National Aeronautics and Space Administration

Overview and Applications of Synthetic Aperture Radar

Erika Podest and Amita Mehta

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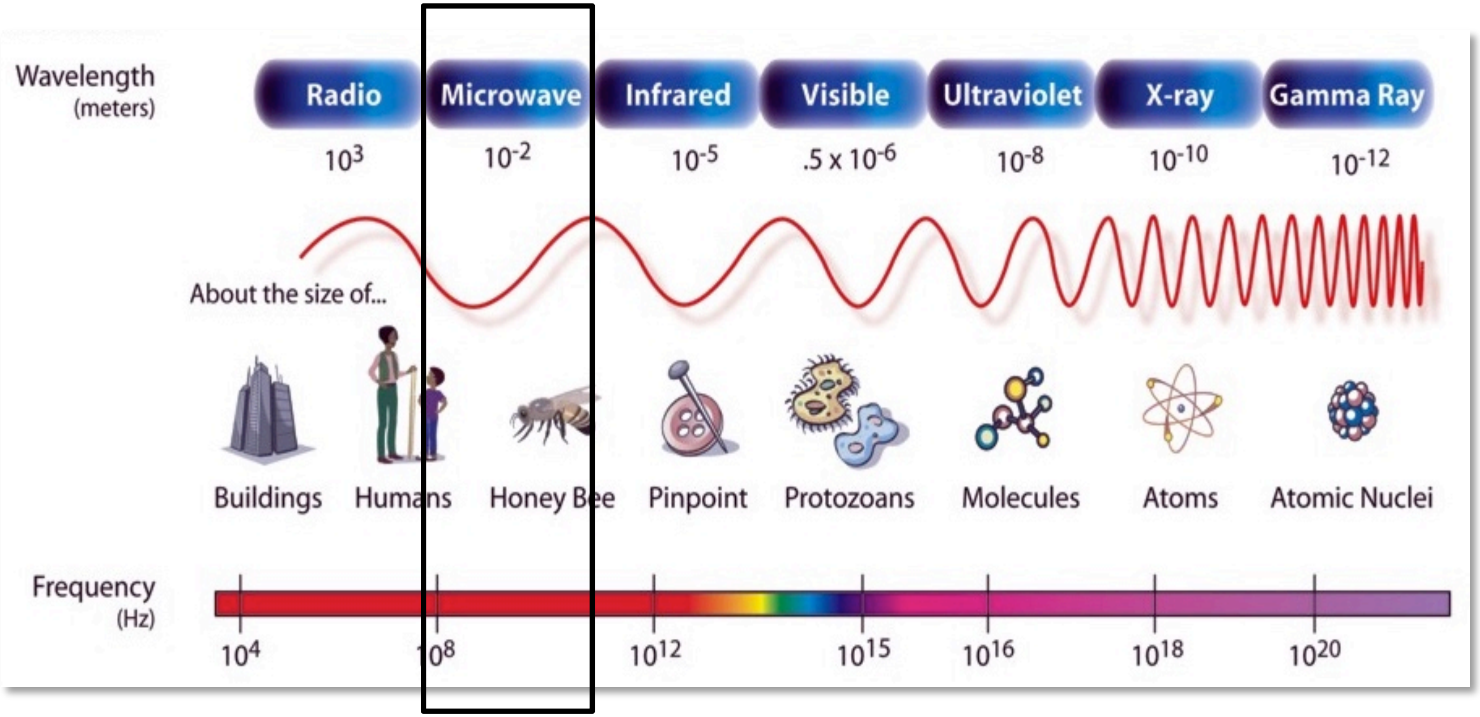
Learning Objectives

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

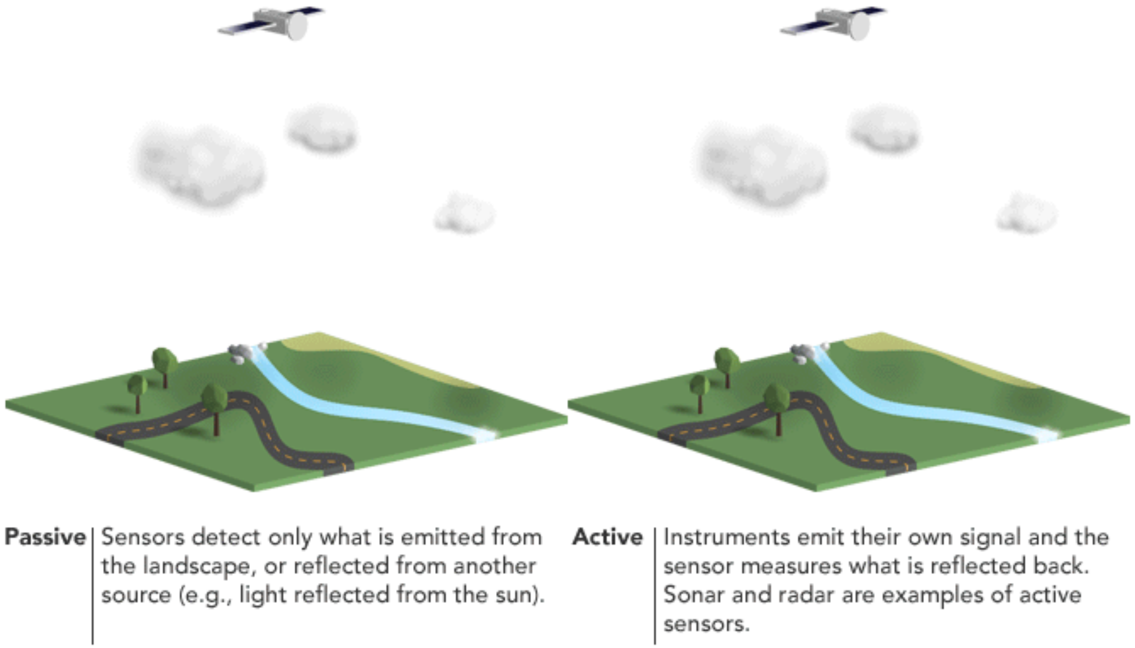
- Understand the basic physics of SAR image formation
- Describe the interaction of SAR with the land surface
- Describe the necessary data processing steps
- Understand the information content in SAR images

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:

- 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

Advantages and Disadvantages of Radar Over Optical Remote Sensing

Advantages

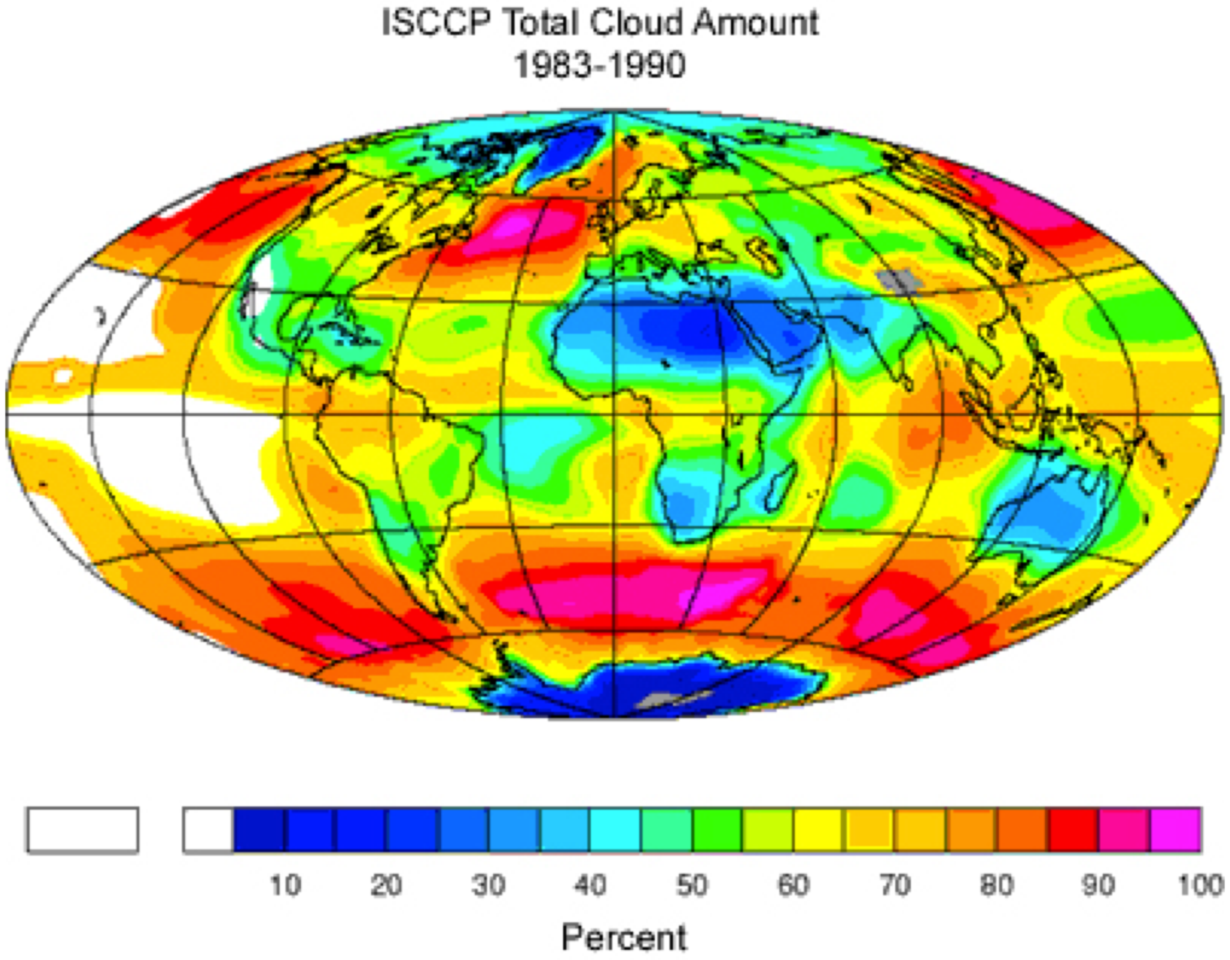
- Nearly all weather capability
- Day or night capability
- Penetration through the vegetation canopy
- Penetration through the soil
- Minimal atmospheric effects
- Sensitivity to dielectric properties (liquid vs. frozen water)
- Sensitivity to structure

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 annual cloud cover 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

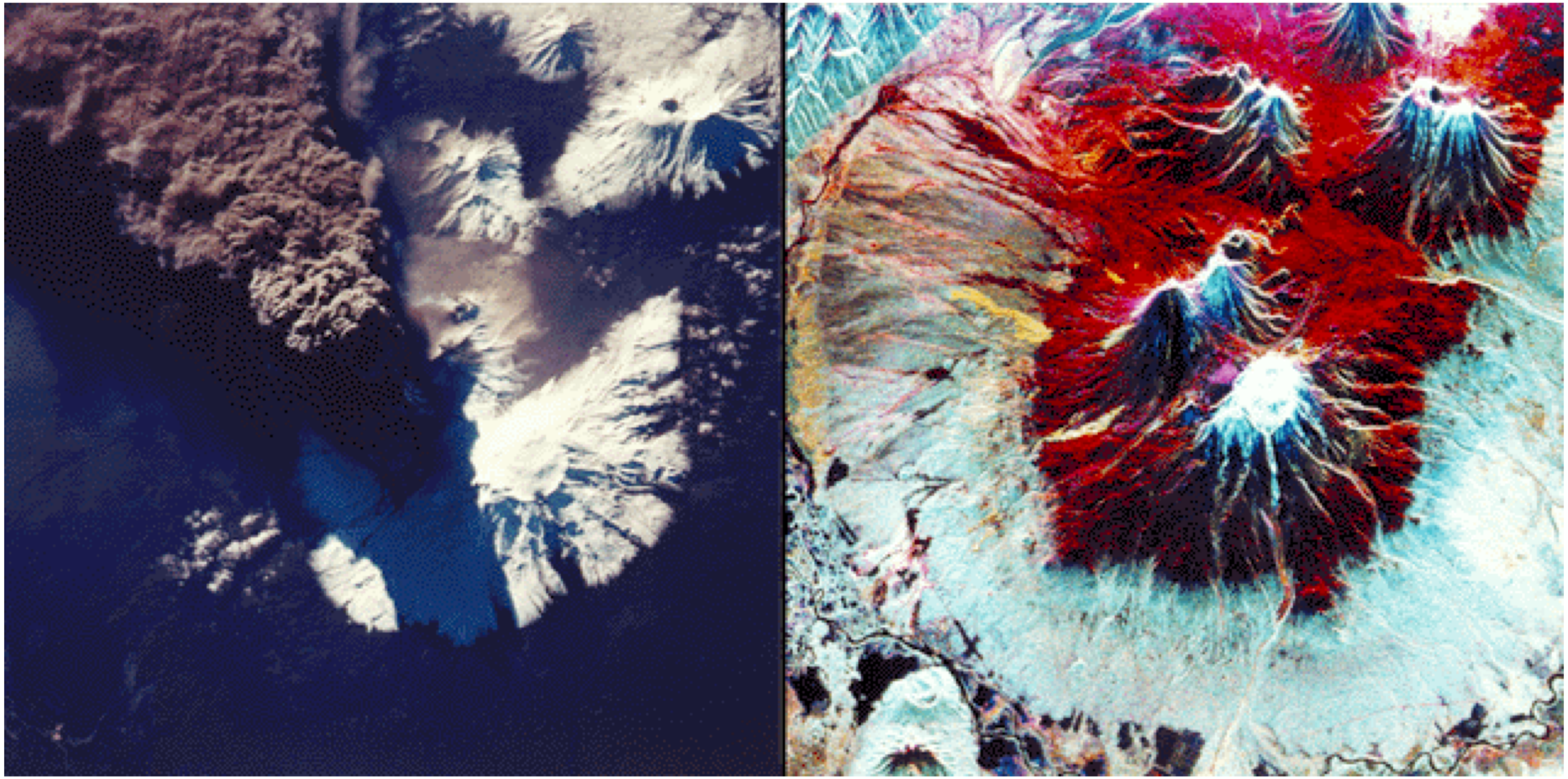
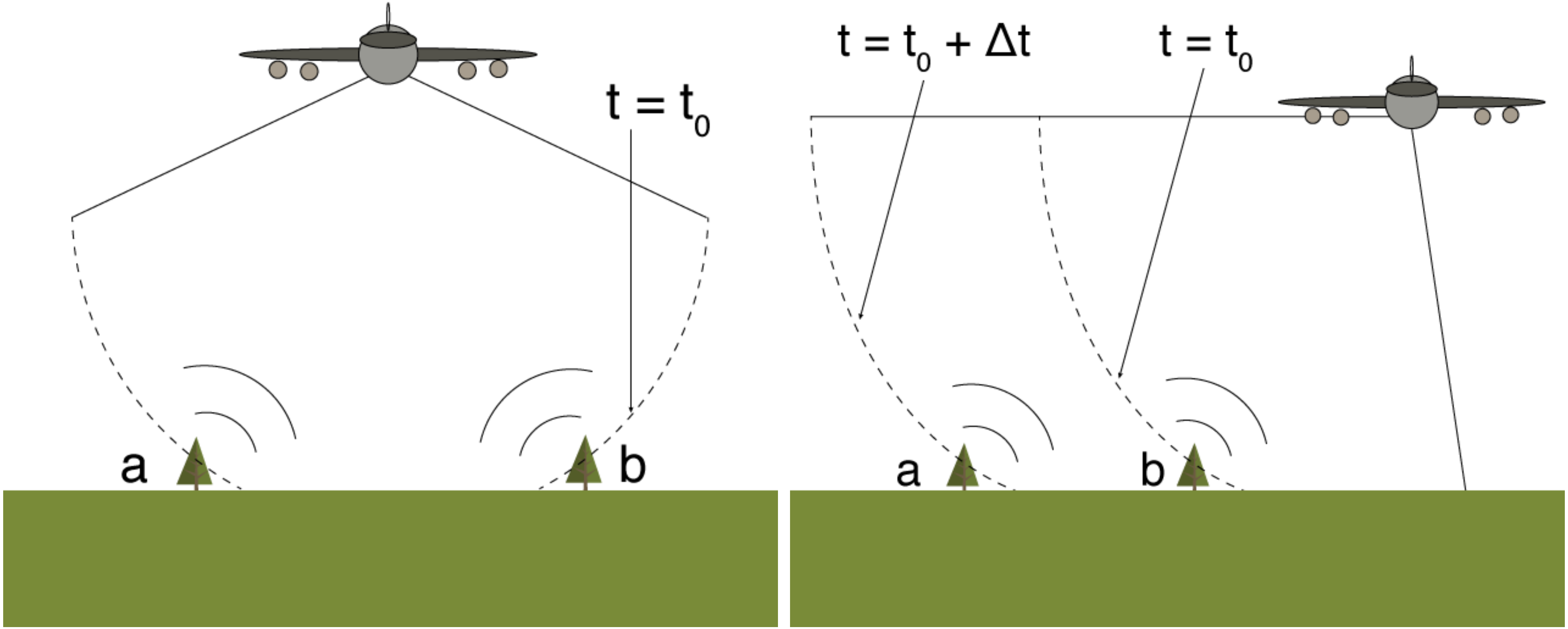


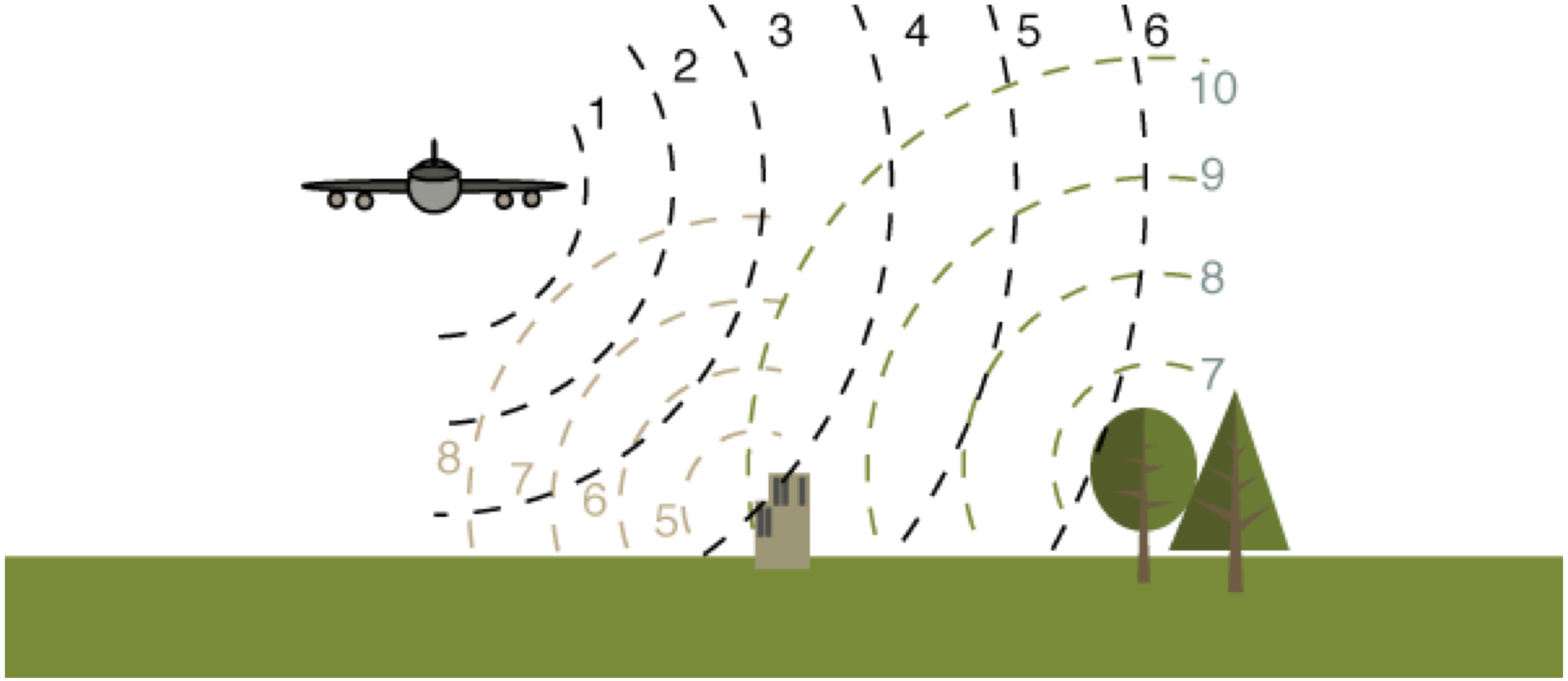
Image Credit: Michigan Tech Volcanology

Basic Concepts: Down Looking vs. Side Looking Radar



Basic Concepts: Side Looking Radar

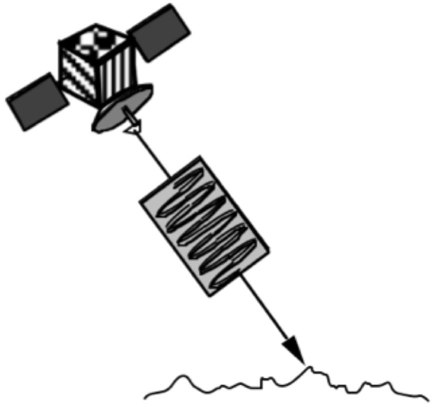
- Each pixel in the radar image represents a complex quantity of the energy that was reflected back to the satellite
- The magnitude of each pixel represents the intensity of the reflected echo



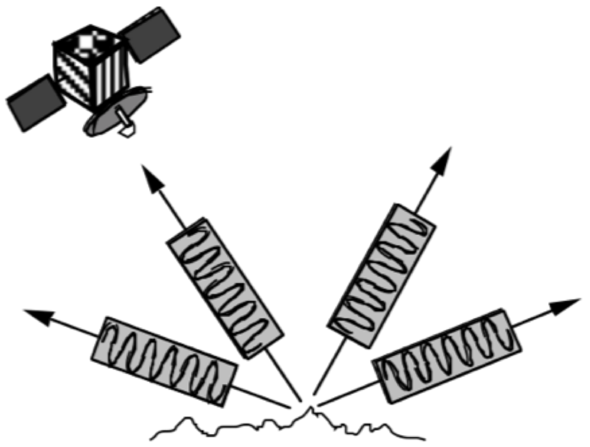
Credit: Paul Messina, CUNY NY, after Drury 1990, Lillesand and Kiefer, 1994

Review of Radar Image Formation

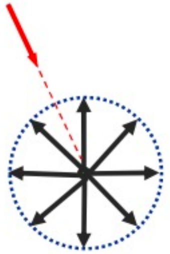
1. Radar can measure amplitude (the strength of the reflected echo) and phase (the position of a point in time on a waveform cycle)
2. Radar can only measure the part of the echo reflected back towards the antenna (backscatter)
3. Radar pulses travel at the speed of light
4. The strength of the reflected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



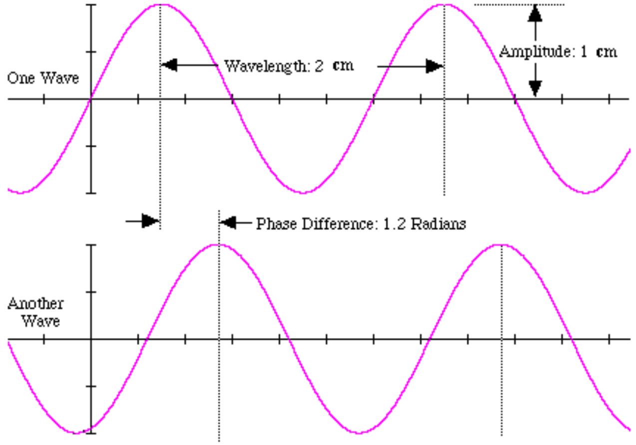
RADAR TRANSMITS A PULSE



MEASURES REFLECTED ECHO (BACKSCATTER)



Isotropic scatterer



Source: ESA- ASAR Handbook

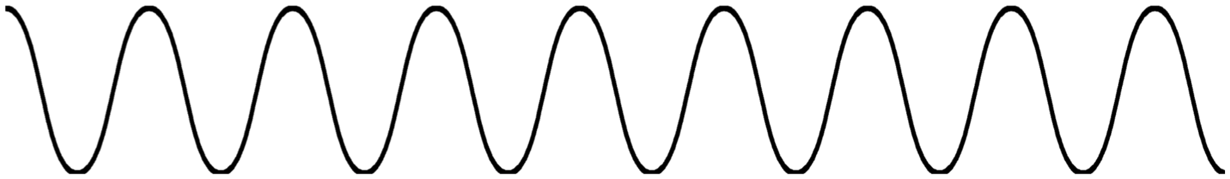
Radar Parameters to Consider for a Study

- Wavelength
- Polarization
- Incidence Angle

Radar Parameters: Wavelength

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

Higher Frequency



Shorter Wavelength

Lower Frequency

Longer Wavelength

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

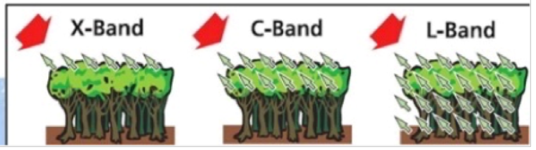


Image Credit: DLR

Penetration as a Function of Wavelength

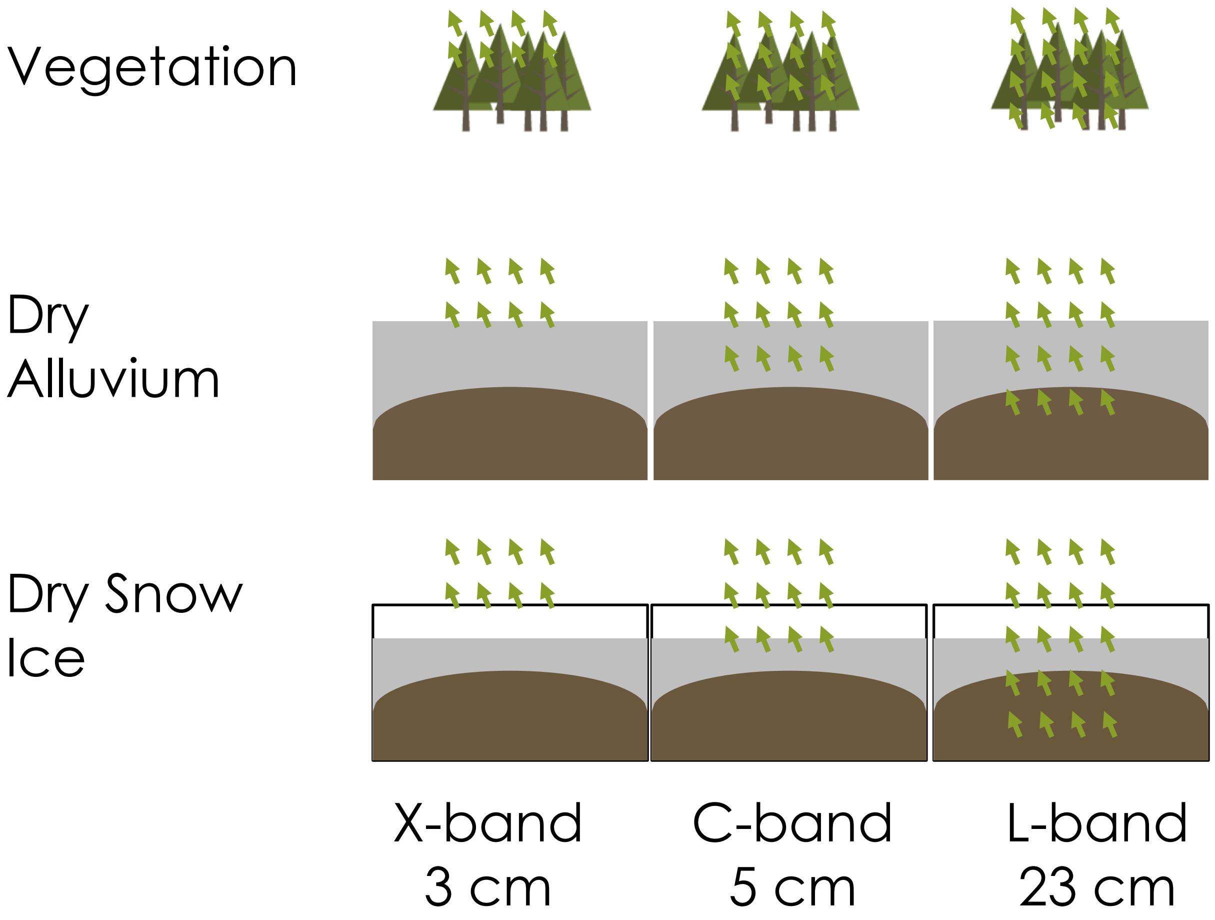


Image based on ESA [Radar Course 2]

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

Example: Radar Signal Penetration into Dry Soils

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

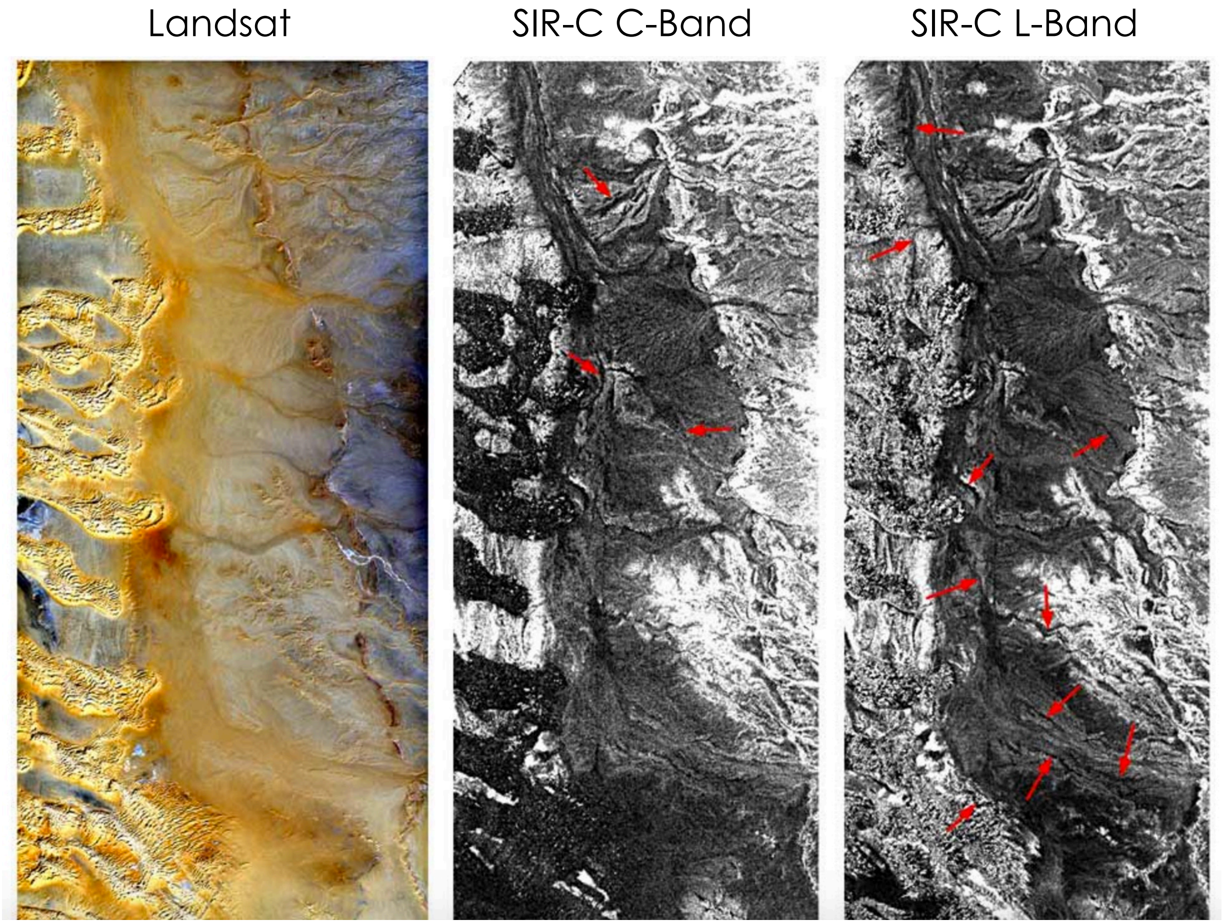
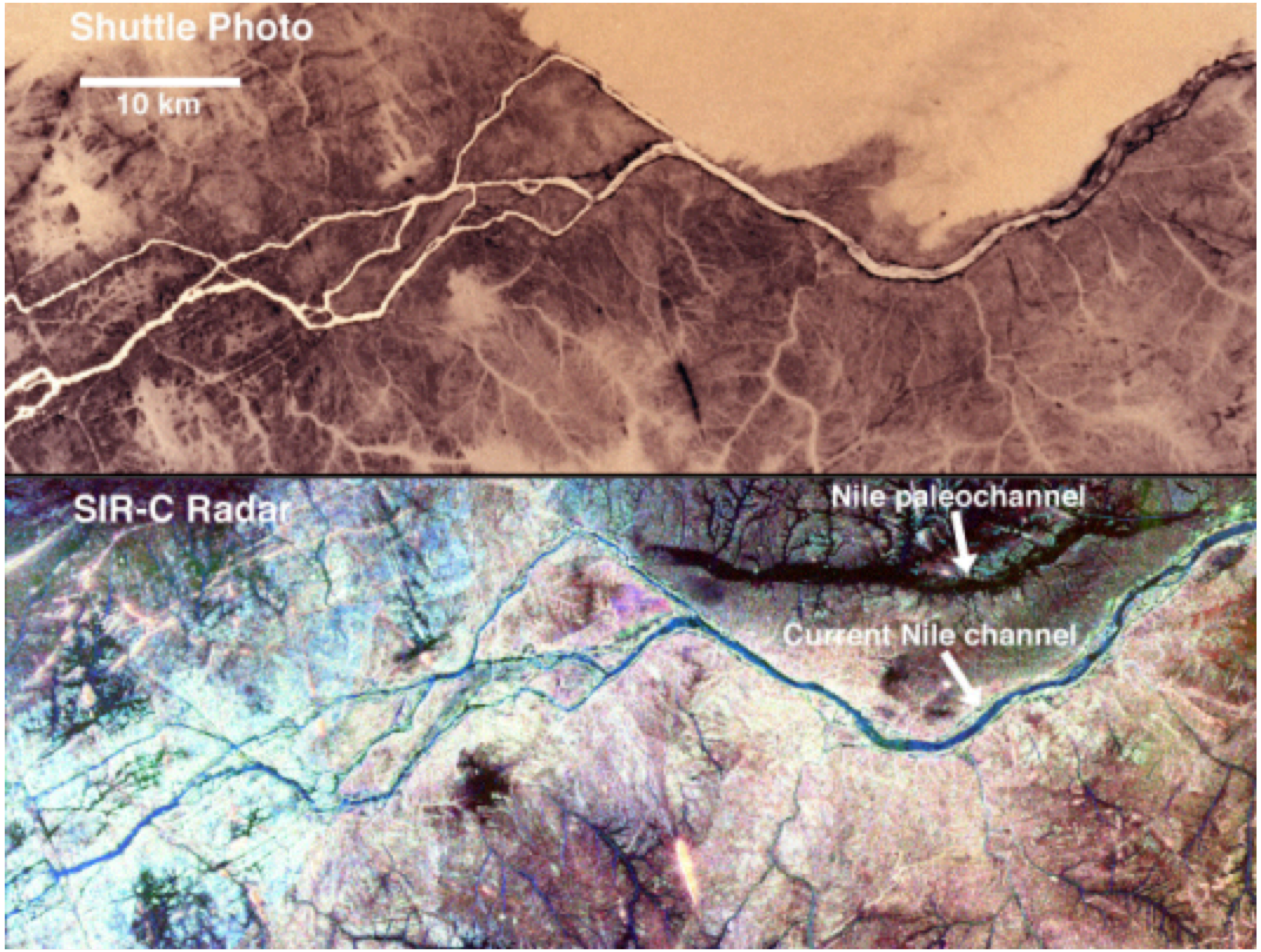


Image Credit: A Perego

Example: Radar Signal Penetration into Dry Soils



Example: Radar Signal Penetration into Vegetation

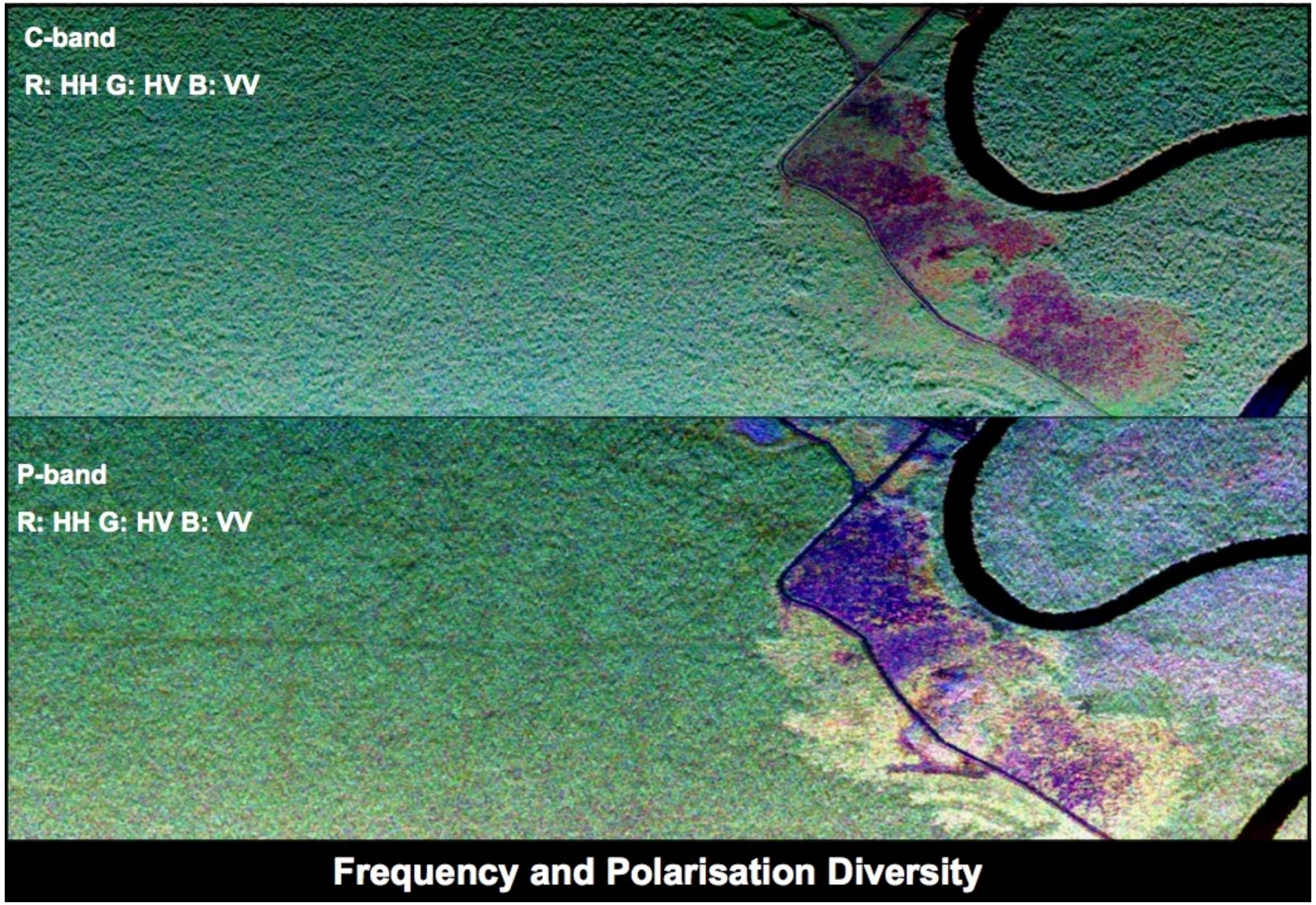
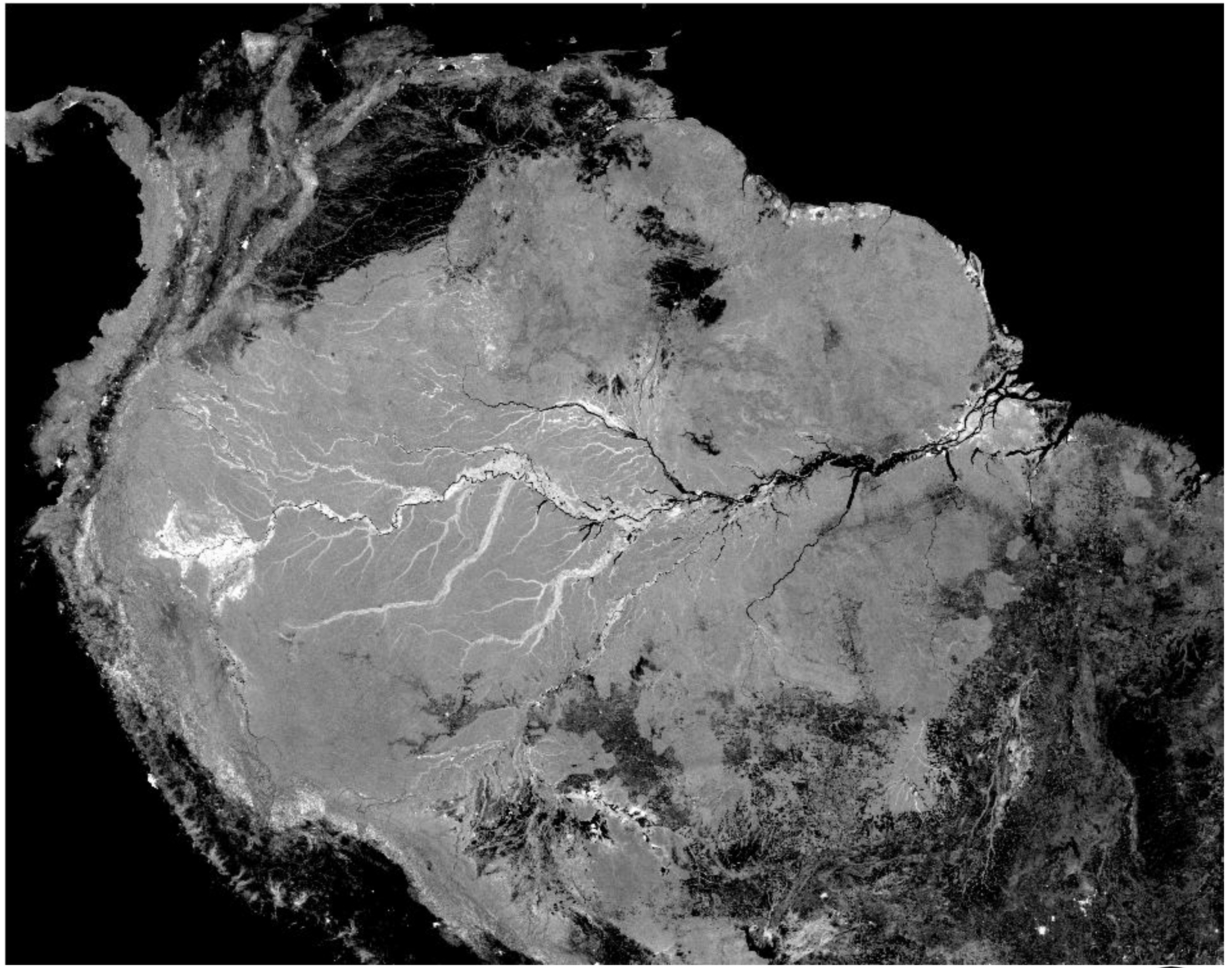


Image Credit: A Moreira - ESA

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

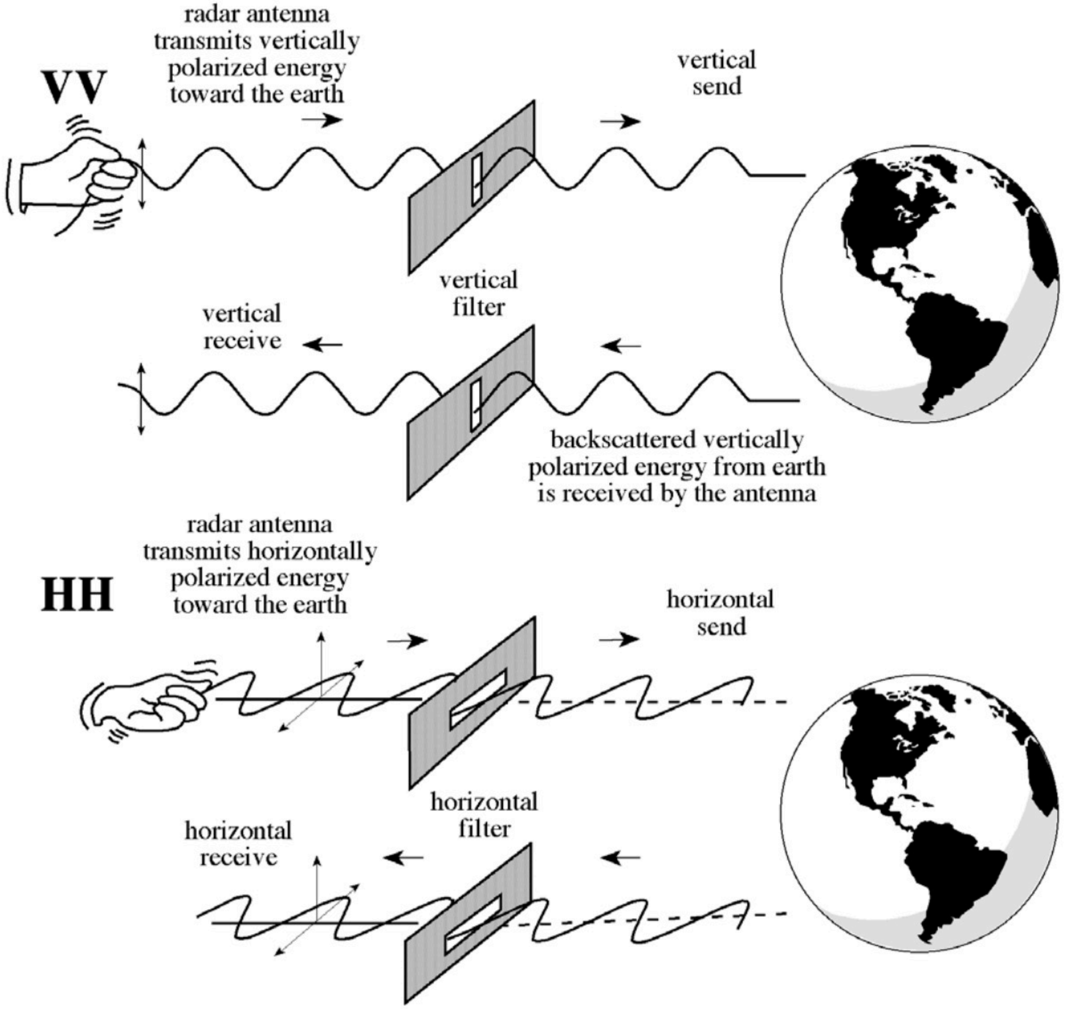
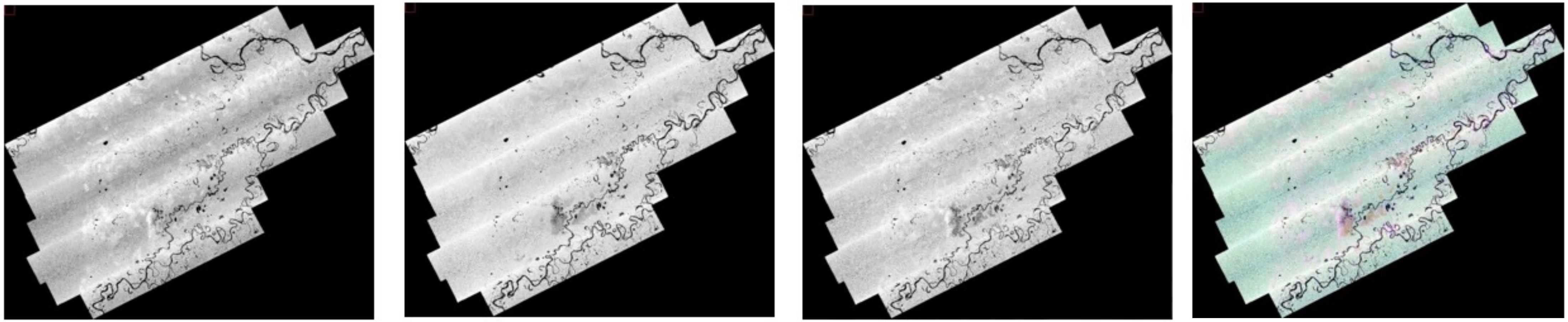


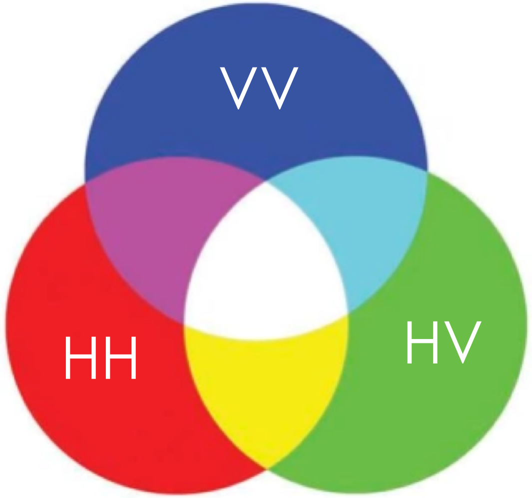
Image Credit: J.R. Jensen, 2000. Remote Sensing of the Environment

Example of Multiple Polarizations for Vegetation Studies

Pacaya-Samiria Forest Reserve in Peru

Images from UAVSAR (HH, HV, VV)





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

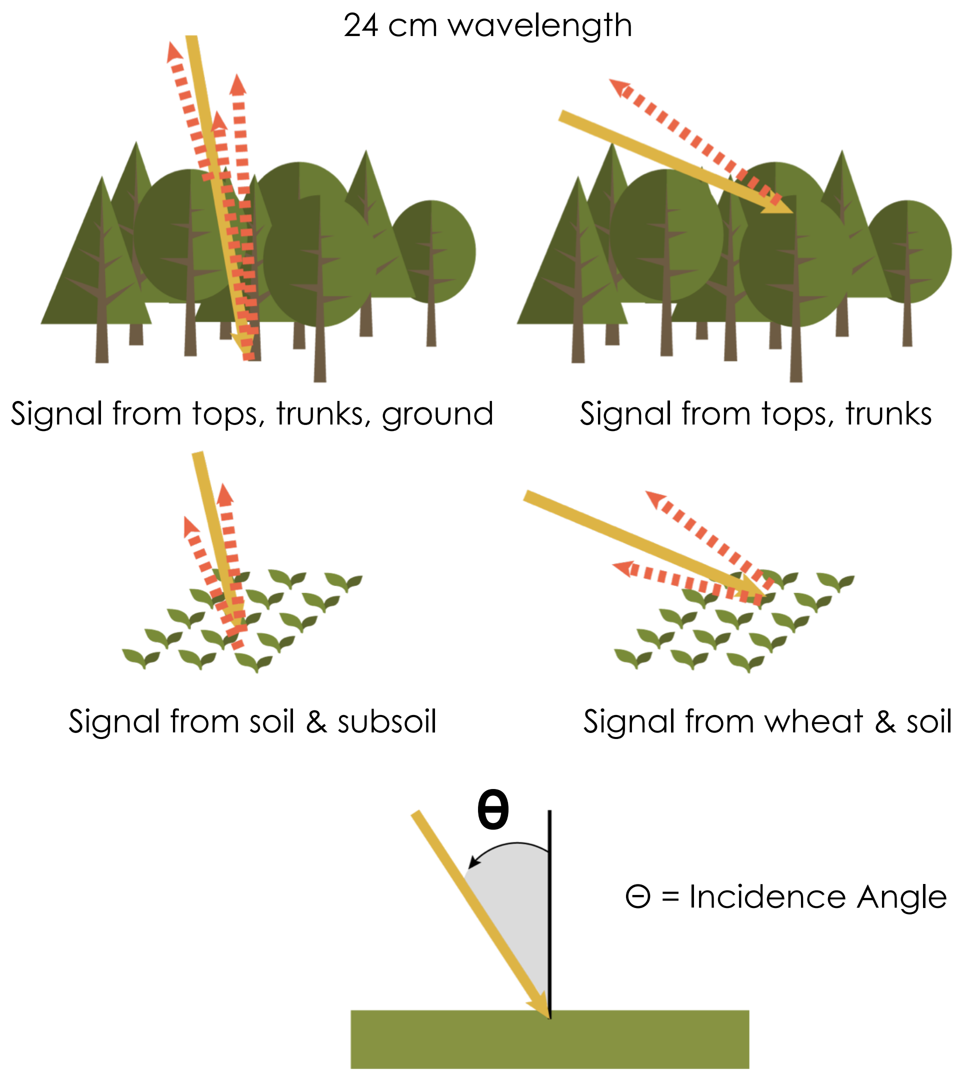
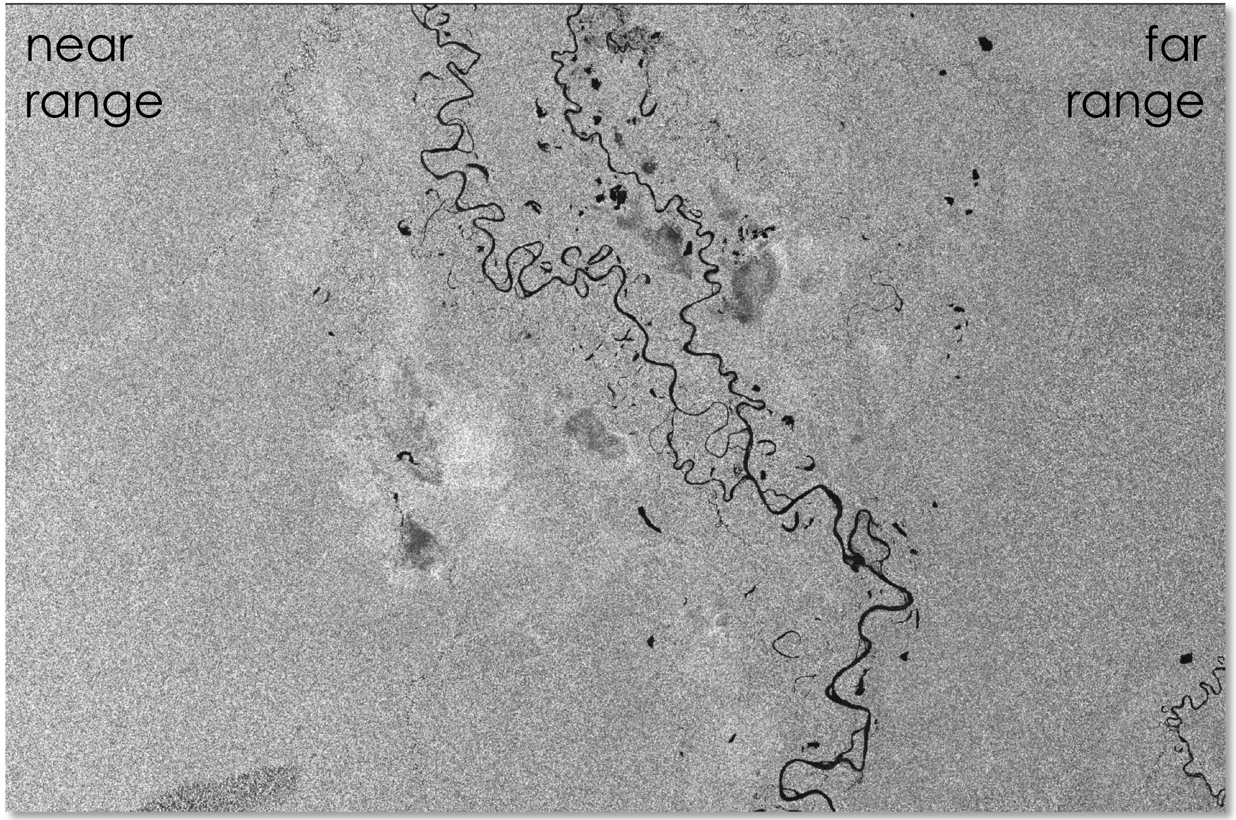
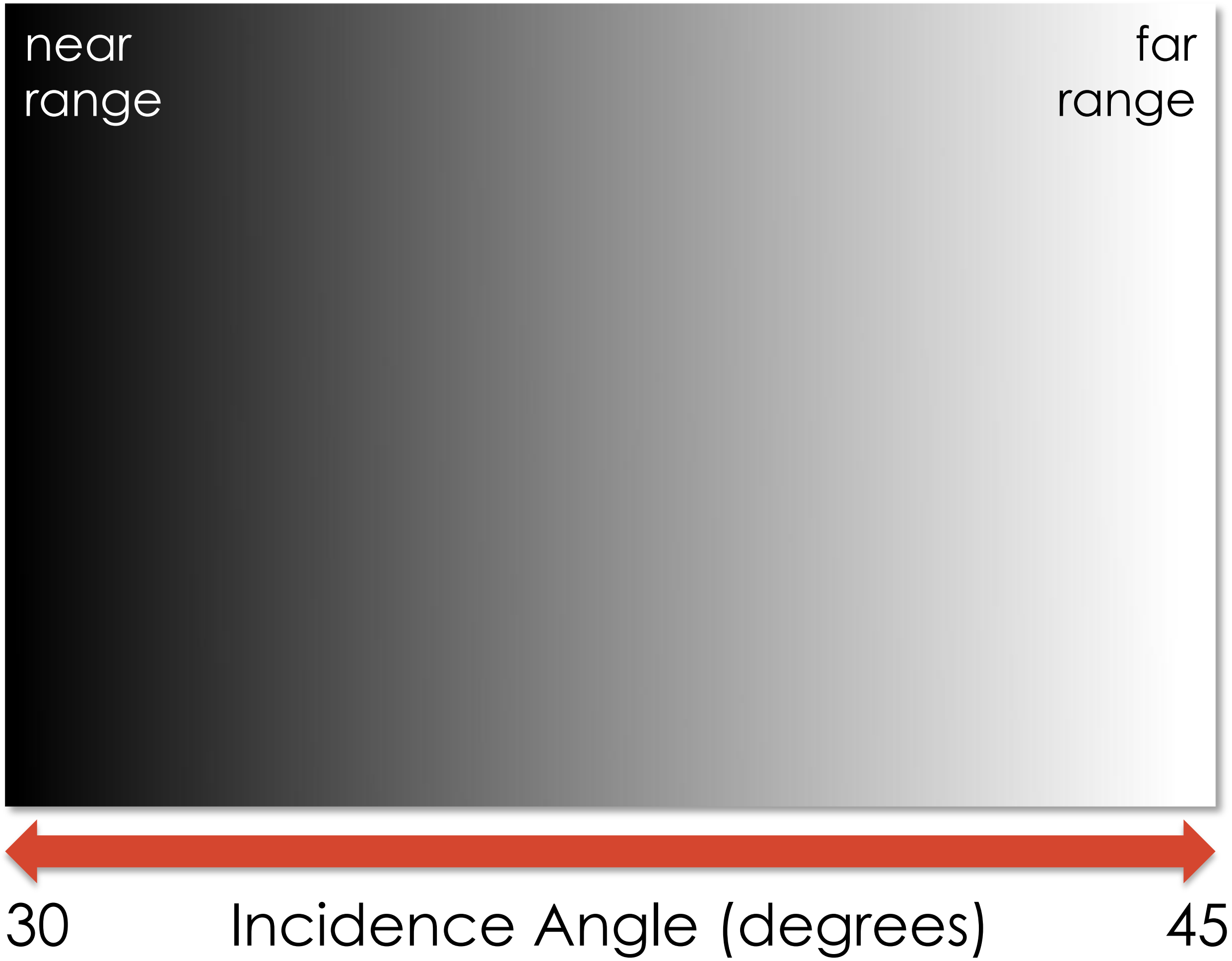


Image Credit: Ulaby et al. (1981);ESA

Effect of Incidence Angle Variation



Sentinel-1



Questions

1. What are the advantages of radar sensors?
2. What are three main radar parameters that need to be considered for a specific study?
3. What is the relationship between wavelength and penetration?
4. What's the usefulness of having different polarizations?
5. What's the effect of varying incidence angle?

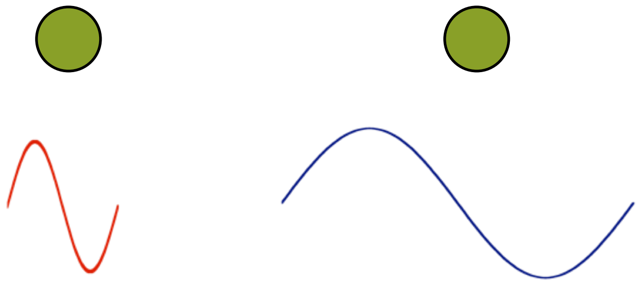
Radar Backscatter

Radar Backscatter

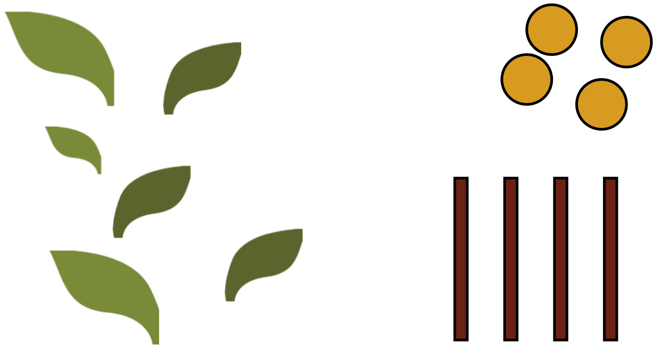
- The radar backscatter contains information about the Earth's surface, which drives the reflection of the radar signal
- This reflection is driven by:
  - The frequency or wavelength: radar parameter
  - Polarization: radar parameter
  - Incidence angle: radar parameter
  - Dielectric constant: surface parameter
  - Surface roughness relative to the wavelength: surface parameter

Surface Parameters Related to Structure

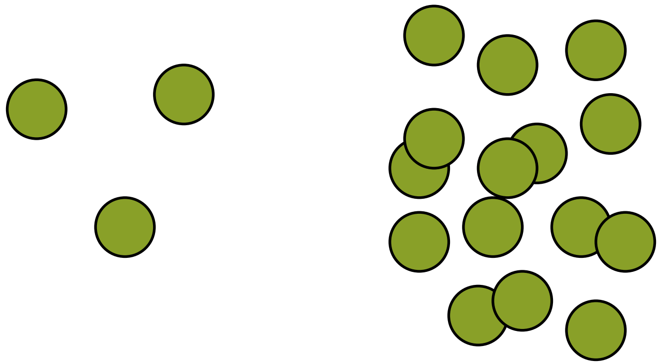
Size Relative to Wavelength



Orientation



Density



Size in Relation to Wavelength

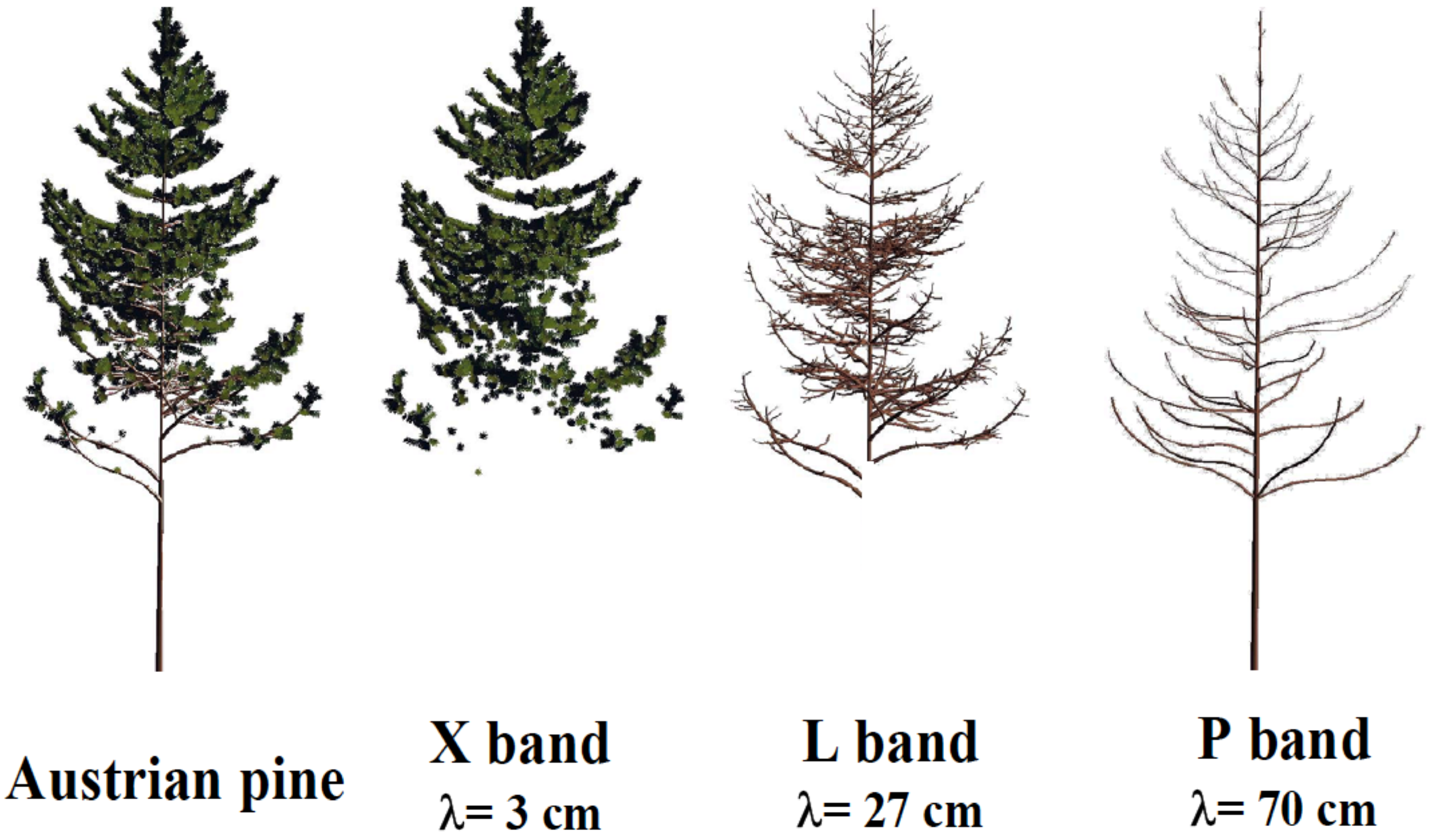
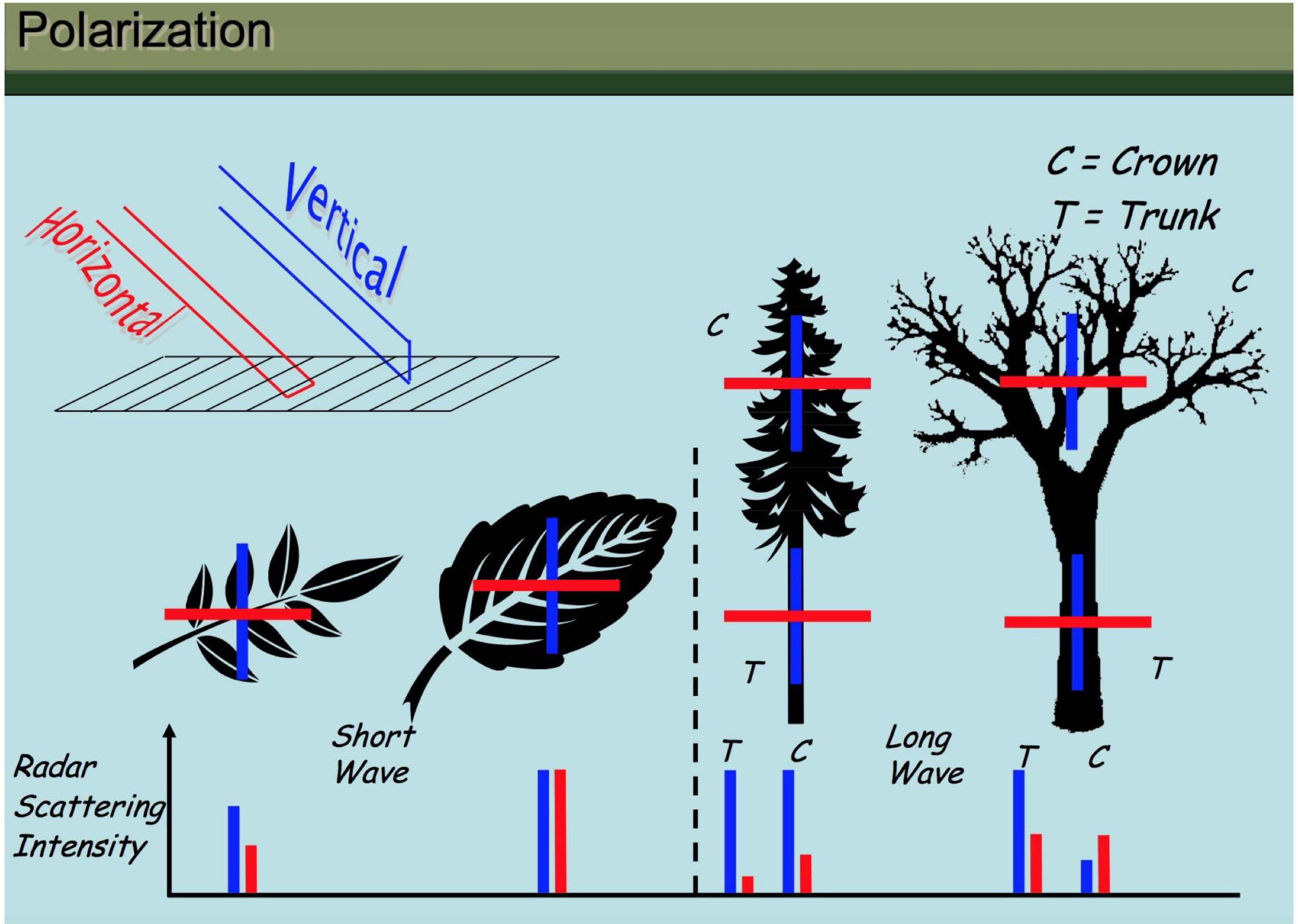


Image Credit: Thuy le Toan

Orientation



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

Density

- Saturation Problem
- Data/Instrument
  - NASA/JPL polarimetric AIRSAR operating at C-, L-, and P-band
  - Incidence angle 40°-50 °

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

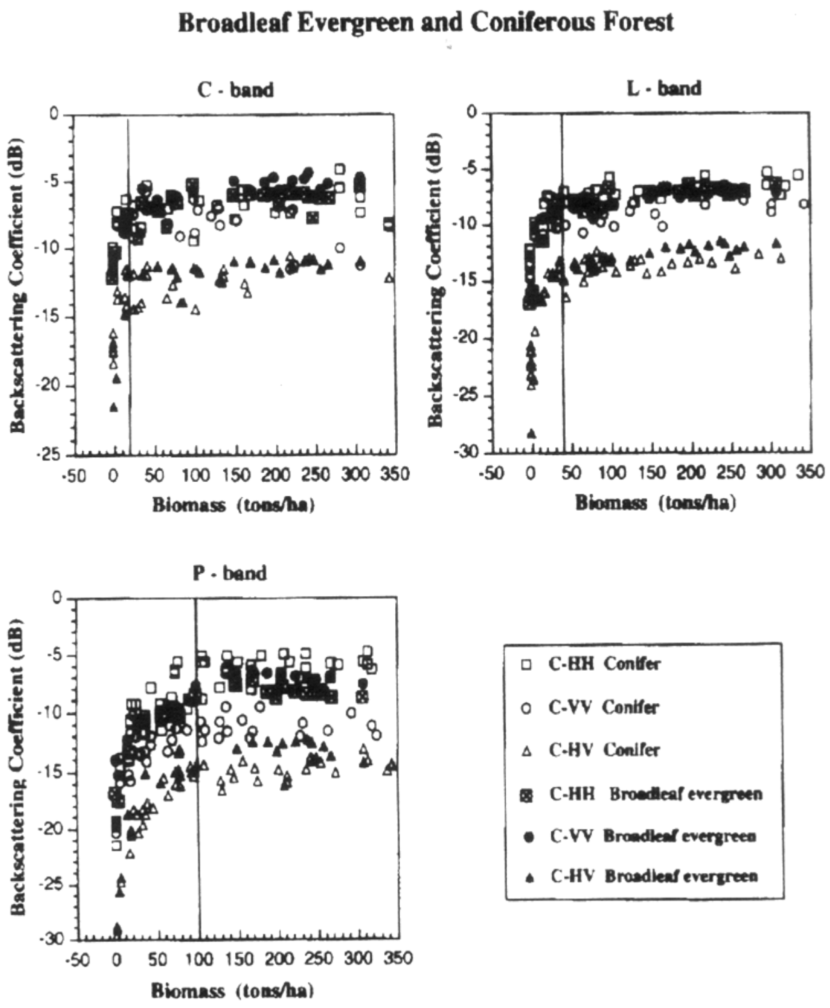
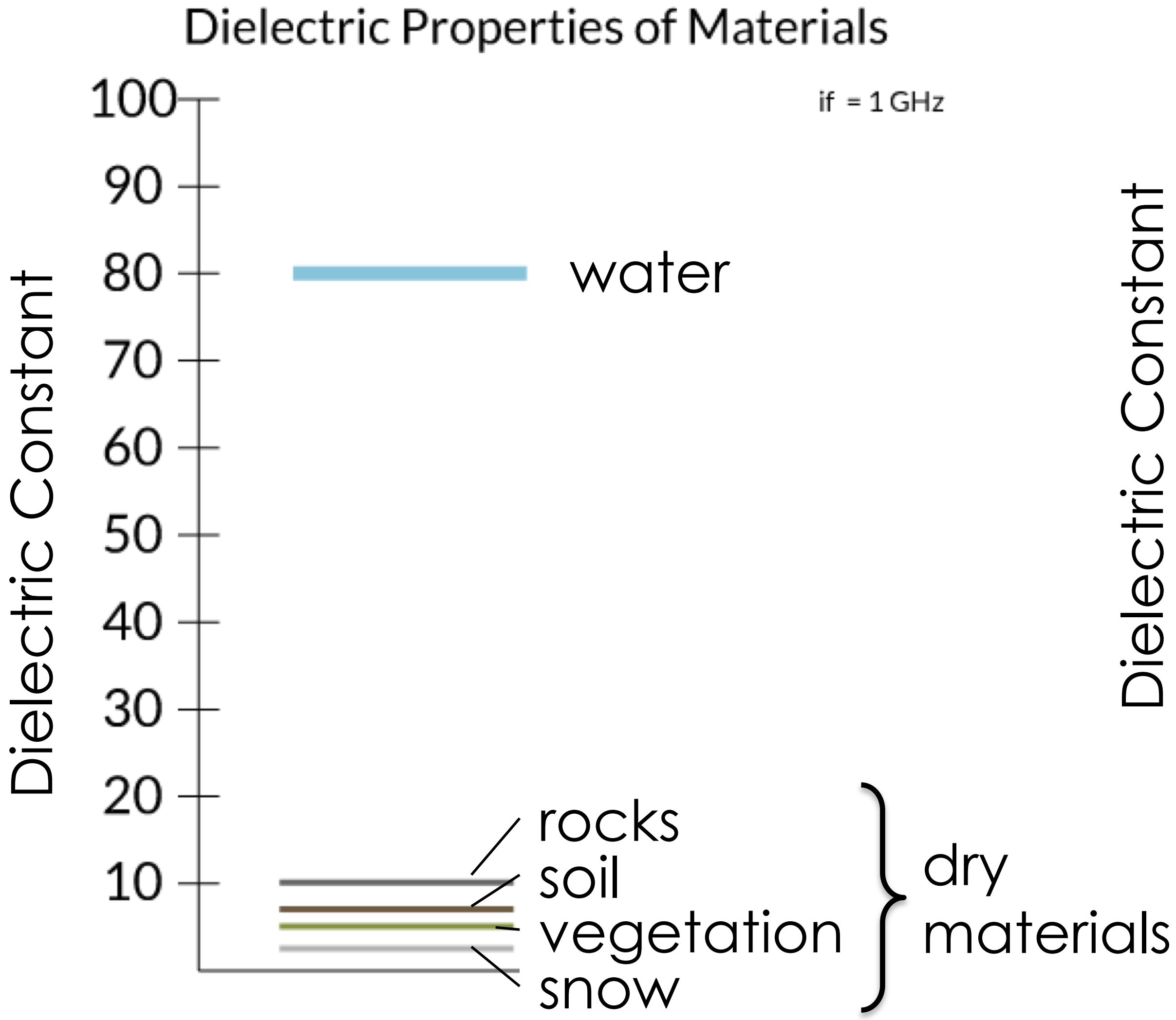
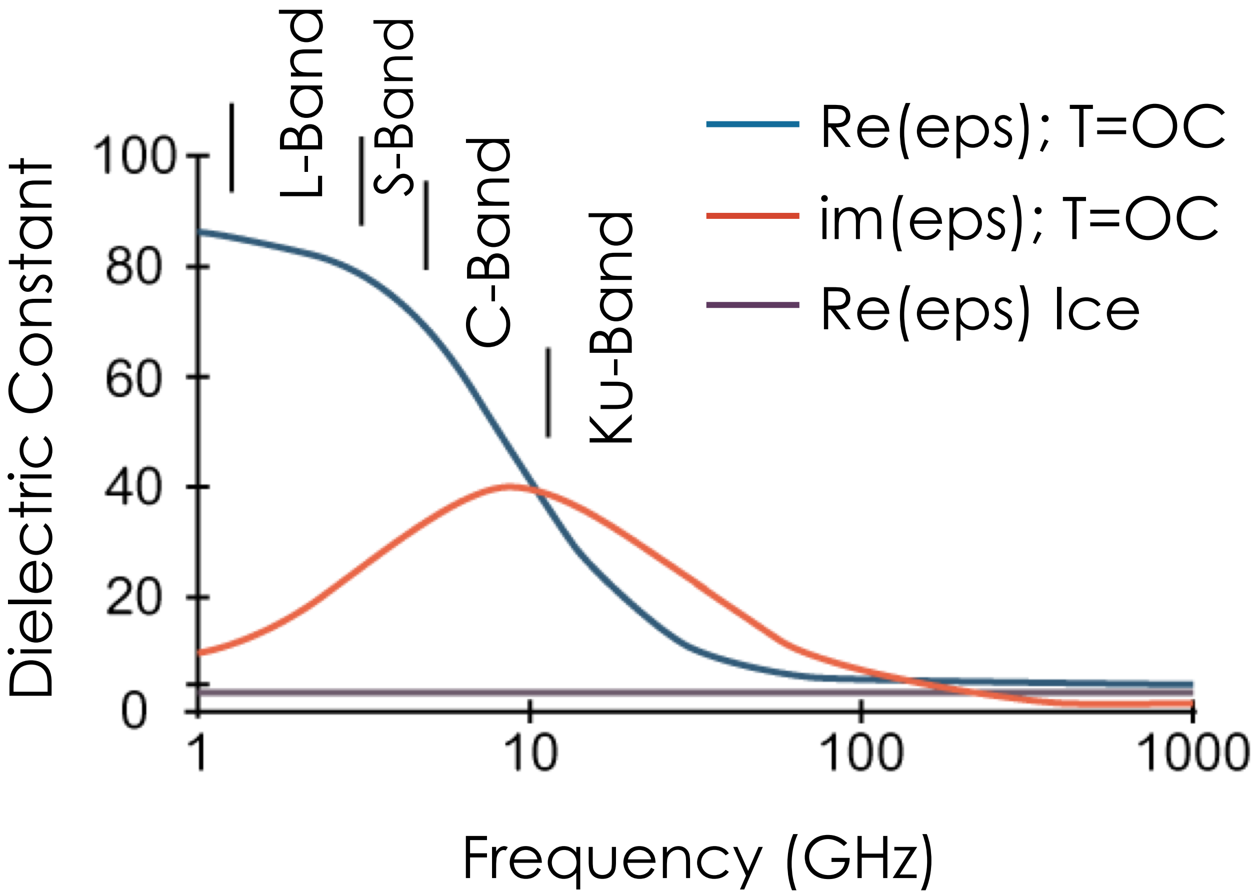


Image Source: Imhoff, 1995:514)

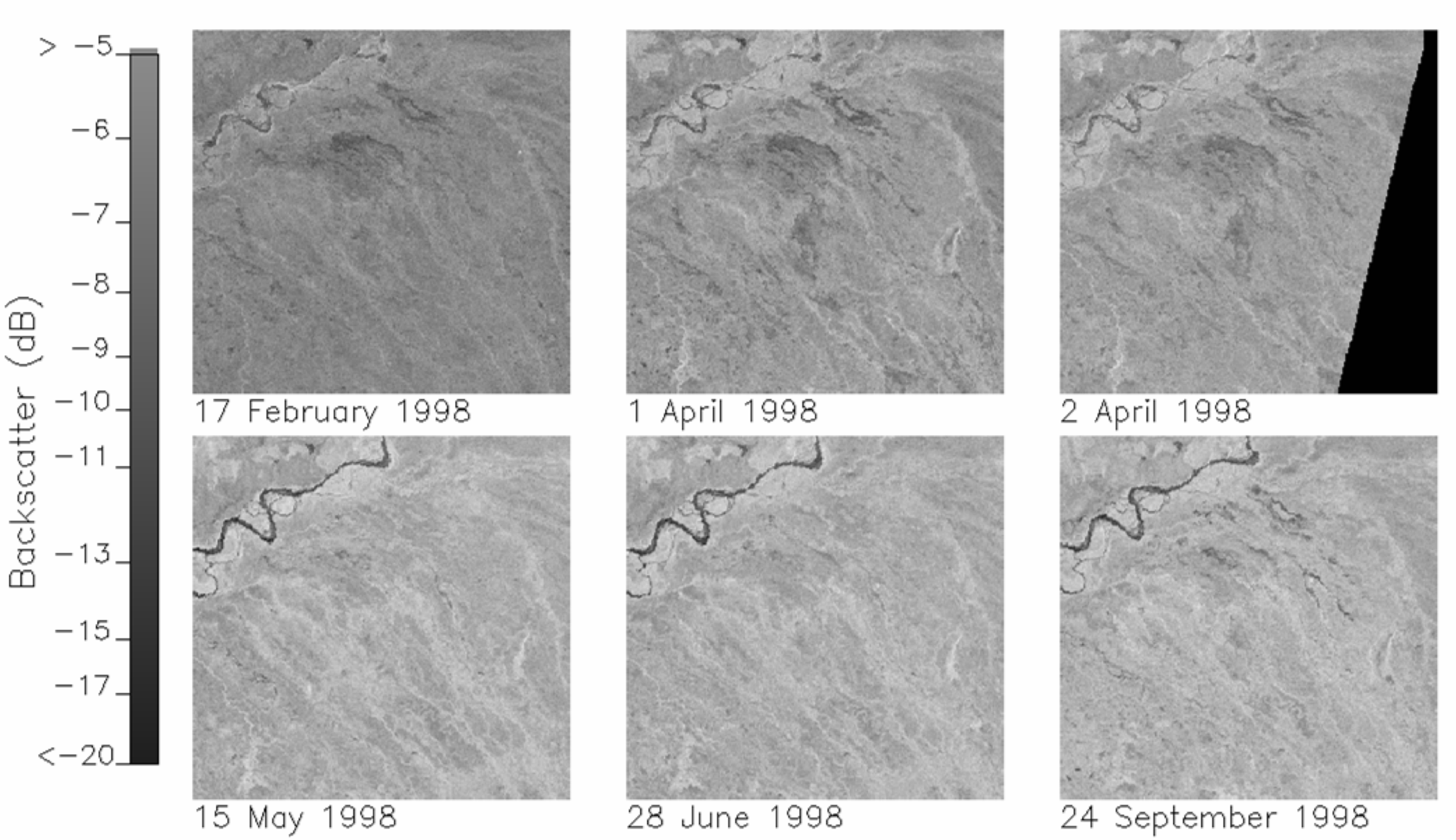
Surface Parameters: Dielectric Constant





Dielectric Properties of the Surface and its Frozen or Thawed State

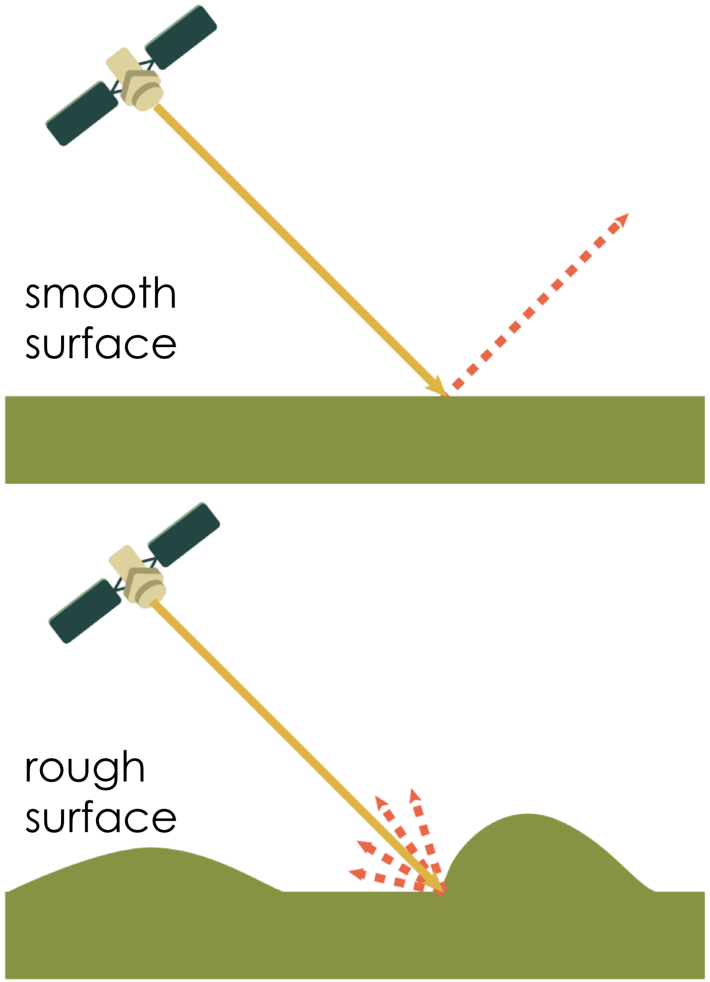
- During the land surface freeze/thaw transition there is a change in the dielectric properties of the surface
- This causes a notable increase in backscatter



Radar Backscatter Sources: Part 1

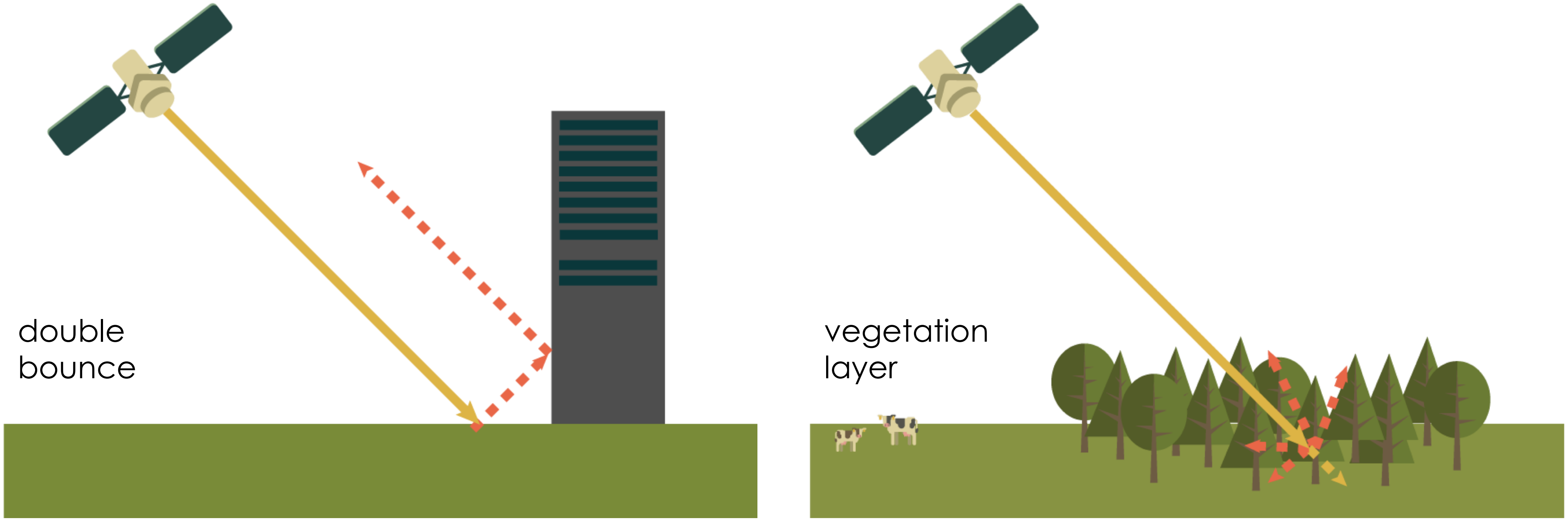
- The radar signal is primarily sensitive to surface structure.
- The scale of the objects on the surface relative to the wavelength determine how rough or smooth they appear to the radar signal and how bright or dark they will appear on the image.

Backscattering Mechanisms

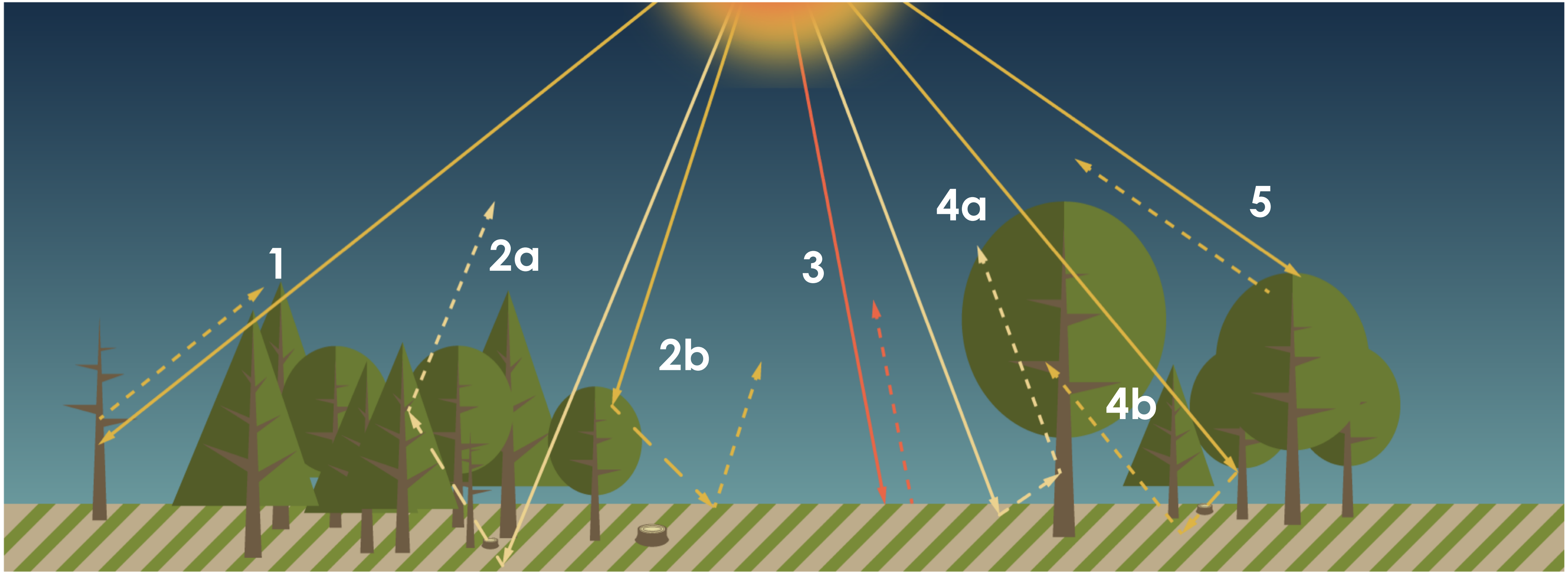


Radar Backscatter Sources: Part 2

Backscattering Mechanisms



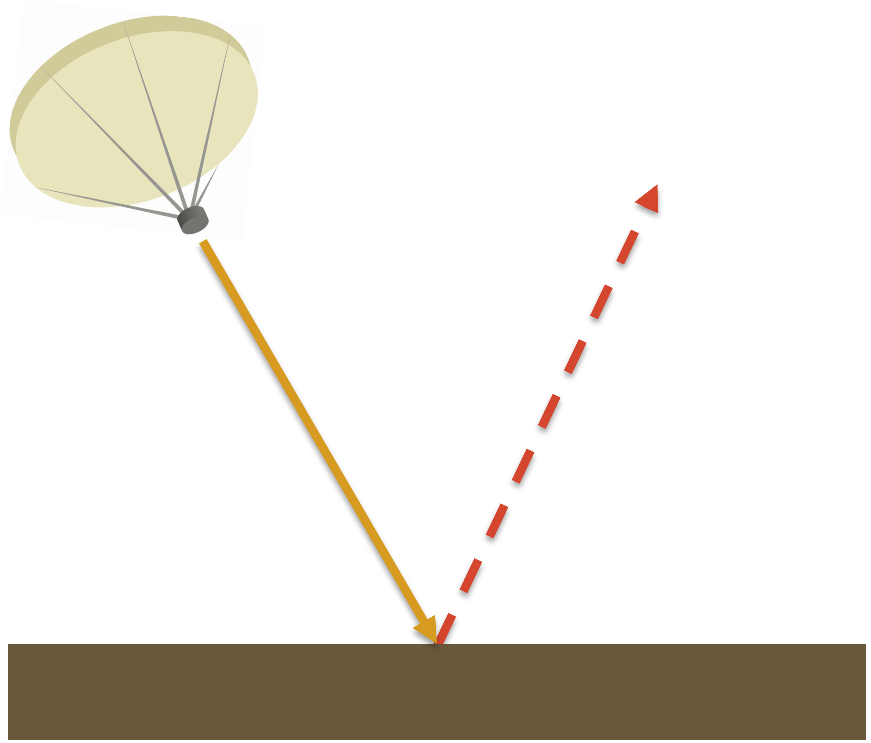
Radar Backscattering in Forests



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

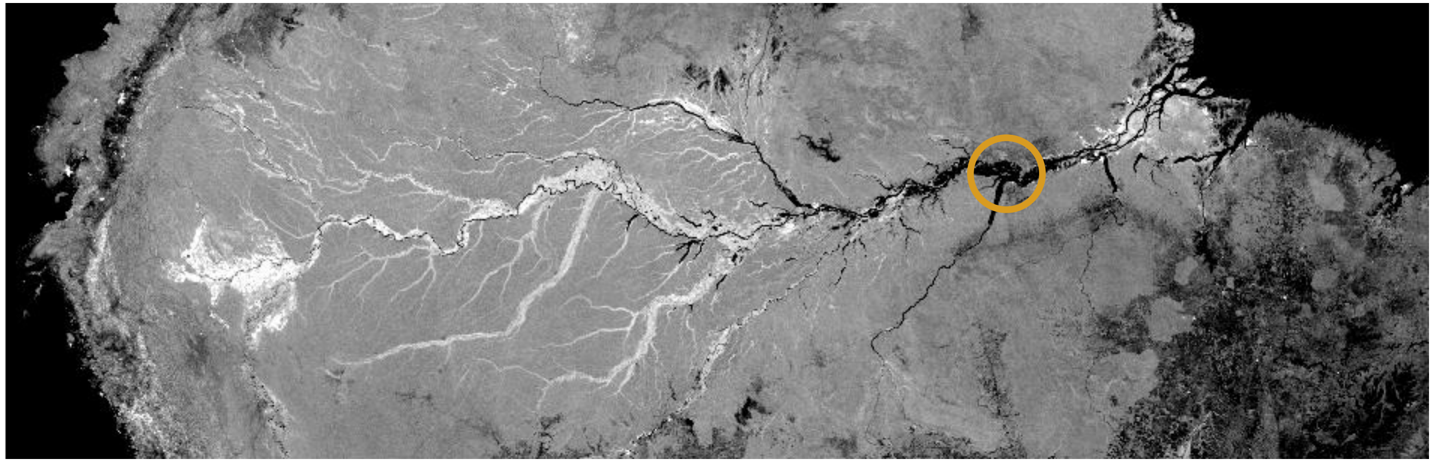
Examples of Radar Interaction

Smooth Surface Reflection (Specular Reflection)



Smooth, Level Surface
(Open Water, Road)

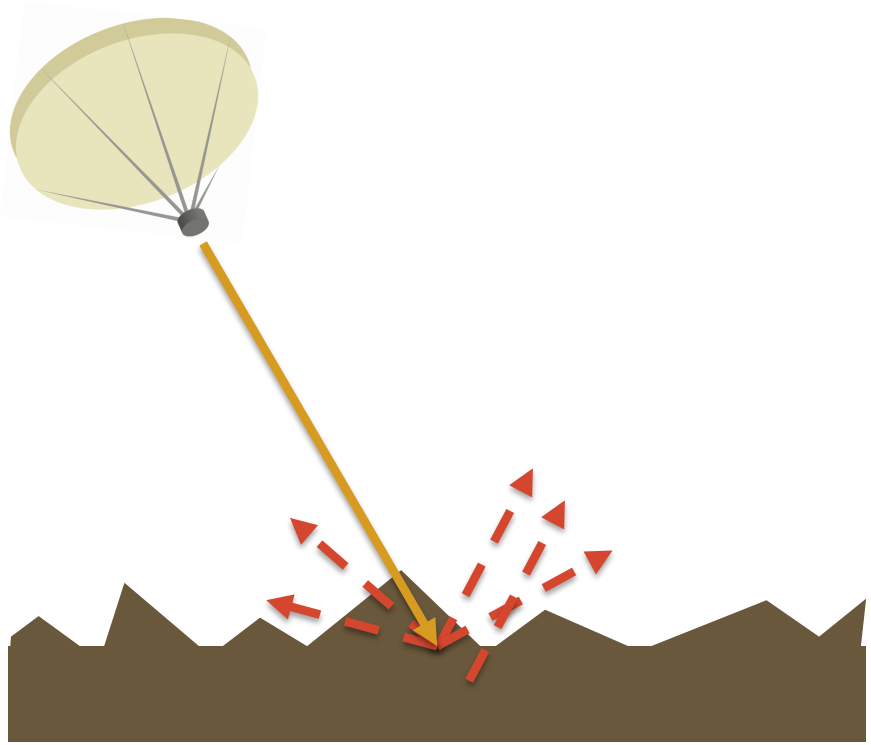
SMAP Radar Mosaic of the Amazon Basin
April 2015 (L-band, HH, 3 km)



Pixel Color

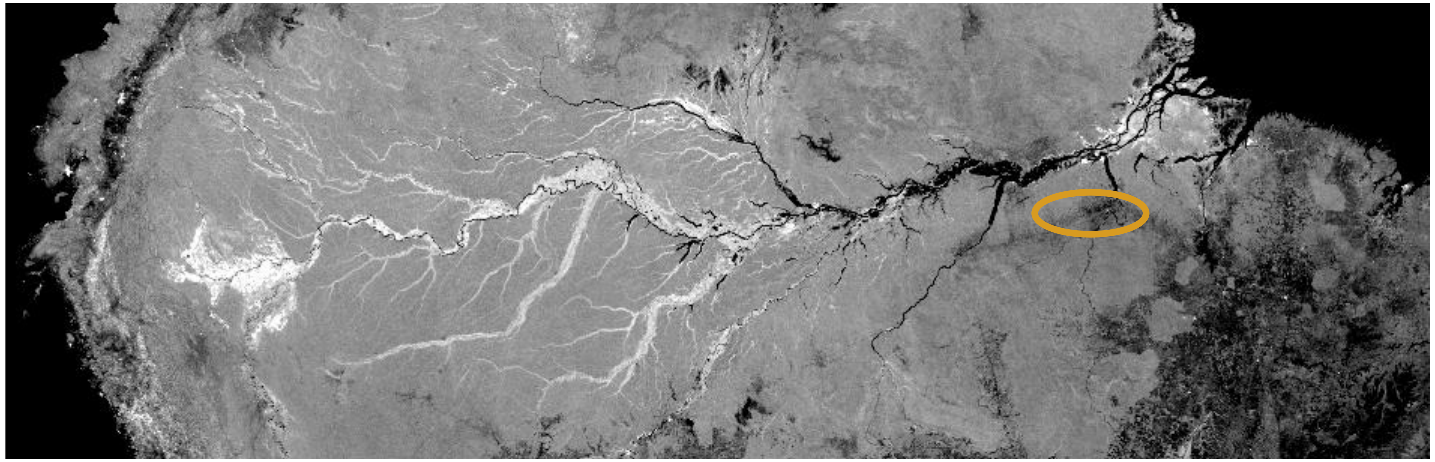
Examples of Radar Interaction

Rough Surface Reflection



Rough, Bare Surface
(deforested areas, tilled agricultural fields)

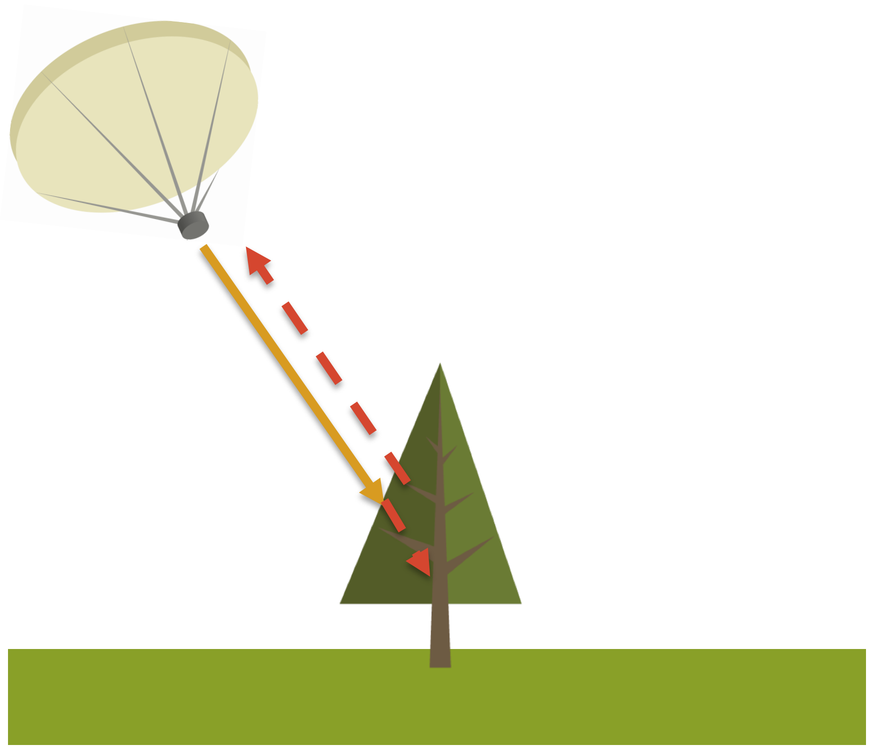
SMAP Radar Mosaic of the Amazon Basin
April 2015 (L-band, HH, 3 km)



Pixel Color

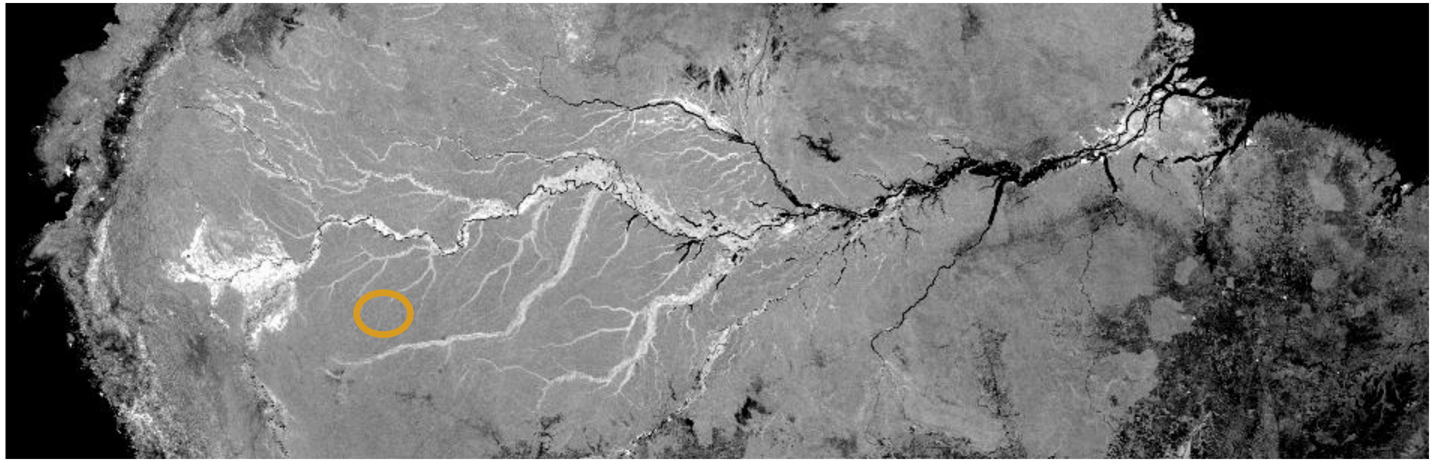
Examples of Radar Interaction

Volume Scattering by Vegetation



Vegetation

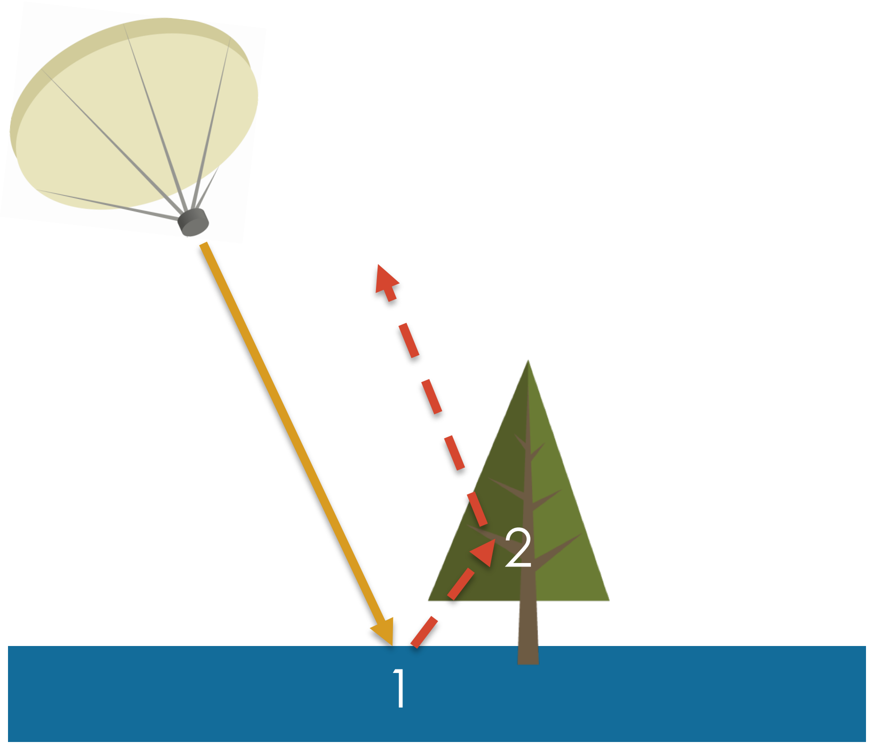
SMAP Radar Mosaic of the Amazon Basin
April 2015 (L-band, HH, 3 km)



Pixel Color

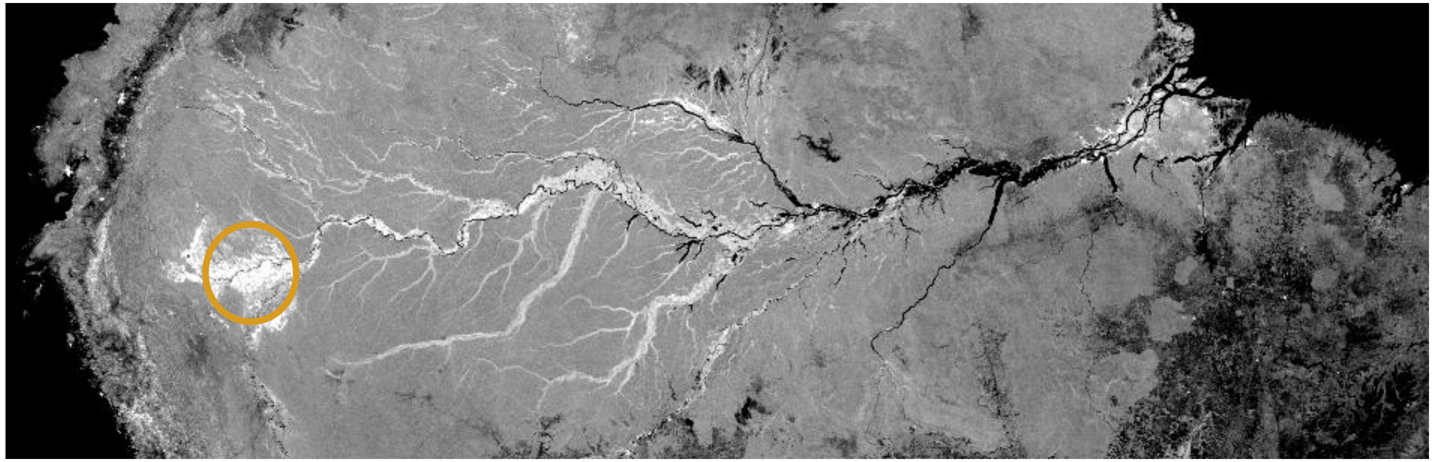
Examples of Radar Interaction

Double Bounce



Inundated Vegetation

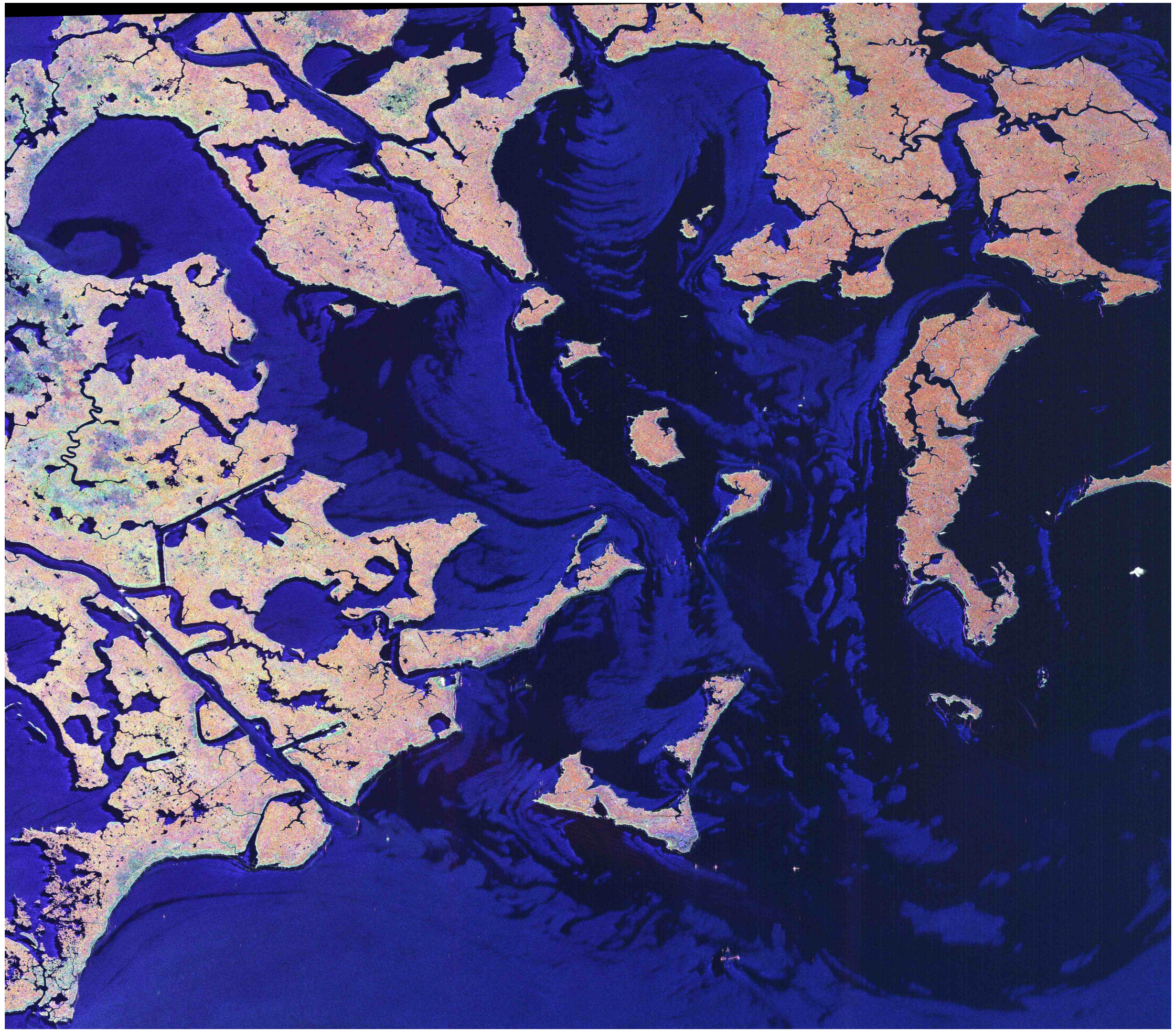
SMAP Radar Mosaic of the Amazon Basin April 2015 (L-band, HH, 3 km)



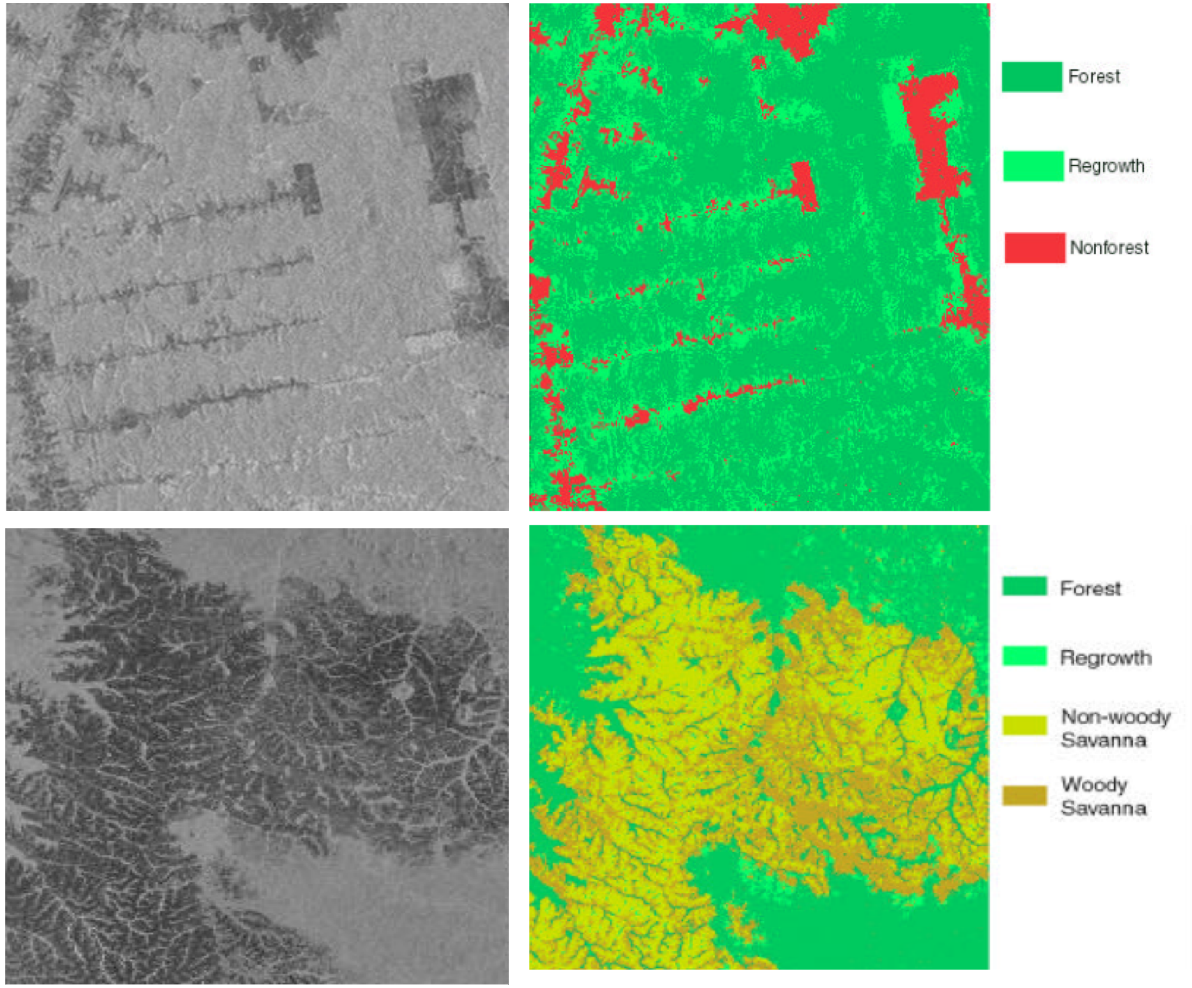
Pixel Color

Example: Detection of Oil Spills on Water

UAVSAR (2 meters):
HH, HV, VV



Example: Land Cover Classification

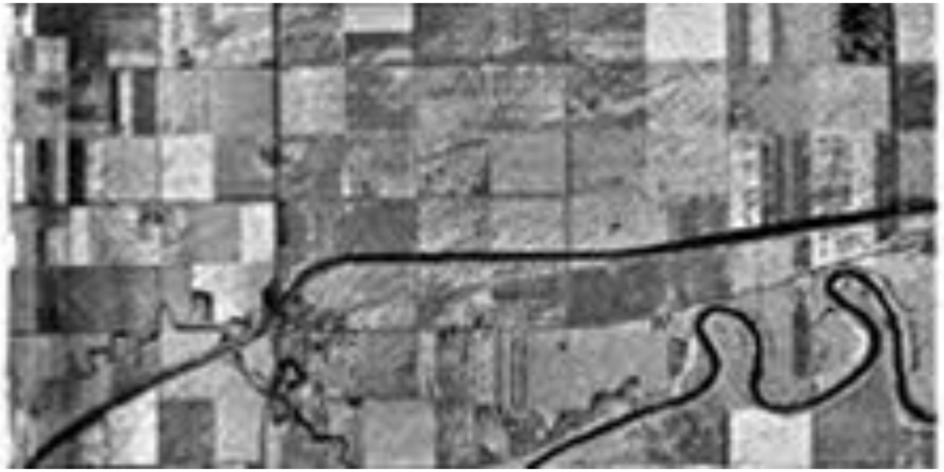


- Brazil
- JERS-1 L-band
- 100 meter resolution

Geometric and Radiometric Distortion of the Radar Signal

Slant Range Distortion

Slant Range



Ground Range

Source: Natural Resources Canada

Shadow

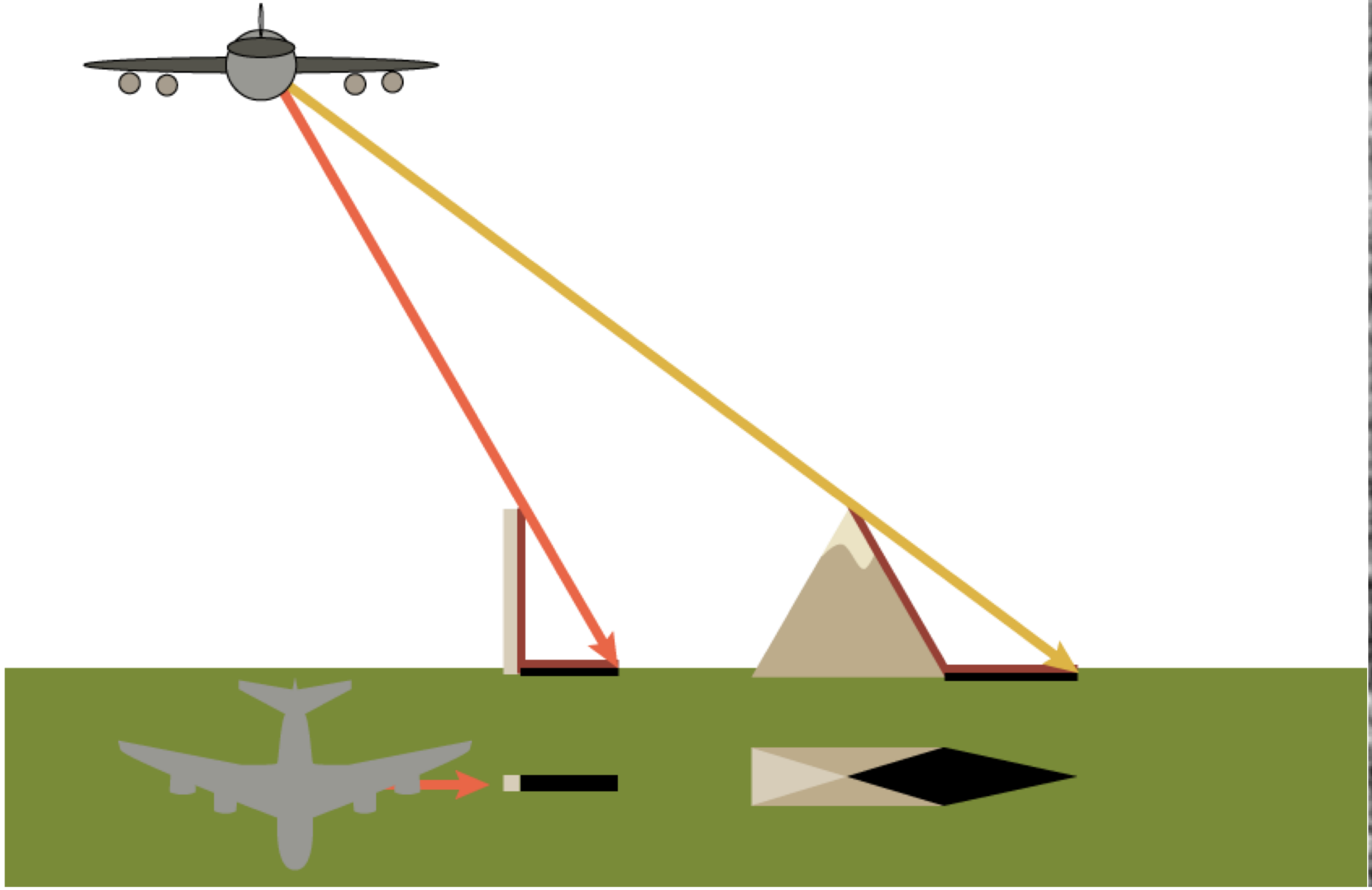
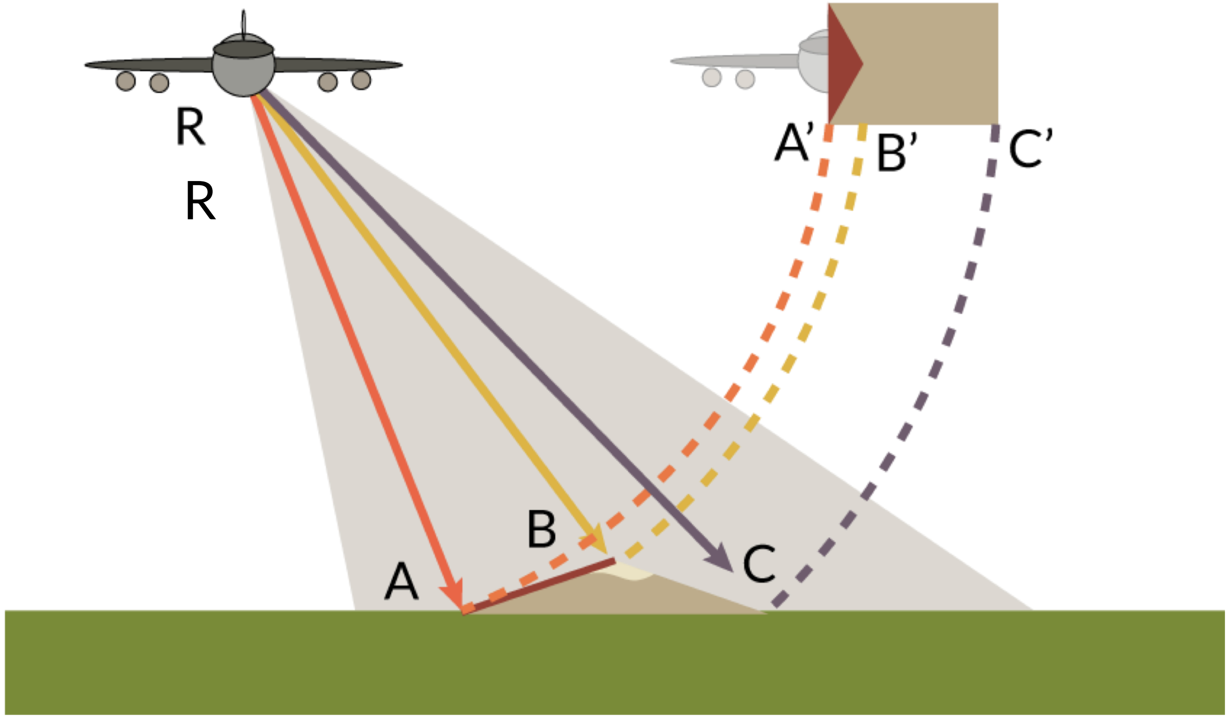


Image (left) based on NRC

Geometric Distortion

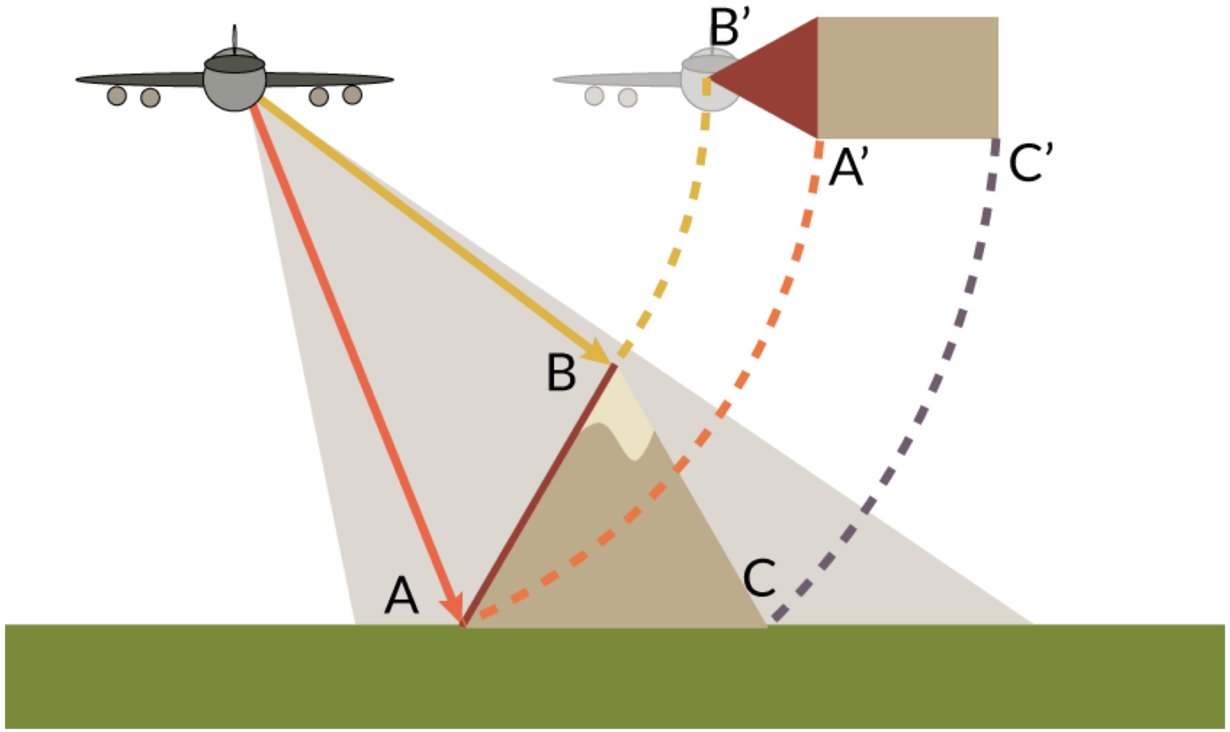
Layover

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



Foreshortening

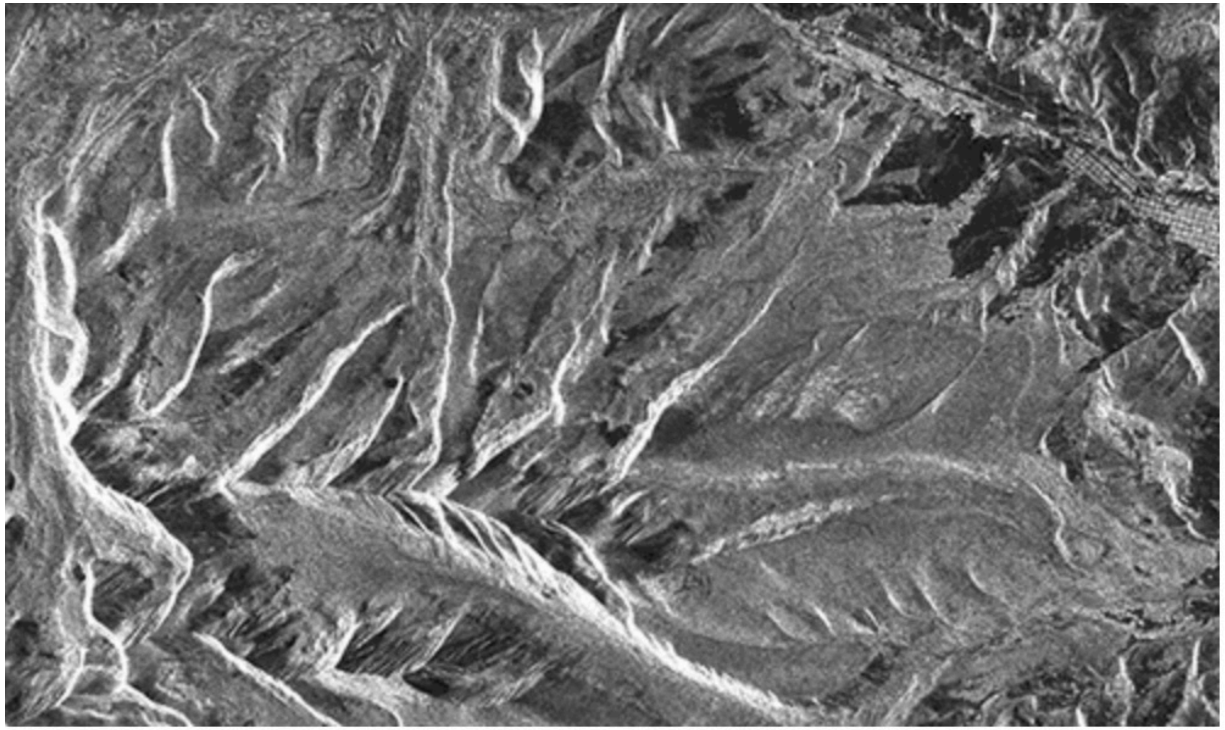
RA < RB < RC
AB = BC
A'B' < B'C'



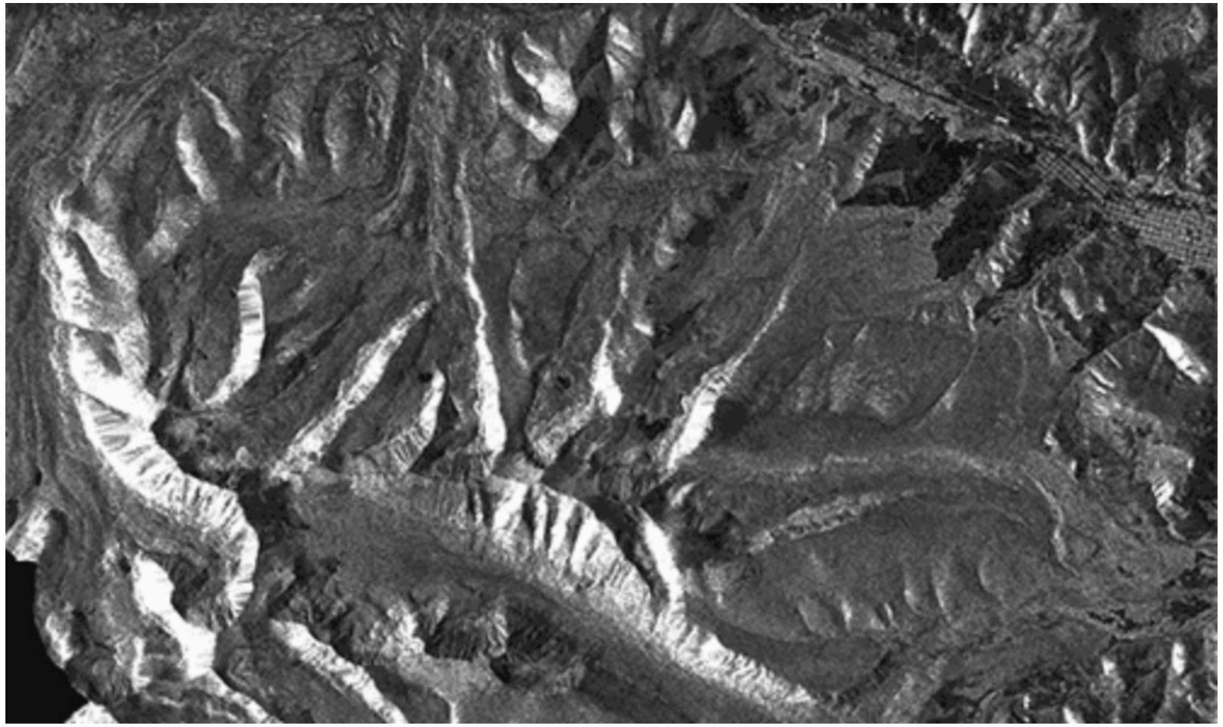
Images based on NRC images

Foreshortening

Before Correction



After Correction

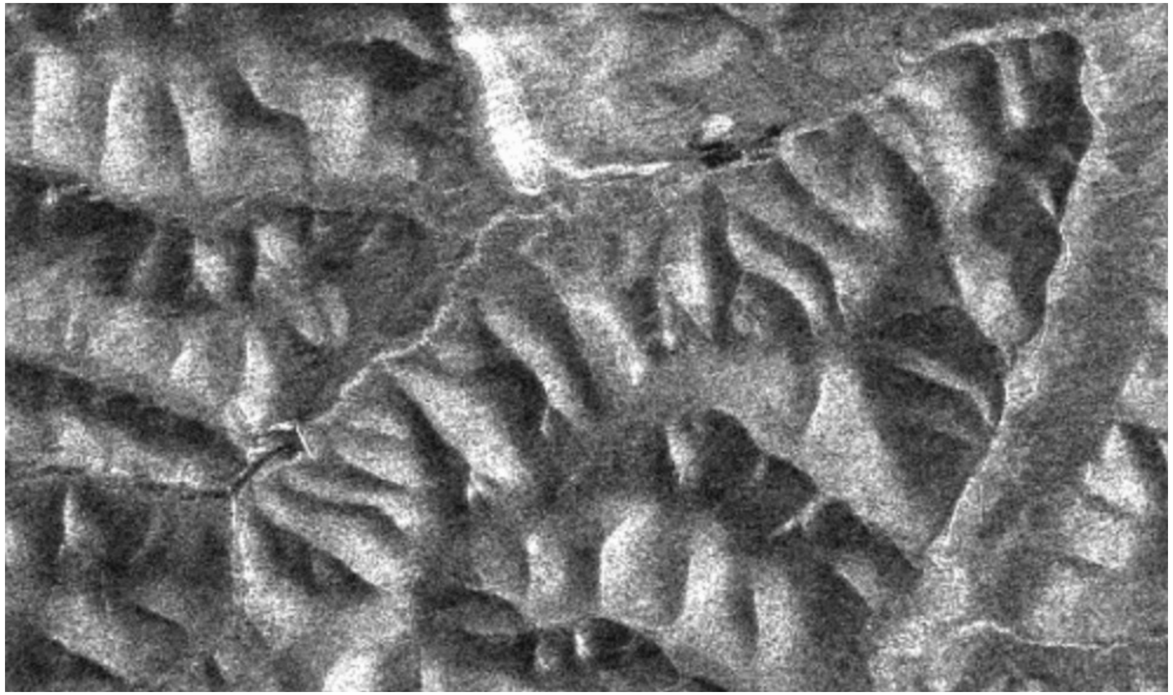


Source: ASF

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

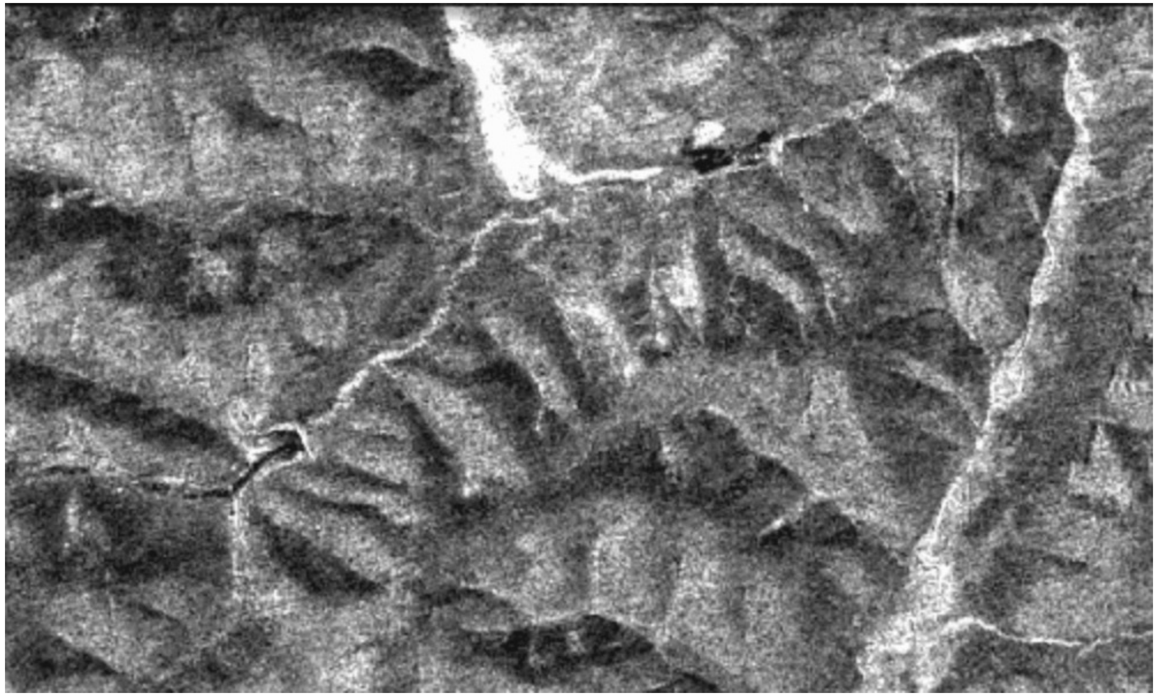
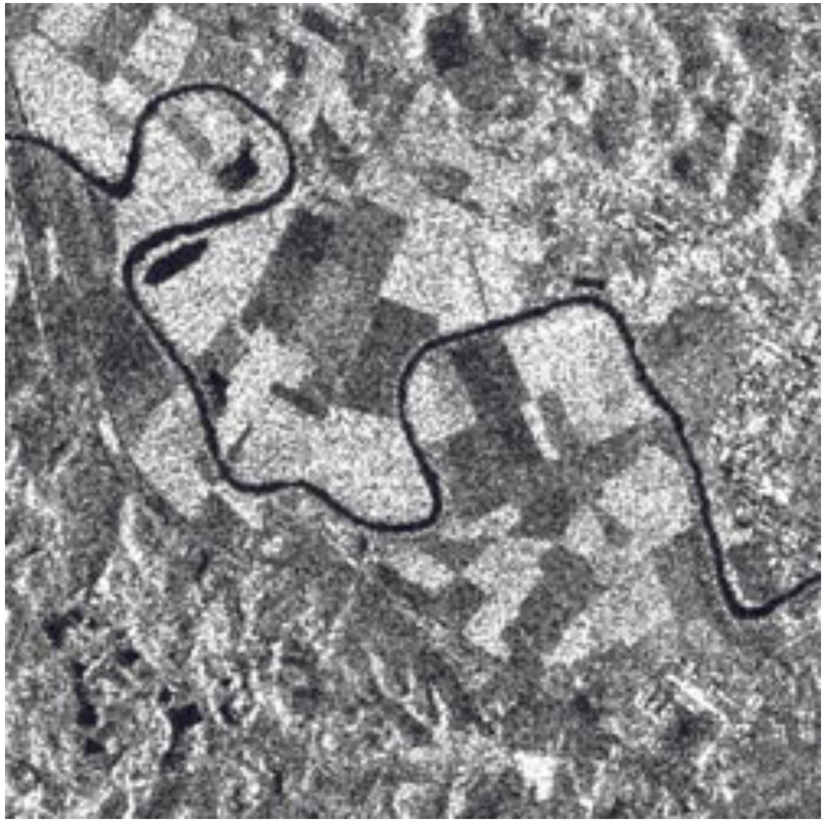


Image Credits: ASF

Speckle

Speckle

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



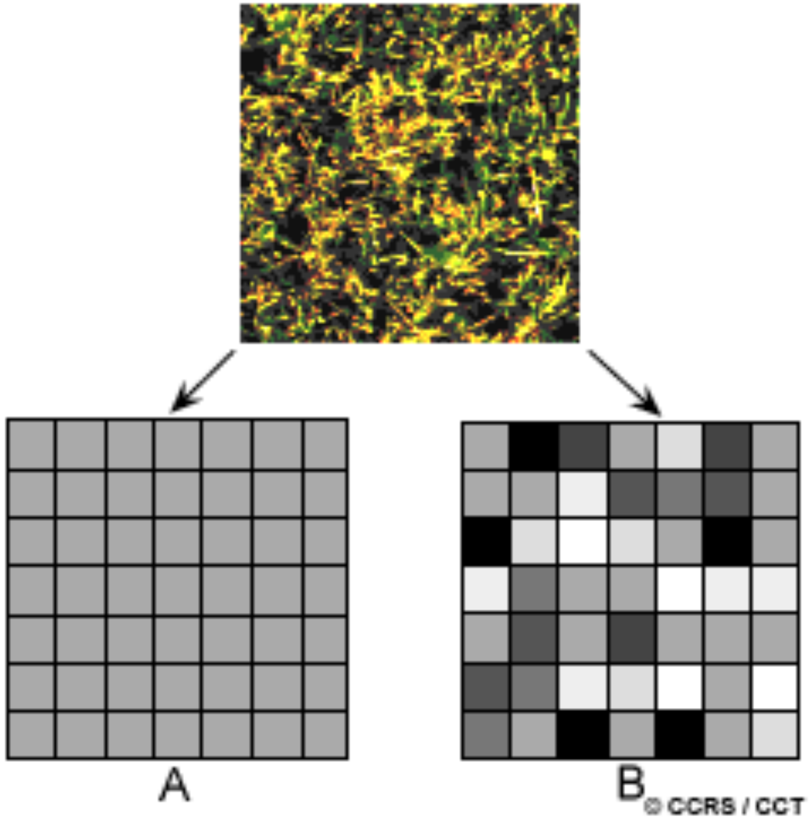
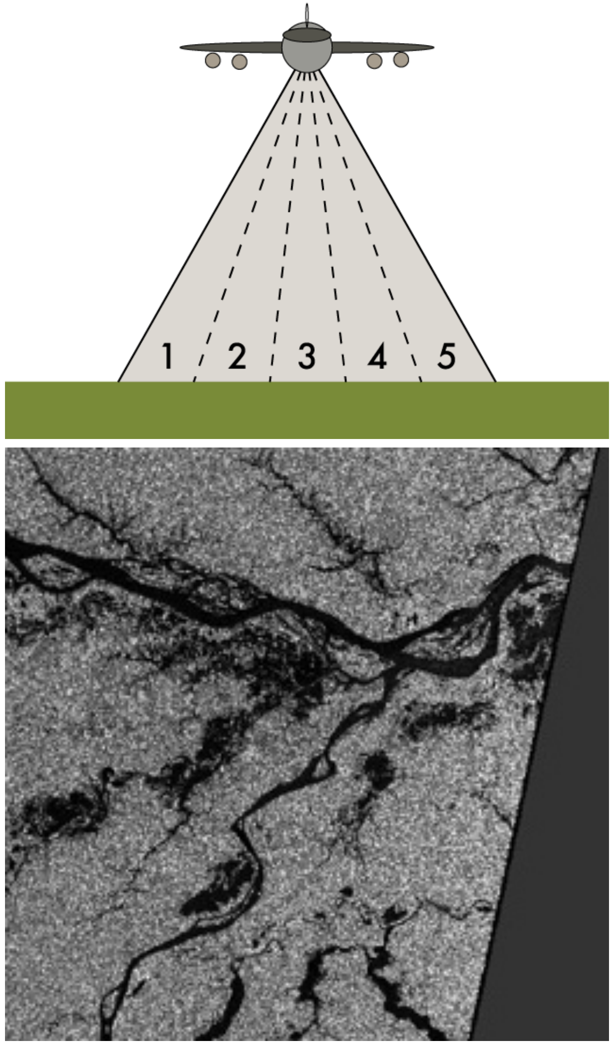


Image Credit: (left) ESA, (right) Natural Resources Canada

Speckle Reduction: Multi-Look Processing

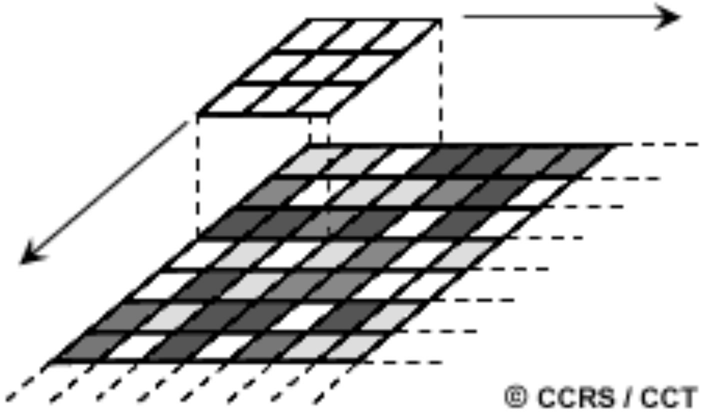
- Divides radar beam into several, narrower sub-beams – e.g. 5 beams on the right
- Each sub-beam is a "look" at the scene
- These "looks" are subject to speckle
- By summing and averaging the different "looks" together, the amount of speckle will be reduced in the final output image

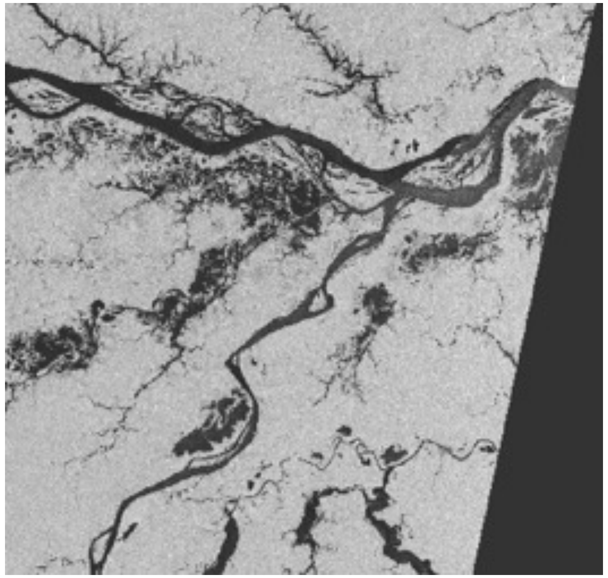


Source: Natural Resources Canada

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



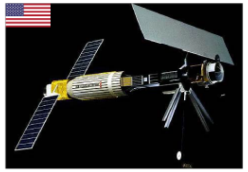


Source: Natural Resources Canada

Radar Data from Different Satellites

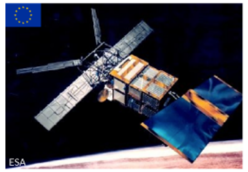
Legacy:

SeaSAT
1978



JERS-1
1992-1998

ERS 1/2
1991-2011



ENVISAT
2002-2012

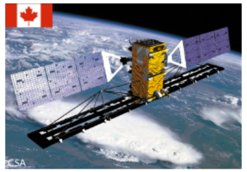
ALOS-1
2002-2012

Radarsat-1
1995-2013

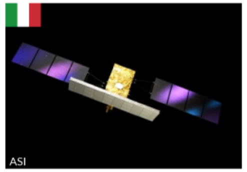
Current:

TanDEM-X
2007

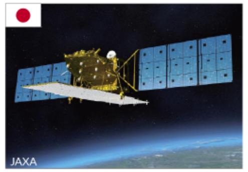
Radarsat-2
2007



COSMO-SkyMed
2007

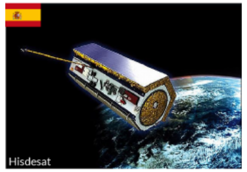


ALOS-2
2014



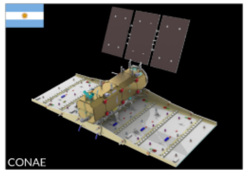
Sentinel-1
2014

PAZ SAR
2018

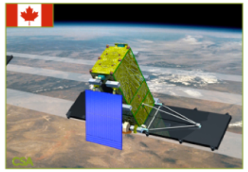


Future:

SAOCOM
2018

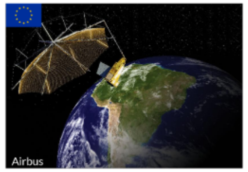


RCM
2018



NISAR
2021

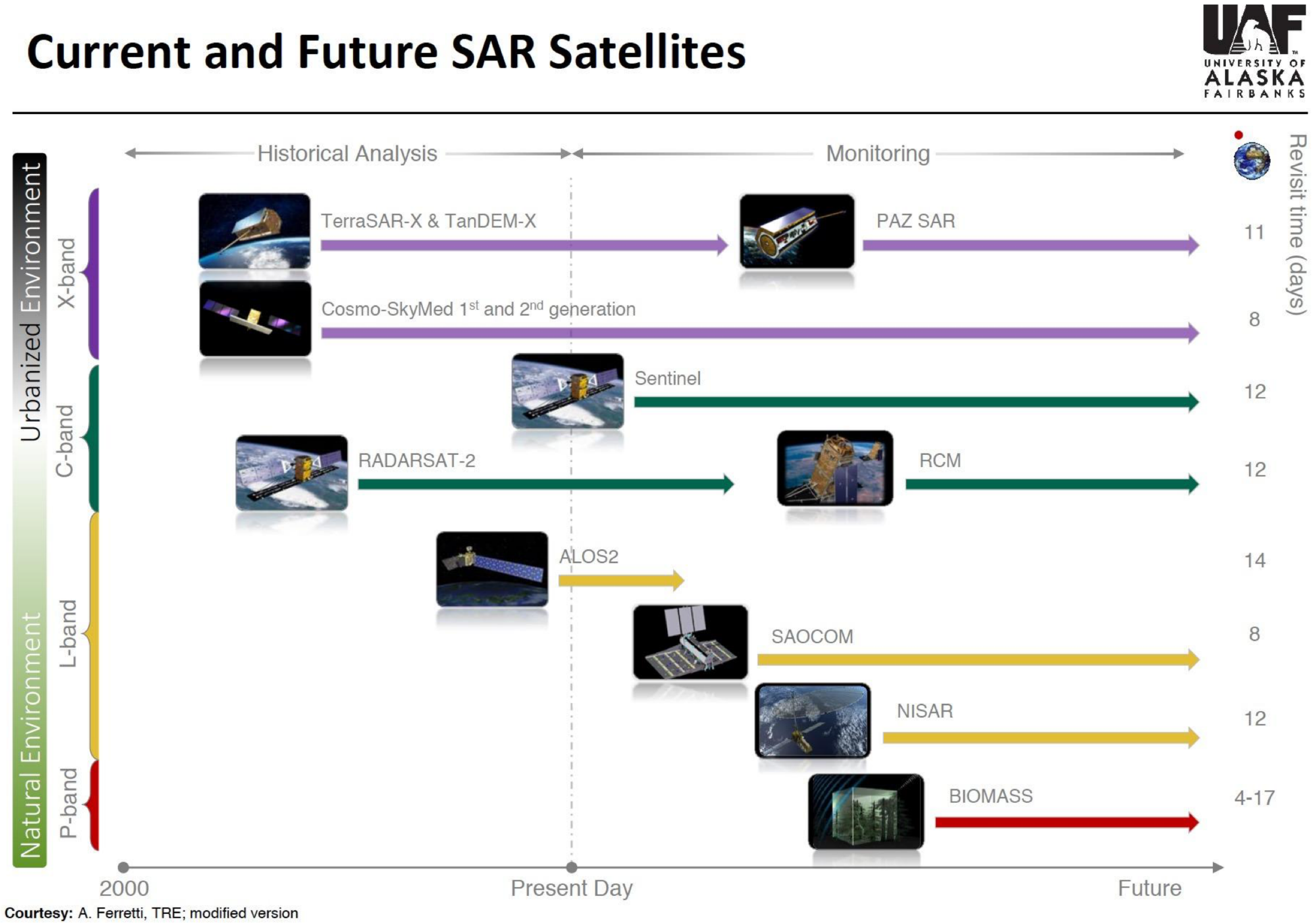
Biomass
2021



freely accessible

Credit: Franz Meyer, University of Alaska, Fairbanks

Current and Future SAR Satellites



Credit: Franz Meyer, University of Alaska, Fairbanks

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

Courtesy: 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