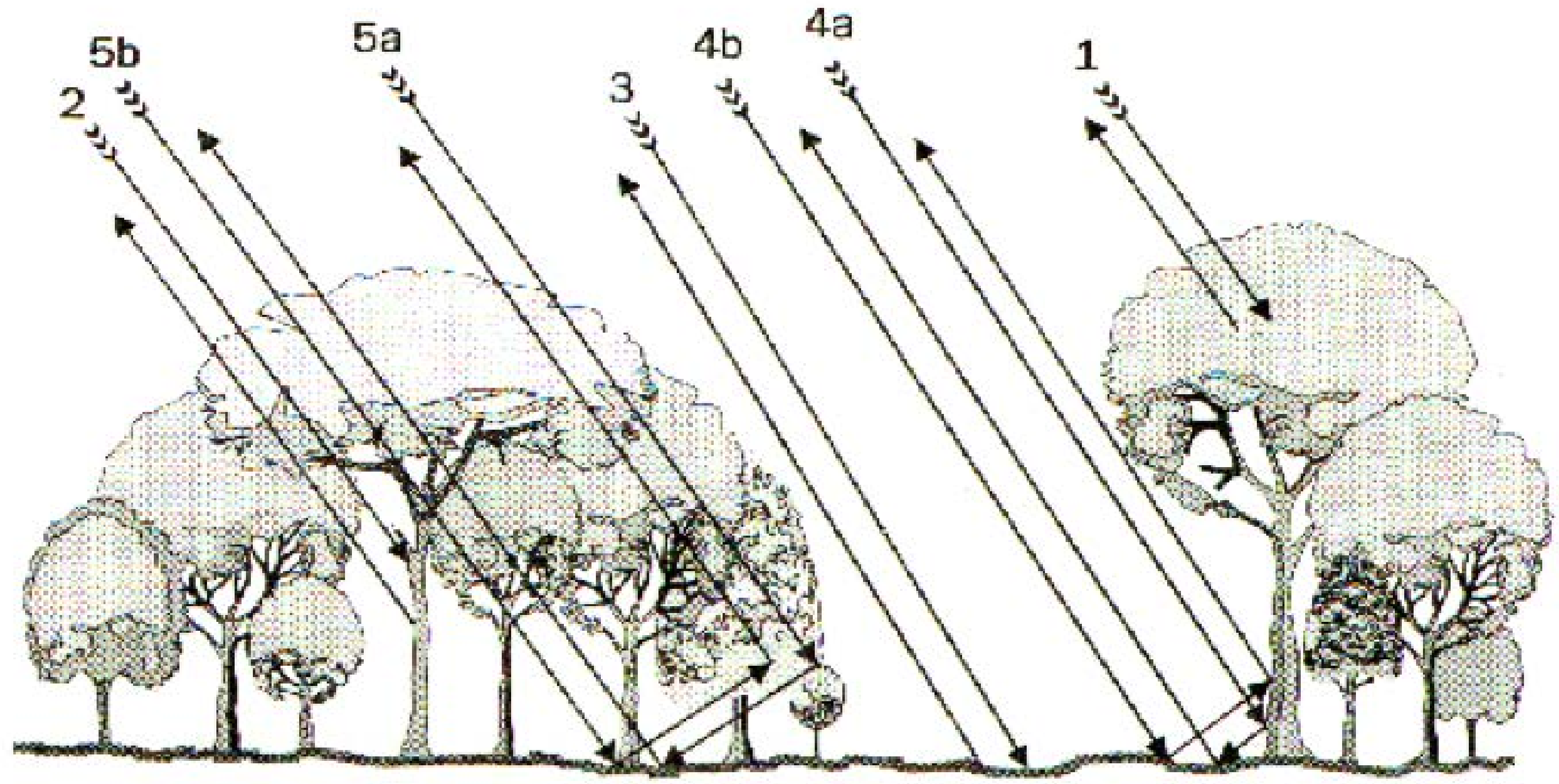
Radar Signal Interaction

- The radar signal is primarily sensitive to surface structure
- The scale of surface relative to the wavelength determine how rough or smooth they appear and how bright or dark they will appear on the image





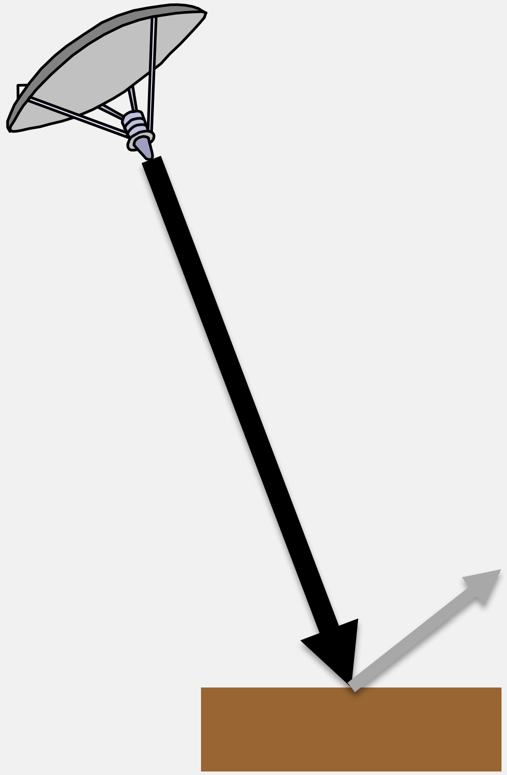
Radar Backscatter in Forests



Dominant backscattering sources in forests: (1) crown volume scattering, (2) direct scattering from tree trunks, (3) direct scattering from the soil surface, (4a) trunk - ground scattering, (4b) ground - trunk scattering, (5a) crown - ground scattering, (5b) ground - crown scattering.

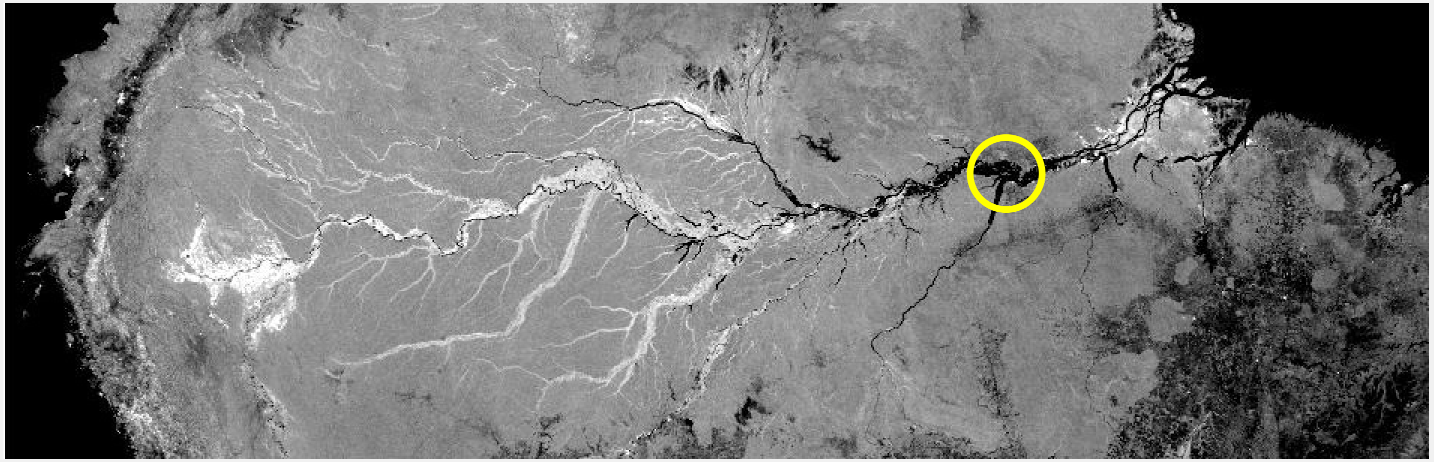
Examples of Radar Interaction

Smooth Surface Reflection (Specular Reflection)



Smooth, level surface
(open water, road)

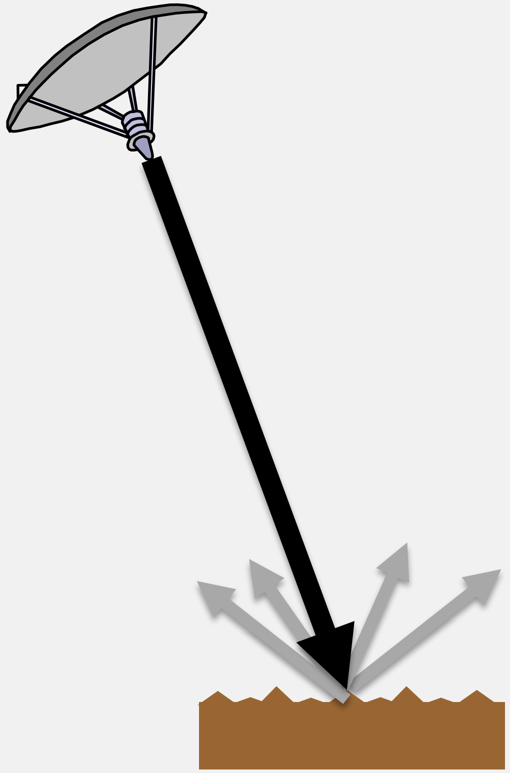
SMAP Radar Mosaic of the Amazon Basin
April 2015 (L-band, HH, 3 km)



Pixel Color

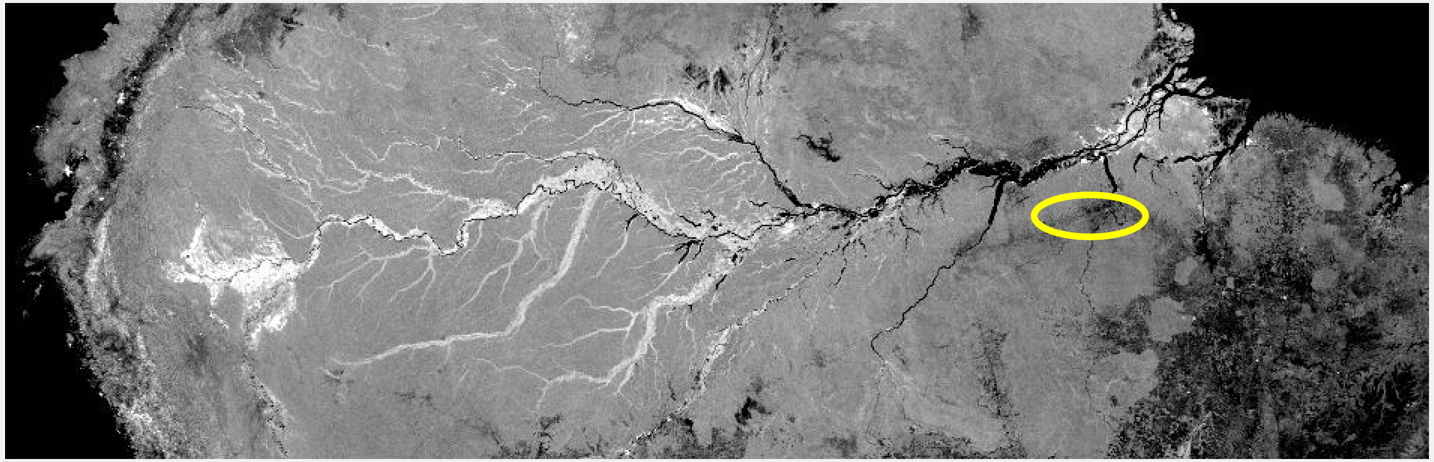
Examples of Radar Interaction

Rough Surface Reflection

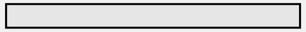


rough bare surface
(deforested areas, tilled agricultural fields)

SMAP Radar Mosaic of the Amazon Basin
April 2015 (L-band, HH, 3 km)

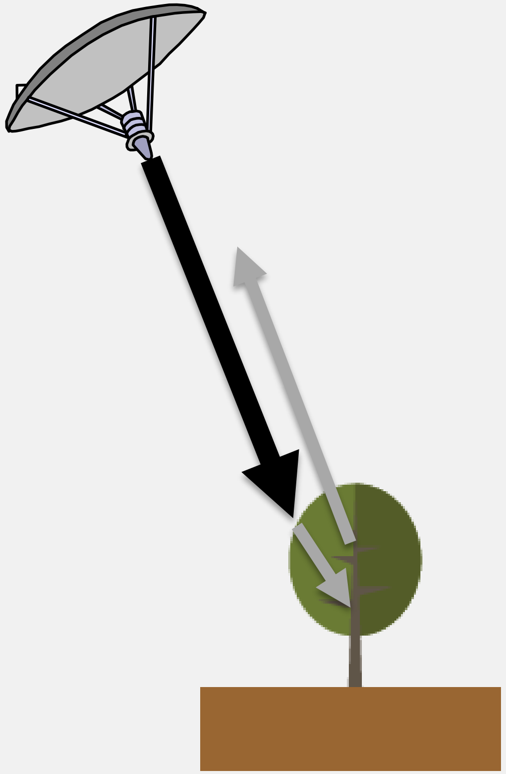


Pixel Color



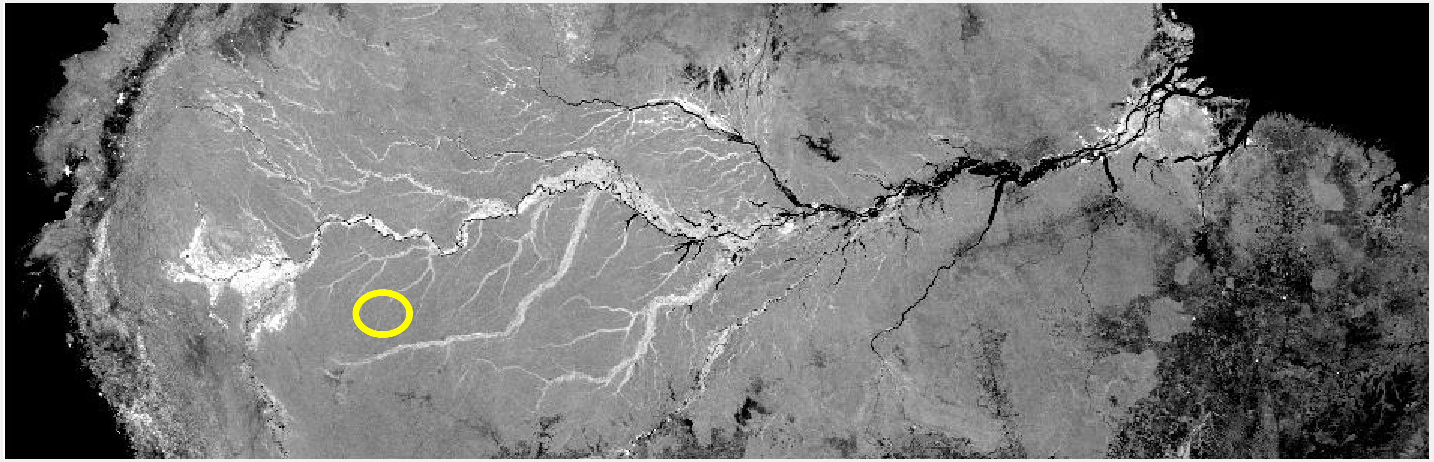
Examples of Radar Interaction

Volume Scattering by Vegetation



Vegetation

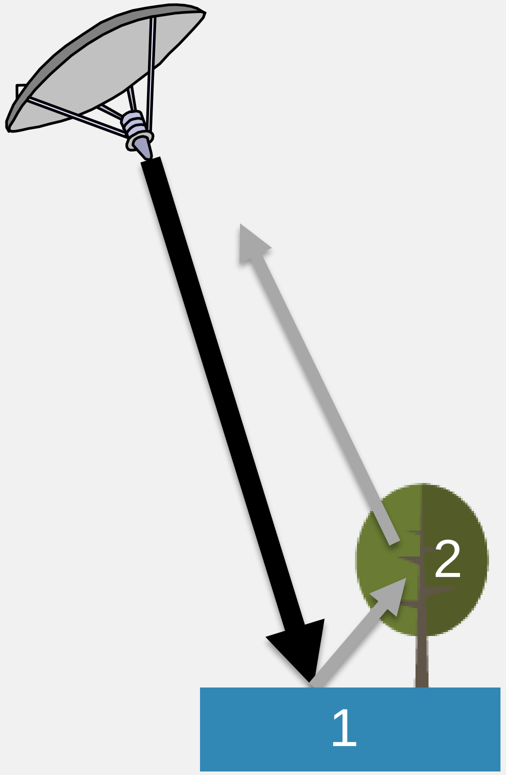
SMAP Radar Mosaic of the Amazon Basin
April 2015 (L-band, HH, 3 km)



Pixel Color

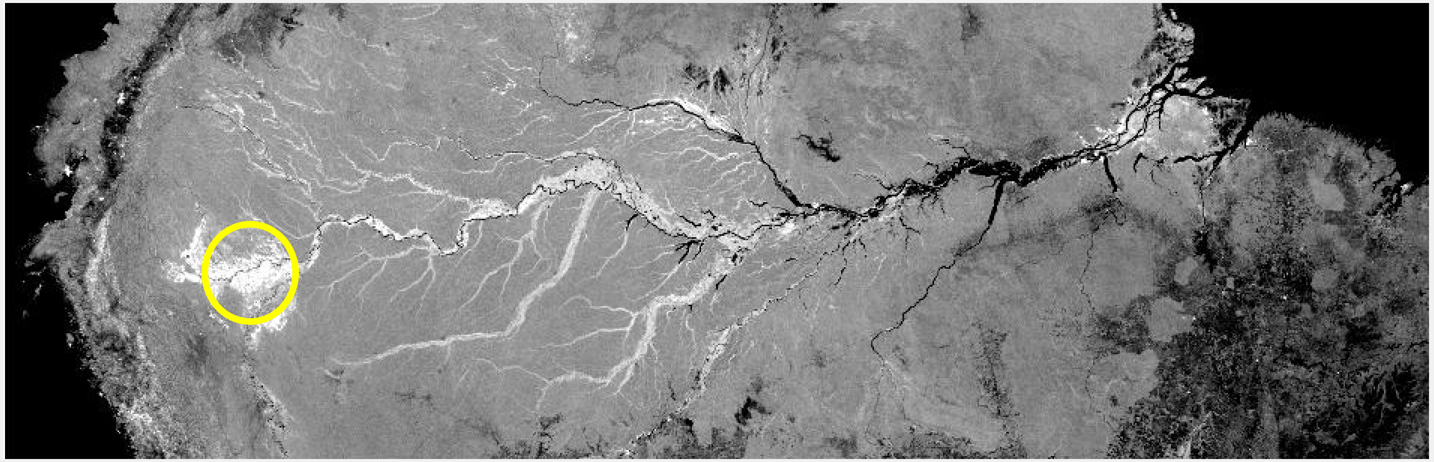
Examples of Radar Interaction

Double Bounce



Inundated Vegetation

SMAP Radar Mosaic of the Amazon Basin
April 2015 (L-band, HH, 3 km)

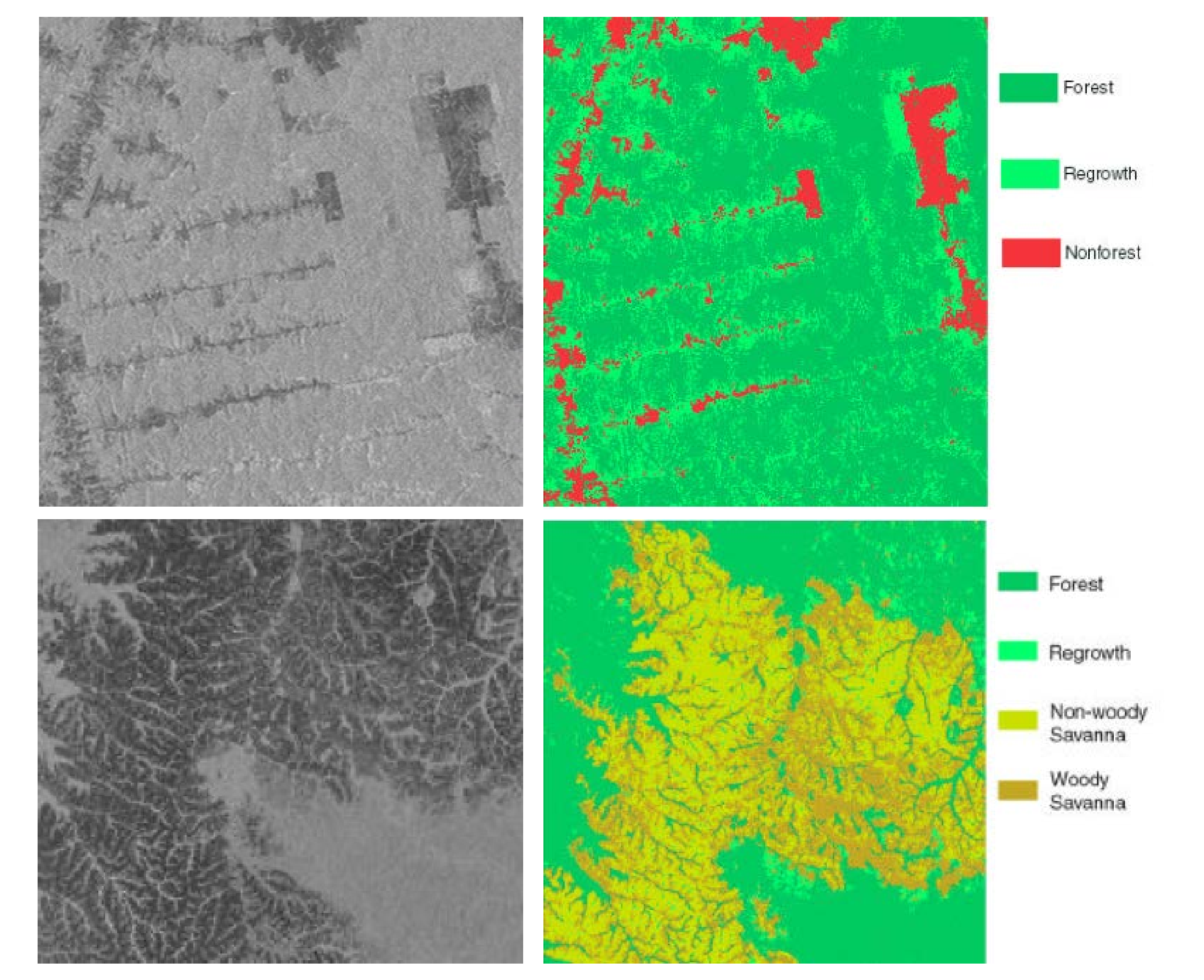


Pixel Color

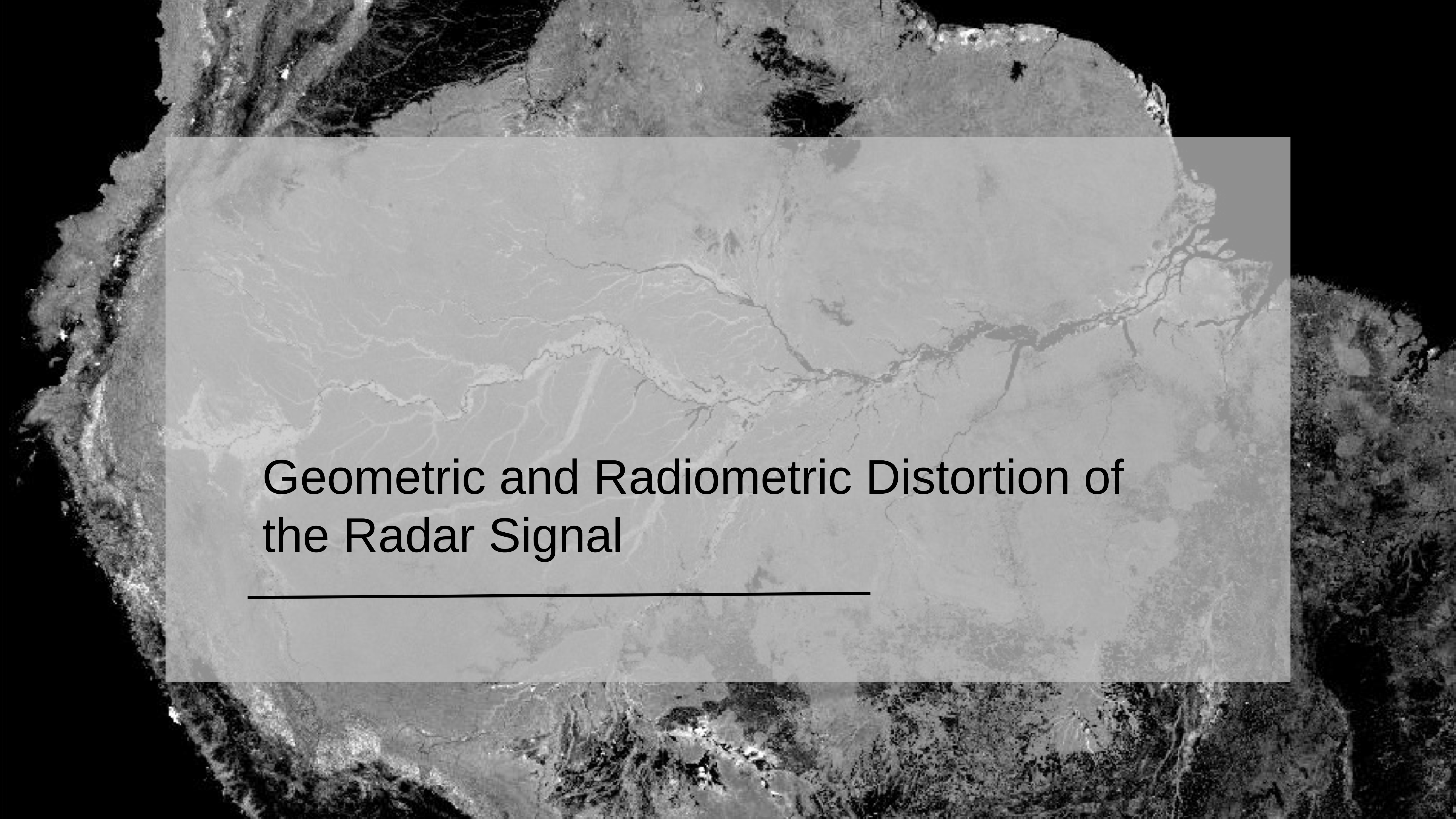
Example: Detection of Oil Spills on Water

UAVSAR (2 meters):
HH, HV, VV

Example: Land Cover Classification



- Brazil
- JERS-1 L-band
- 100 meter resolution



Geometric and Radiometric Distortion of the Radar Signal

Slant Range Distortion

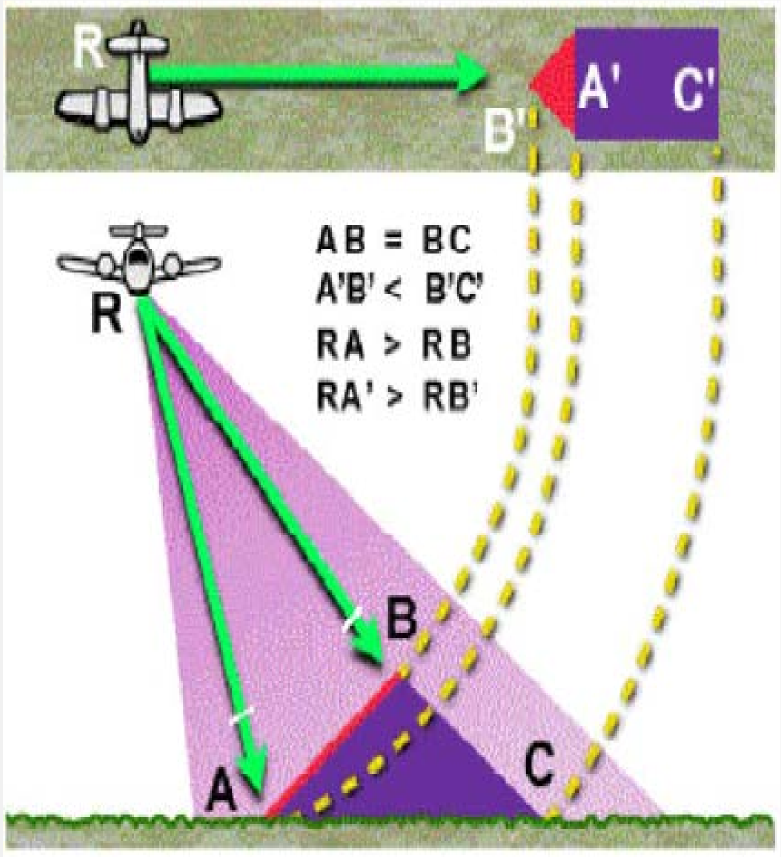
Slant Range

Ground Range

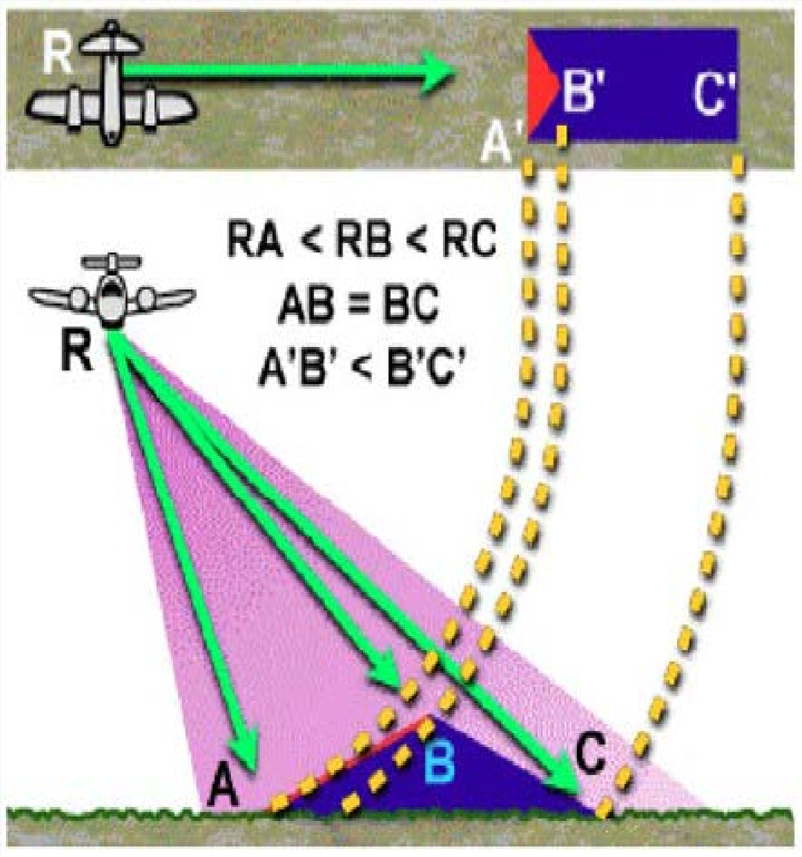
Source: Natural Resources Canada

Geometric Distortion

Layover



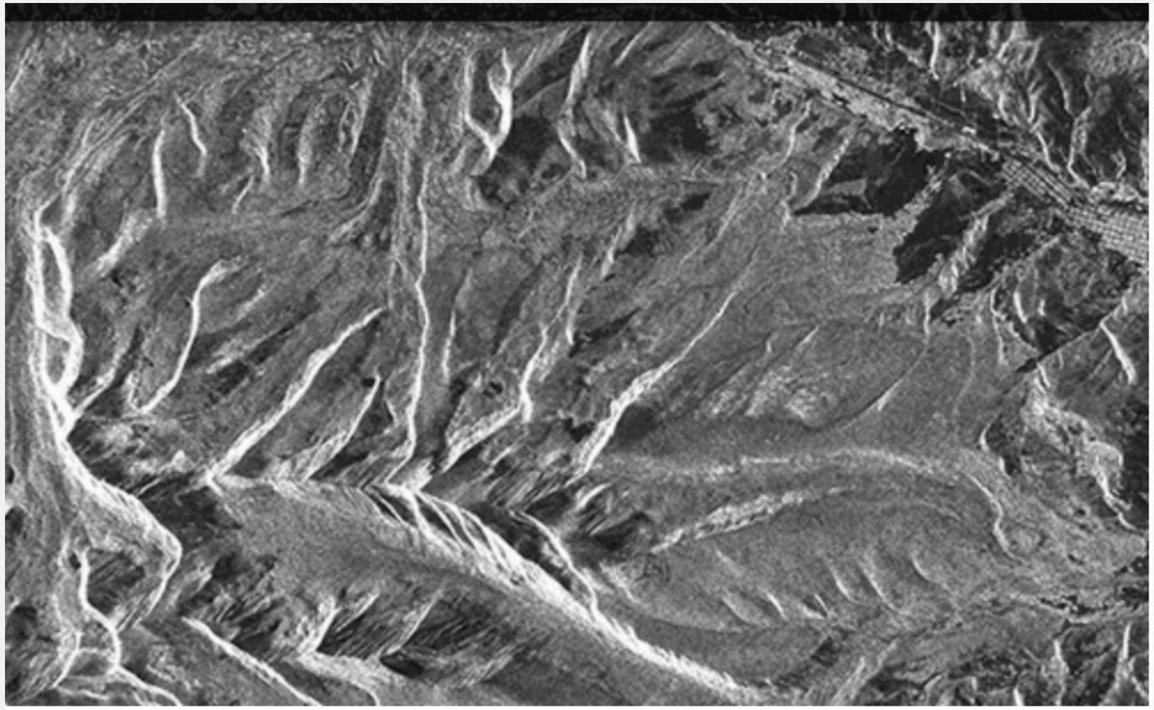
Foreshortening



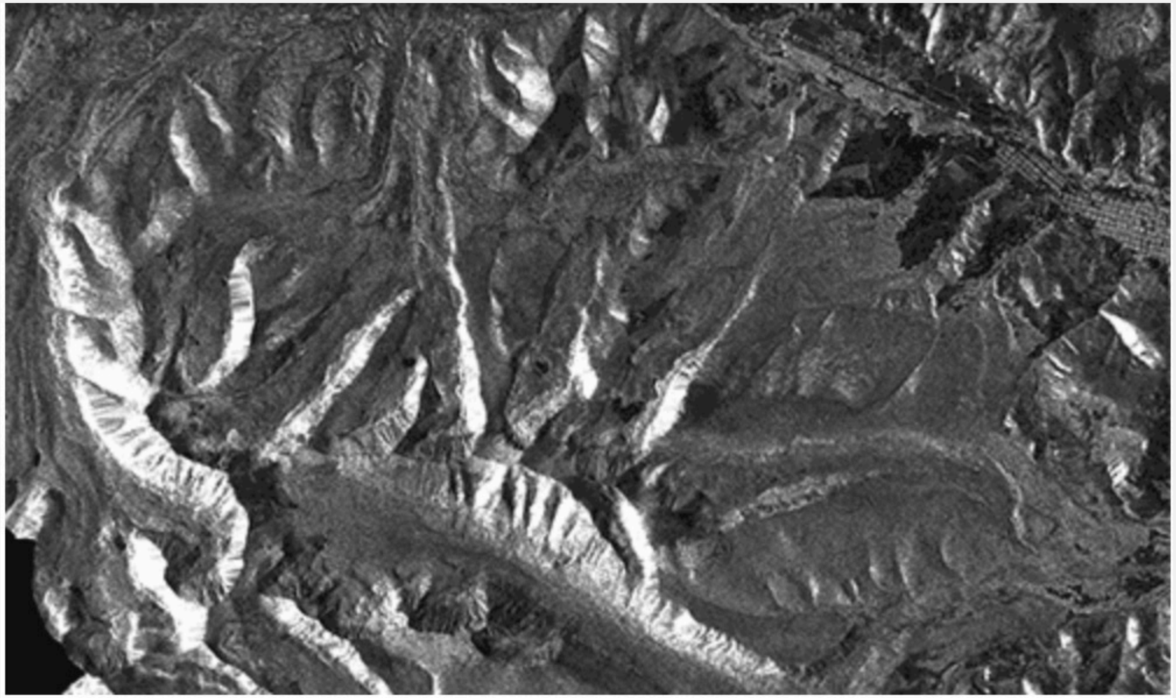
Source: Natural Resources Canada

Foreshortening

Before Correction

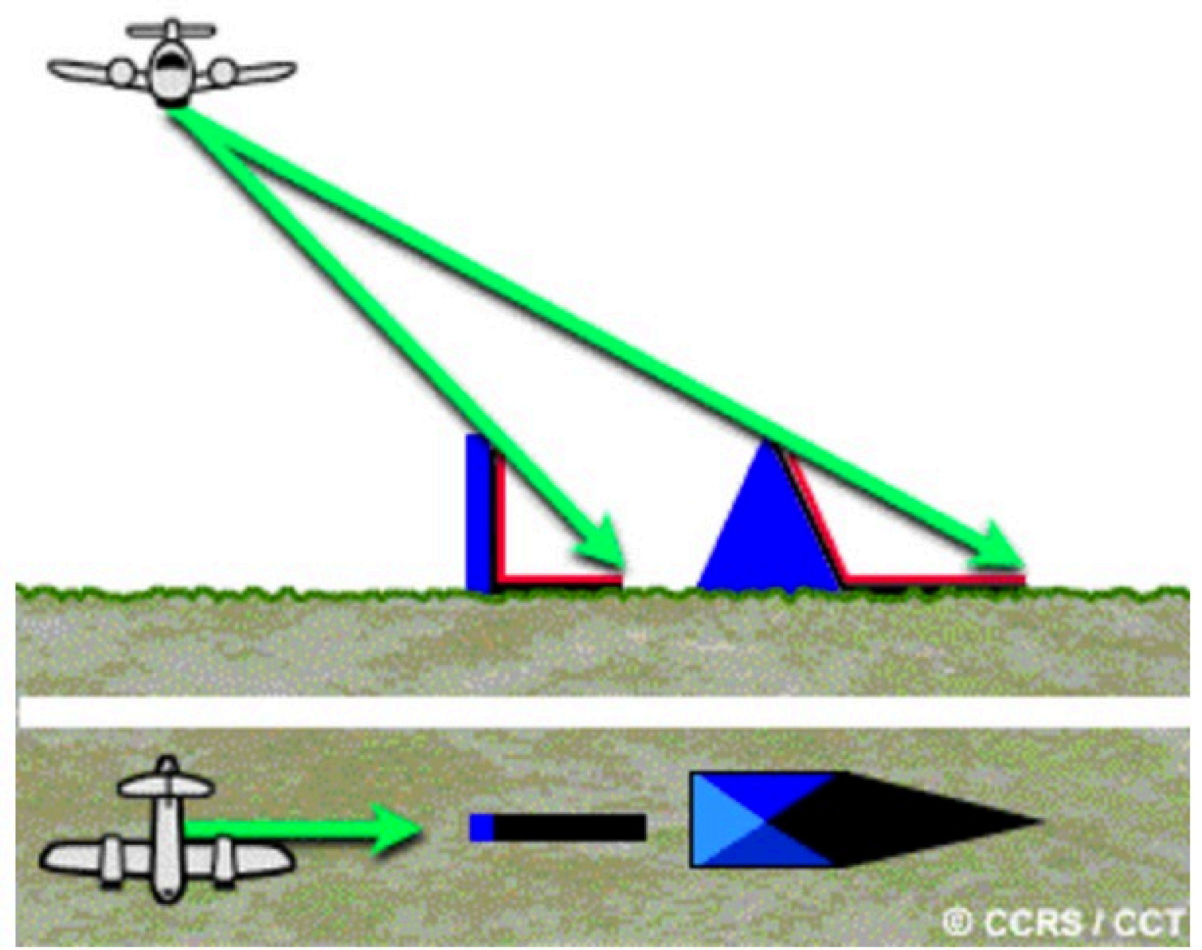


After Correction



Source: ASF

Shadow

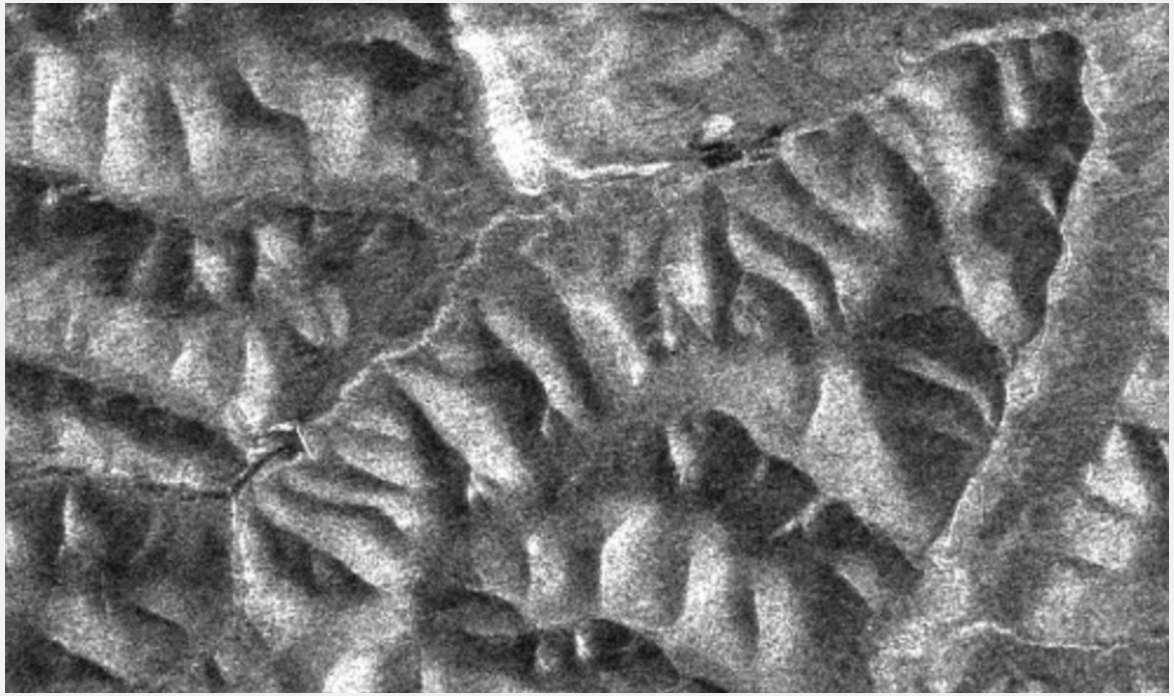


Source: Natural Resources Canada

Radiometric Distortion

- The user must correct for the influence of topography on backscatter
- This correction eliminates high values in areas of complex topography

Before Correction



After Correction

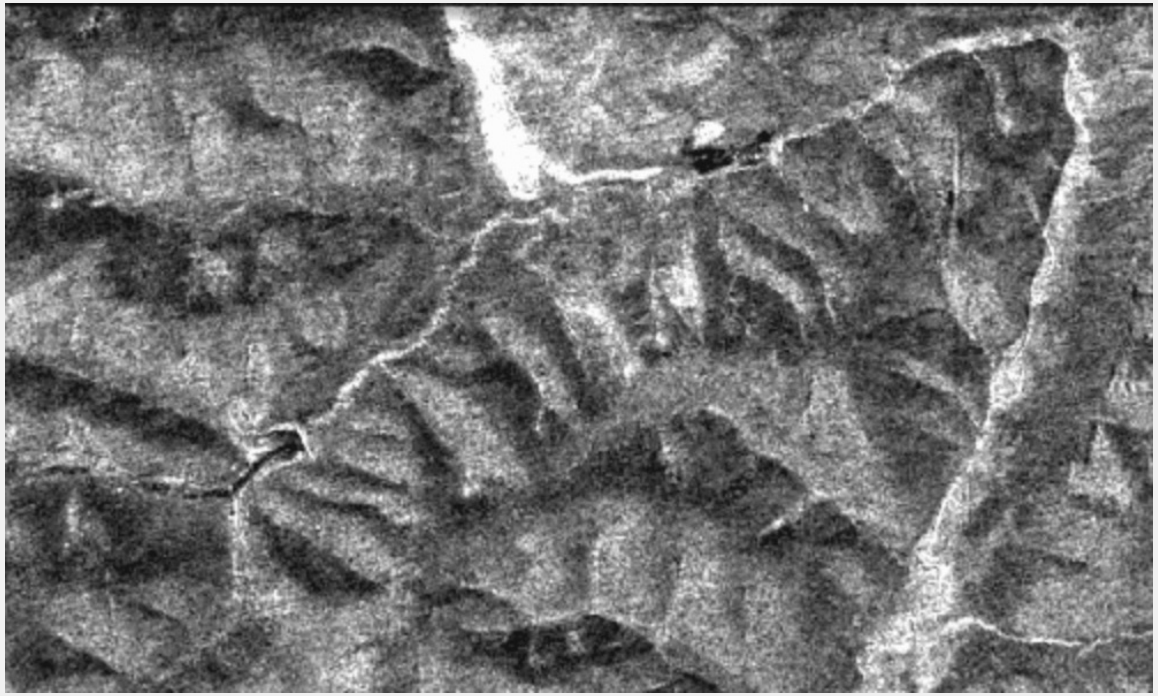
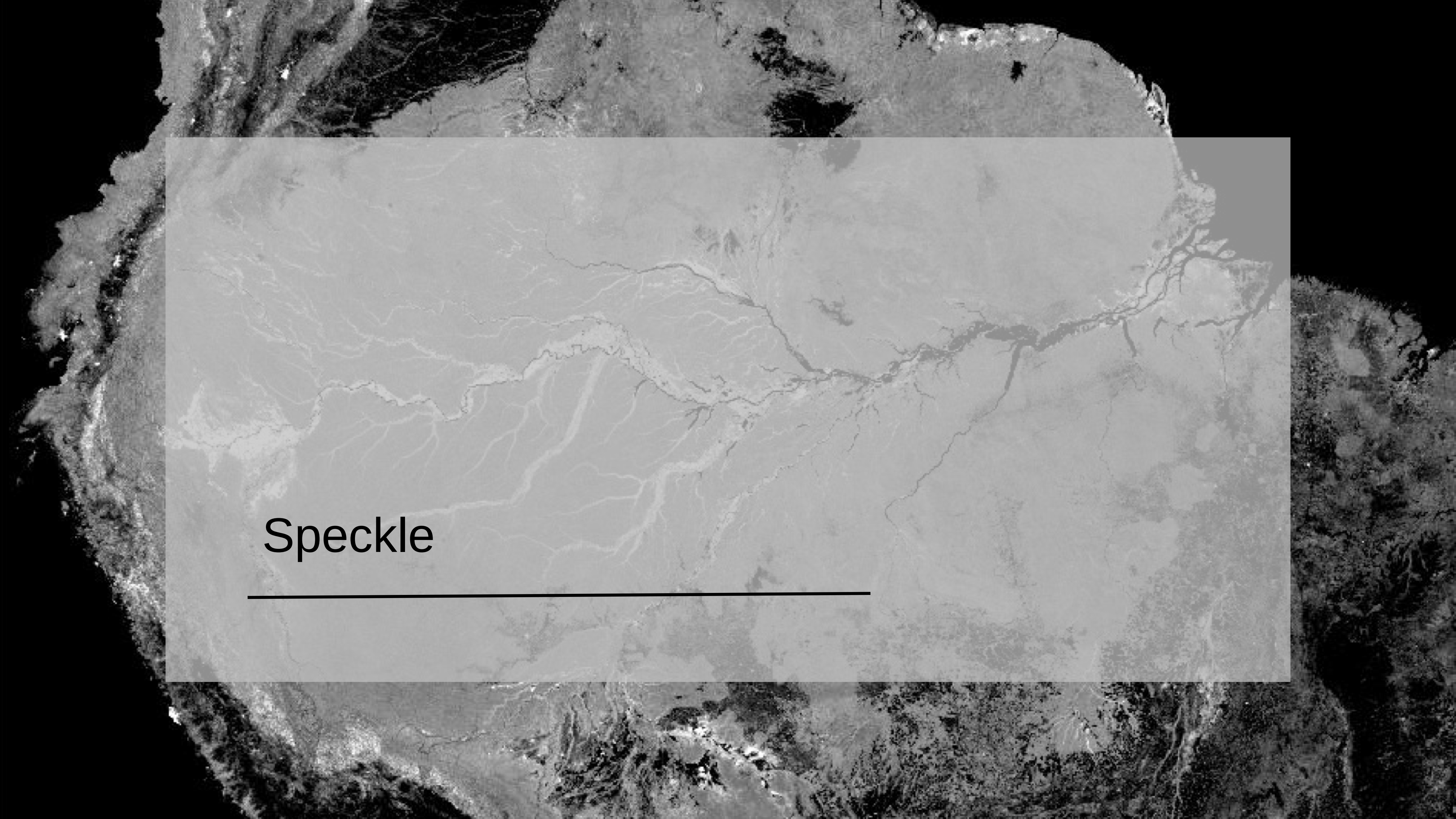


Image Credits: ASF

Speckle



Speckle

Speckle is a granular 'noise' that inherently exists in and degrades the quality of SAR images

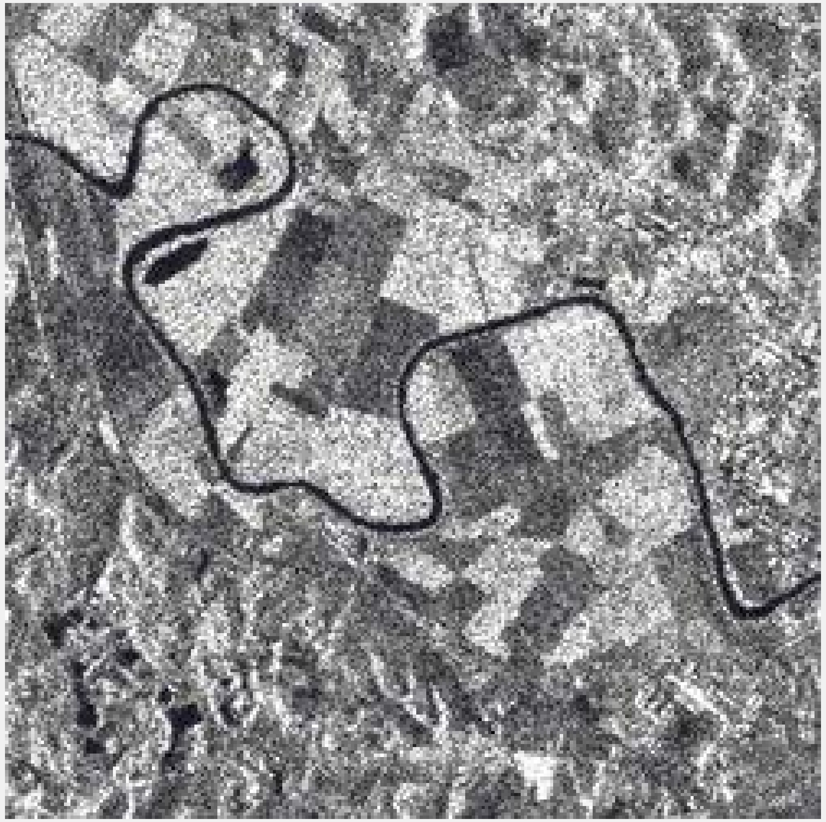


Image Credit: ESA

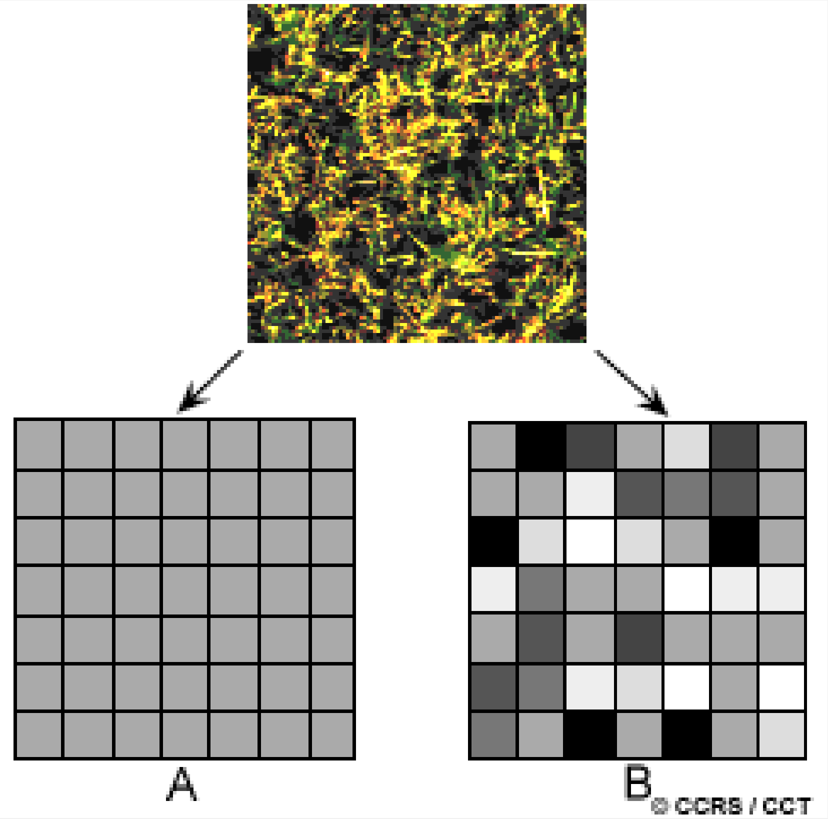
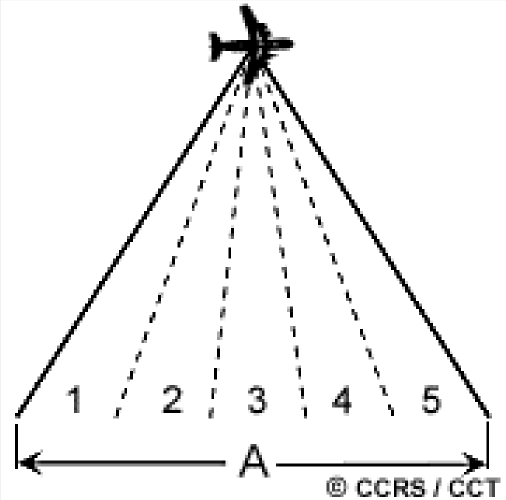
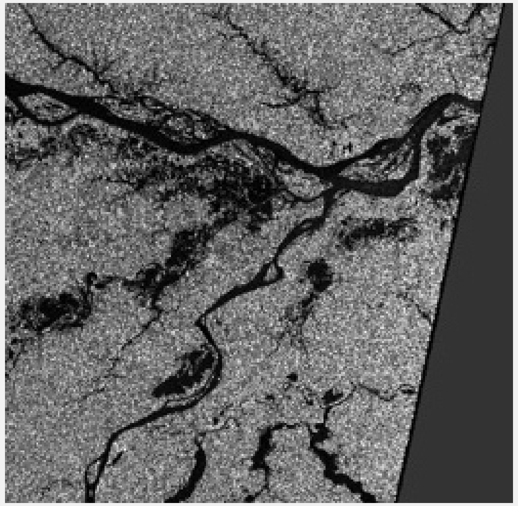


Image Credit: Natural Resources Canada

Speckle Reduction: Multi-Look Processing

- Divides radar beam into several, narrower sub-beams
  – e.g. 5 beams on the right
- Each sub-beam is a “look” at the scene
- These “looks” are subject to speckle
- By summing and averaging the different “looks” together, the amount of speckle will be reduced in the final output image

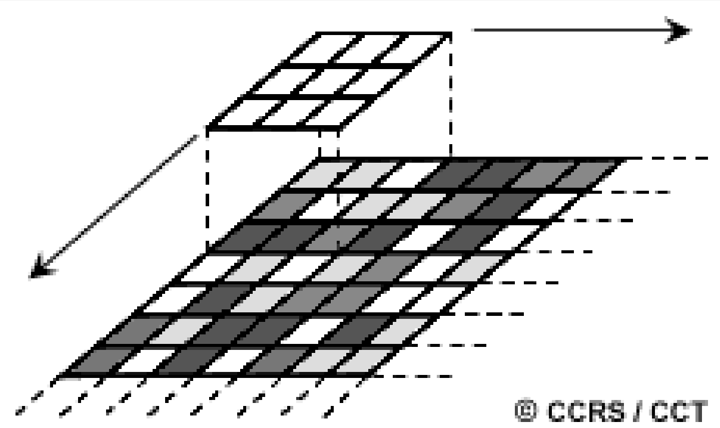


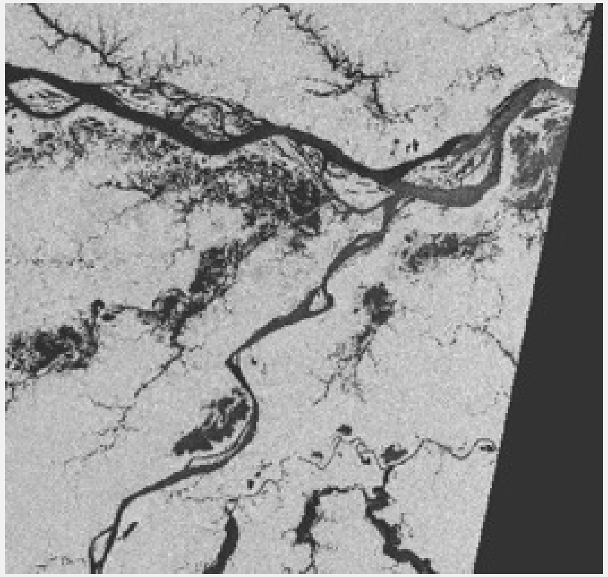


Source: Natural Resources Canada

Speckle Reduction: Spatial Filtering

- Moving window over each pixel in the image
- Applies a mathematical calculation on the pixel values within the window
- The central pixel is replaced with the new value
- The window is moved along the x and y dimensions one pixel at a time
- Reduces visual appearance of speckle and applies a smoothing effect





Source: Natural Resources Canada

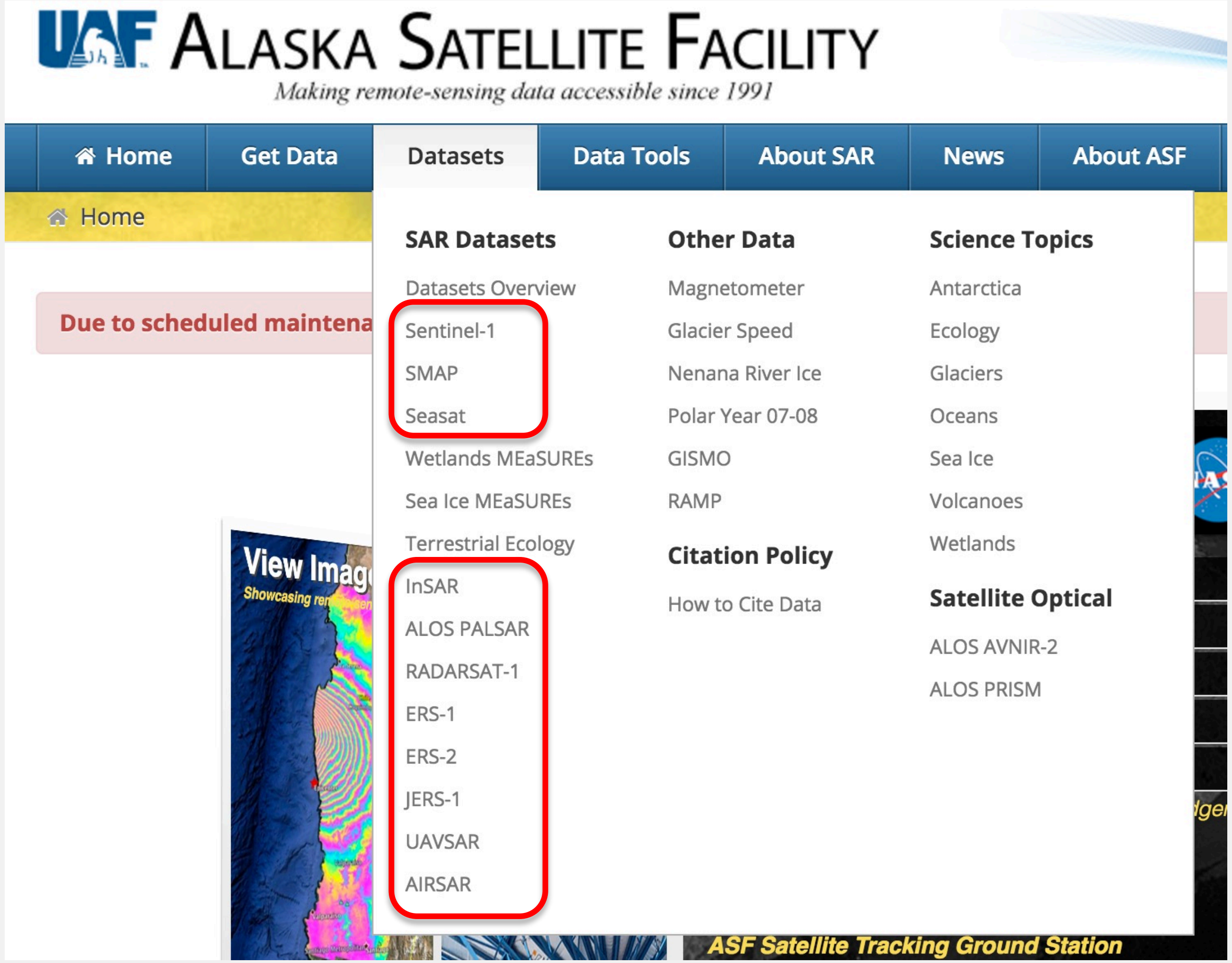
Radar Data from Different Satellite Sensors

Sensor Name	RADARSAT-2	Sentinel-1A	RISAT-1
Agency	Canadian Space Program (CSP)	European Space Agency (ESA)	Indian Space Research Organization (ISRO)
Instrument	C-band SAR (5.4 GHz)	C-band SAR (5.4 GHz)	C-band SAR (5.35 GHz)
Incidence Angle	Side-looking, 15-45° off-nadir	Side-looking, 15-45° off-nadir	36.85°
Polarization	HH, HV, VV, & VH	(VV & VH) or (HH & HV)	HH & HV
Sensor Height at Equator	798 km	693 km	542 km
Orbit	Sun Synchronous (dusk/dawn)	Sun Synchronous (dusk/dawn)	Sun Synchronous (dusk/dawn)
Revisit Time (Orbit Repeat Cycle)	24 days	12 days	25 days

Radar Data from Different Satellites

Sensor Name	RADARSAT-2	Sentinel-1A	RISAT-1
Resolution	100 m	5 m x 20 m	~25 m
Swath Width	500 km (ScanSAR mode)	250 km (IWS mode)	115 km (MRS)
Mean Local Time	6:00 a.m. descending	6:00 a.m. descending	6:00 a.m.
Launch	14 Dec 2007	3 April 2014	26 Apr 2012
Planned Lifetime	7 years minimum	7 years	5 years

SAR Sources at the Alaska Satellite Facility



NASA-ISRO SAR Mission (NISAR)

- High spatial resolution with frequent revisit time
- Earliest baseline launch date: 2021
- Dual frequency L- and S-band SAR
  - L-band SAR from NASA and S-band SAR from ISRO
- 3 years science operations (5+ years consumables)
- All science data will be made available free and open

NISAR Characteristic:	Would Enable:
L-band (24 cm wavelength)	Low temporal decorrelation and foliage penetration
S-band (12 cm wavelength)	Sensitivity to light vegetation
SweepSAR technique with Imaging Swath >240 km	Global data collection
Polarimetry (Single/Dual/Quad)	Surface characterization and biomass estimation
12-day exact repeat	Rapid Sampling
3-10 meters mode-dependent SAR resolution	Small-scale observations
3 years since operations (5 years consumables)	Time-series analysis
Pointing control < 273 arcseconds	Deformation interferometry
Orbit control < 500 meters	Deformation interferometry
>30% observation duty cycle	Complete land/ice coverage
Left/Right pointing capability	Polar coverage, North and South
Noise Equivalent Sigma Zero ≤ -23 db	Surface characterization of smooth surfaces

Slide Courtesy of Paul Rosen (JPL)

NISAR Hydrology & Subsurface Reservoir Applications

Flood Response

Specific Applications	NISAR Data Product (L1 or L2)	Needed Information Product*
Direction of Inundation	• Geocoded and calibrated product • Geocoded/calibrated SLC would be ok • InSAR coherence and repeat pass coregisted imagery	• Change in open water extent • Flooded forest inundation extent
Change in Water Level in Forested and Urban Areas	InSAR phase and coherence	Measure change in water level in areas where forests and urban areas are inundated
Hurricane & Typhoon Inundation (precipitation and storm surge)	Geocoded coherence map	Aerial map of inundation
Flooding from Runoff and Snowmelt	Geocoded coherence map	Aerial map of inundation

NISAR Hydrology & Subsurface Reservoir Applications

Surface Deformation from Volumetric Changes in Subsurface Reservoirs

Specific Applications	NISAR Data Product (L1 or L2)	Needed Information Product*
Aquifer Drawdown and Recharge (both natural and anthropogenic)	• Geocoded unwrapped interferograms • Geocoded coherence maps • Geocoded LOS vector maps	Rates and time series of vertical surface displacement
Oil and Natural Gas Extraction from Onshore Fields		Rates of vertical surface displacement
Extent and Degree of Mine Collapse	• Raw SAR data (rapid response) • Geocoded unwrapped interferograms • Geocoded coherence maps • Geocoded LOS vector maps	Vertical surface displacement for the time period bracketing the event

NISAR Hydrology & Subsurface Reservoir Applications

Specific Applications	NISAR Data Product (L1 or L2)	Needed Information Product*
	Gas & Fluid Reservoirs	
CO_2 Sequestration	SLC InSAR	Time series deformation
Underground Gas Storage (UGS)	SLC InSAR	• Time series deformation • Deformation from leaks
	Fluid Withdrawal & Injection	
Aquifer Production Triggered Earthquakes	SLC InSAR	• Time series deformation • Deformation from leaks
	Snow Water Equivalent	
Estimate Snow Water Equivalent by Groundwater Basin	• Geocoded and calibrated product • InSAR and PolSAR	• Snow water equivalent