Building Capacity to Use Earth Observations in Addressing Environmental Challenges in Bhutan

Day 2 – An Introduction to SAR for Flood Detection

Objectives

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

- Understand the basic physics of SAR image formation
- Describe the interaction of SAR with the land surface
- Understand the information content in SAR images
- Understand how SAR can be used to detect floods

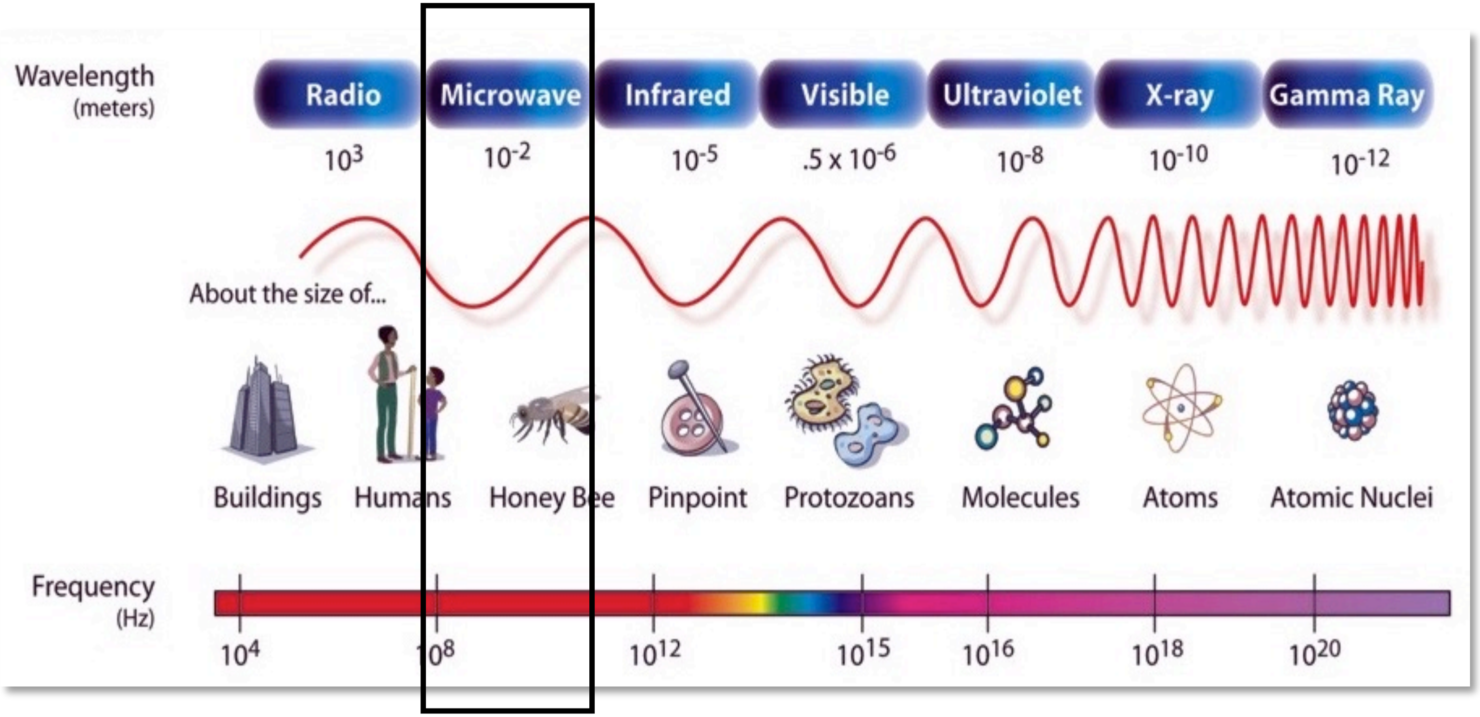
Outline

- Basic concepts of SAR
- Use of SAR for flood detection
- Demonstration:
    - Create a flood map and calculate extent

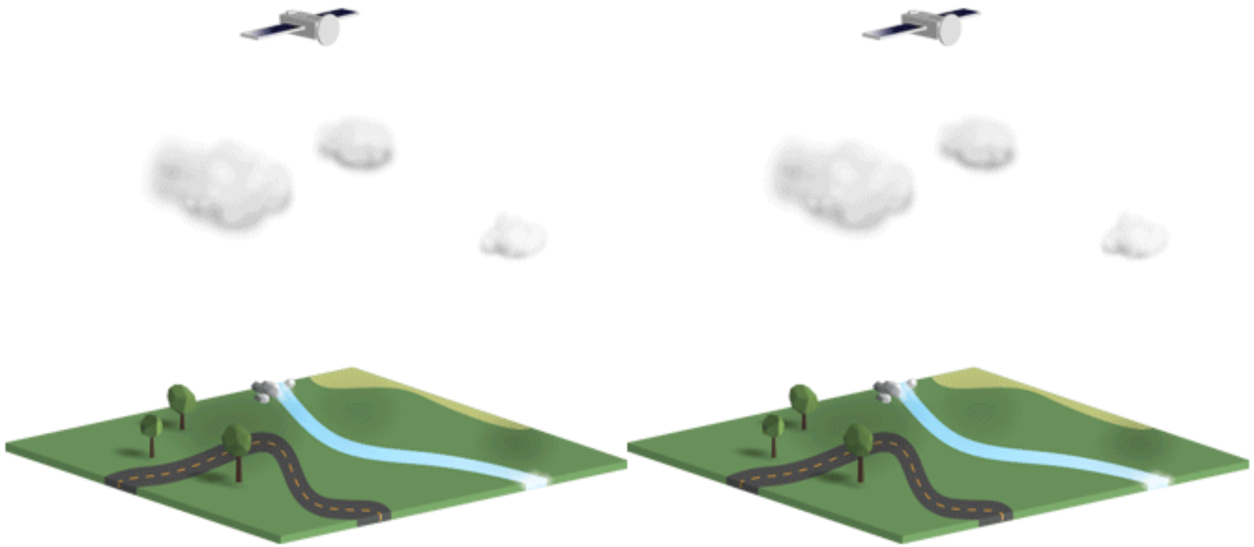
Basic Concepts of SAR

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.



Active and Passive Remote Sensing



Passive | Sensors detect only what is emitted from the landscape, or reflected from another source (e.g., light reflected from the sun).

Active | Instruments emit their own signal and the sensor measures what is reflected back. Sonar and radar are examples of active sensors.

Passive Sensors:

- The source of radiant energy arises from natural sources
- E.g., the Sun, Earth, or other "hot" bodies

Active Sensors:

- Provide their own artificial radiant energy source for illumination
- E.g., **Radar, Synthetic Aperture Radar (SAR)**, LiDAR

Advantages and Disadvantages of Radar 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 surface moisture and its state (frozen or thawed)
- Sensitivity to structure

Disadvantages

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

Optical vs. Radar

Volcano in Kamchatka, Russia, Oct 5, 1994

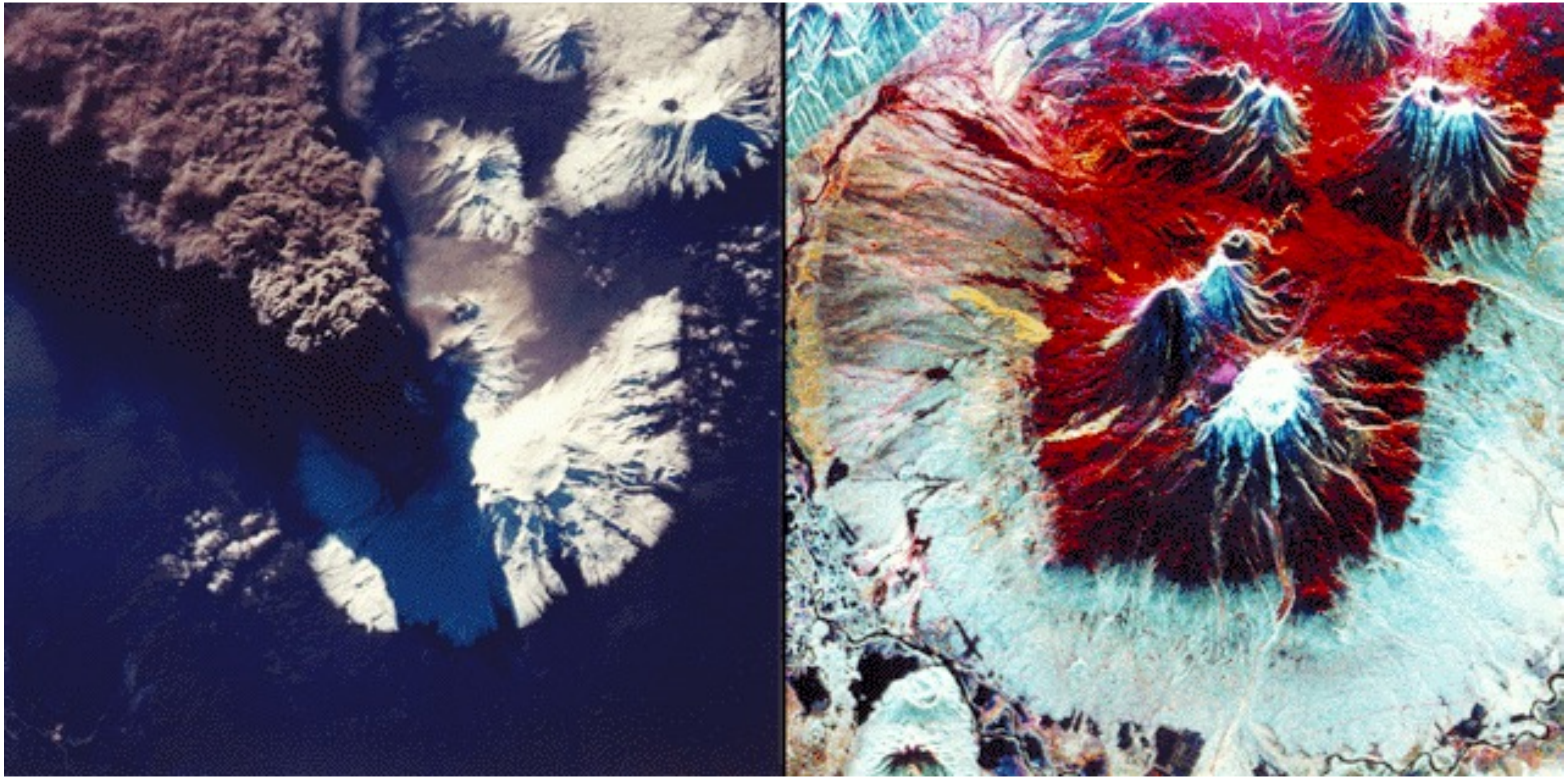
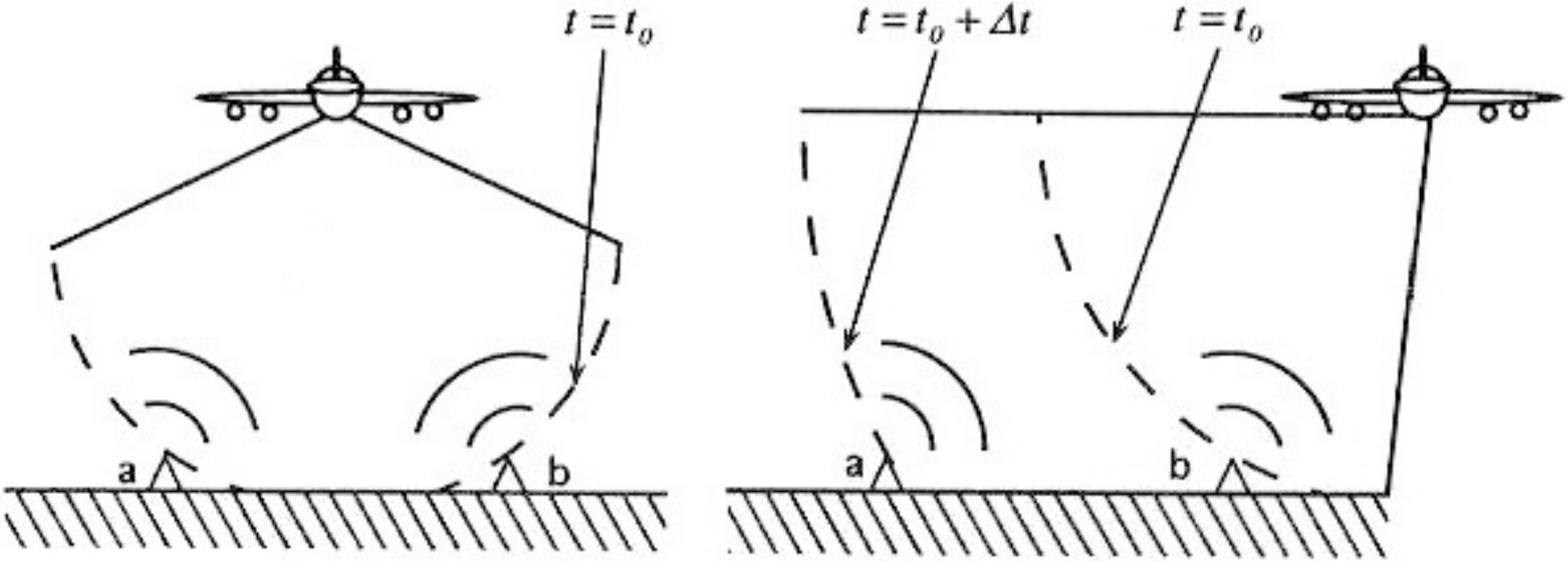


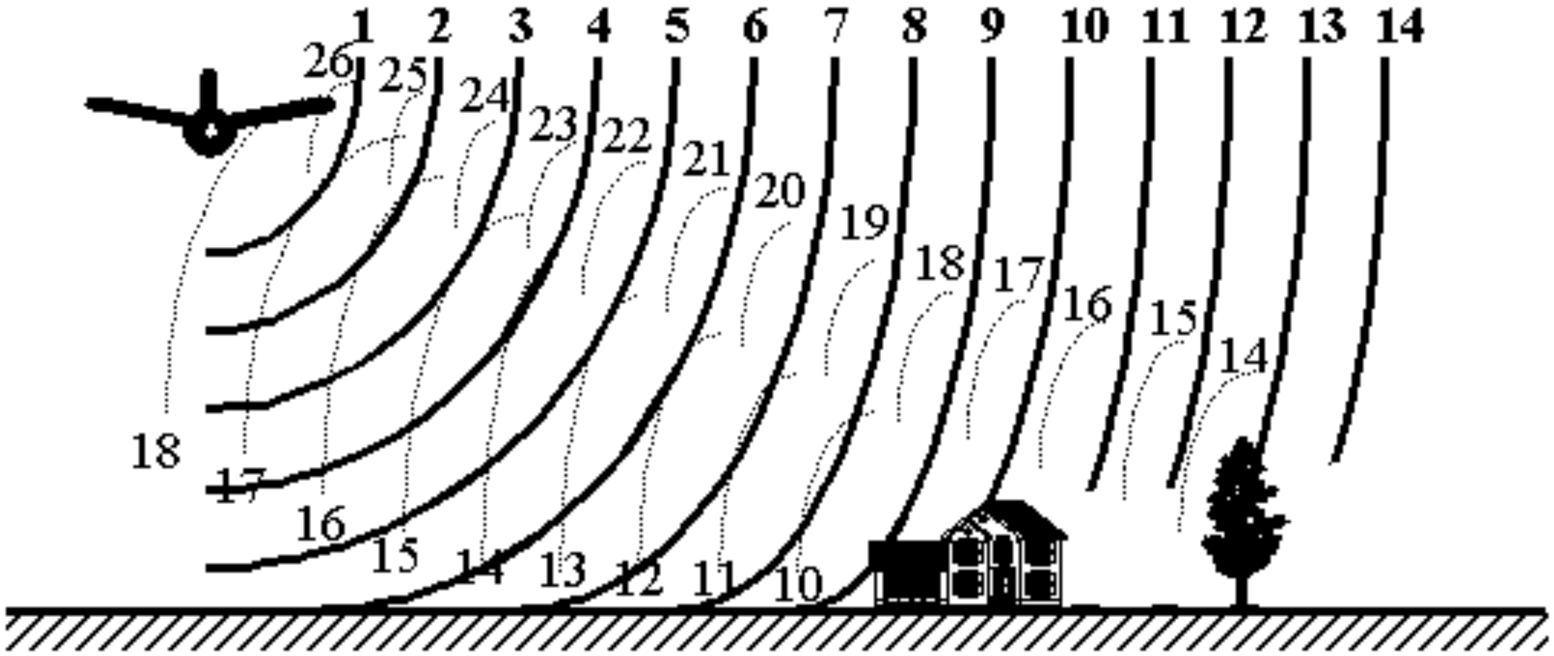
Image Credit: Michigan Tech Volcanology

Basic Concepts: Down Looking vs. Side Looking Radar



Basic Concepts: Side Looking Radar

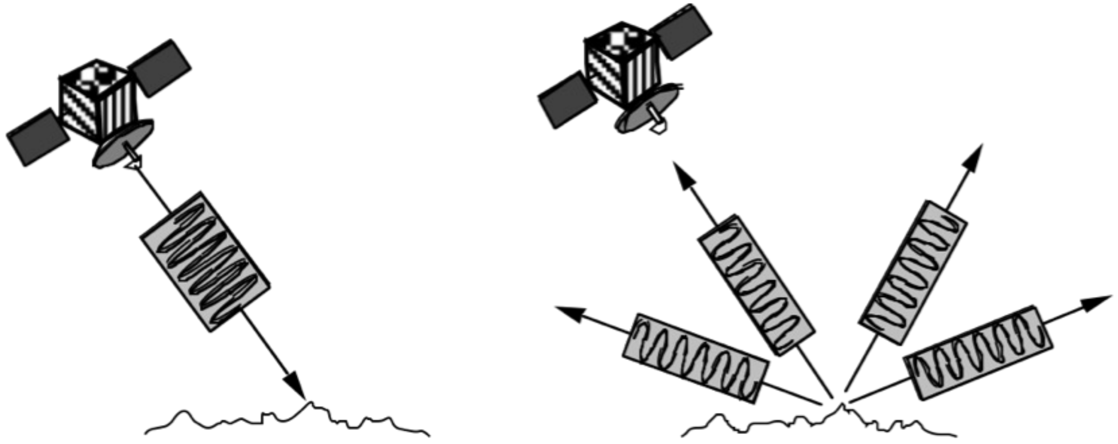
- Each pixel in the radar image represents a complex quantity of the energy that was reflected back to the satellite.
- The magnitude of each pixel represents the intensity of the reflected echo.



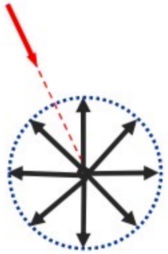
Credit: [Paul Messina, CUNY NY](), after Drury 1990, Lillesand and Kiefer, 1994

Review of Radar Image Formation

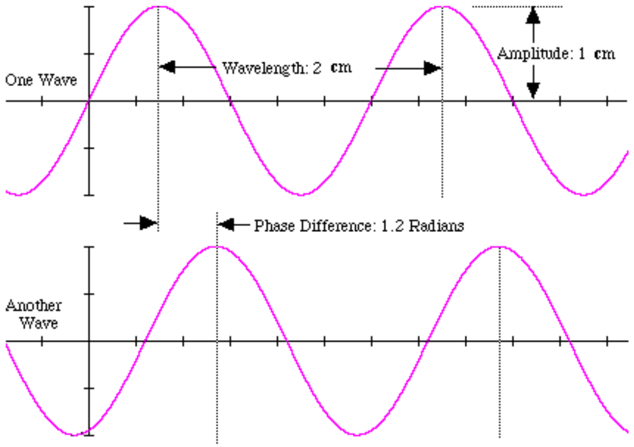
1. Radar can measure **amplitude** (the strength of the reflected echo) and **phase** (the position of a point in time on a waveform cycle).
2. Radar can only measure the part of the echo reflected back towards the antenna (**backscatter**).
3. Radar pulses travel at the **speed of light**.
4. The strength of the reflected echo is the backscattering coefficient (**sigma naught**) and is expressed in decibels (dB).



RADAR TRANSMITS A PULSE MEASURES REFLECTED ECHO (BACKSCATTER)



Isotropic scatterer



Source: ESA- ASAR Handbook

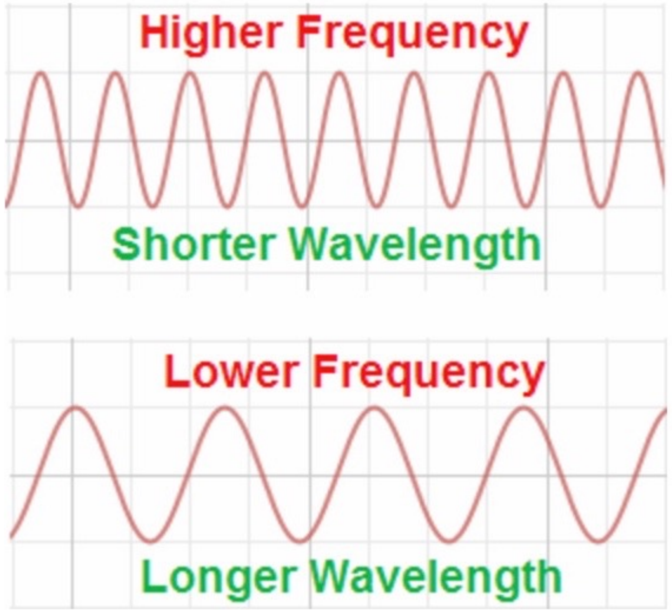
Radar Parameters

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), GH$_z$ (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 parentheses.

Radar Parameters: Wavelength

- Penetration is the **primary factor** in wavelength selection.
- Generally, the longer the wavelength, the greater the penetration into the target.

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

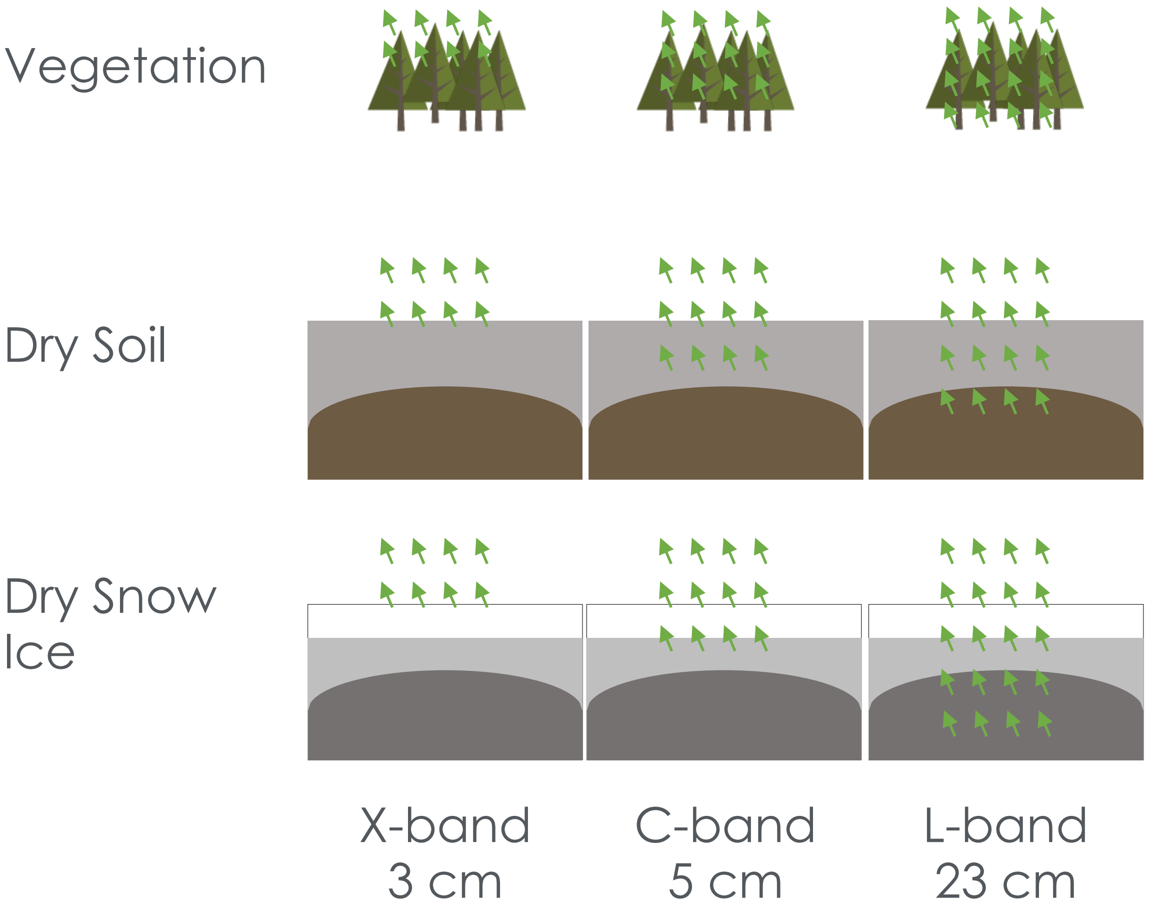
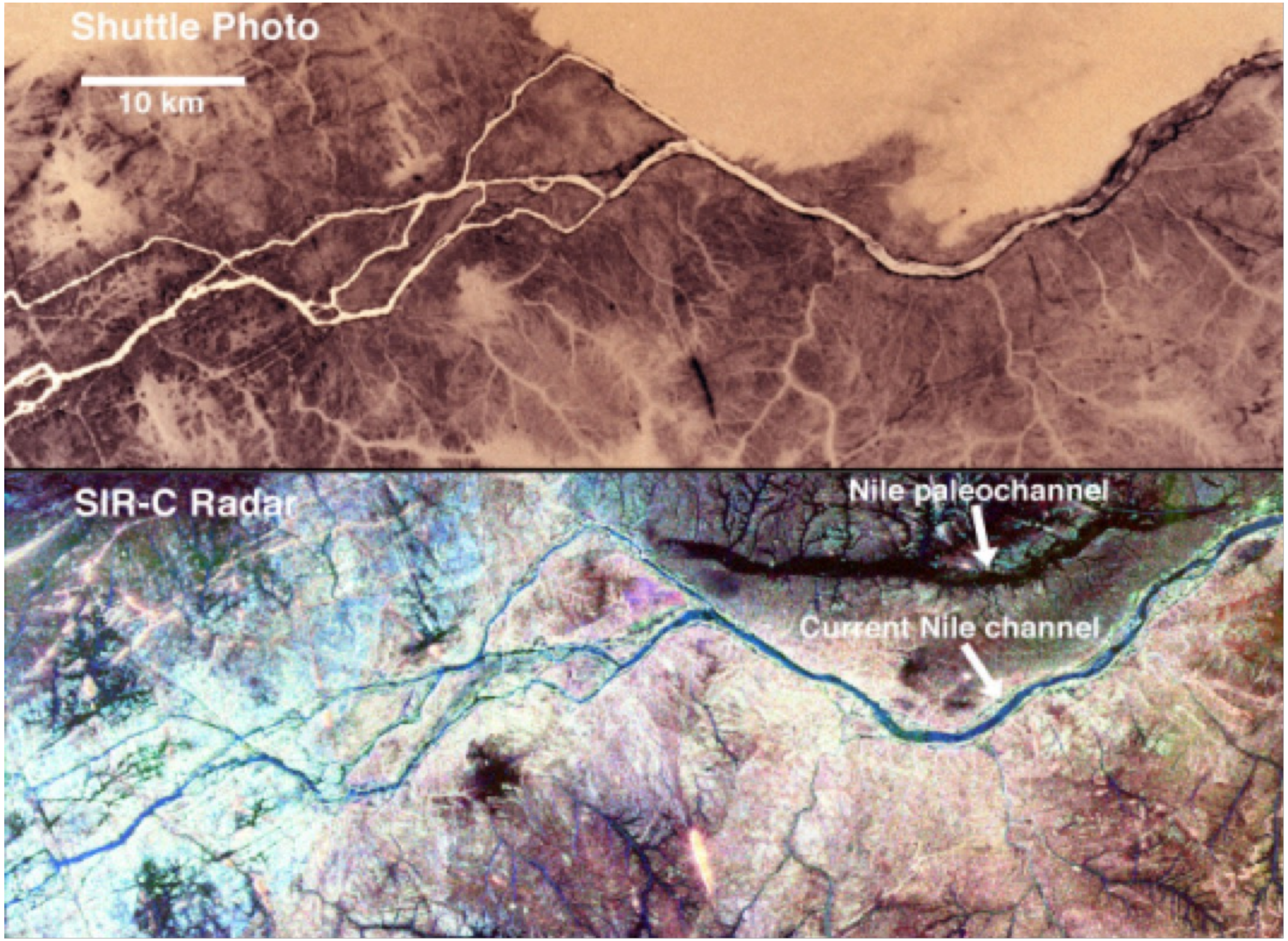


Image (right) based on ESA Radar Course 2; Table (left) Credit: DLR

Radar Signal Penetration into Dry Soils



Radar Signal Penetration into Vegetation

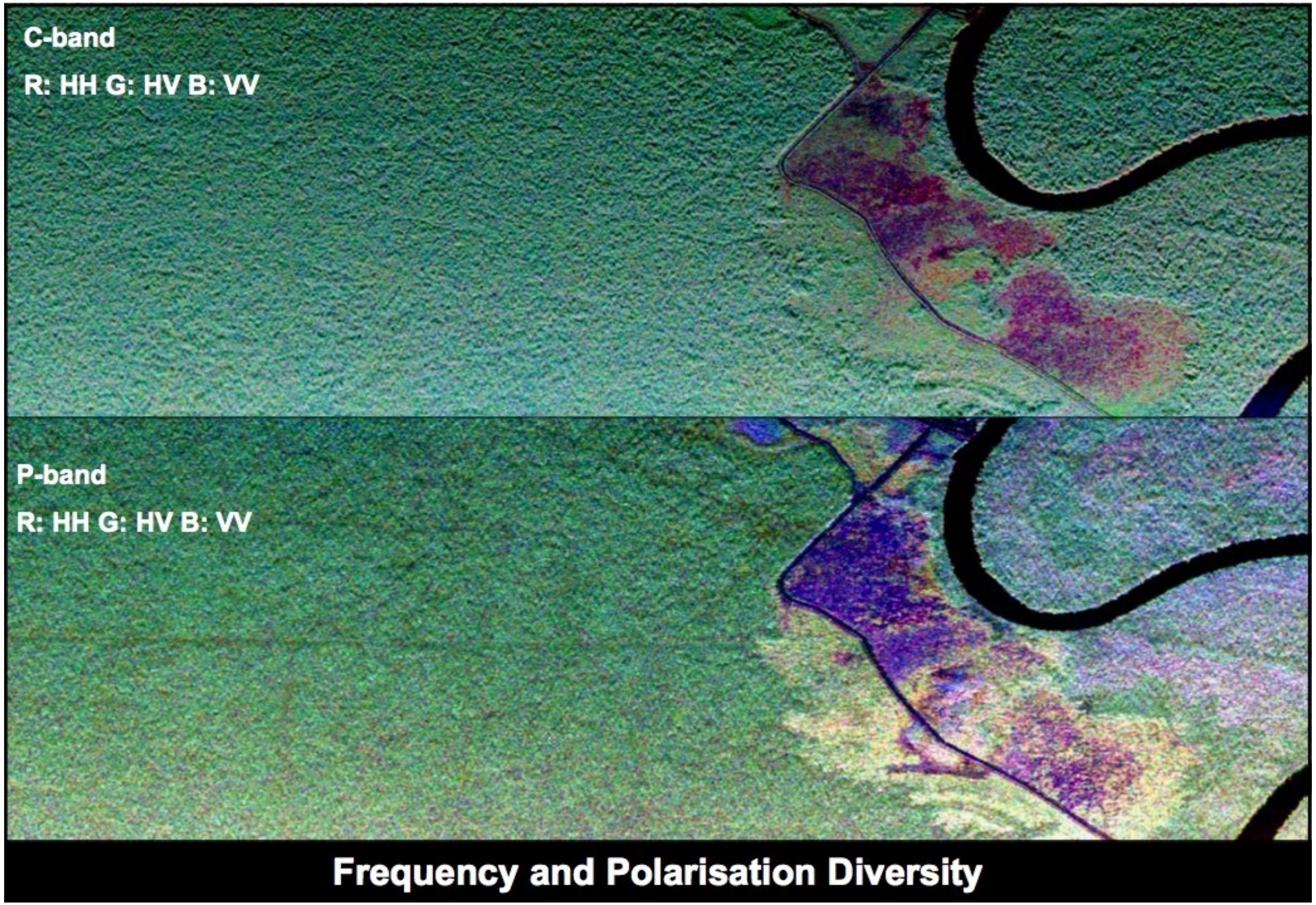


Image Credit: A Moreira - ESA

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 structural properties of the object observed.

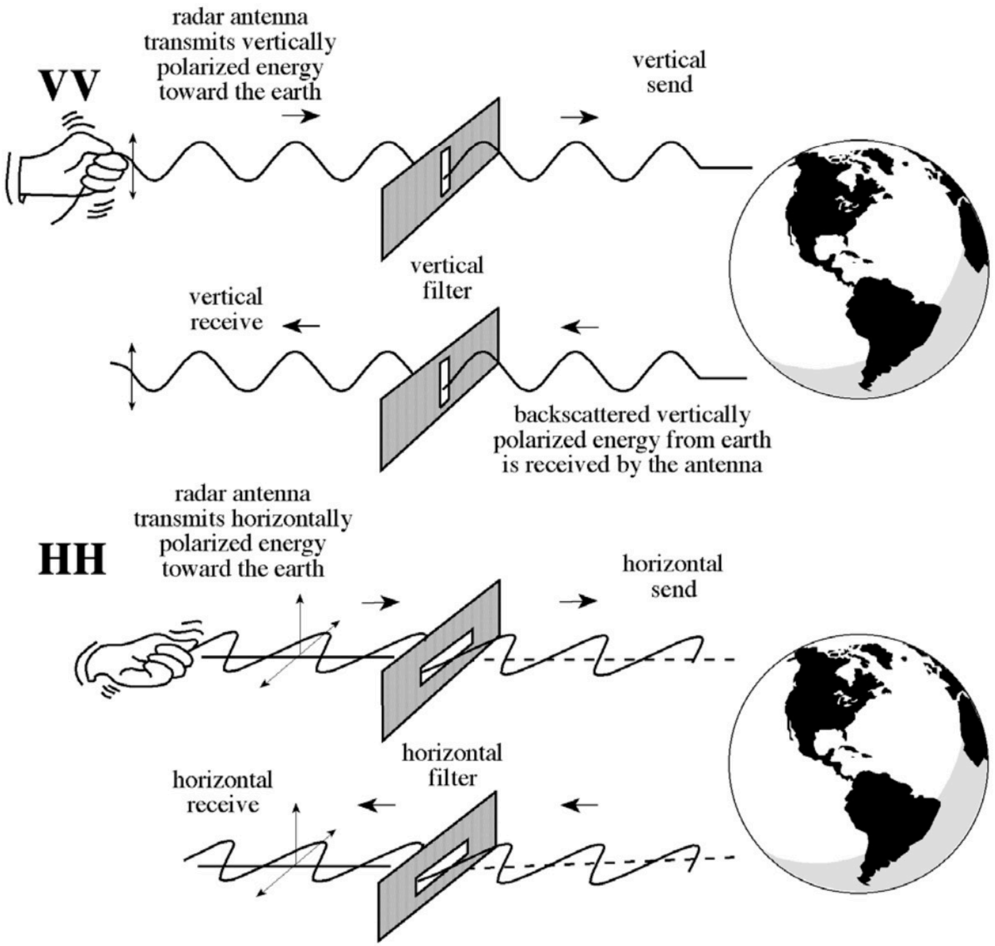


Image Credit: J.R. Jensen, 2000. Remote Sens Env

Multiple Polarizations for Vegetation Studies

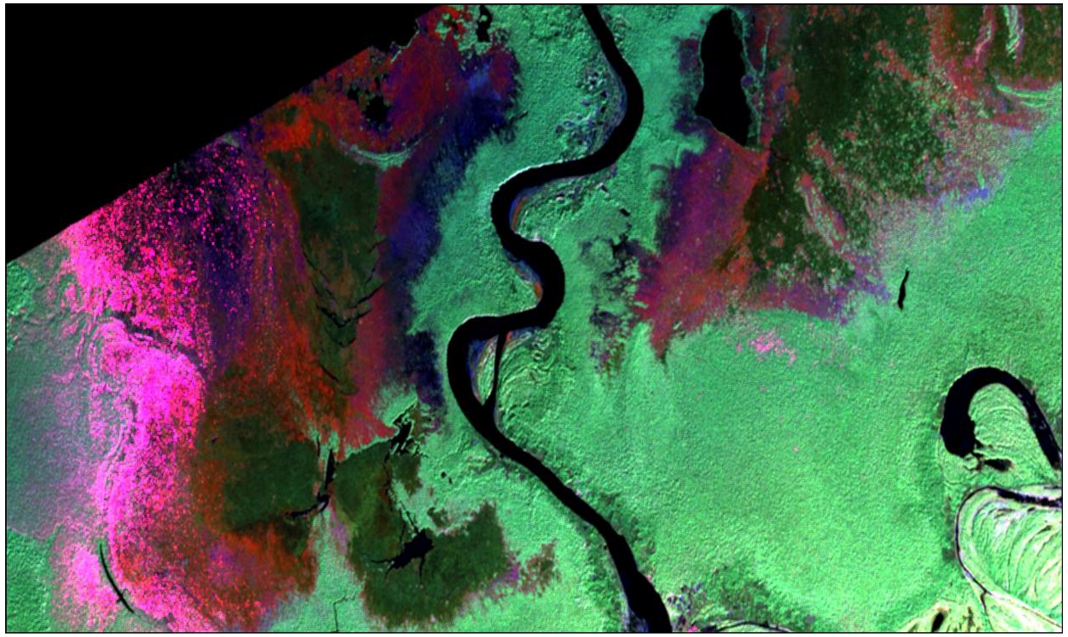
Pacaya-Samiria Forest Reserve in Peru

Images from UAVSAR (HH, HV, VV)

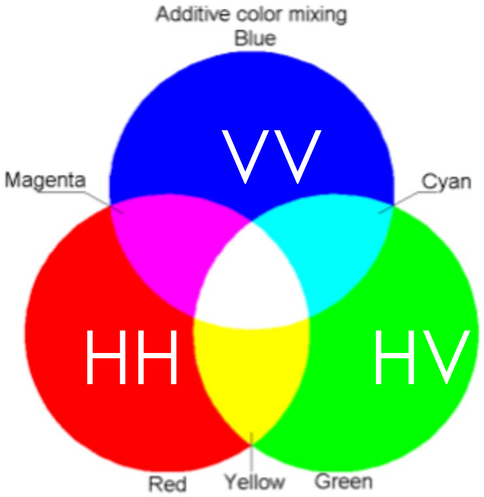
Multiple Polarizations for Vegetation Studies

Pacaya-Samiria Forest Reserve in Peru

Images from UAVSAR (HH, HV, VV)



Img Layer 1	*Img Layer 2*	*Img Layer 3*	*Resultant*
Blue	Green	Red	Color
	Tonal Change on Image		
White	Black	Black	Blue
Black	White	Black	Green
Black	Black	White	Red
White	White	Black	Cyan
White	Black	White	Magenta
Black	White	White	Yellow
	No Tonal Change on Image		
White	White	White	White
Black	Black	Black	Black
Grey	Grey	Grey	Grey

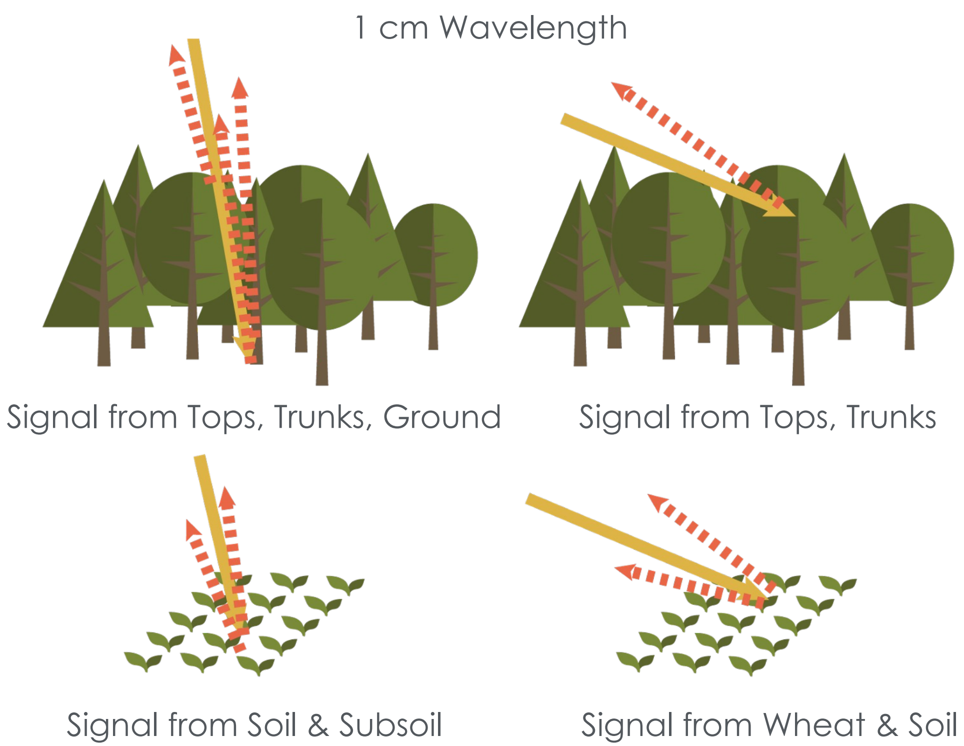


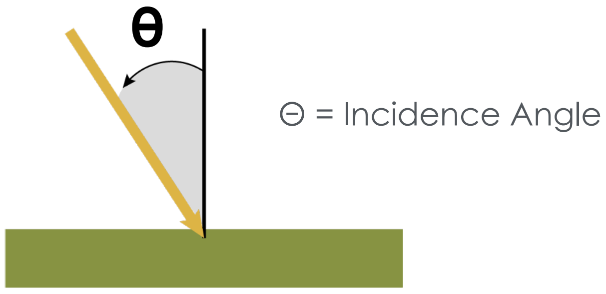
Source: SAR Handbook, Chapter 2 by J. Kellndorfer

Radar Parameters: Incidence Angle

Local Incidence Angle:

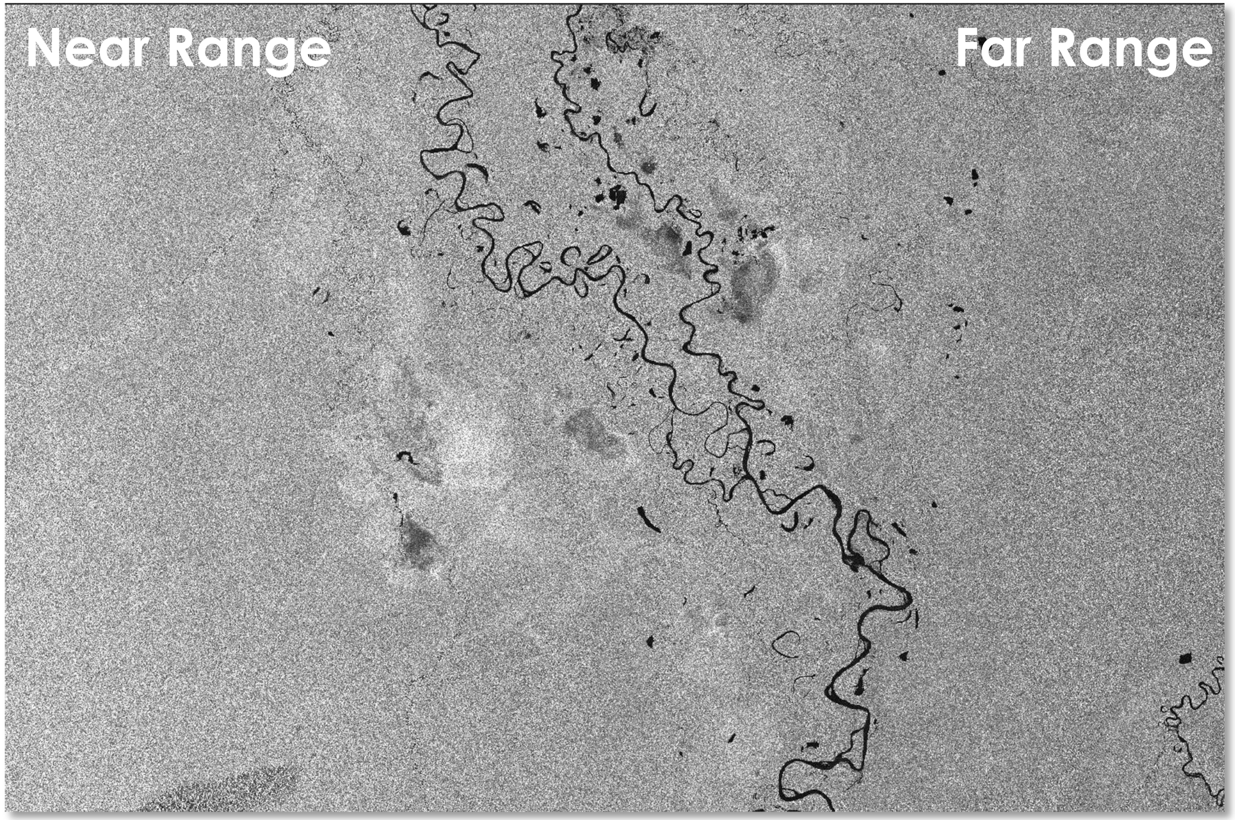
- The angle between the direction of illumination of the radar and the Earth's surface plane
- Accounts for local inclination of the surface
- Influences image brightness
- Is dependent on the height of the sensor
- The geometry of an image is different from point to point in the range direction



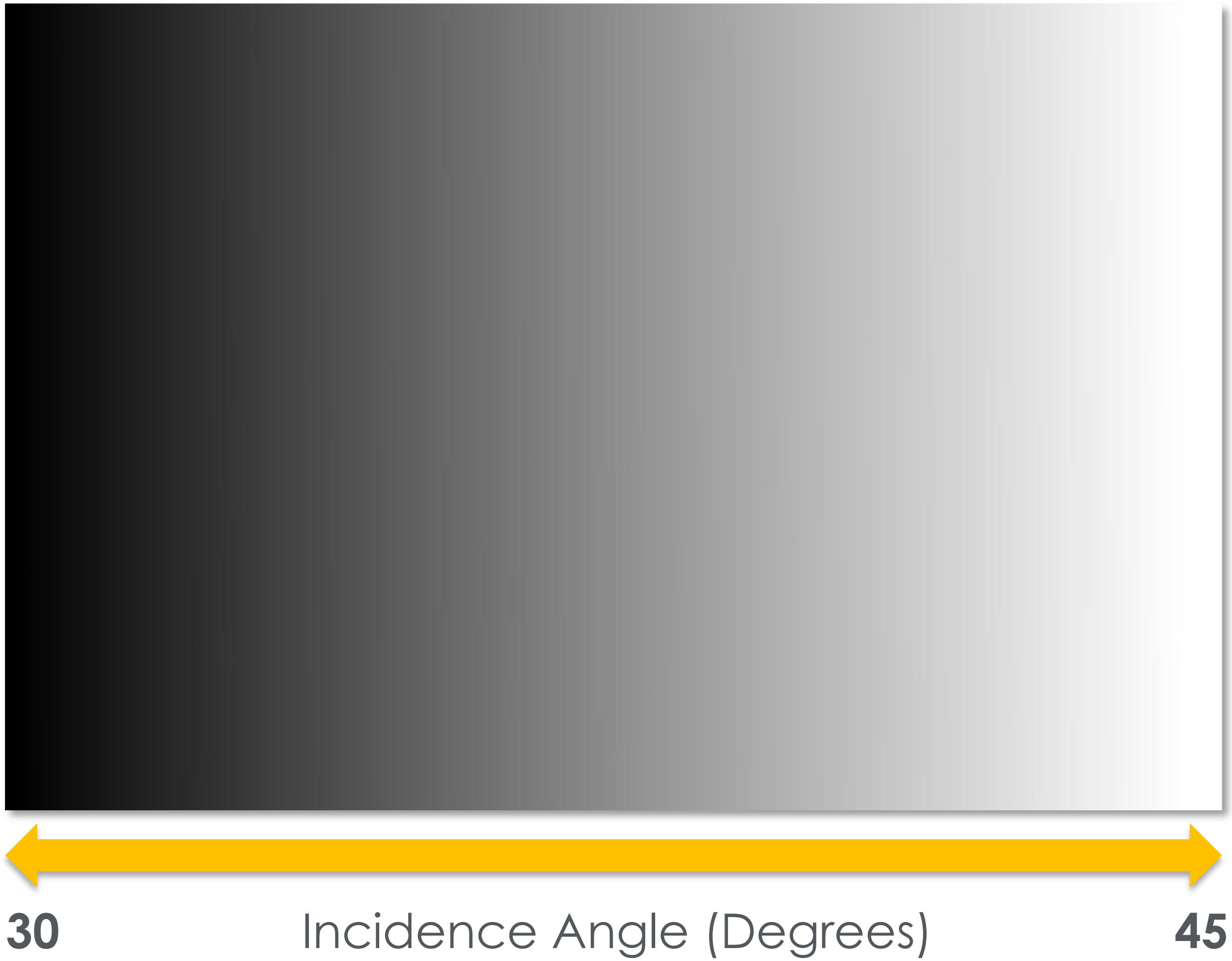


Images Based On: Top: Ulaby et al. (1981a), Bottom: ESA

Effect of Incidence Angle Variation



Sentinel-1



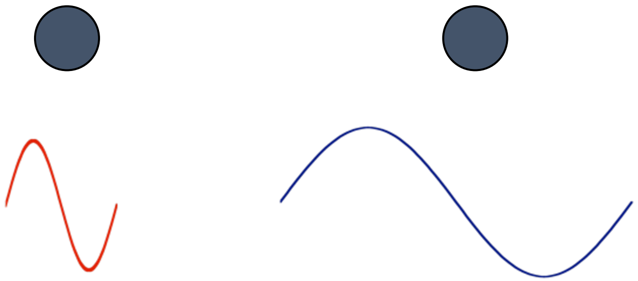
Surface Parameters

Surface Parameters that Influence the Radar Signal

- **Structure** and **moisture** influence the radar signal.
- The radar backscatter 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)

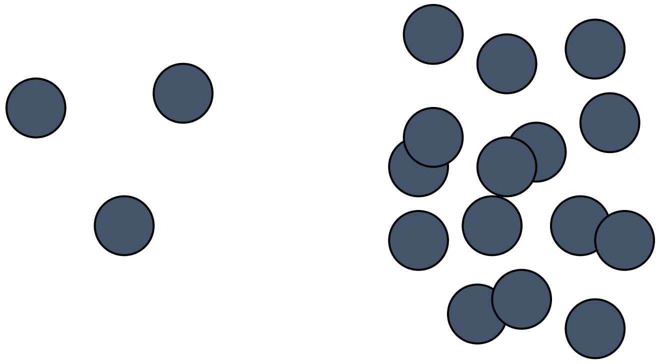
Surface Parameters Related to Structure

Size Relative to Wavelength

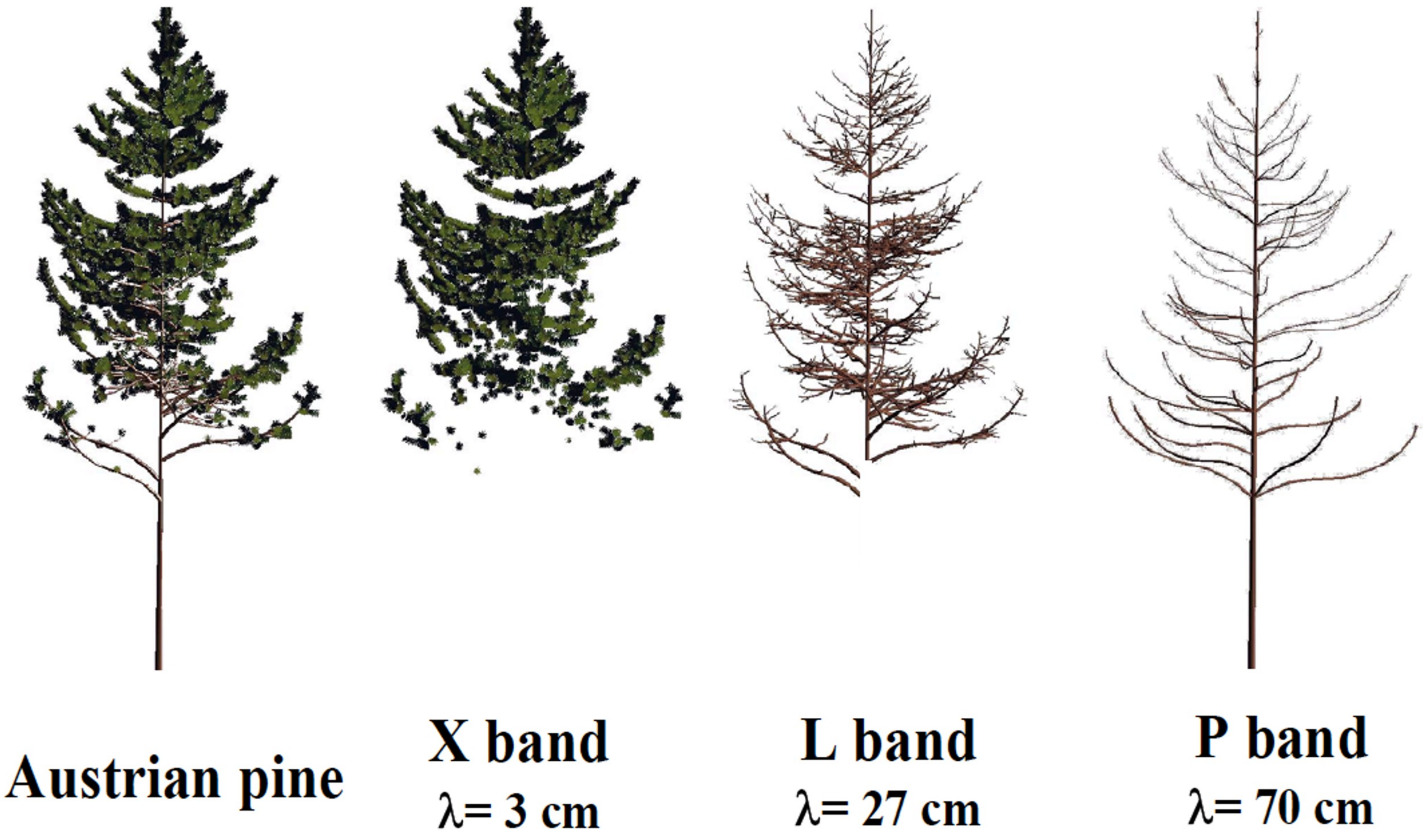


Size & Orientation

Density

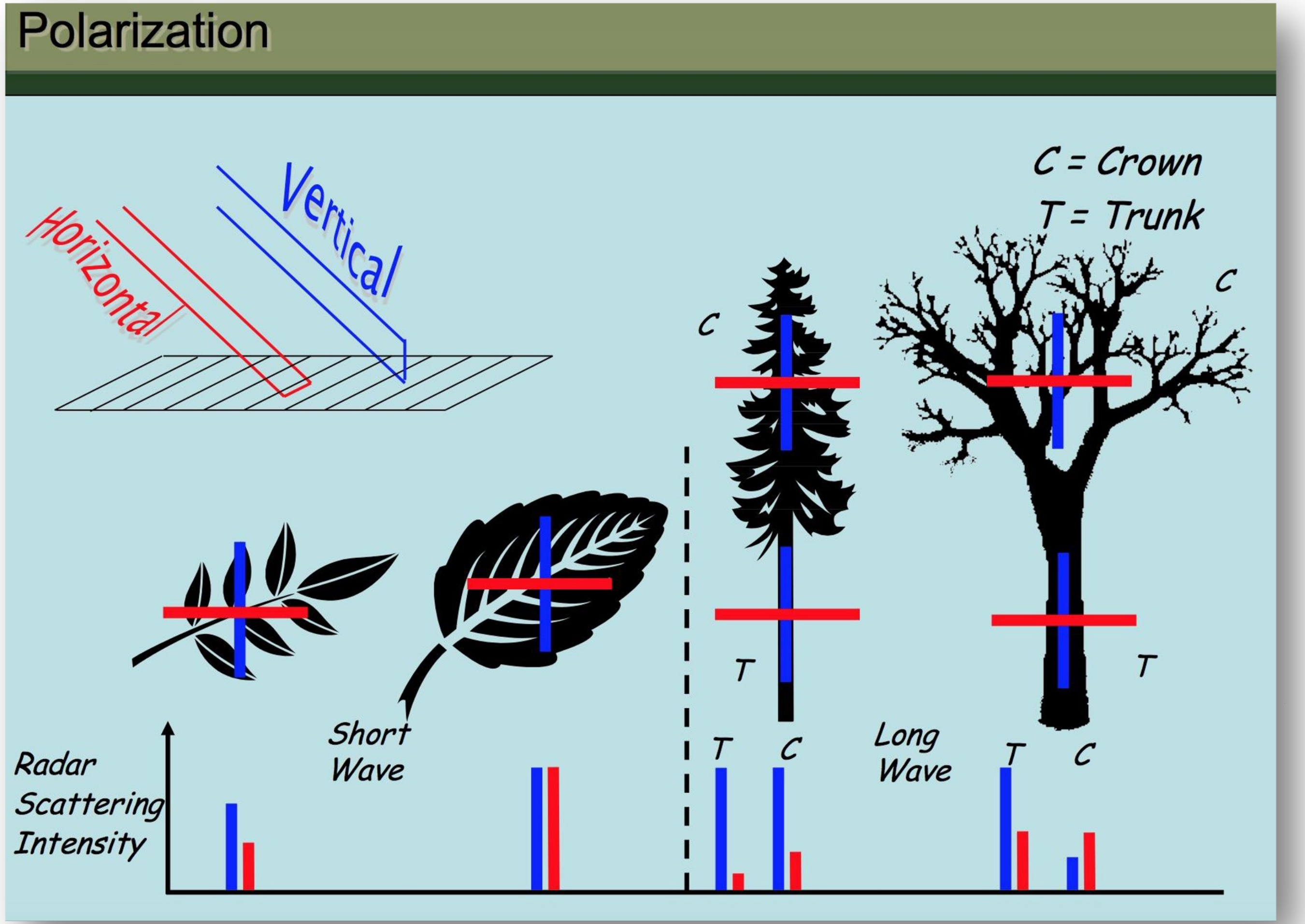


Size Relative to Wavelength



Source: Thuy le Toan

Size and Orientation



RELATIVE SCATTERING STRENGTH BY POLARIZATION:

Rough Surface Scattering $|S_{VV}| > |S_{HH}| > |S_{HV}|$ or $|S_{VH}|$

Double Bounce Scattering $|S_{HH}| > |S_{VV}| > |S_{HV}|$ or $|S_{VH}|$

Volume Scattering Main source of $|S_{HV}|$ and $|S_{VH}|$

Source: SAR Handbook

Source: Walker, W. *Introduction to Radar Remote Sensing for Vegetation Mapping and Monitoring*

Vegetation Density

The denser the vegetation, the less likely for the signal to penetrate through the canopy. This is a function of wavelength.

- Saturation Problem - The signal saturates at a certain biomass level, which is wavelength dependent.

- C-band ≈ 20 tons/ha (2 kg/m2)
- L-band ≈ 40 tons/ha (4 kg/m2)
- P-band ≈ 100 tons/ha (10 kg/m2)

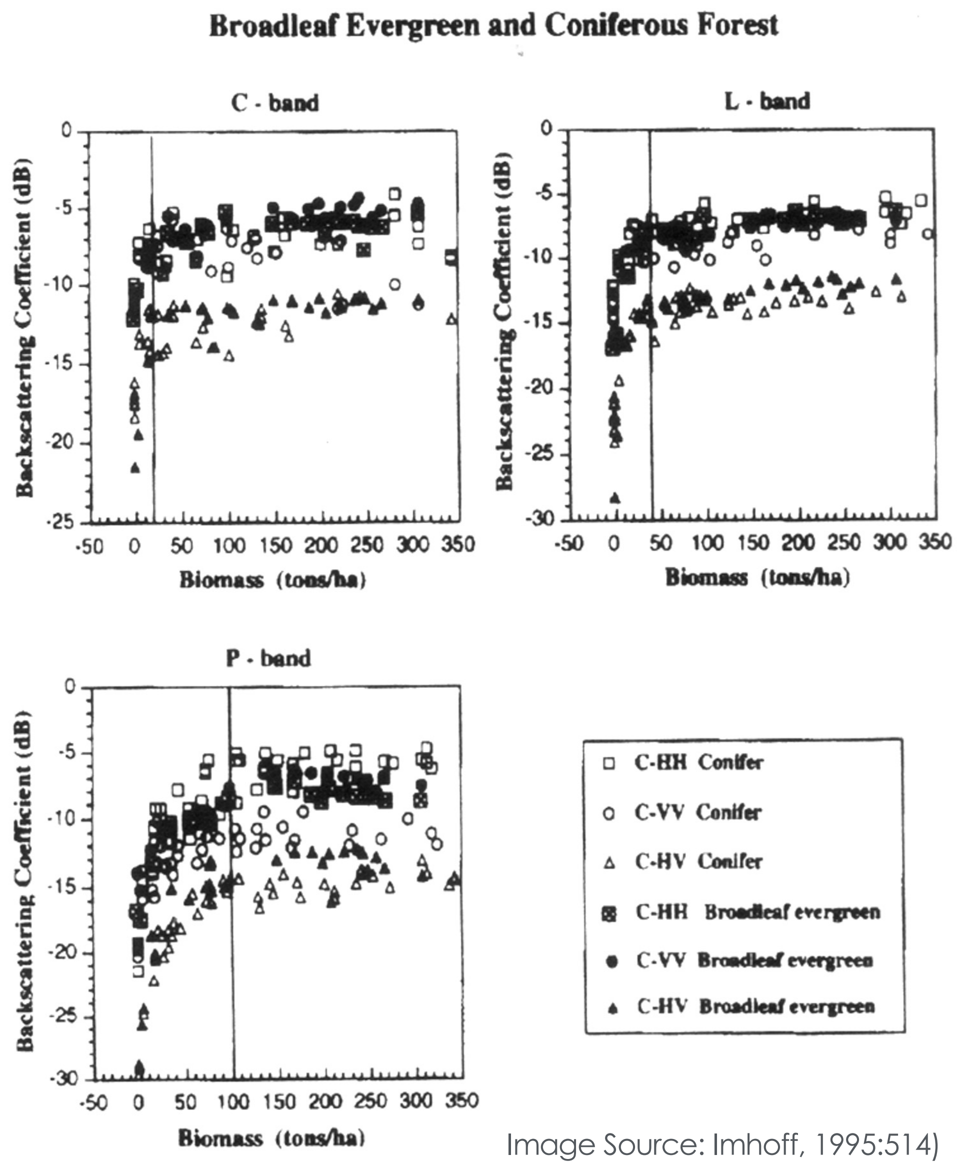
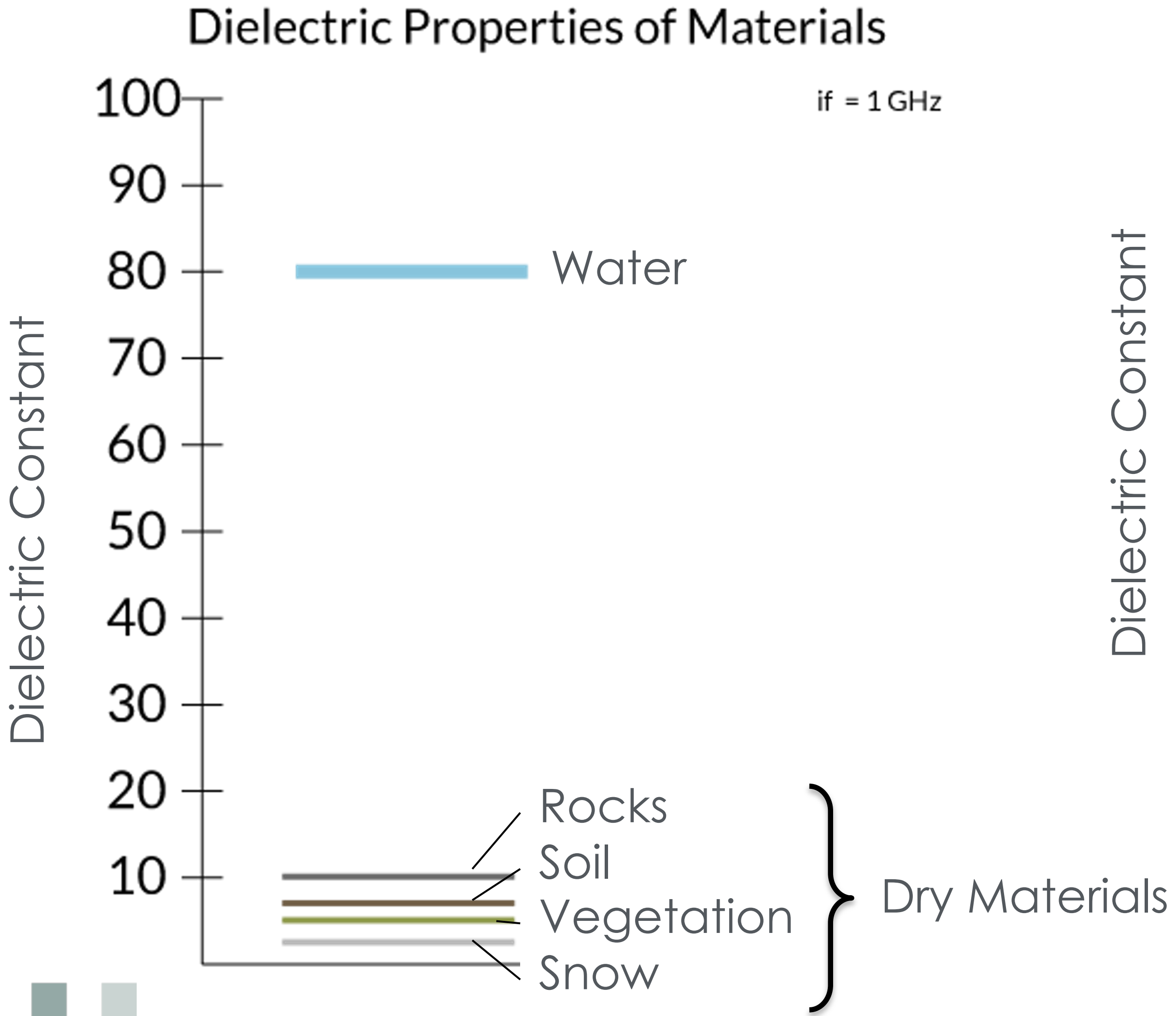
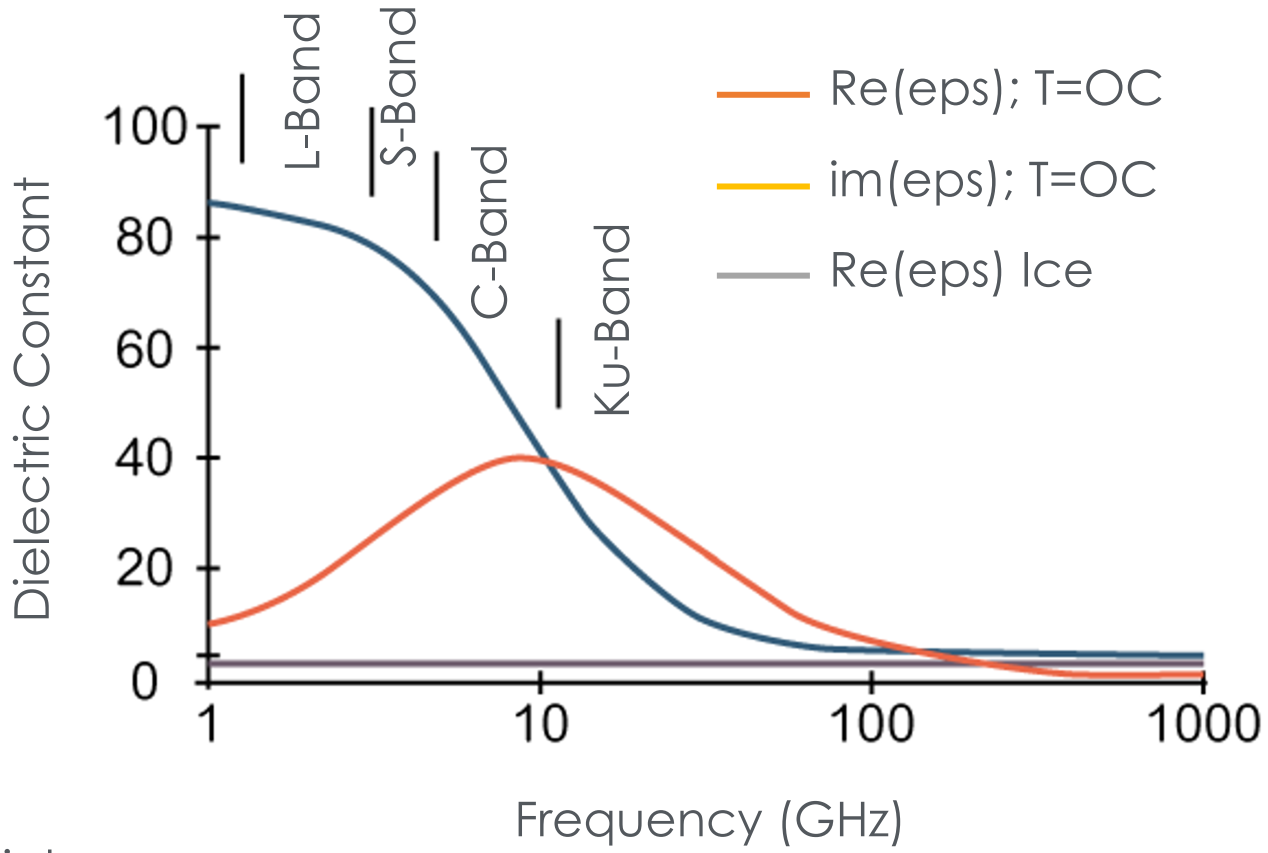


Image Source: Imhoff, 1995:514)

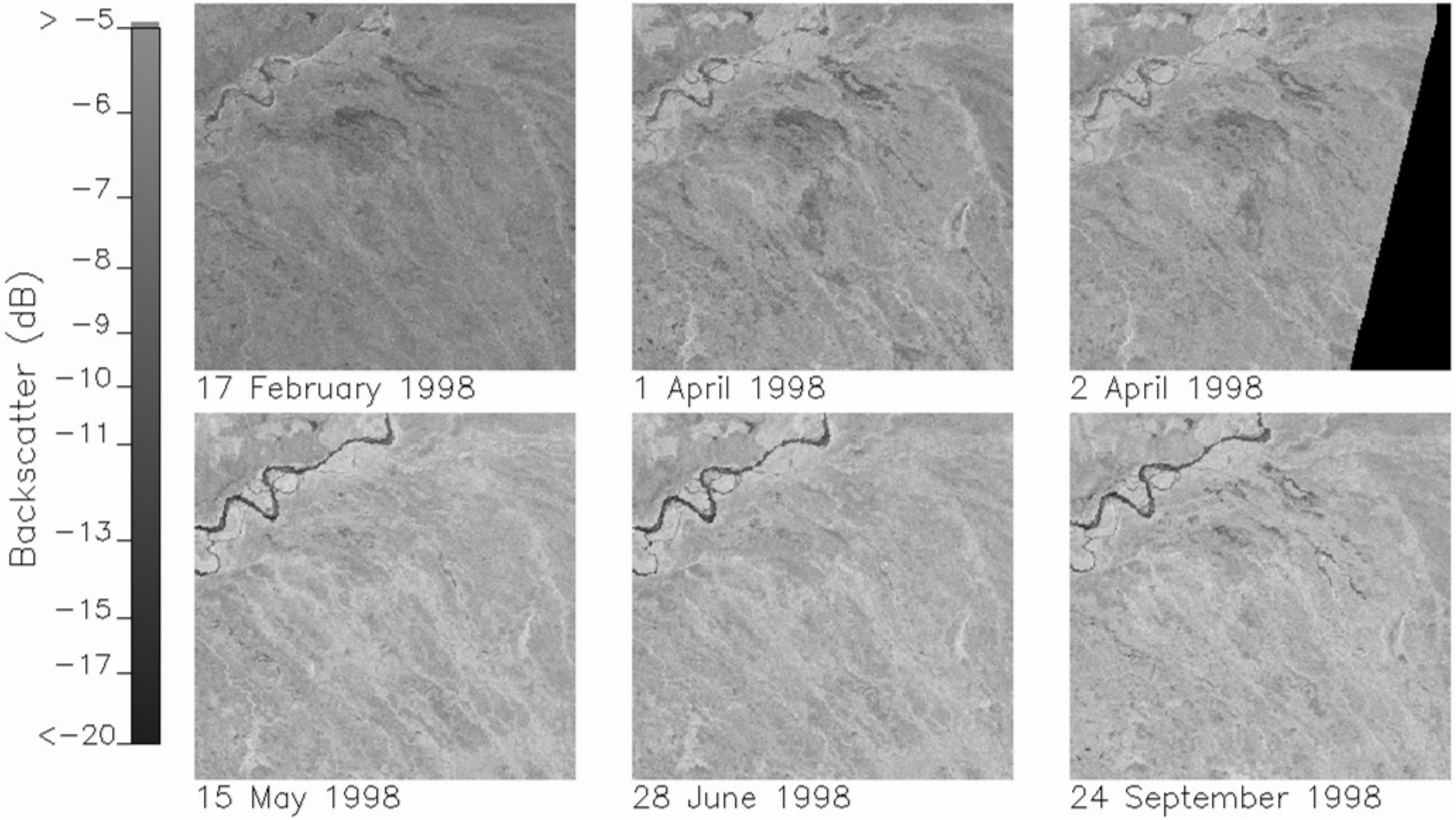
Surface Parameters: Dielectric Constant





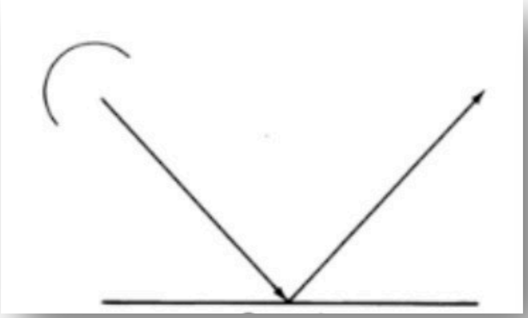
Surface Parameters: Dielectric Properties of the Surface

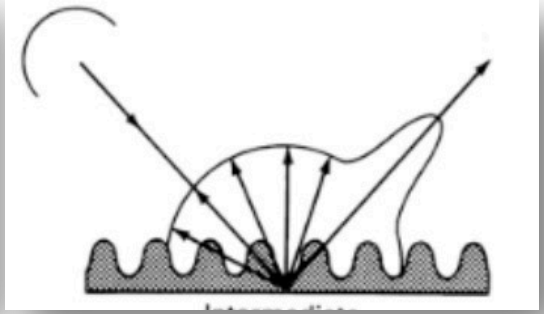
- During the land surface freeze/thaw transition, there is a change in dielectric properties of the surface.
- This causes a notable increase in backscatter.

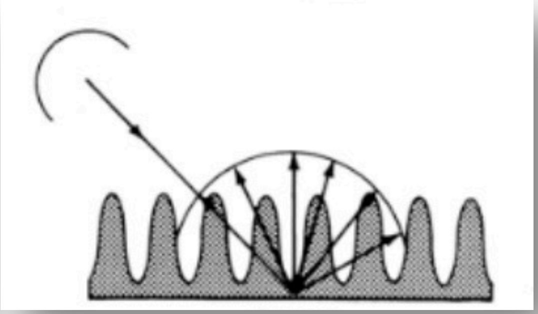


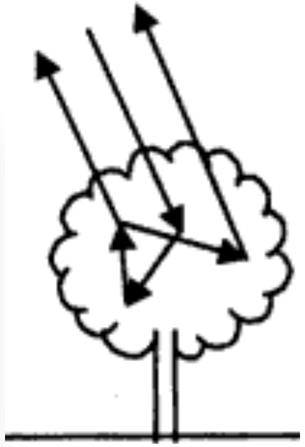
Surface Parameters: Structure and Roughness of the Surface

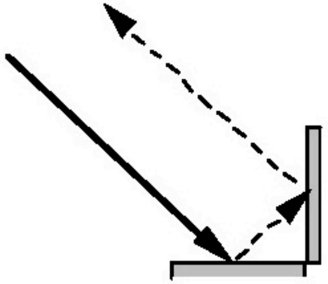
- The scale of the surface relative to the wavelength determines how rough or smooth it appears and how bright or dark it will appear on the image.


Smooth Surface

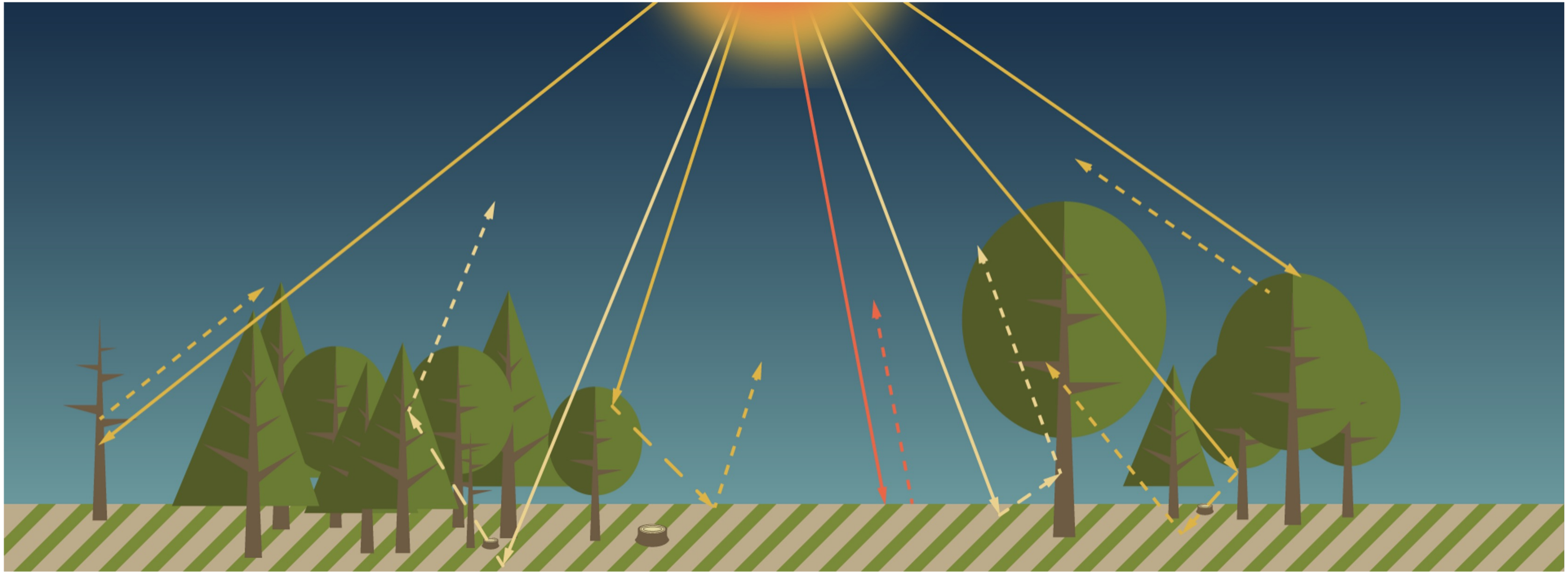

Rough Surface


Rougher Surface


Volume Scattering


Double Bounce

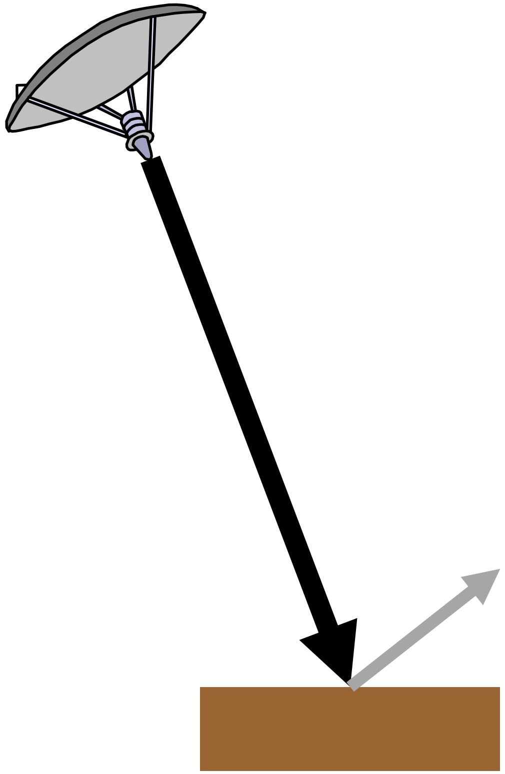
Radar Backscatter in Forests



Dominant Backscattering Sources in Forests: (1) Direct Scattering from Tree Trunks, (2a) Ground-Crown Scattering, (2b) Crown-Ground Scattering, (3a) Ground-Trunk Scattering, (3b) Trunk-Ground Scattering, (4) Crown Volume Scattering.

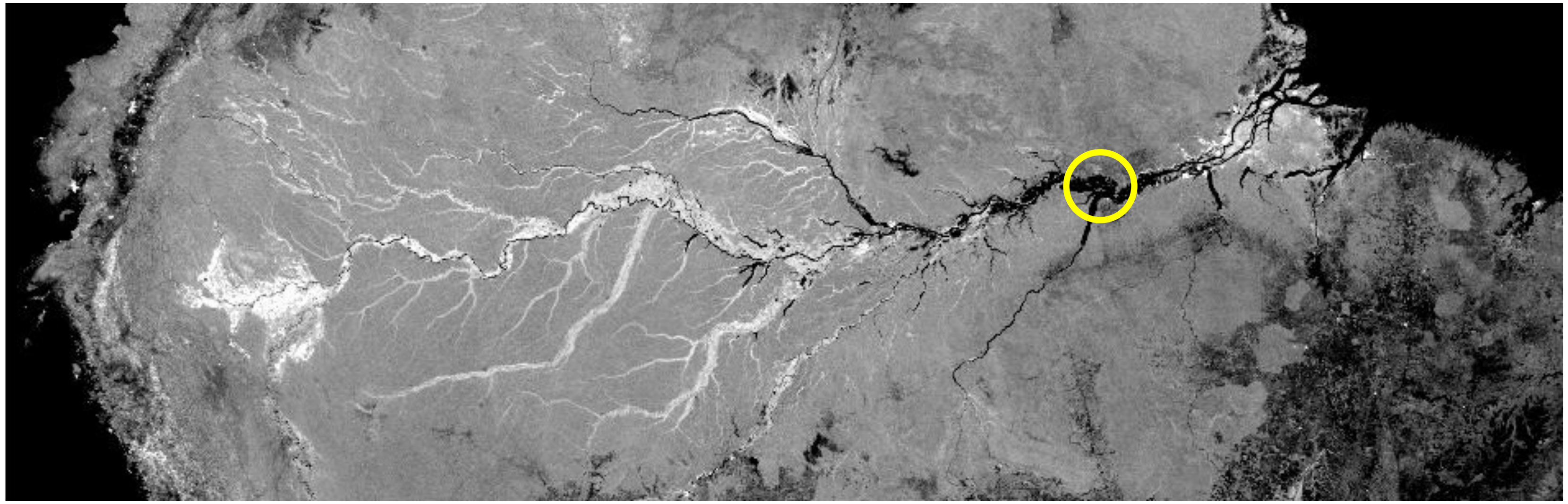
Radar Backscatter: Specular Reflection

Smooth Surface Reflection (Specular Reflection)



Smooth, Level Surface
(Open Water, Road)

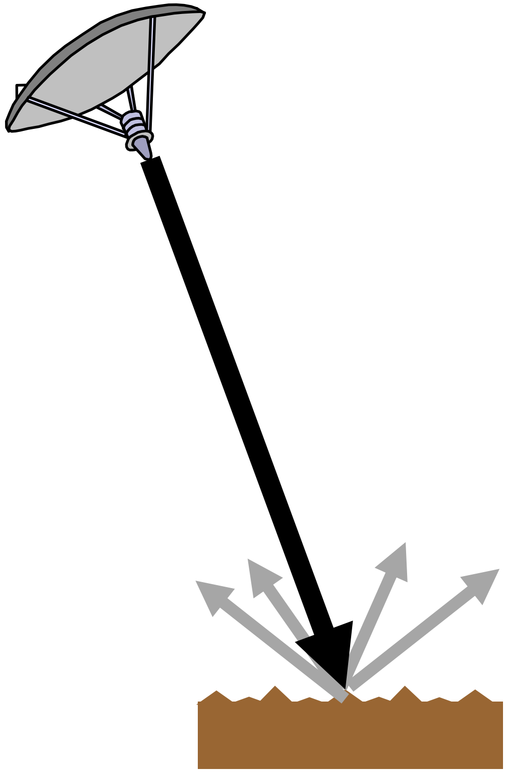
SMAP Radar Mosaic of the Amazon Basin
April 2015 (L-band, HH, 3 km)



Pixel Color

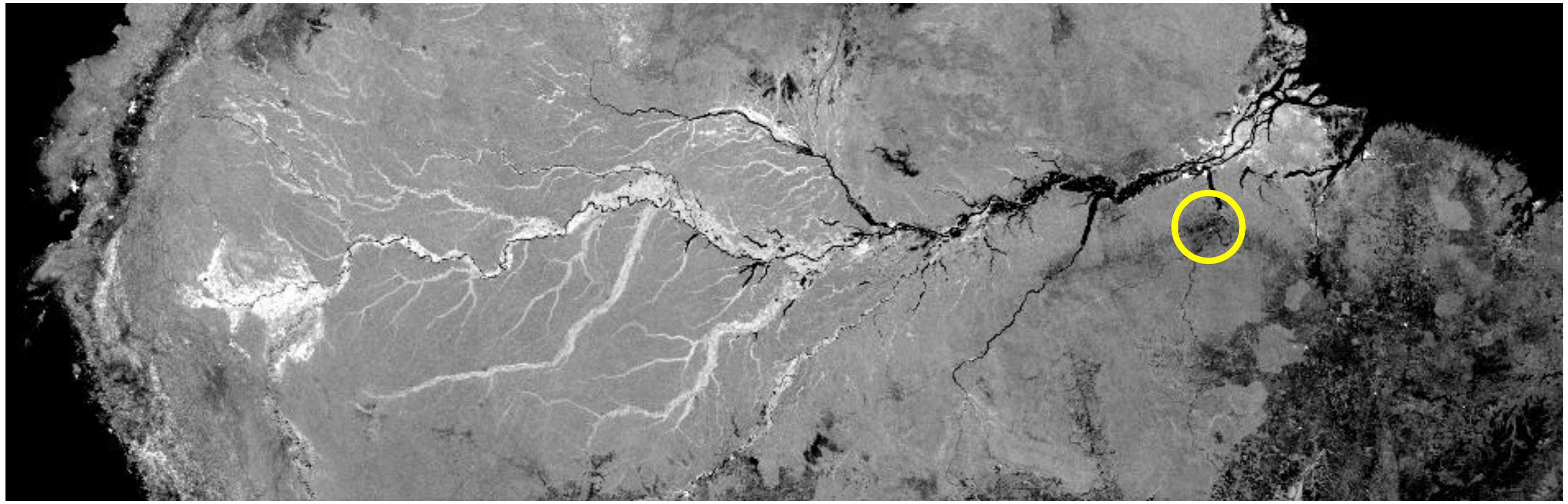
Radar Backscatter: Rough Surface Reflection

Rough Surface Reflection



Rough Bare Surface (Deforested Areas, Tilled Agricultural Fields)

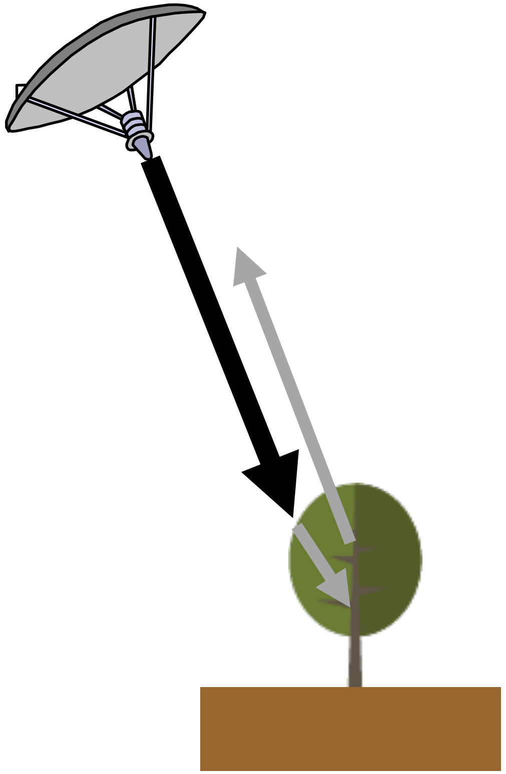
SMAP Radar Mosaic of the Amazon Basin
April 2015 (L-band, HH, 3 km)



Pixel Color

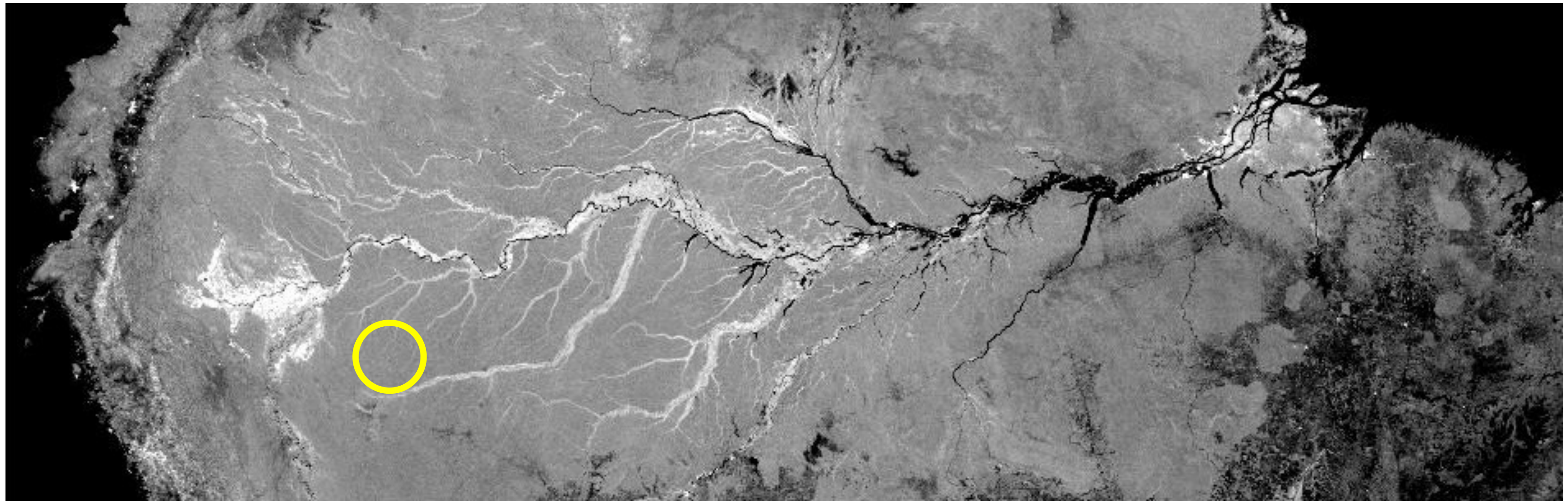
Radar Backscatter: Volume Scattering

Volume Scattering by Vegetation



Vegetation

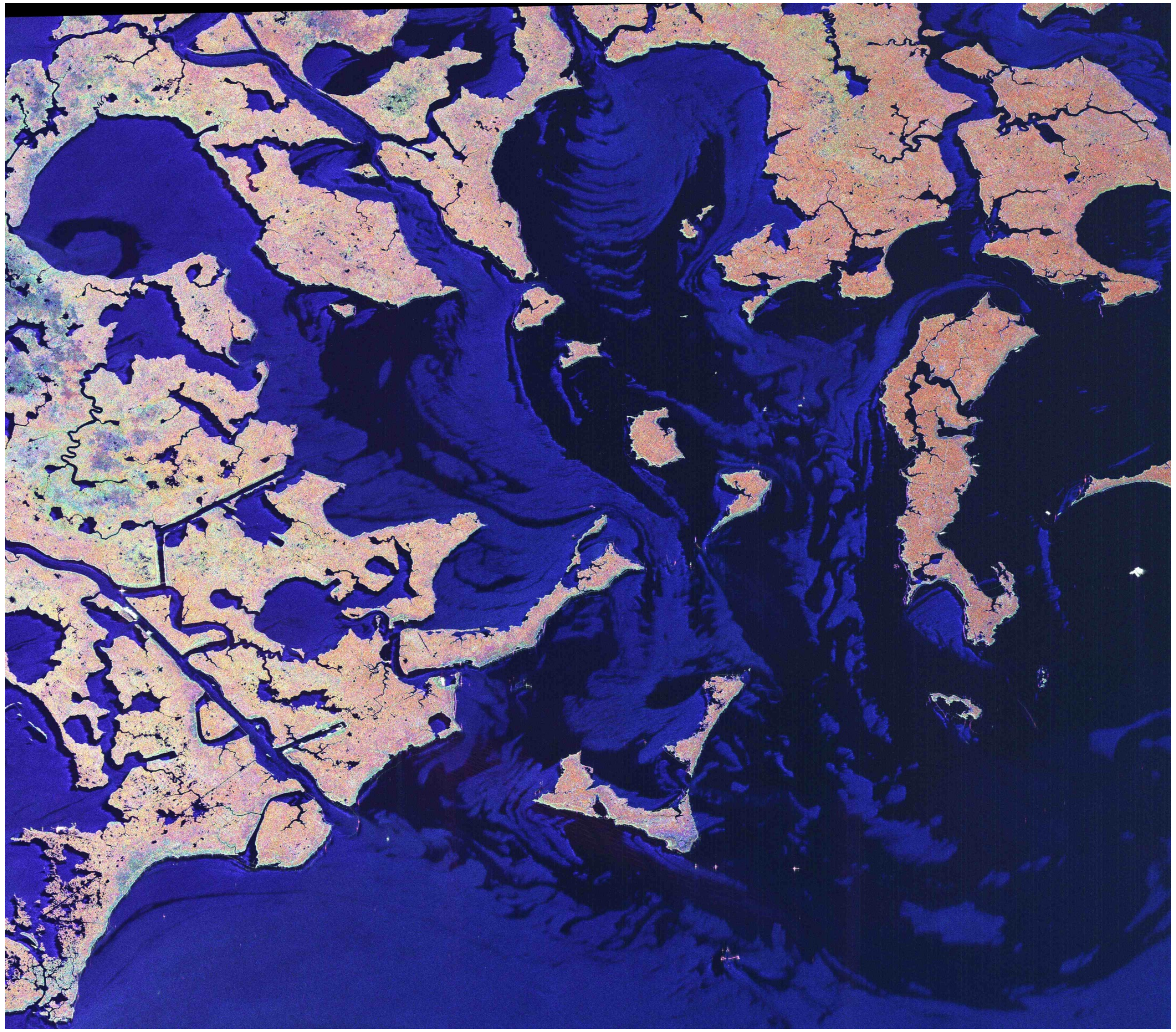
SMAP Radar Mosaic of the Amazon Basin
April 2015 (L-band, HH, 3 km)



Pixel Color

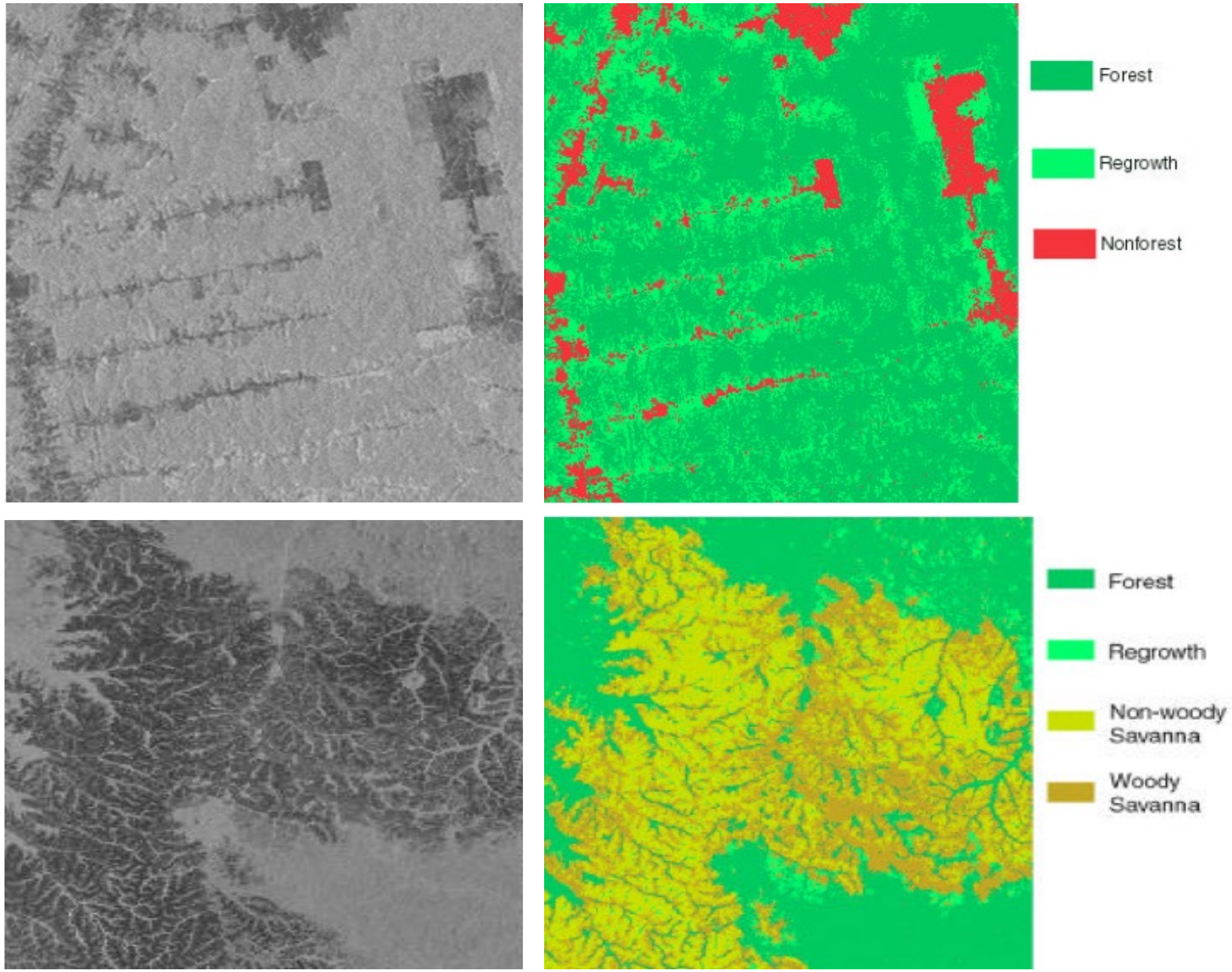
Detection of Oil Spills on Water – Surface Roughness

UAVSAR (2 meters): HH, HV, VV



Landcover Classification

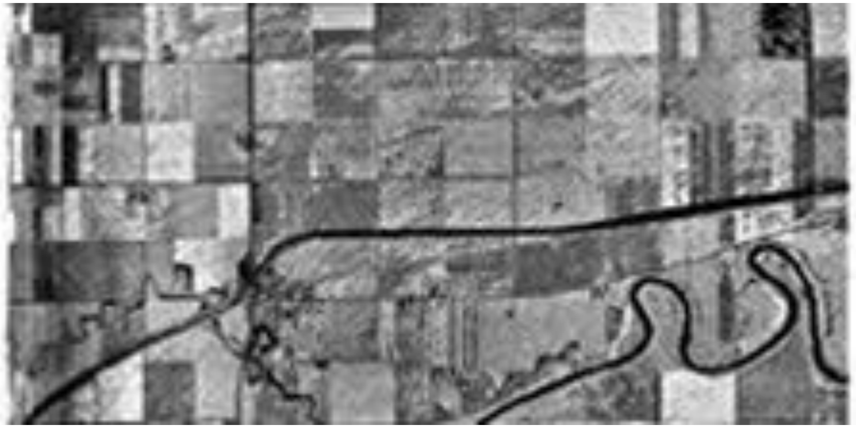
- Brazil
- JERS-1 L-band
- 100-meter Resolution



Geometric and Radiometric Distortions of the Radar Signal

Slant Range Distortion

Slant Range



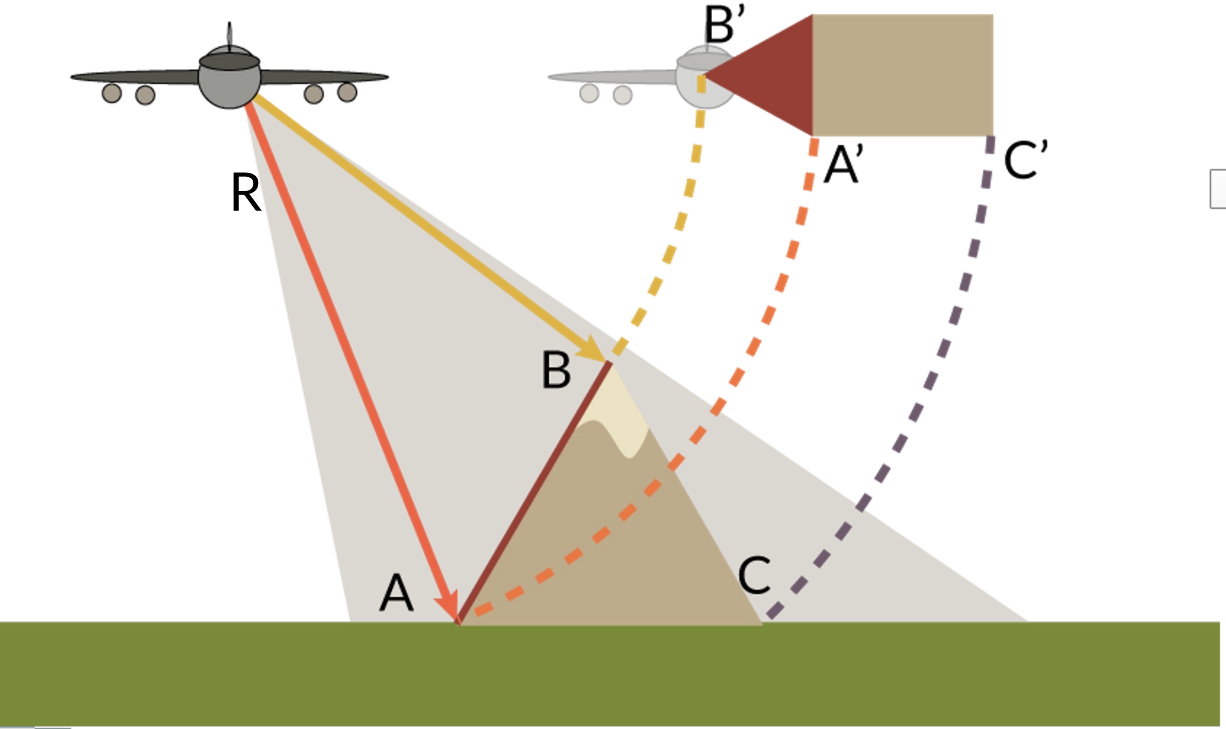
Ground Range

Source: Natural Resources Canada

Geometric Distortion

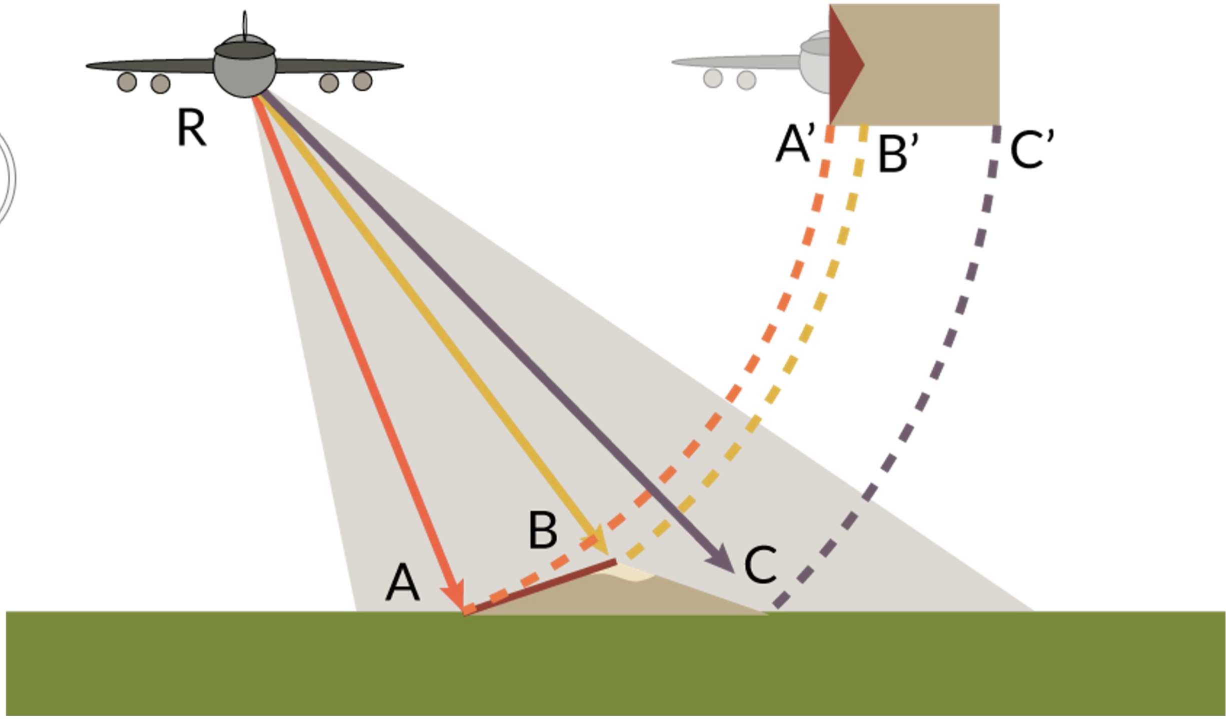
Layover

AB = BC
A'B' < B'C'
RA > RB
RA' > RB'

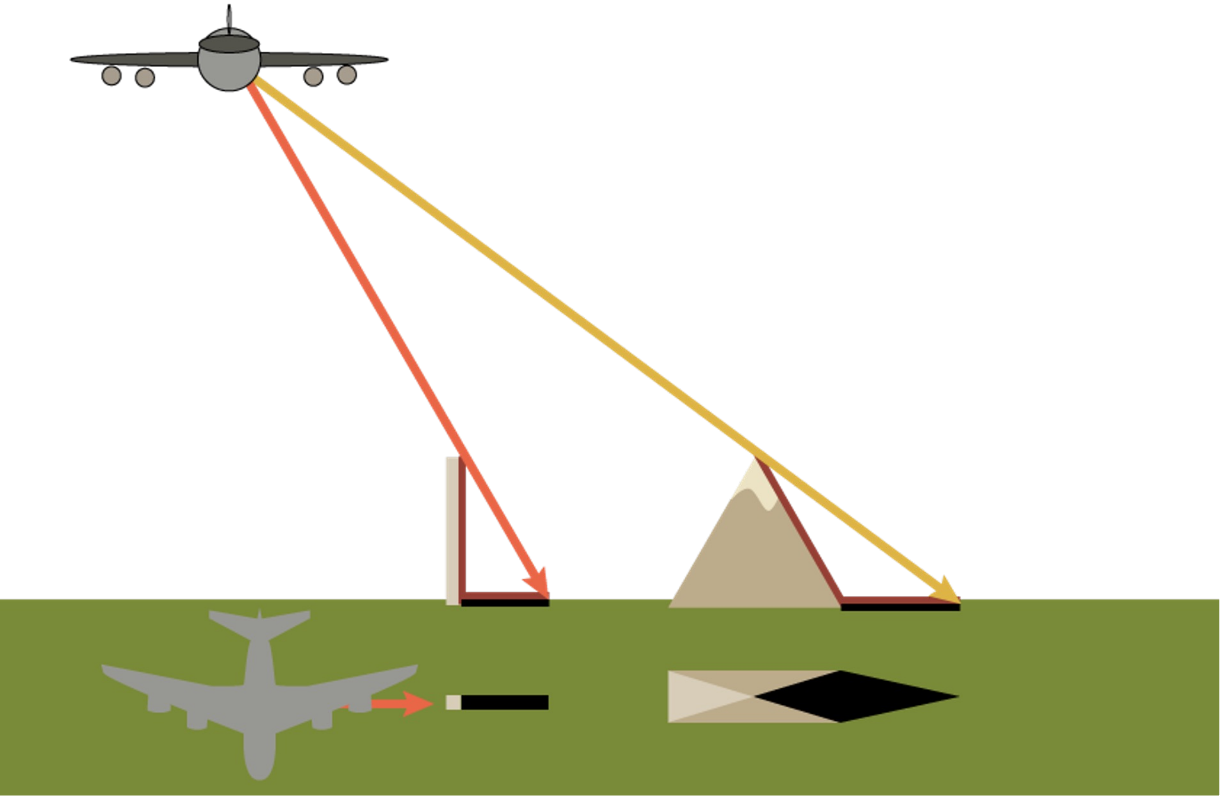


Foreshortening

RA < RB < RC
AB = BC
A'B' < B'C'

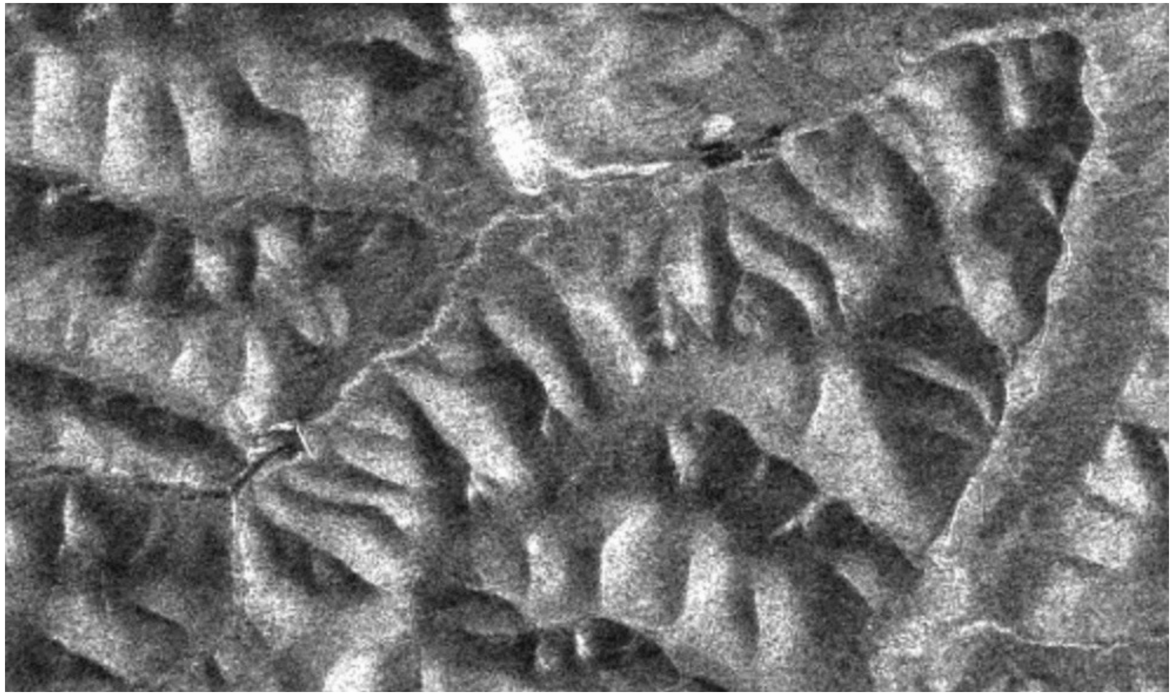


Shadow



Radiometric Distortion

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



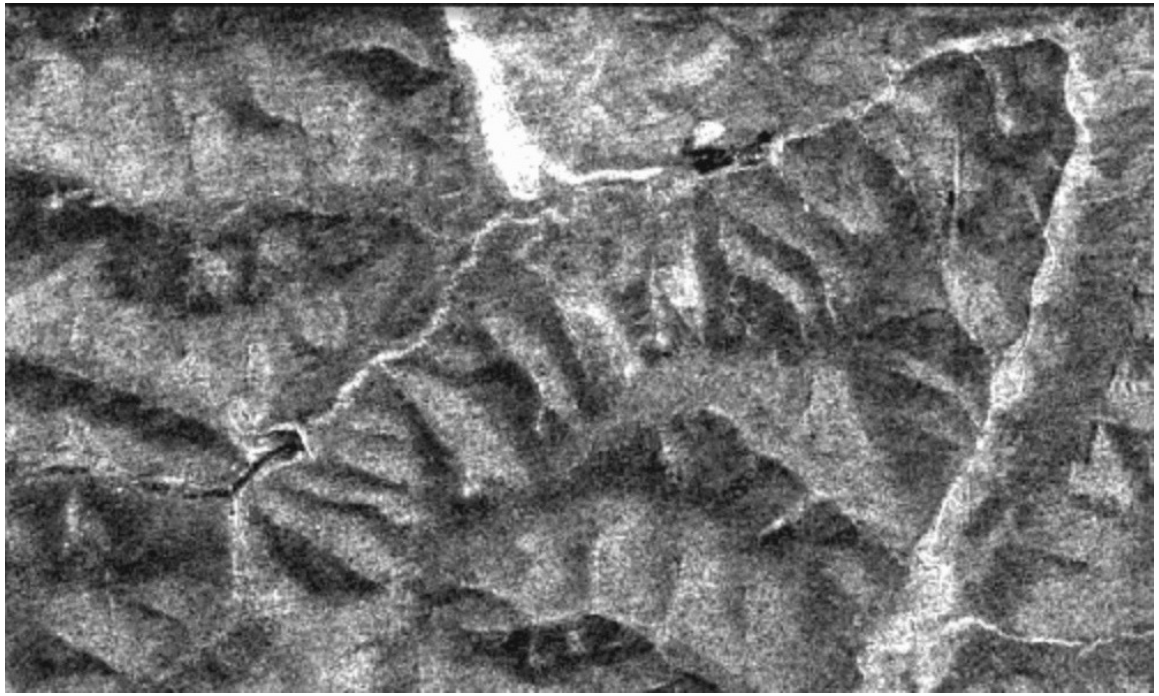


Image Credit: ASF

Speckle

Speckle

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

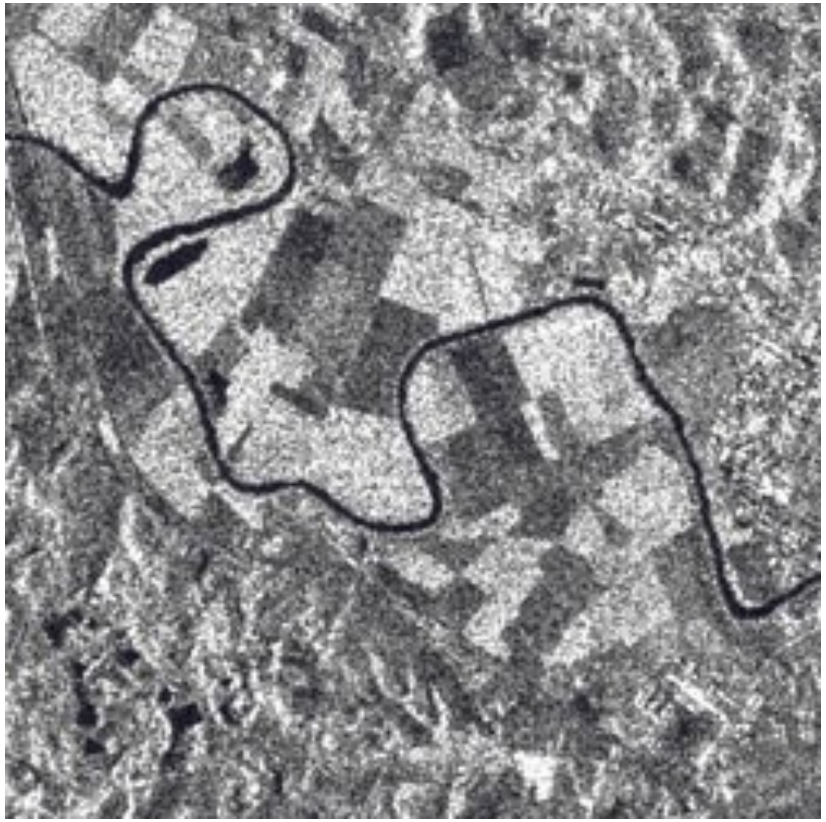


Image Credit: ESA

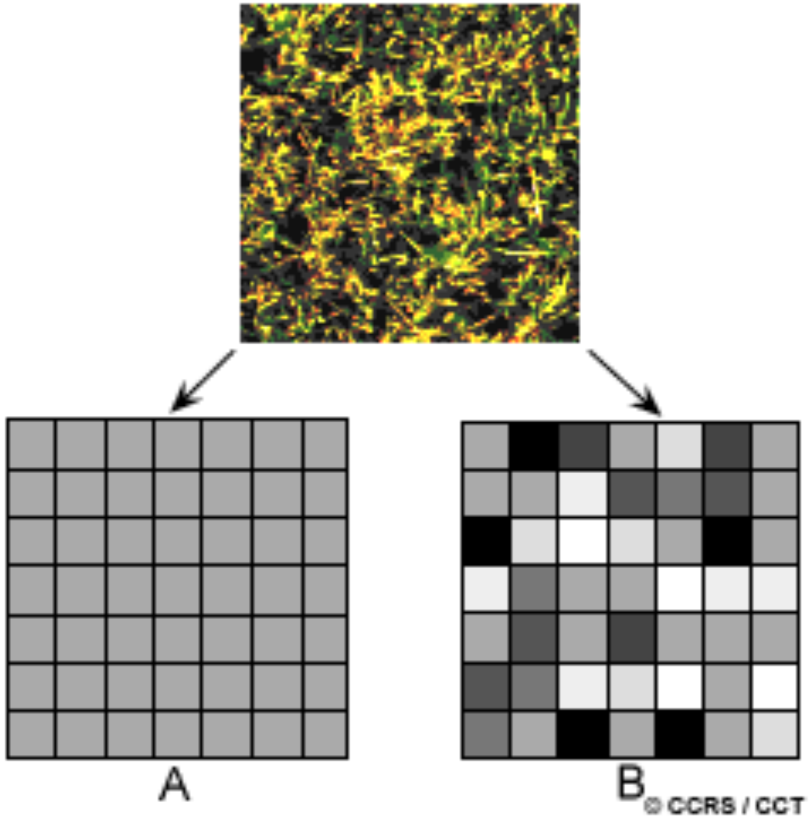
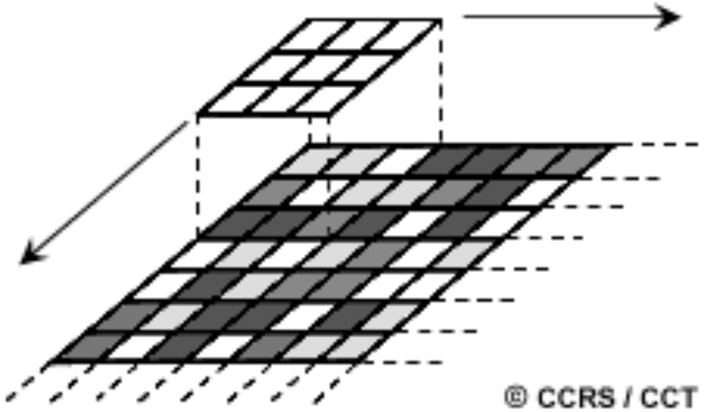
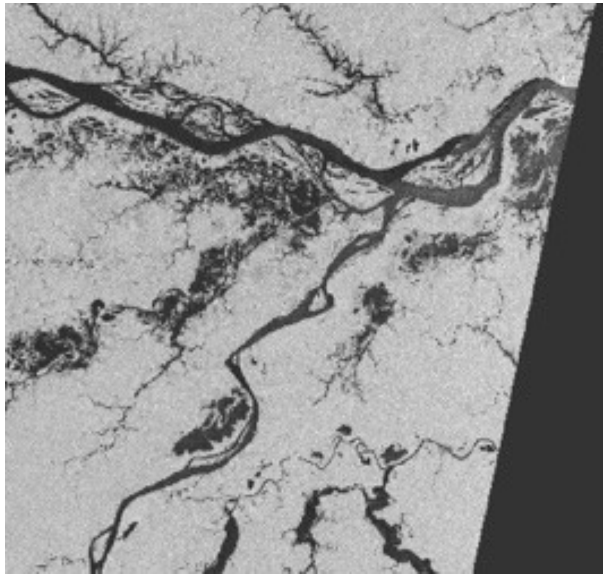


Image Credit: Natural Resources Canada

Speckle Reduction: 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

SAR Satellites

Radar Data Available

Legacy:

SeaSAT
1978

JERS-1
1992-1998

ERS 1/2
1991-2011

ENVISAT
2002-2012

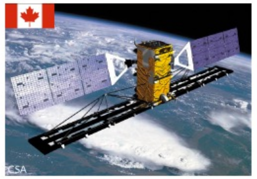
ALOS-1
2002-2012

Radarsat-1
1995-2013

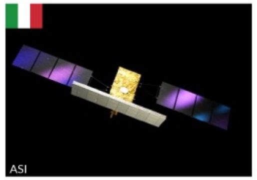
Current:

TanDEM-X
2007

Radarsat-2
2007



COSMO-SkyMed
2007

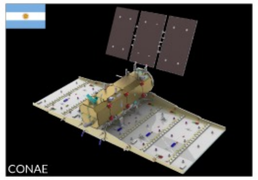


ALOS-2
2014

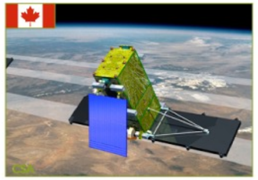
Sentinel-1
2014

PAZ SAR
2018

SAOCOM
2018



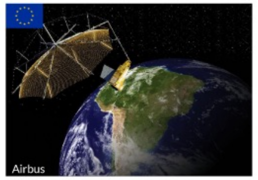
RCM
2018



Future:

NISAR
2024

Biomass
2024



Freely Accessible

Image Credit: Franz Meyer, University of Alaska, Fairbanks

NASA-ISRO SAR Mission (NISAR)

- High spatial resolution with frequent revisit time
- Launch Date: Aug-Sep 2024
- 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.

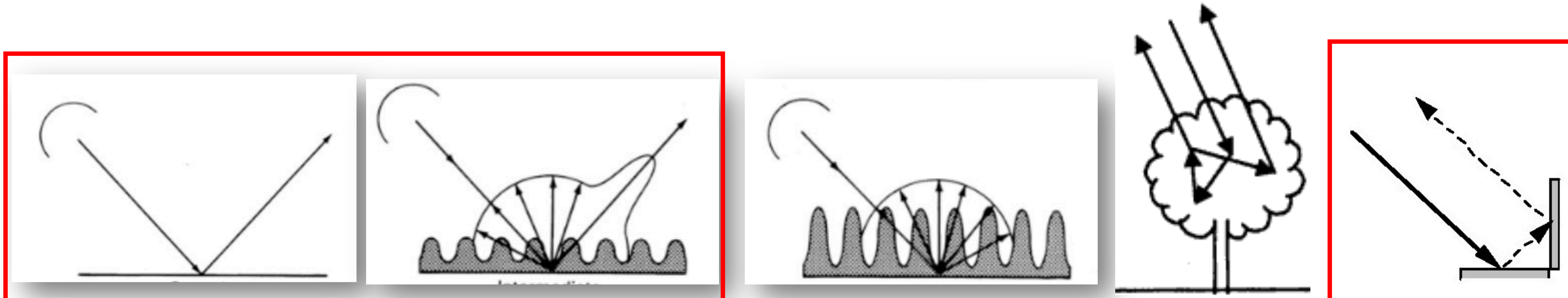
NISAR Characteristic:	Would Enable:
L-band (24 cm wavelength)	Low temporal decorrelation and foliage penetration
S-band (12 cm wavelength)	Sensitivity to light vegetation
SweepSAR technique with Imaging Swath >240 km	Global data collection
Polarimetry (Single/Dual/Quad)	Surface characterization and biomass 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

Flood Mapping with SAR

NASA-ISRO SAR Mission (NISAR)

- The temporary or permanent occurrence of a water surface beneath a vegetation canopy
- Water without any standing vegetation

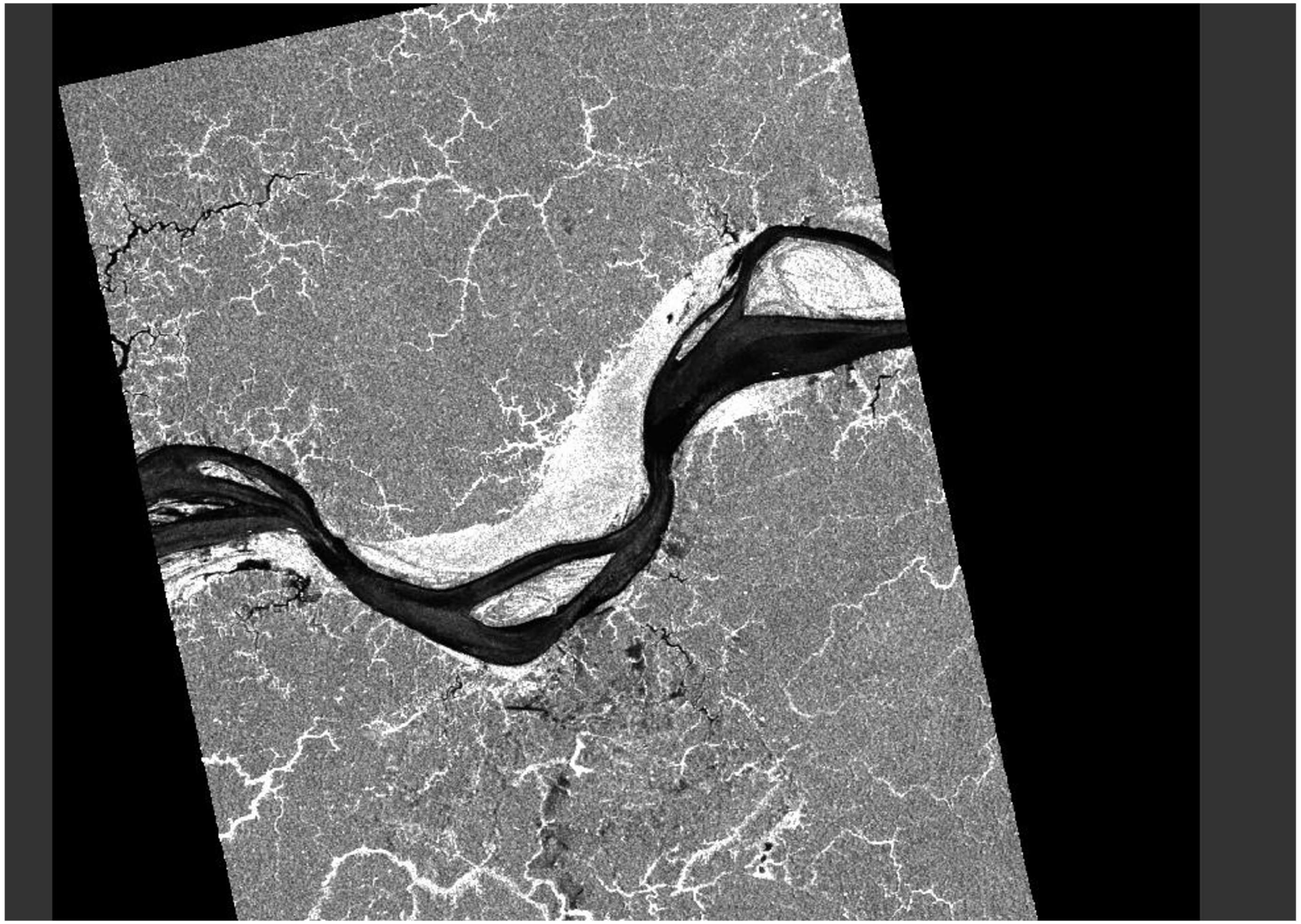
SAR Signal Scattering Over Inundated Regions



Smooth Surface | Rough Surface | Rougher Surface | Volume Scattering | Double Bounce

SAR Signal Scattering Over Inundated Regions

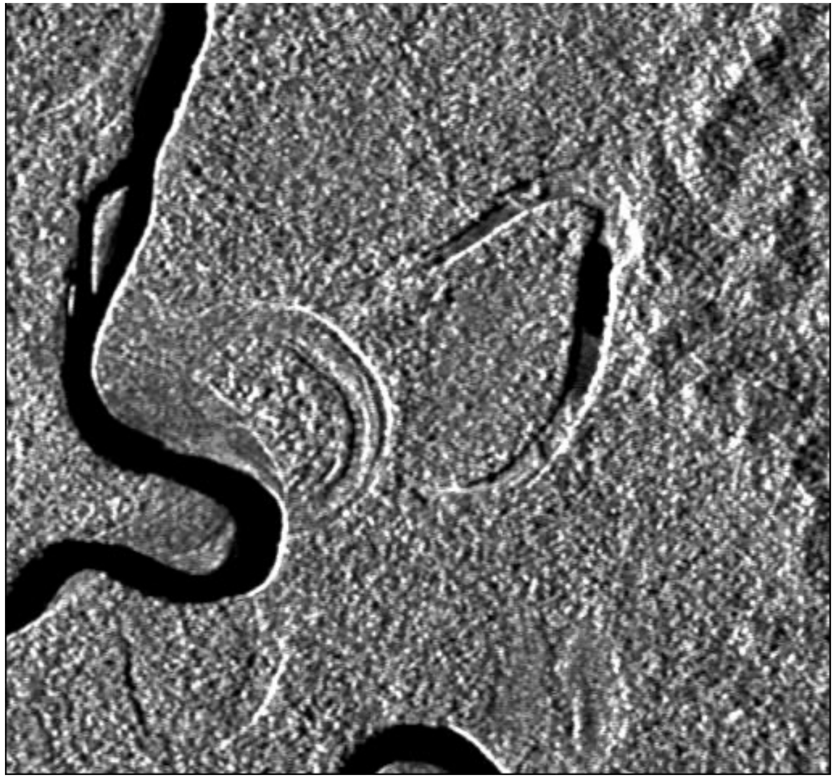
Palsar Image (L-band) Near Manaus, Brazil



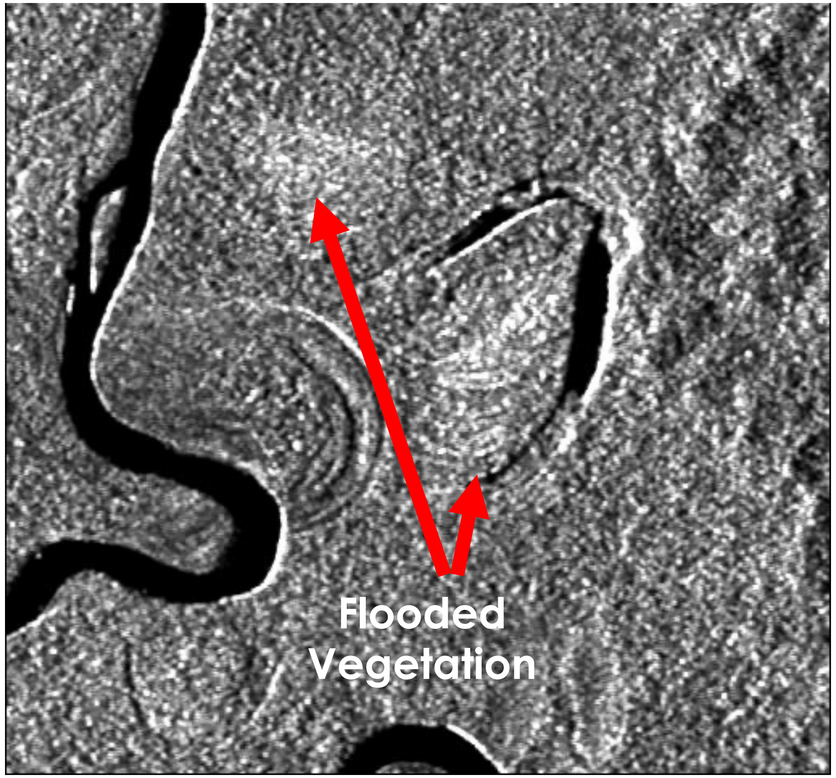
Signal Penetration Over Flooded Inundation

Multi-Frequency AIRSAR Data in Manu National Park, Peru

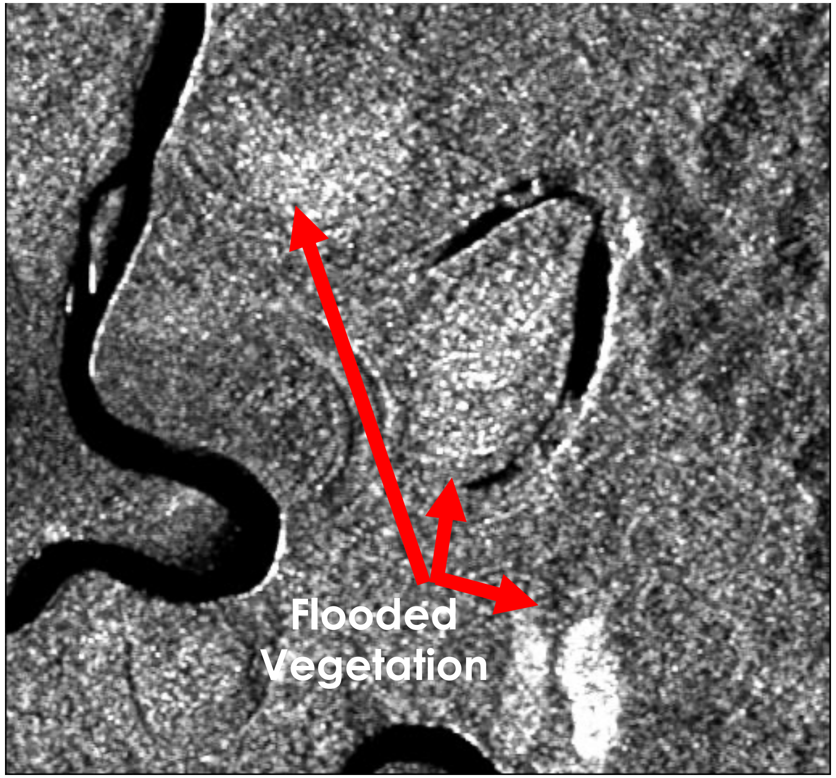
C-Band



L-Band

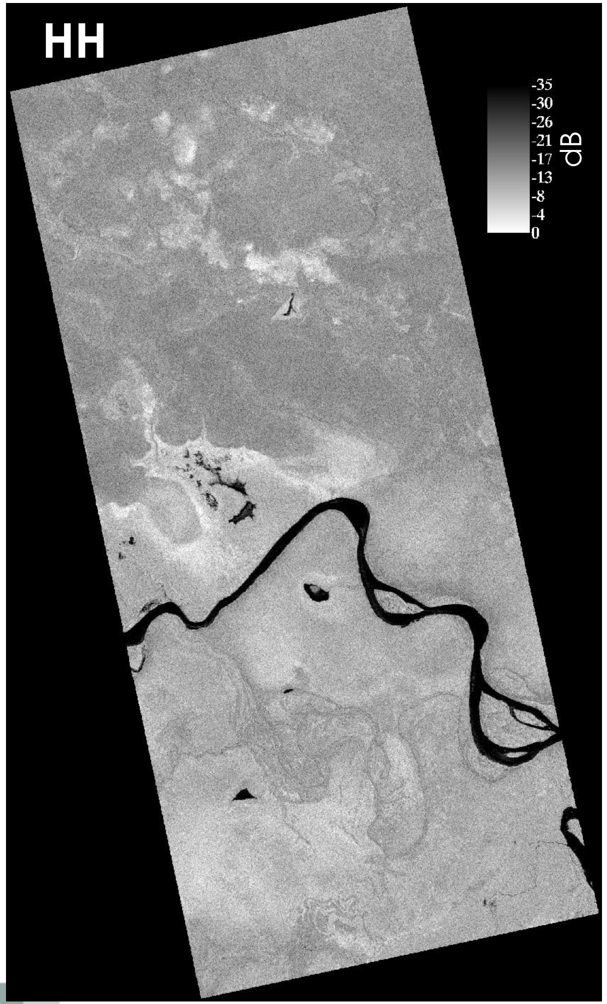


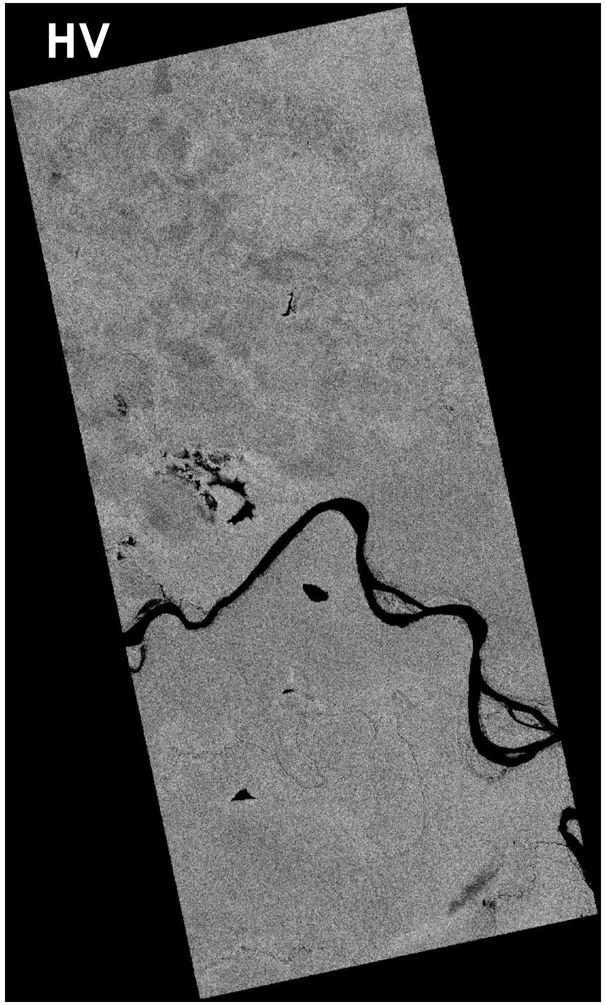
P-Band

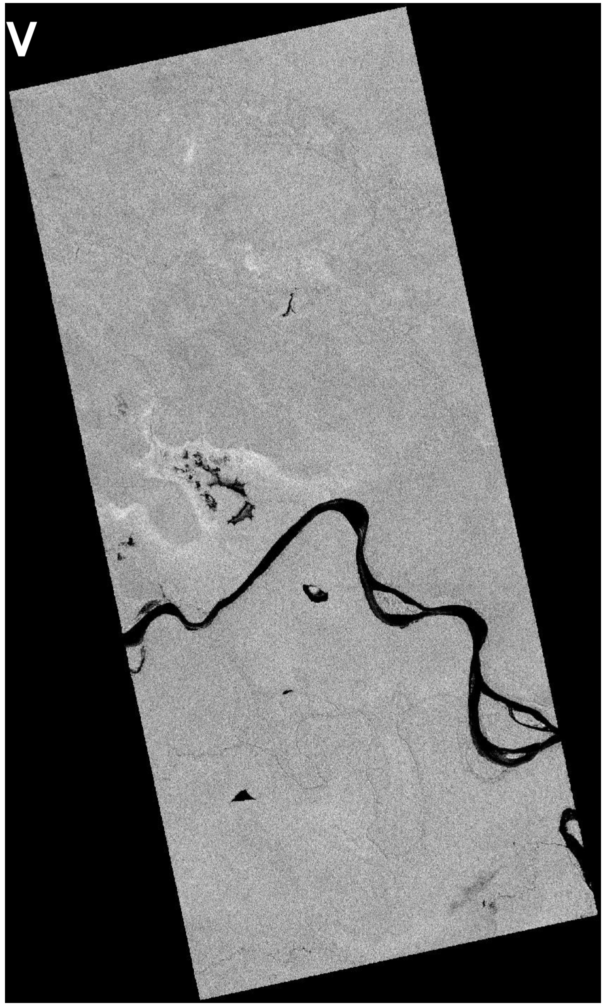


Multiple Polarizations for Detecting Inundated Vegetation

Images from Palsar (L-band) over Pacaya-Samiria in Peru

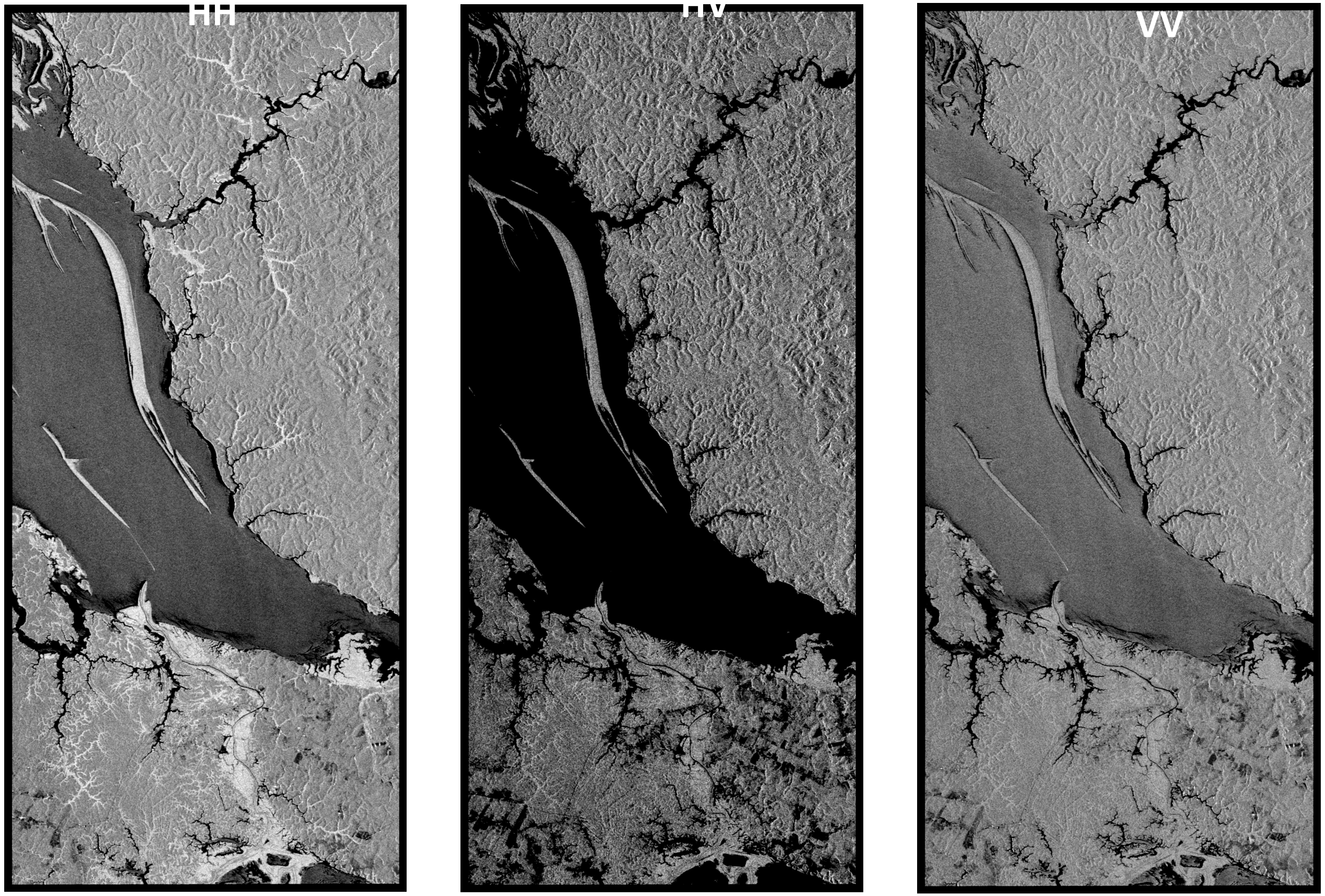






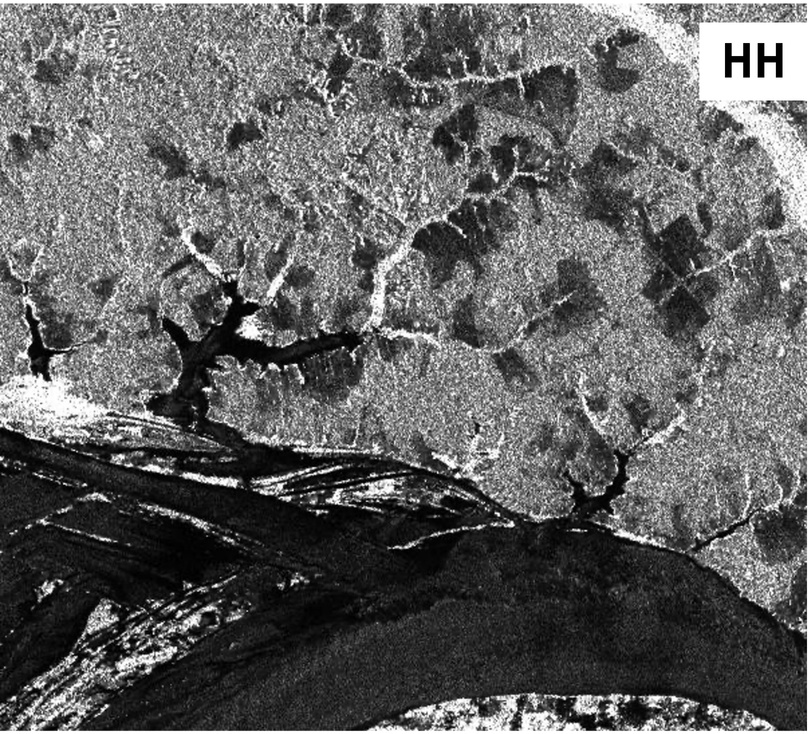
Multiple Polarizations for Detecting Open Water

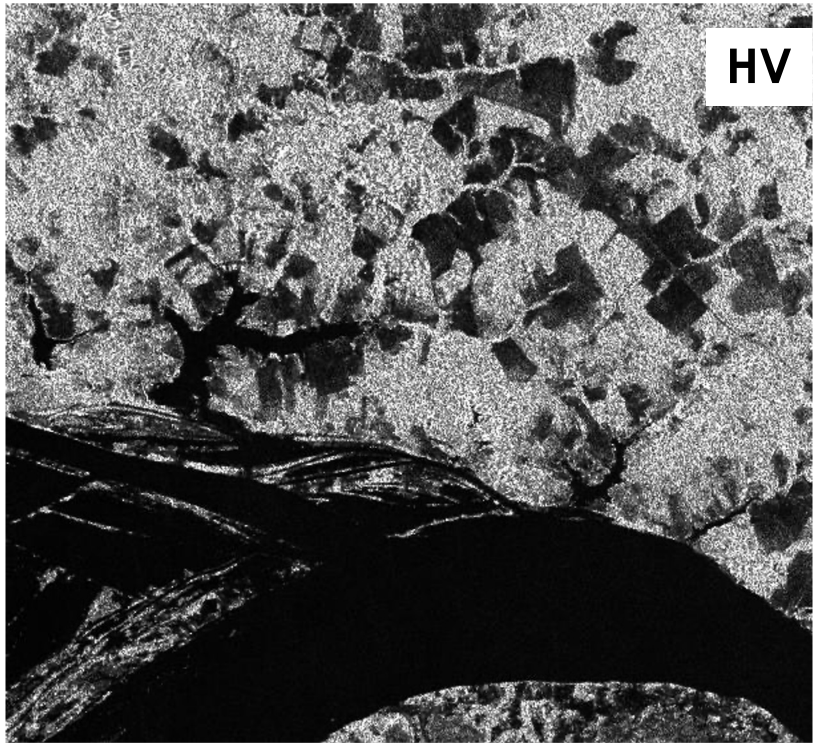
Images from Palsar (L-band) over Pacaya-Samiria in Peru

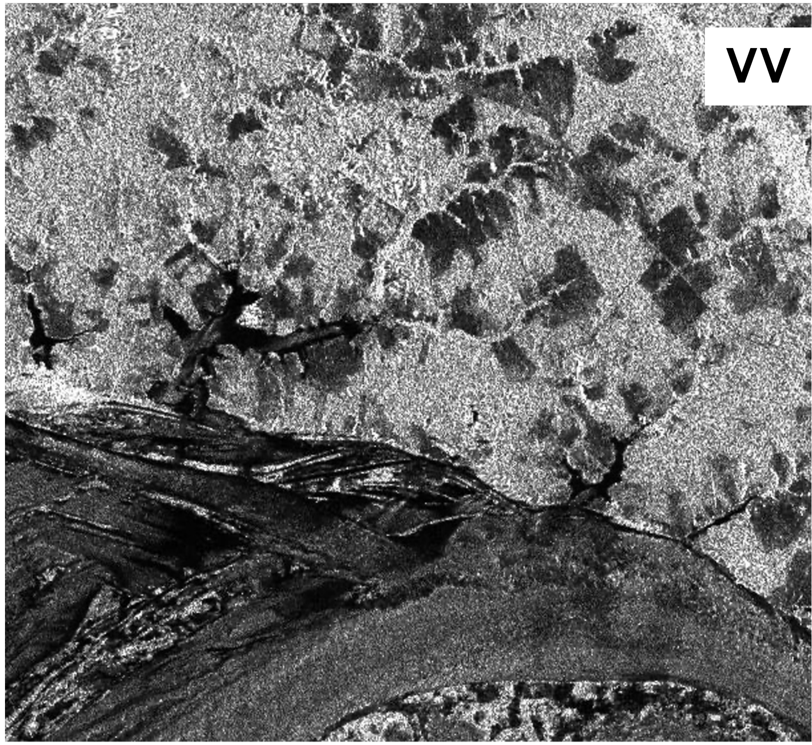


Source of Confusion: Wind

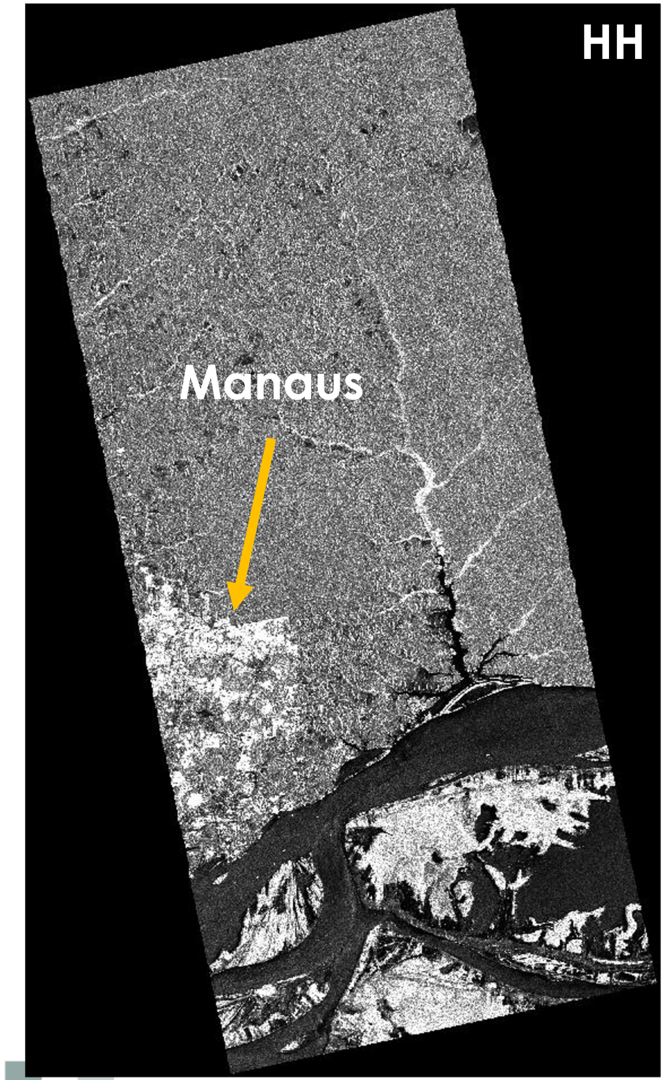
Images from Palsar (L-band) Near Manaus, Brazil

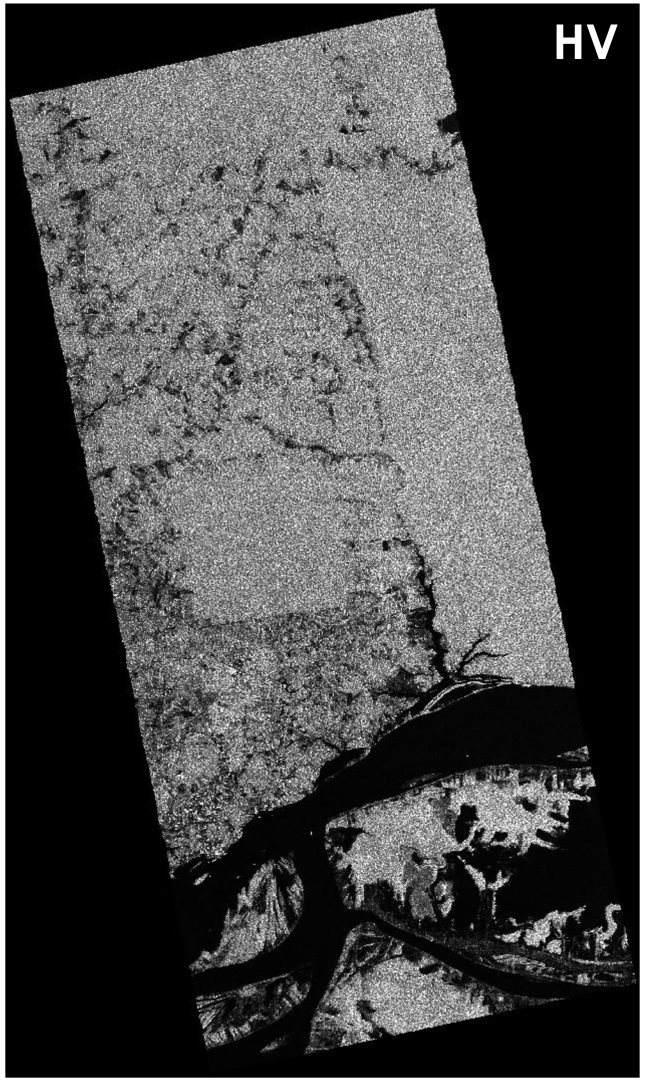


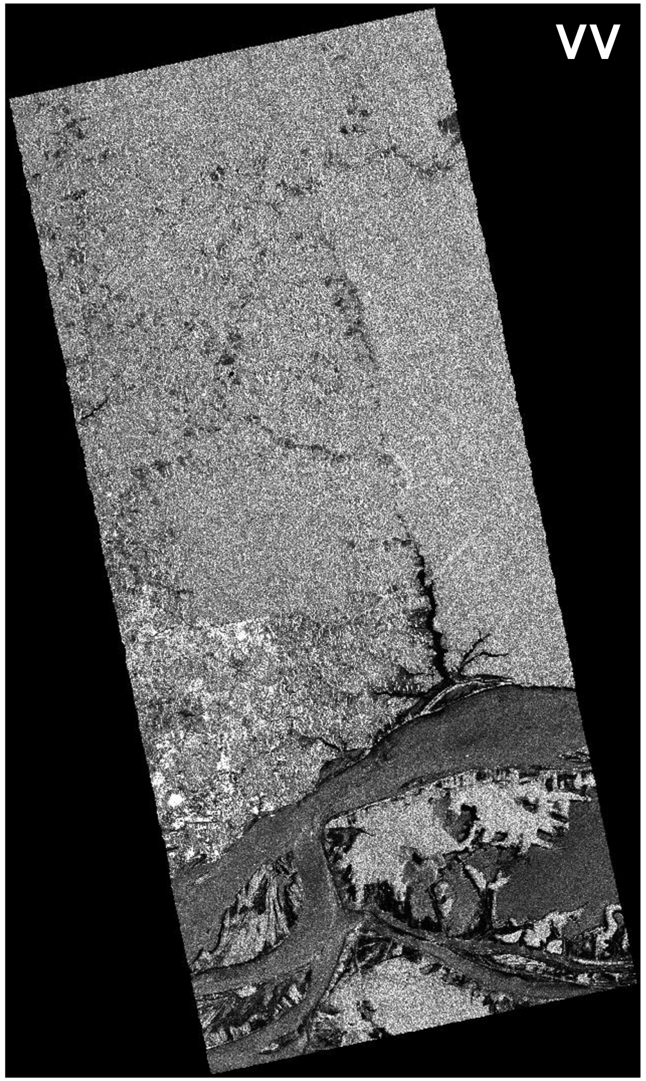




Source of Confusion: Urban Areas

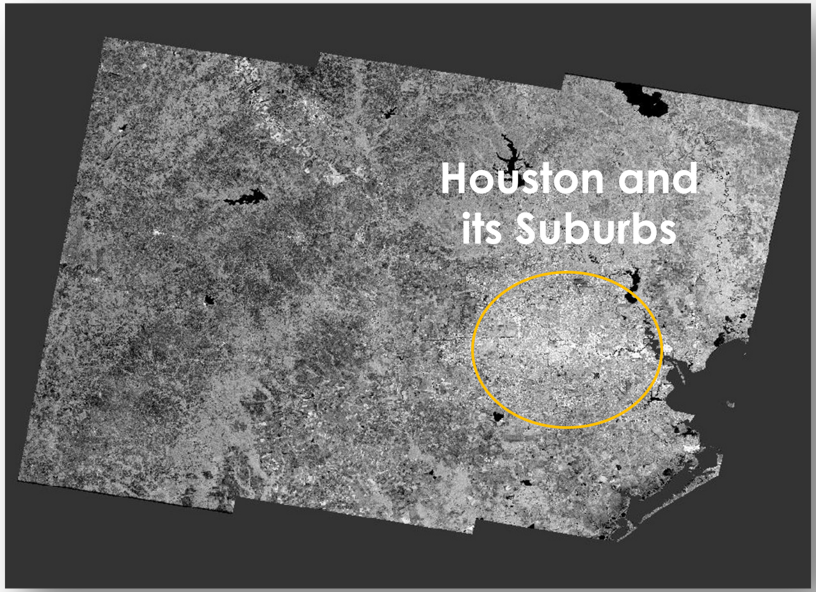




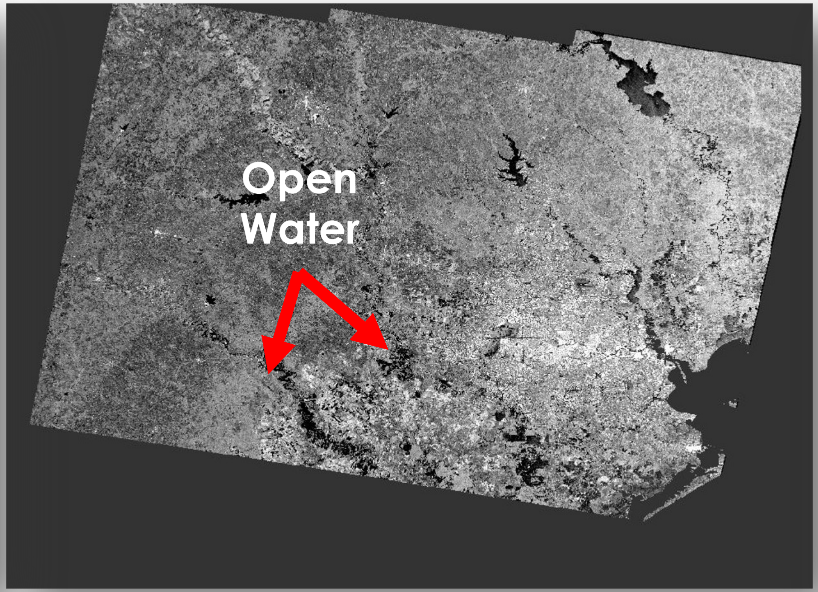


Hurricane Harvey in Houston Texas – August 2017

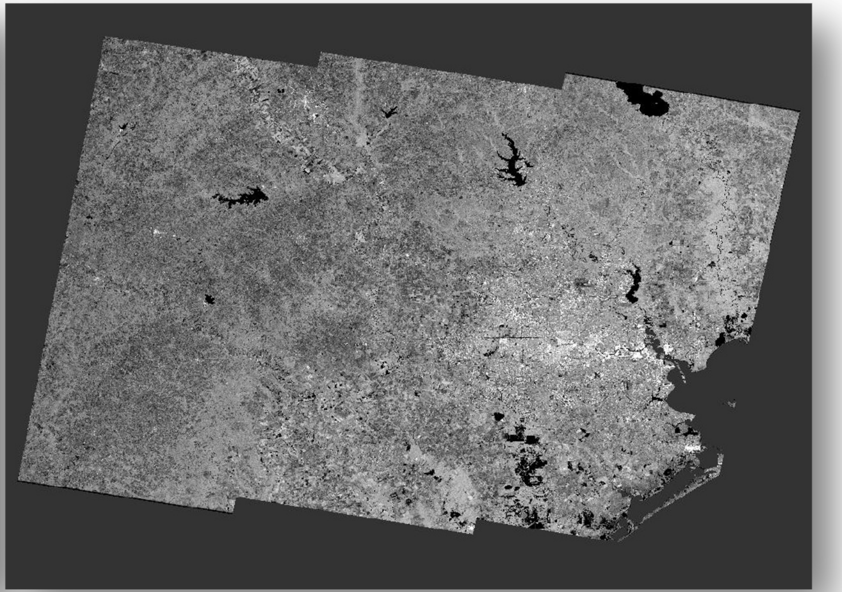
Aug 18, 2017
(Before the Event)



Aug 30, 2017
(During the Event)



Sep 5, 2017
(After the Event)



Demonstration:
Create a Flood Map using GEE