SYNTHETIC APERTURE RADAR FOR MAPPING OF FOREST DEGRADATION AND DEFORESTATION

A ONE-WEEK TRAINING ON SAR

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Lecture 1: General Concepts and Benefits of SAR

Outline:

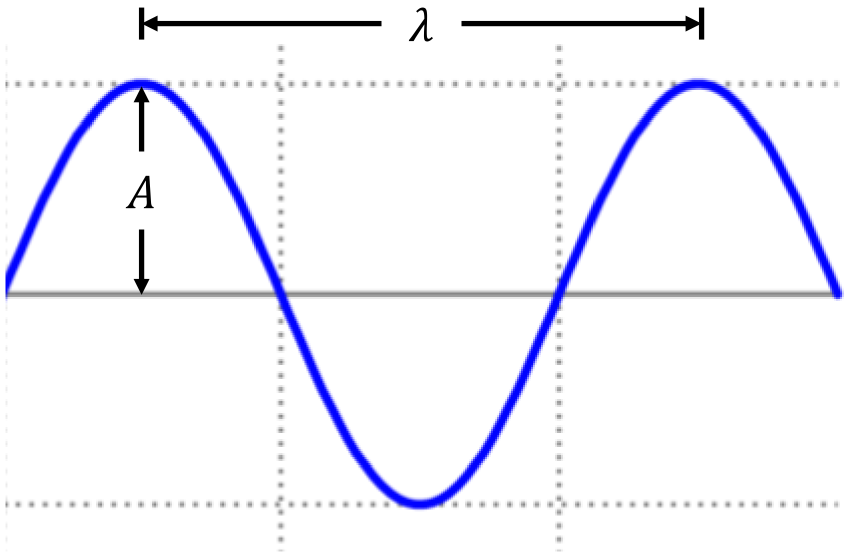
PRINCIPLES OF IMAGING RADAR

- **PROPERTIES OF MICROWAVES**
- HOW TO CREATE IMAGES WITH RADARS – REAL APERTURE RADARS
- SYNTHETIC APERTURE RADARS
- GEOMETRIC AND RADIOMETRIC PROPERTIES OF RADAR IMAGES

WHAT'S NEXT

Describing Microwave Signals

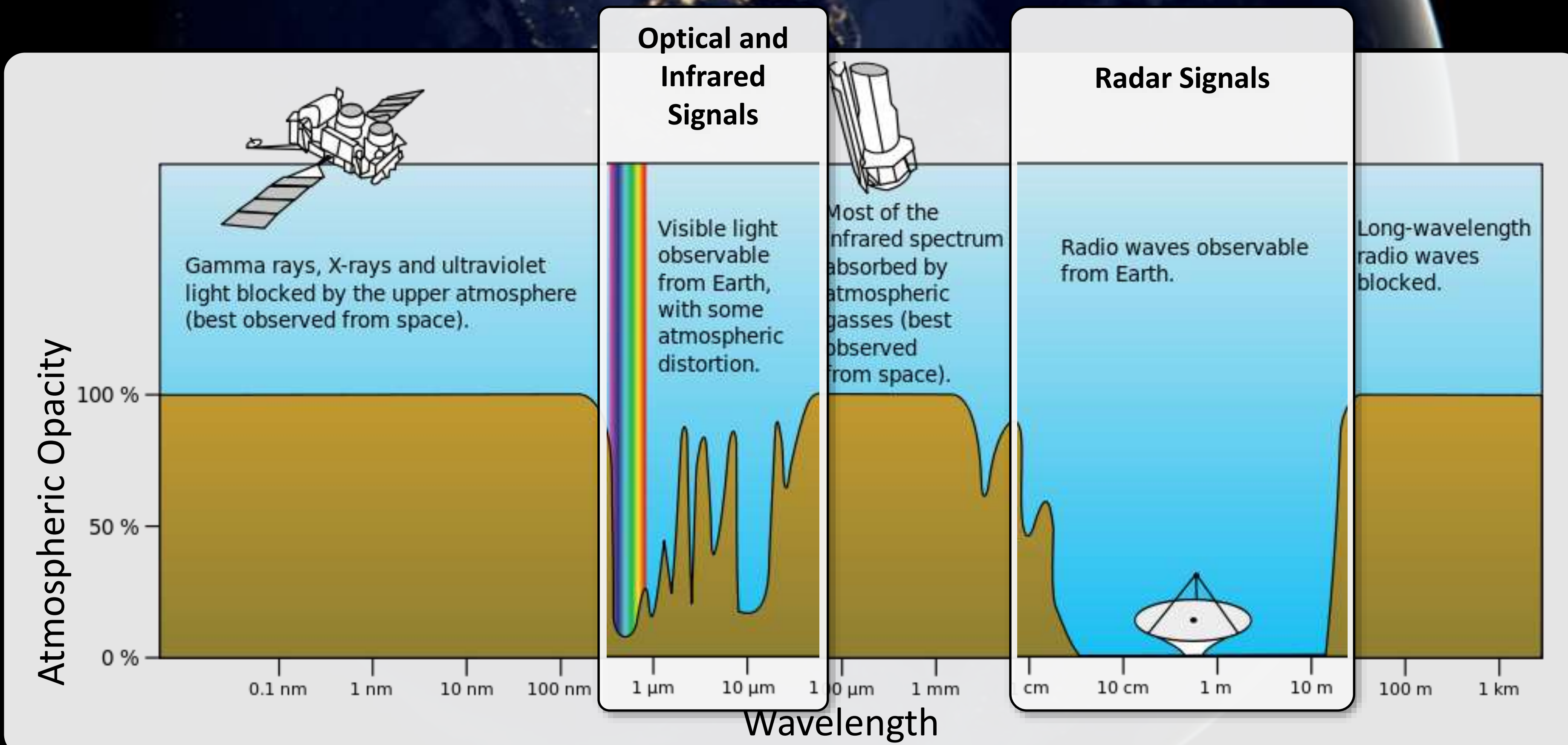
- **Electromagnetic (EM) radiation can be described by wave theory:**
  - Wavelength – lambda (λ)
  - Frequency – ($f = {}^{c}/_{\lambda}$)
  - Period – Pulse length (τ)
  - Amplitude (A)
  - Energy (E)



- These descriptors provide fundamental information about how EM waves interact with matter and hence can be utilized (inversely) to yield information about the object of study.

Wavelength Discriminates Radar from Optical Data

- **Radar has excellent capabilities for routine global change monitoring**
  - **24/7 imaging capabilities:** due to weather and illumination independence
  - **Advanced change detection performance**: due to stable image geometry and own signal source
  - **Complementary to optical sensors**: provides independent information about surface



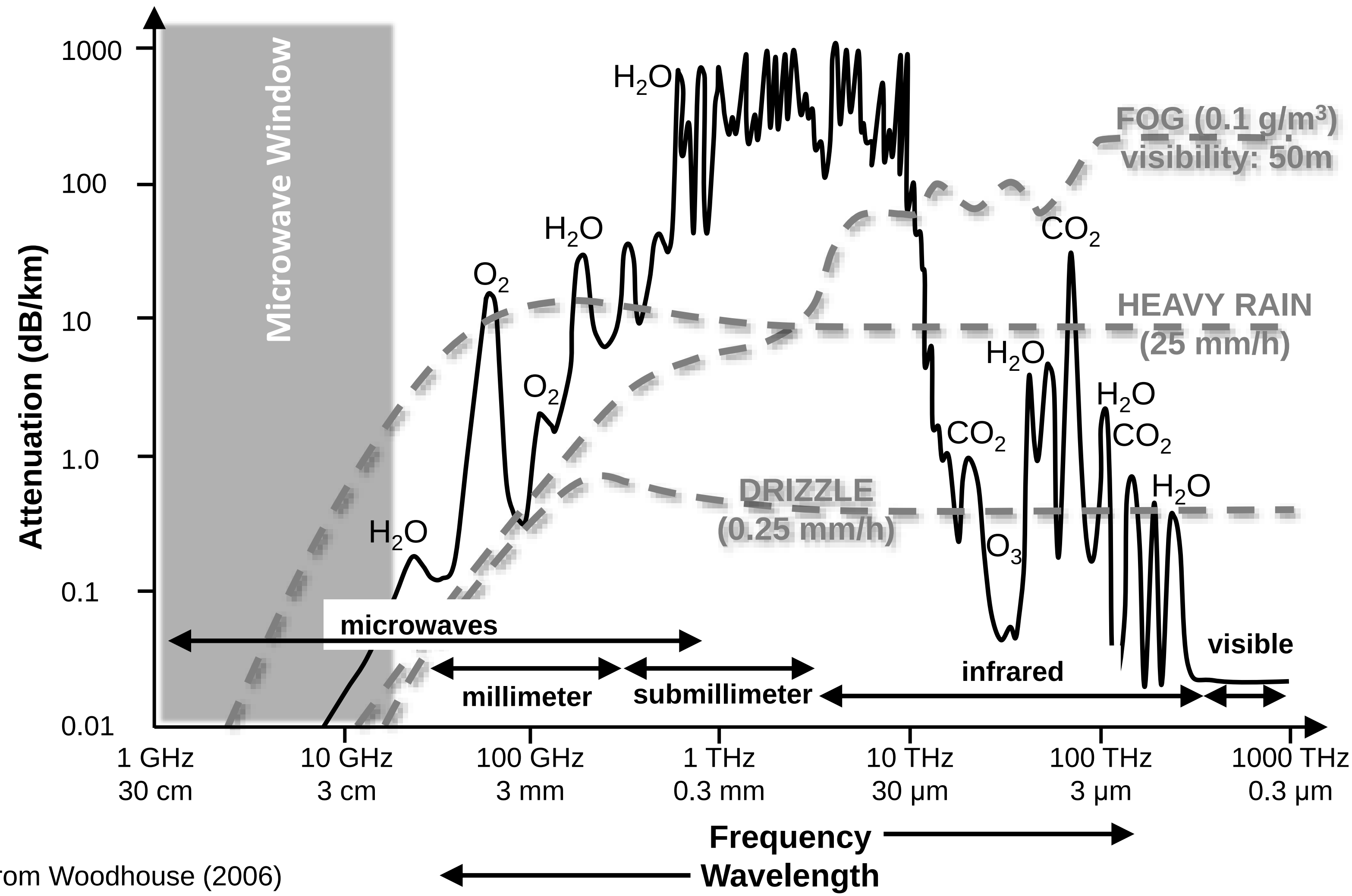
NASA Earth Observatory images by Robert Simmon, using Suomi NPP VIIRS data from Chris Elvidge (NOAA National Geophysical Data Center)

The Microwave Spectrum

(approximate)

band	**frequency** f_0	**wavelength** $\lambda = c / f_0$	**typical application**
Ka	27 – 40 GHz	1.1 – 0.8 cm	airport surveillance
K	18 – 27 GHz	1.7 – 1.1 cm	little used (H_2O absorption)
Ku	12 – 18 GHz	2.4 – 1.7 cm	**satellite altimetry**
X	8 – 12 GHz	3.8 – 2.4 cm	**SAR**, marine radar, weather radar
C	4 – 8 GHz	7.5 – 3.8 cm	**SAR**, weather radar
S	2 – 4 GHz	15 – 7.5 cm	long-range weather radar
L	1 – 2 GHz	30 – 15 cm	**SAR**, traffic control
P	0.3 – 1 GHz	100 – 30 cm	experimental SAR

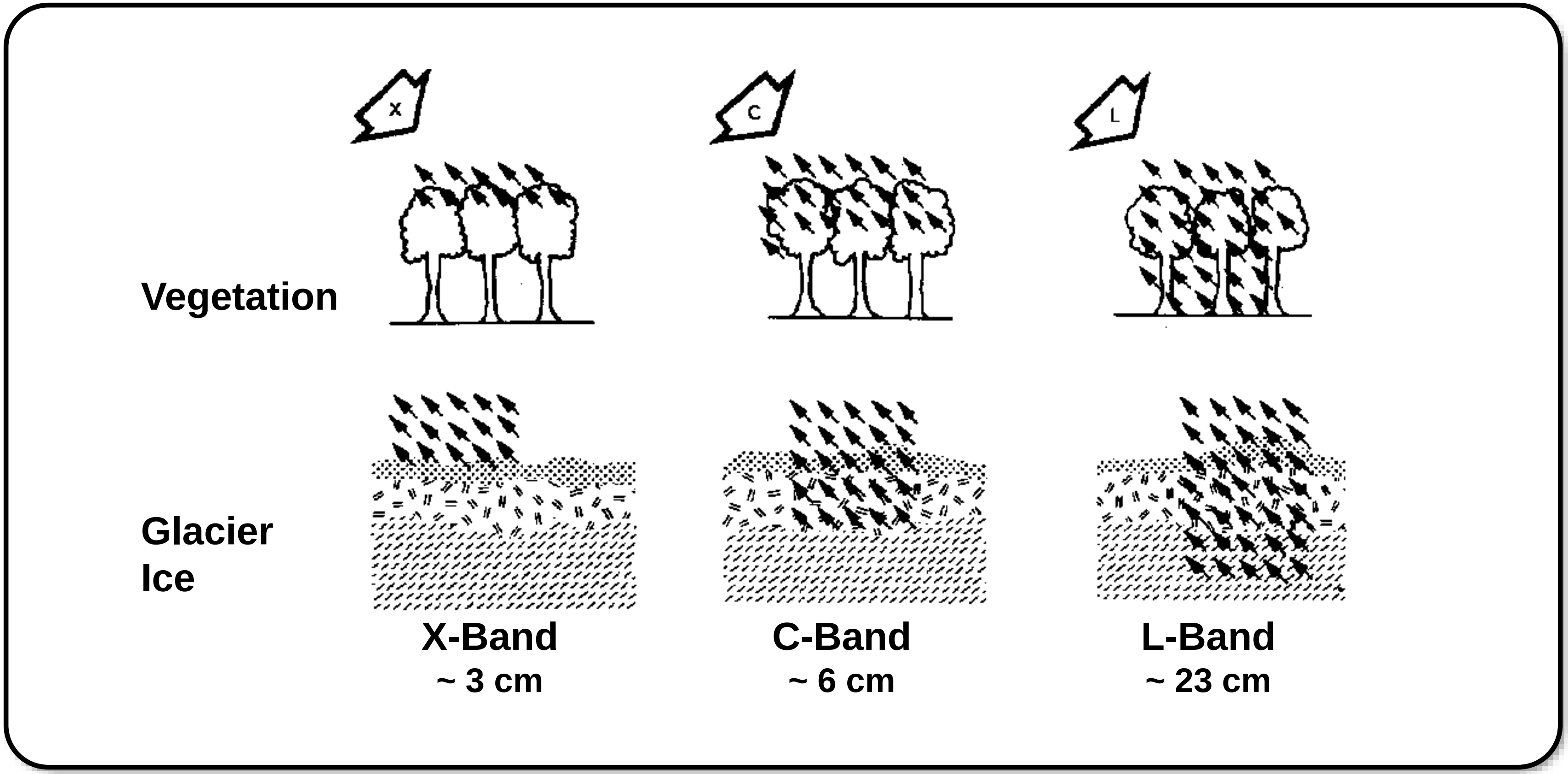
Atmosphere almost Transparent at Microwave Window



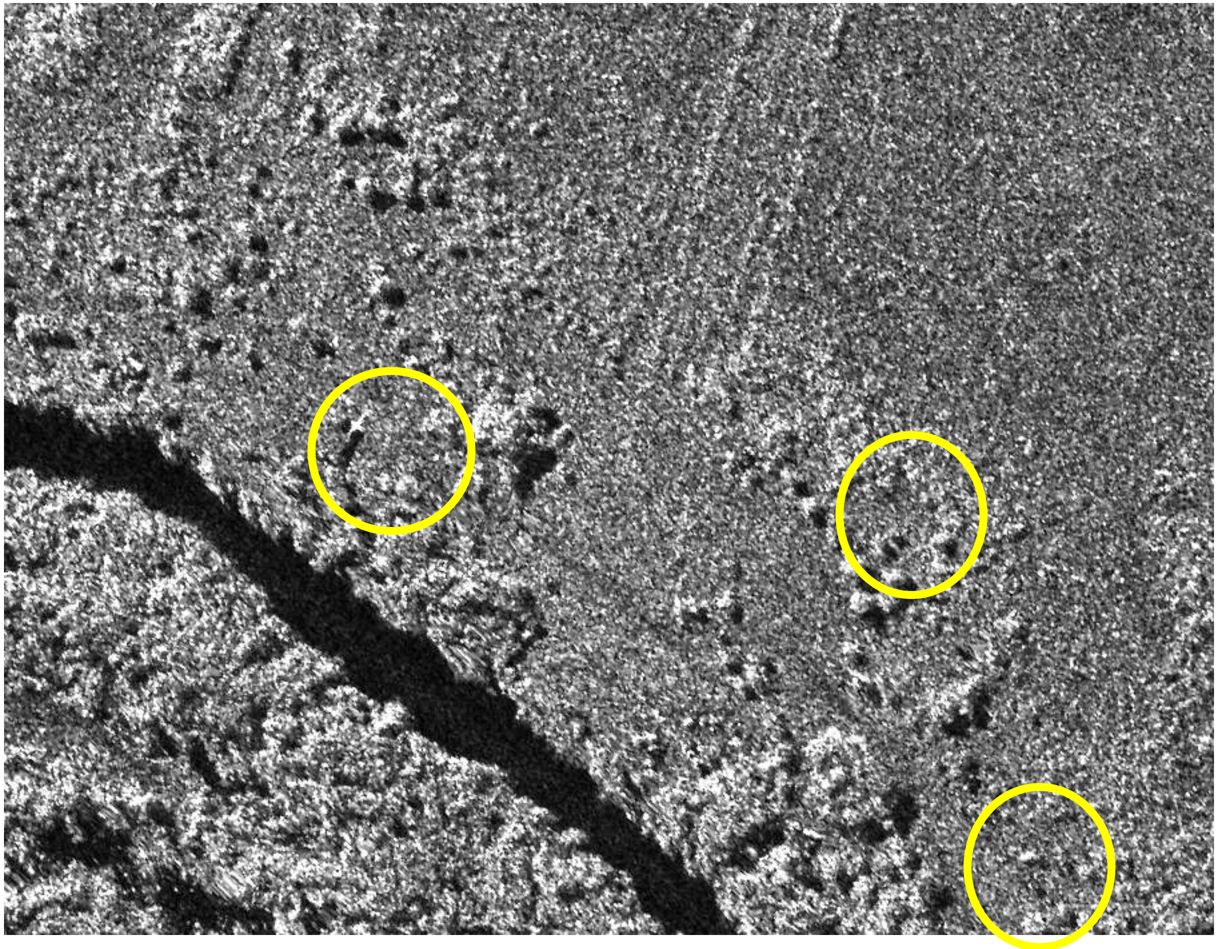
From Woodhouse (2006)

Advantages of Microwave Signals

- **Penetration into the top surface layer**

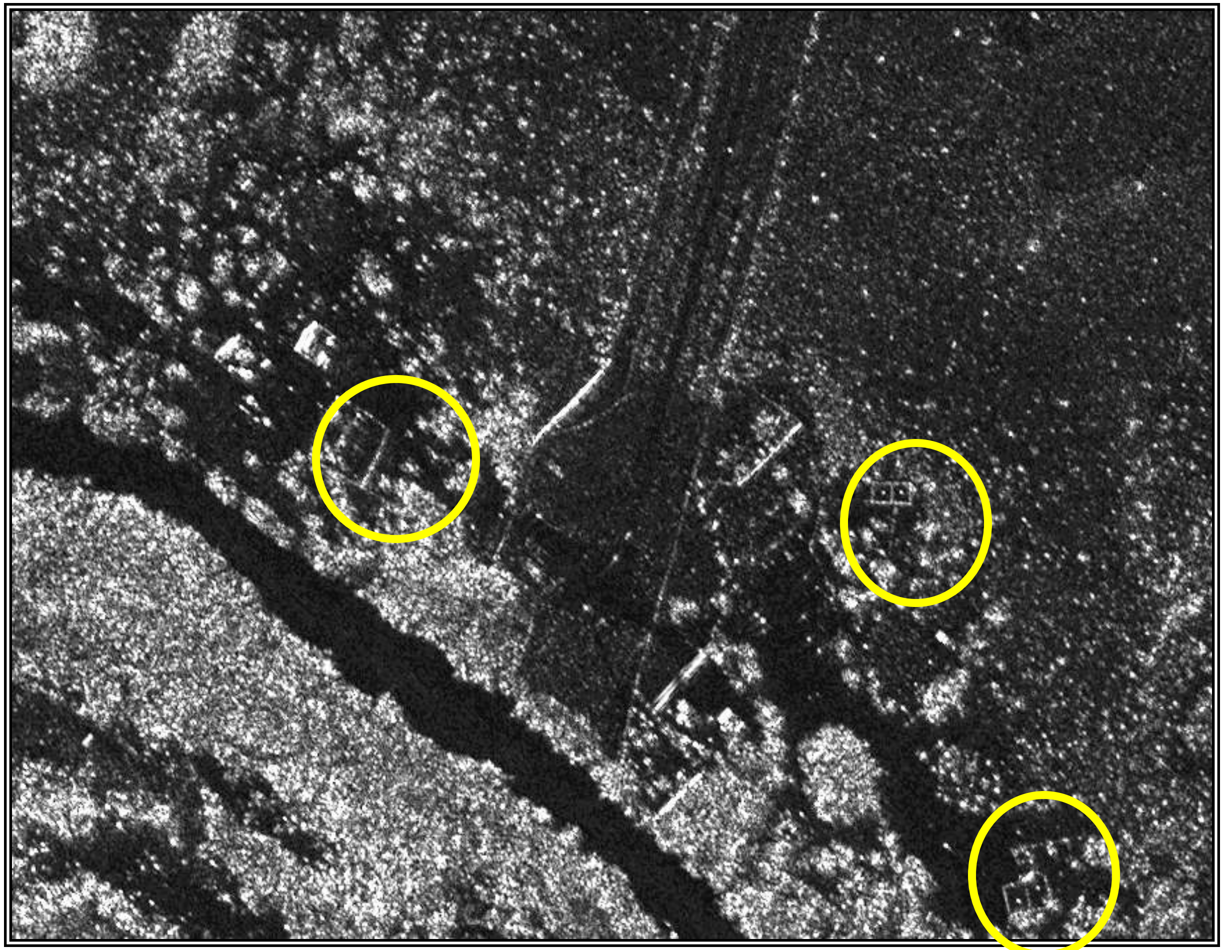


Different Frequency Bands Carry Different Information



X-band radar image of forested area

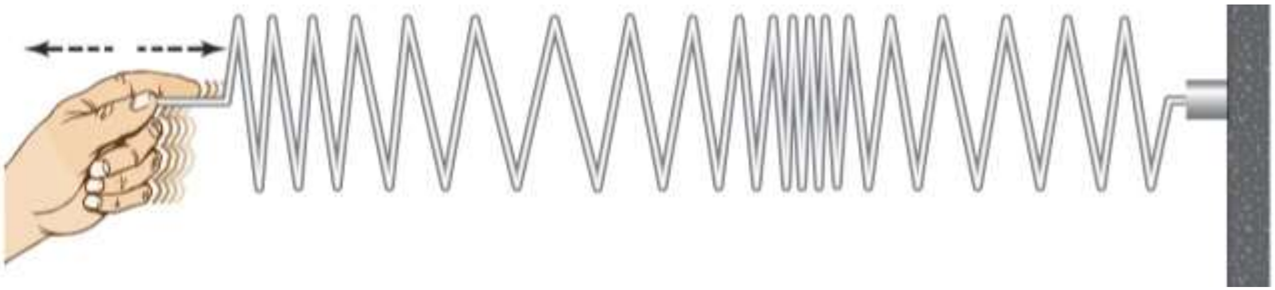
Different Frequency Bands Carry Different Information



P-band radar image of forested area

Radar like Optical EM Signals are Transverse Oscillating Waves

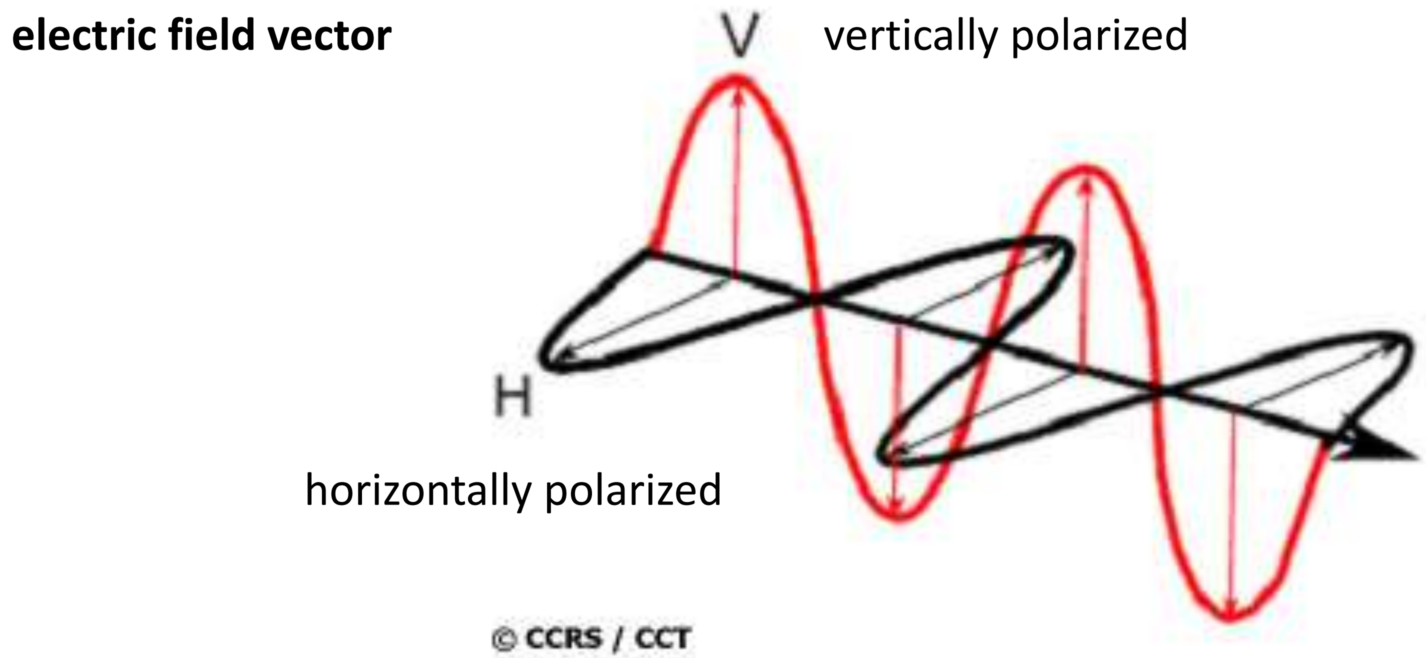
Longitudinal oscillating waves (sound waves, waves on oceans)



Transverse oscillating waves (e.g., EM waves)

Traverse oscillating waves (like EM waves) have one additional degree of freedom: Direction in which oscillation takes place, **called Polarization**

In Radar, we can Control the Polarization of the Transverse Oszillating Signal → Its Polarization



- Polarization planes are perpendicular – orientation technically arbitrary
- Usually, horizontal and vertical planes are chosen
- The terms horizontal and vertical then refer to either the earth or the antenna surface

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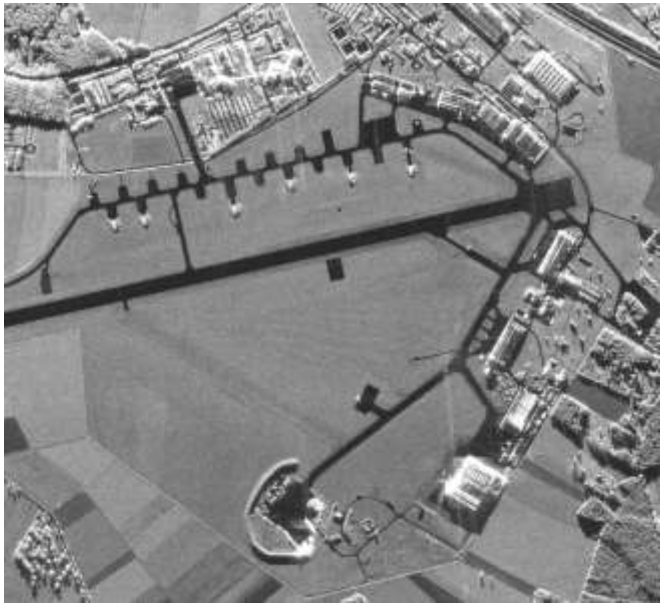
WHAT'S NEXT

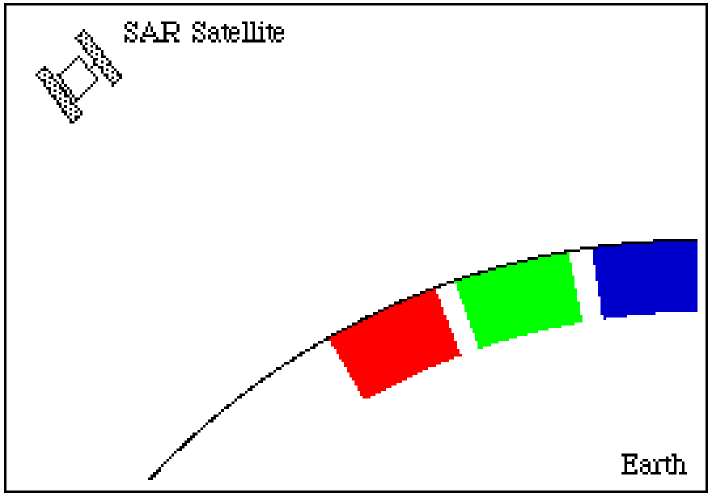
Active Microwave Systems are called RADARs

- **Radars actively transmit microwave signals (usually a radar pulse)**
- Radar antenna provides directivity for transmitted signal
- **A radar sensor records two different parameters**: **Amplitude** and **Phase** of the reflected microwave signals

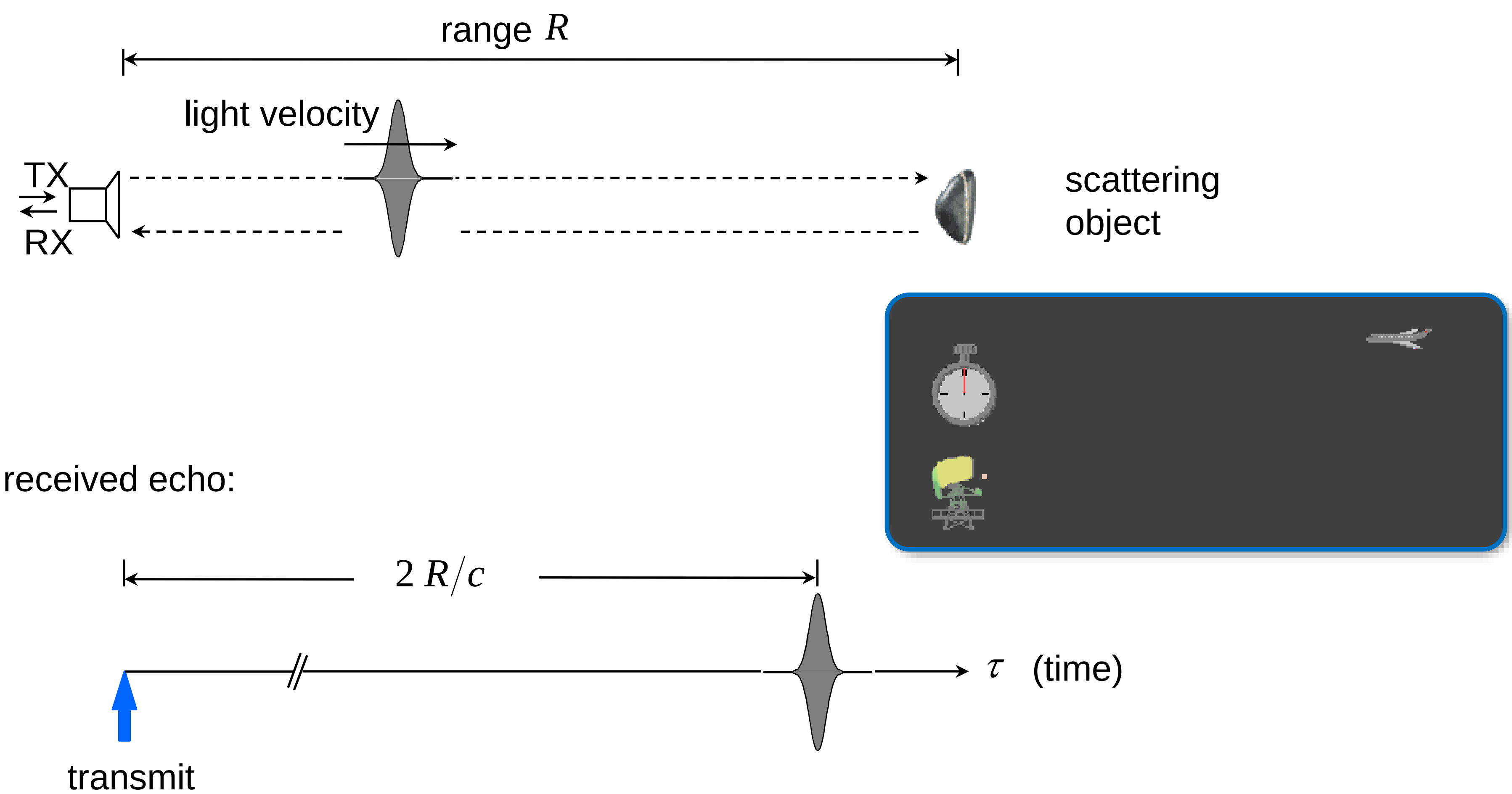
Detected amplitude measures surface radar cross section (RCS)



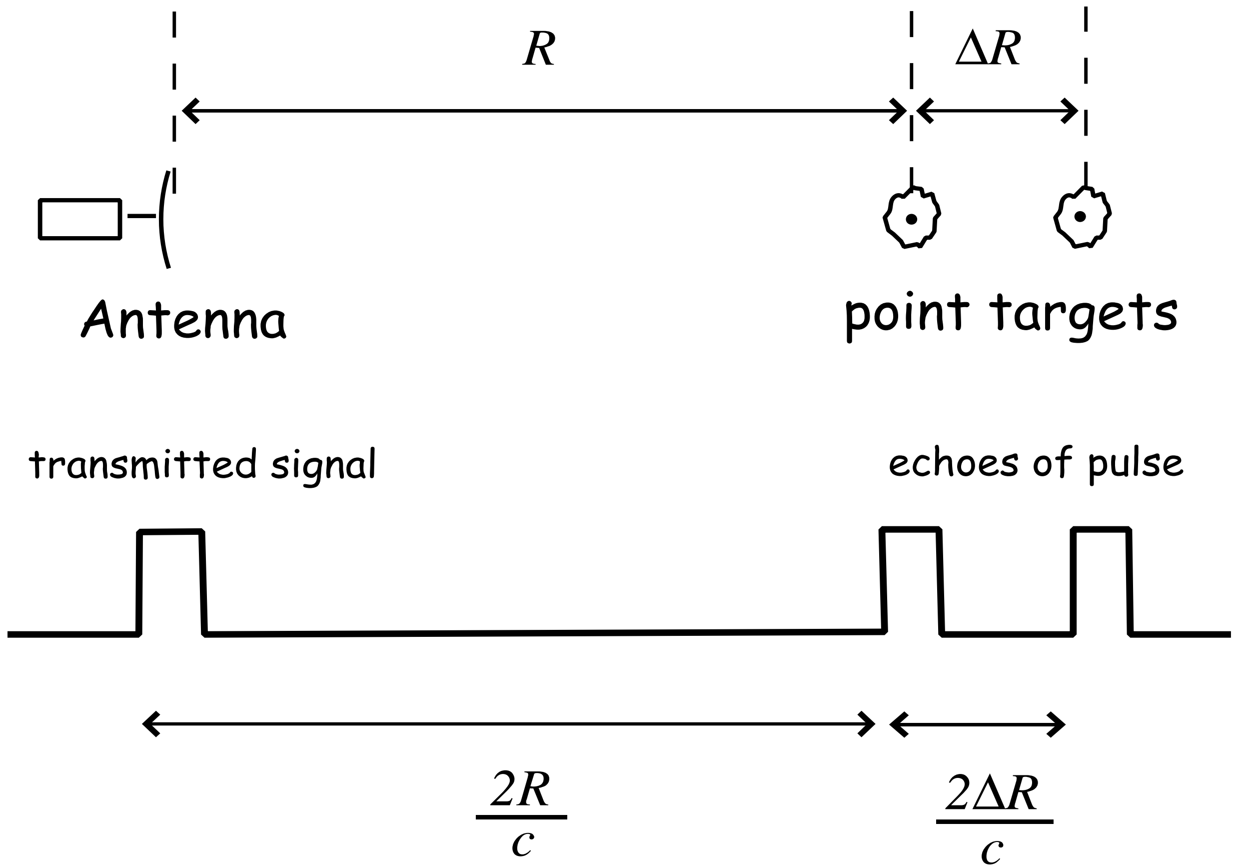
Timing of transmitted signal (radar pulse) provides information about distance between satellite and ground



Radar Principle



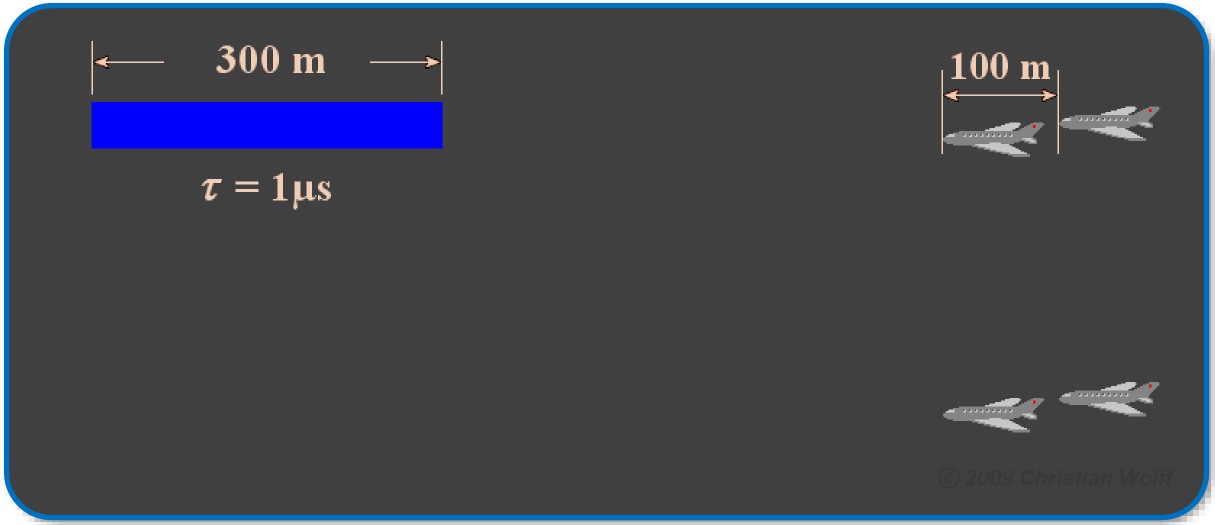
Achieving Resolution in Range



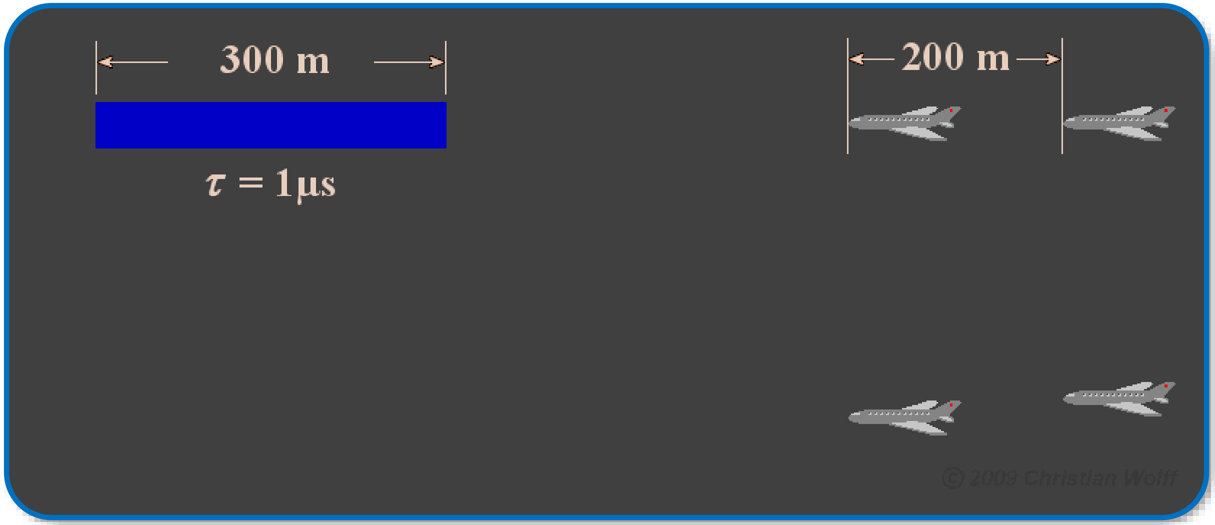
If possible, use a narrow pulse to resolve close targets

Range Resolution Example

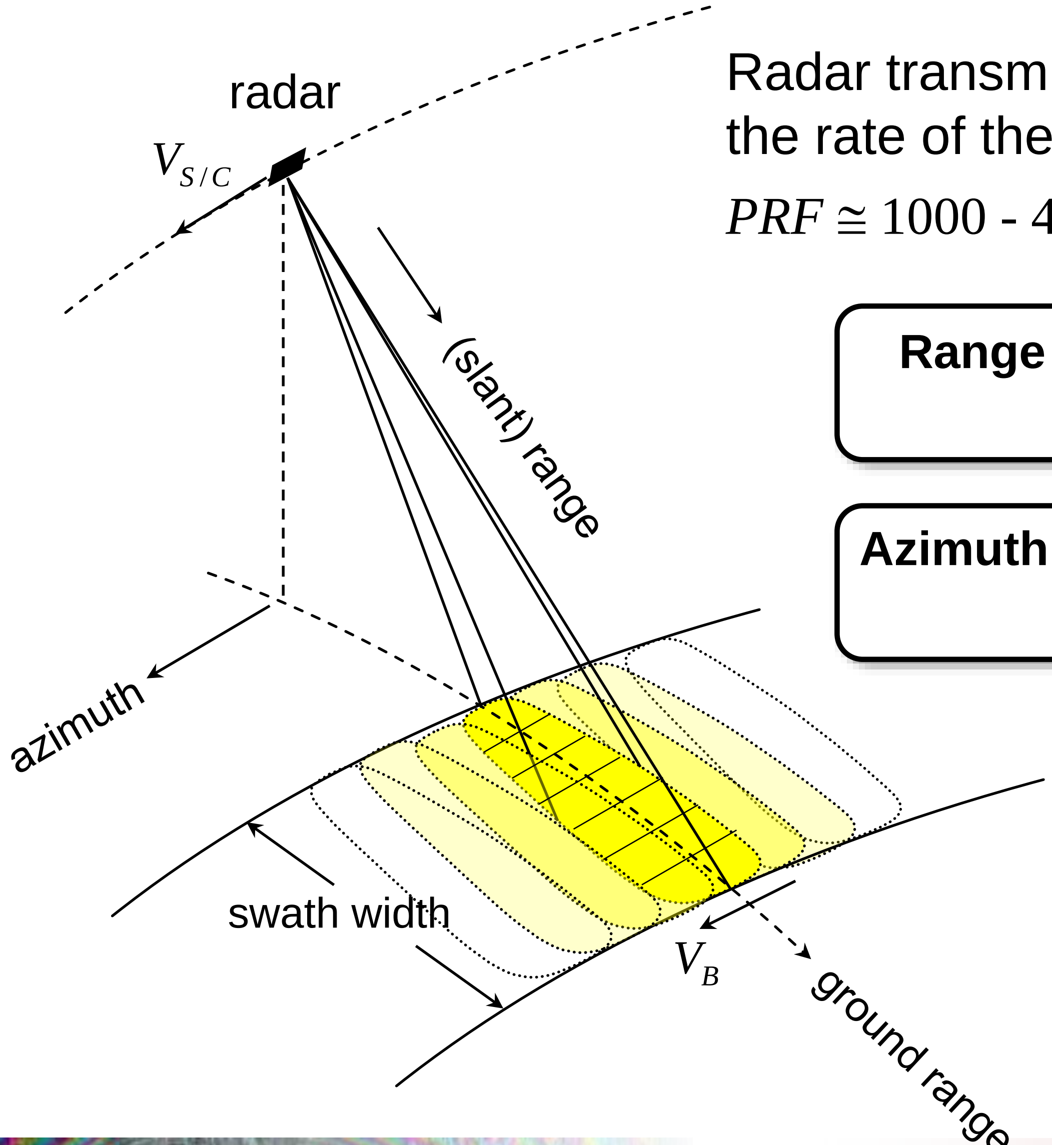
- Insufficient Target Separation



- Sufficient Target Separation



How to Form a Radar Image



Radar transmits pulses and receives echoes at the rate of the pulse-repetition frequency (PRF):

$PRF \cong 1000$ - 4000 Hz

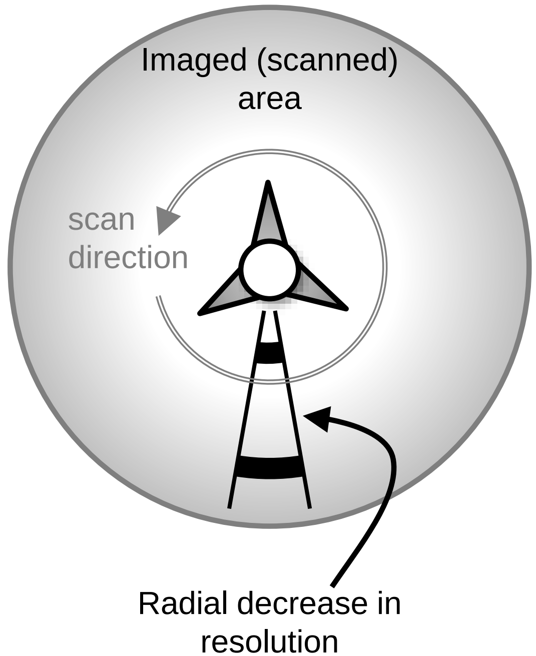
Range pixels: pixel size defined by pulse width (radar principle)

Azimuth pixels: scanning in flight direction at $V_{S/C}$

Imaging the Surface with SLARs

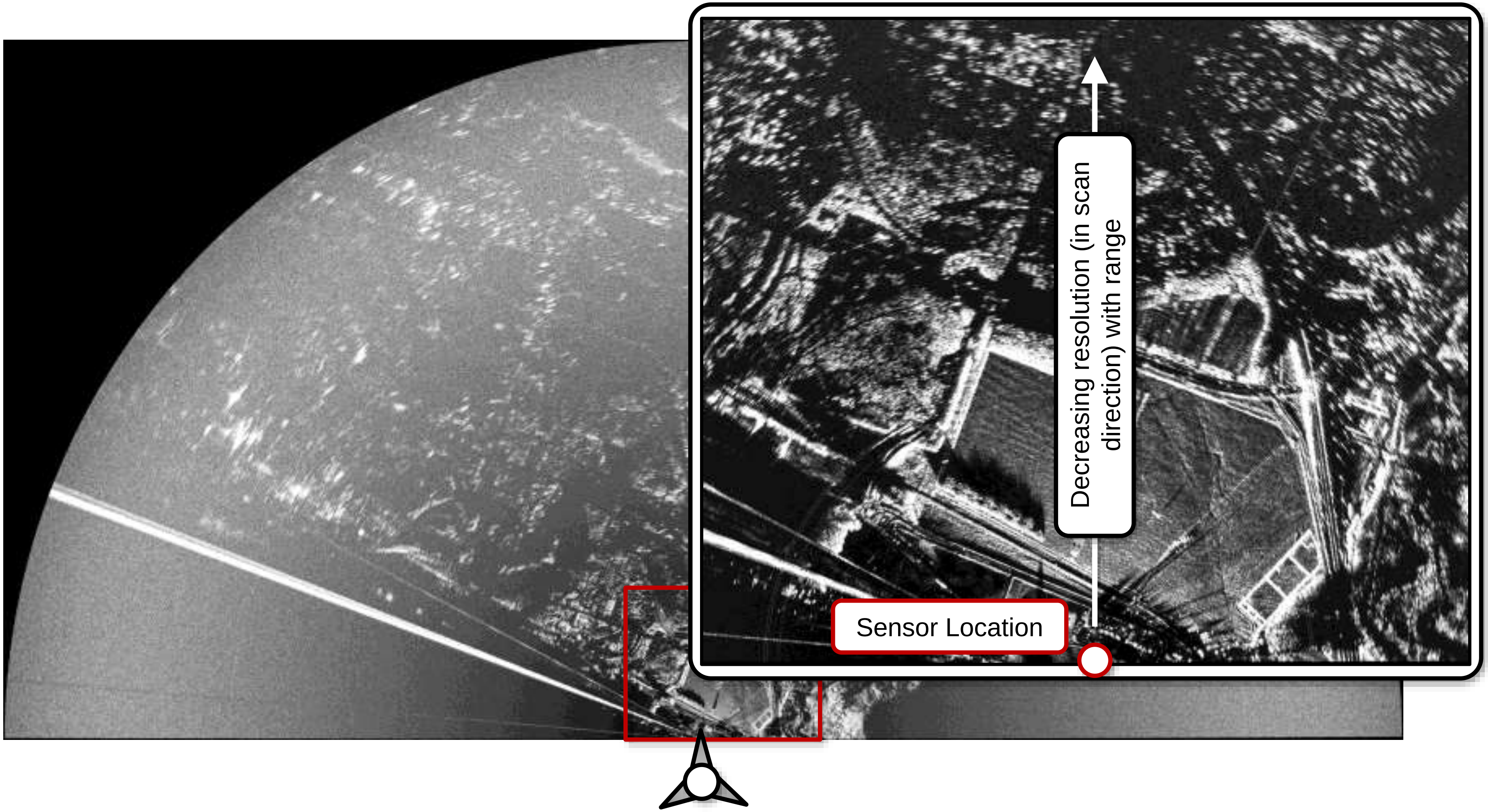
Scanning Ground-based Radar System as a SLAR Example

- Resolution defined by pulse length & length of antenna



Example of Scanning Ground-Based Radar Acquisition

- 180 degrees scan angle – location: Fairbanks, Alaska



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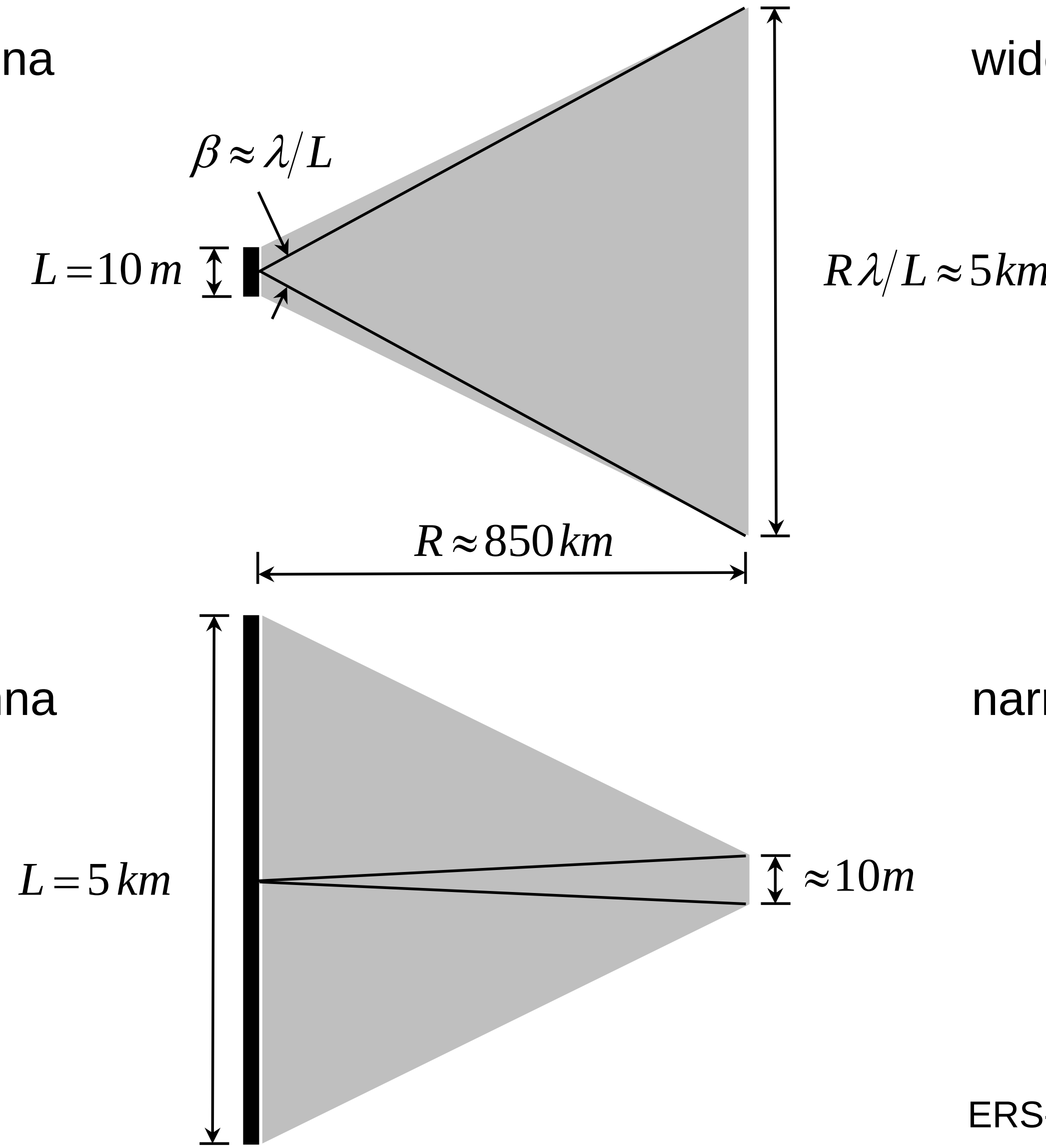
WHAT’S NEXT

Antenna Size vs. Beam Width

short antenna

wide beam

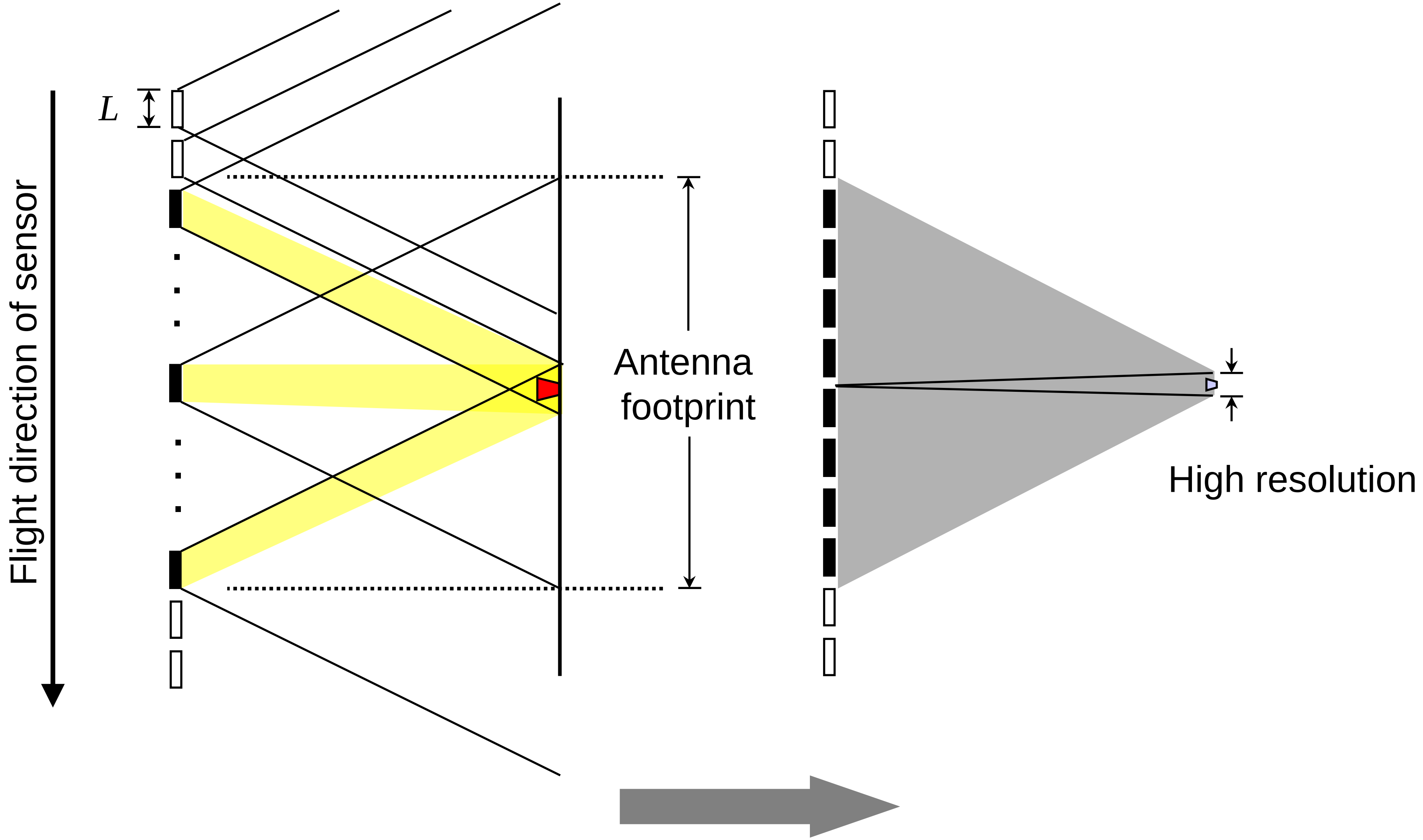


long antenna

narrow beam

ERS-1/2 parameters

Formation of a Synthetic Aperture — SAR Principle

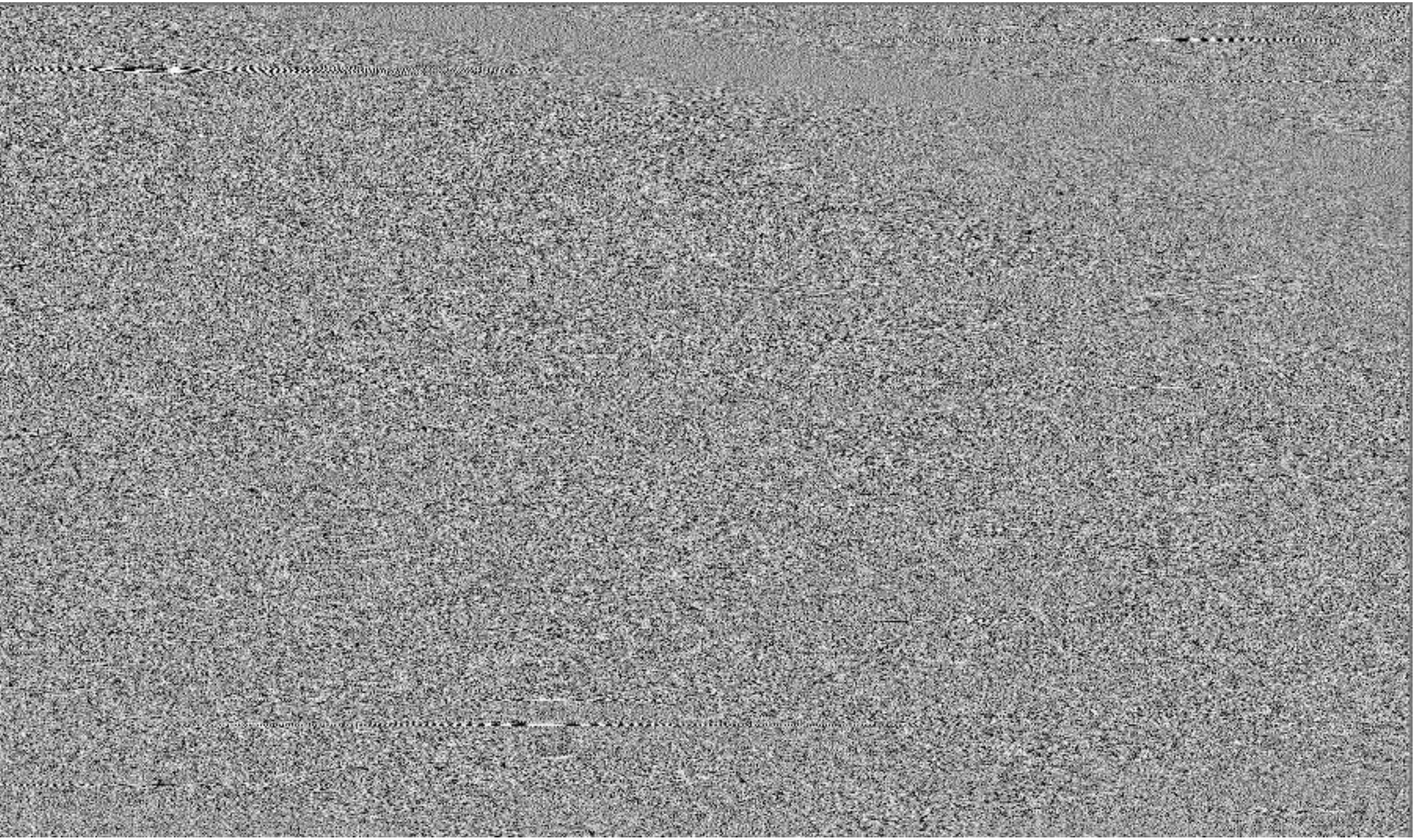


Combination of overlapping acquisitions

Original SAR Observations

azimuth

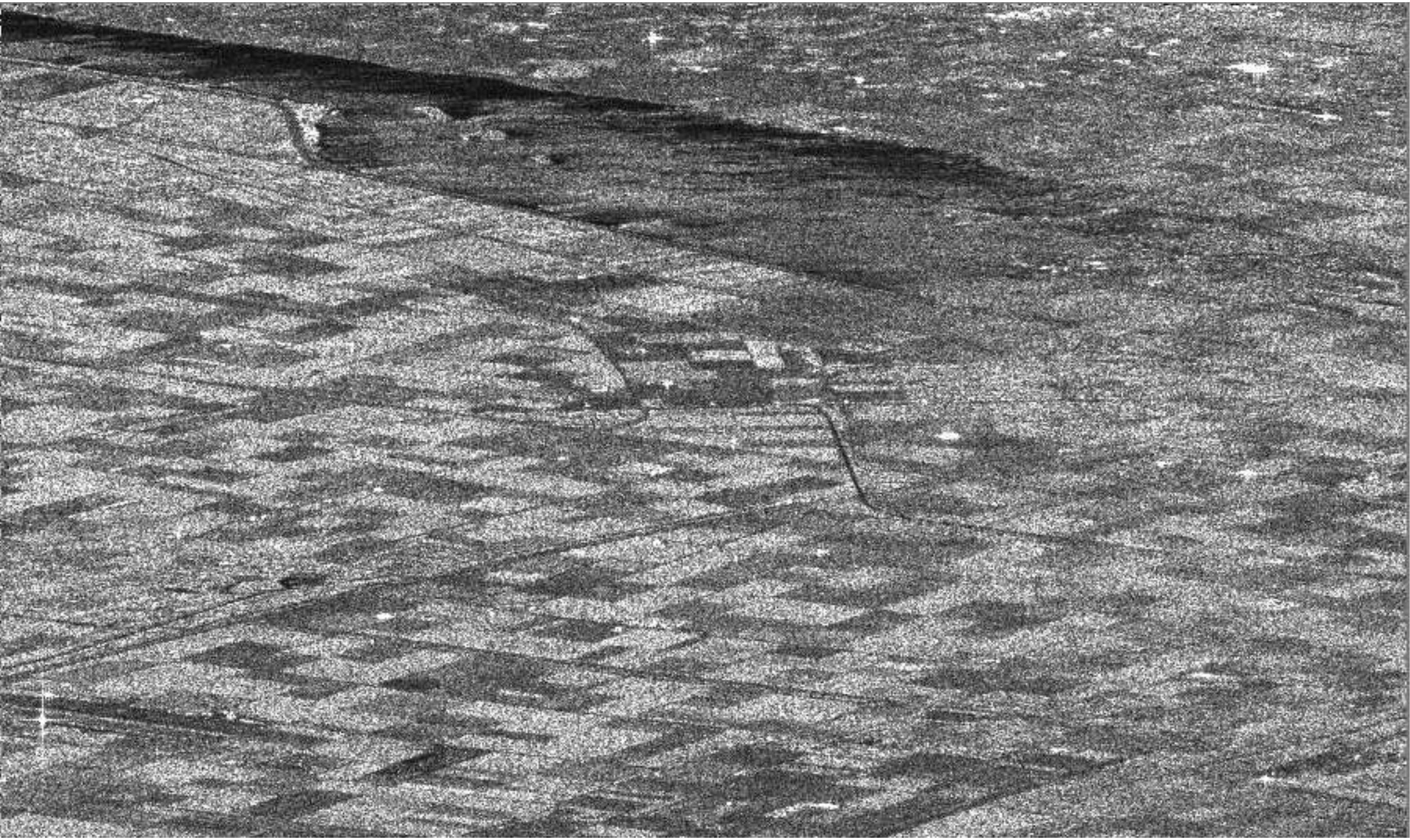
data ERS-1 © ESA



SAR Data After Image Formation

azimuth

data ERS-1 © ESA



SAR Data After Image Formation and Multi-Looking to Reduce Noise

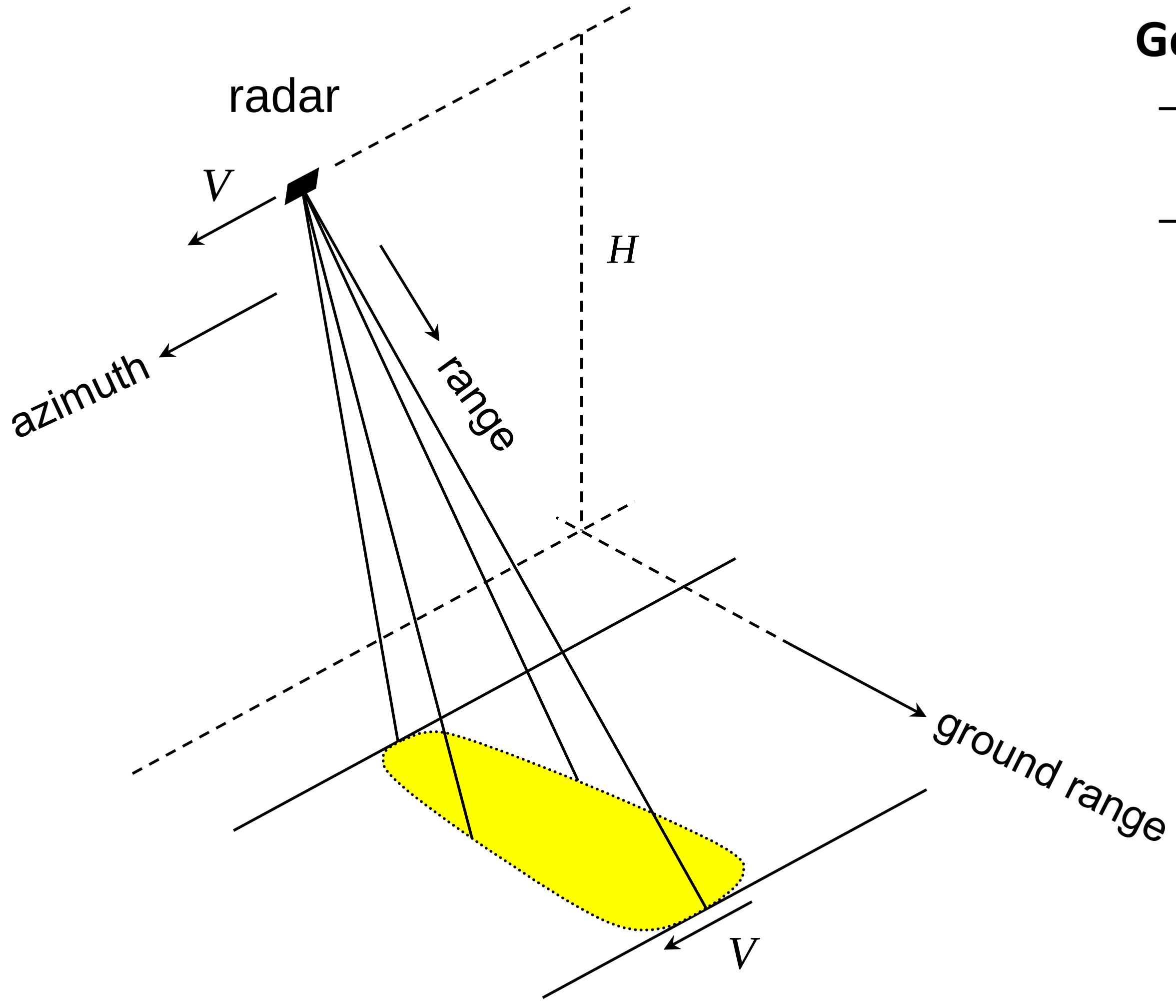
azimuth

data ERS-1 © ESA

after
azimuth pixel averaging by 4
to achieve approximately
square pixels

Different SAR Modes for different Applications

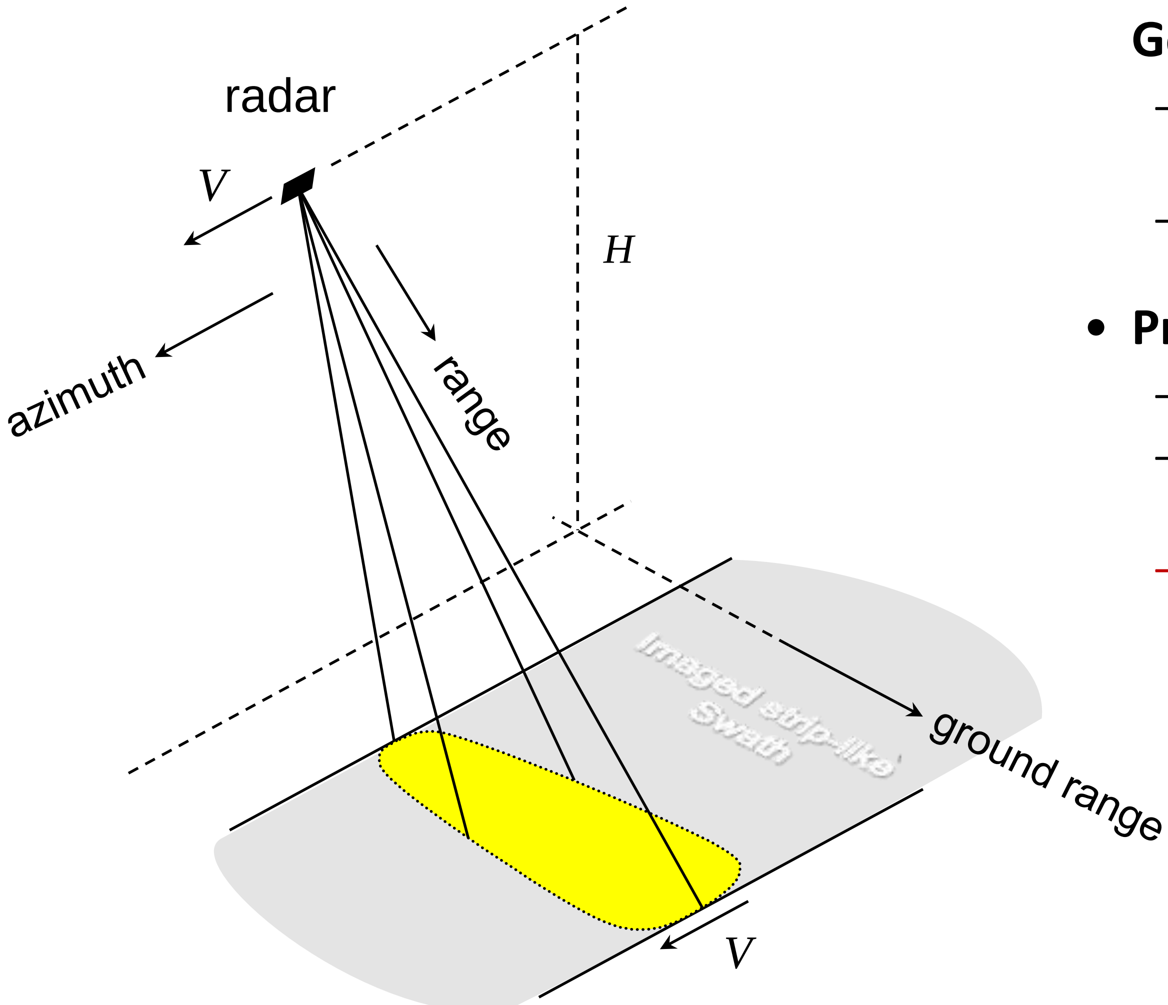
Mode 1: Stripmap Mode SAR



- **Stripmap Mode Observation Geometry:**
  - Radar images a **strip-like swath** parallel to satellite orbit
  - Standard operational mode

Different SAR Modes for different Applications

Mode 1: Stripmap Mode SAR



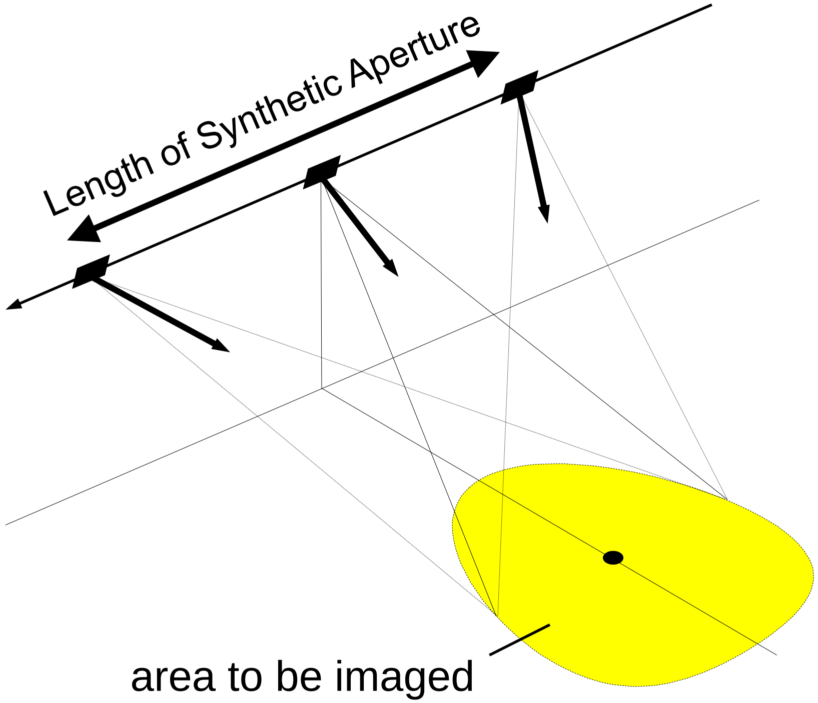
- **Stripmap Mode Observation Geometry:**
  - Radar images a **strip-like swath** parallel to satellite orbit
  - Standard operational mode

- **Properties:**
  - **Intermediate resolution (~10m)**
  - ***Continuous mode → complete areal coverage***
  - **Main application: continuous monitoring of signals of intermediate scale (e.g. sinkholes; road network; surface subsidence)**

Different SAR Modes for different Applications

Mode 2: Spotlight Mode SAR

- **To increase resolution, synthetic aperture length is increased by beam steering to selected area**



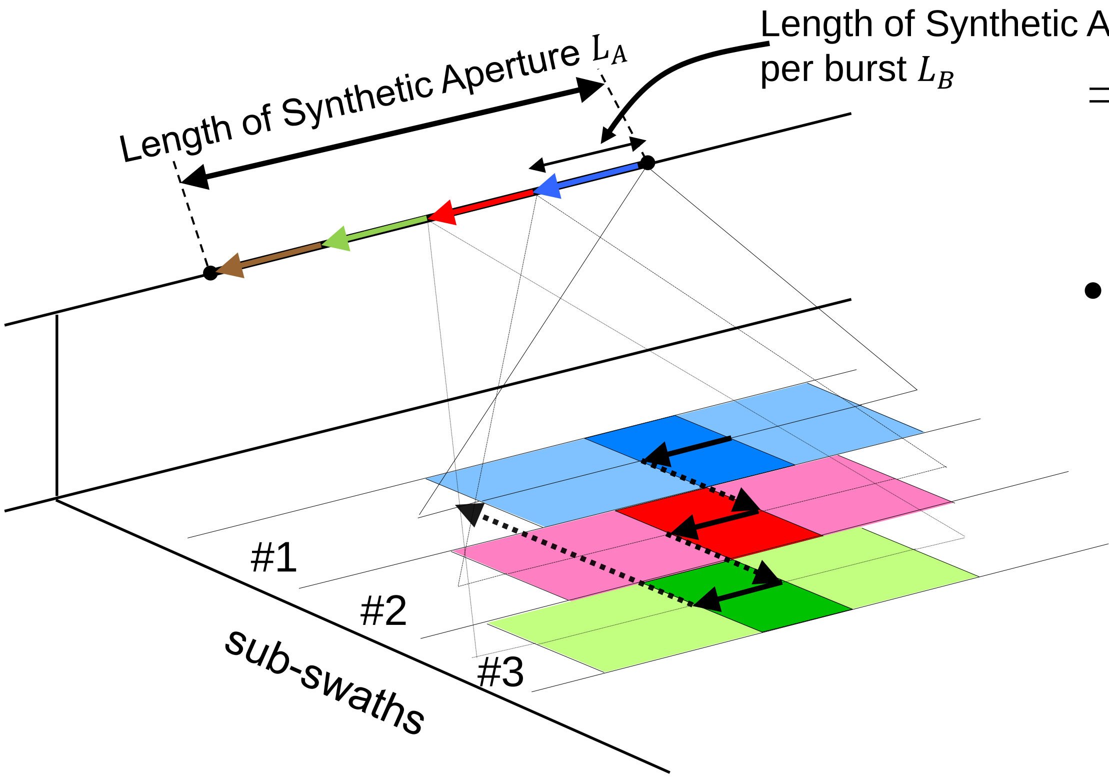
- Non-continuous imaging (areas before and after the selected area cannot be imaged!)
- **Properties:**
  - **Highest spatial resolution (1m-scale)**
  - ***Non-continuous imaging***
  - **Best equipped for high-resolution monitoring of high-priority objects (e.g., bridges, dams, …)**

Summary: higher resolution at the expense of spatial coverage

Different SAR Modes for different Applications

Mode 3: ScanSAR Mode

- **To achieve wider swaths, synthetic aperture is divided into short pieces (bursts)**

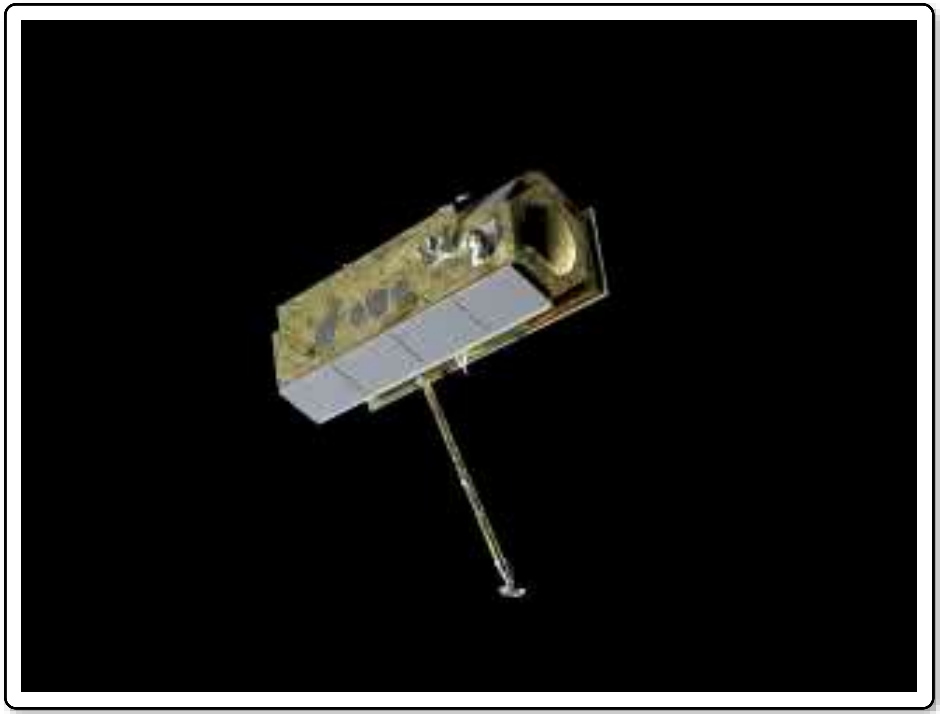


$\Rightarrow$ successive illumination of several parallel swaths for **increased swath width** (100 to 500km)

- **Properties:**
  - **Lowest resolution mode (10s of meters)**
  - ***Highest spatial coverage***
  - **Best suited for quick mapping of large areas → analysis of large-scale signals such as tectonic motion or flooding extent**

Examples of SAR Image Acquisition Modes

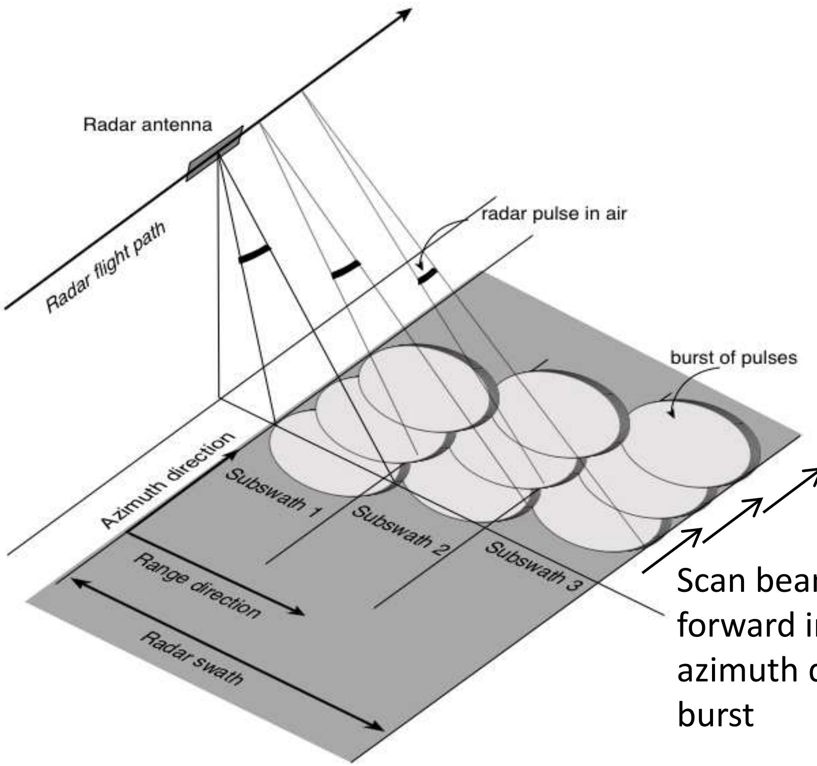
- **Available Image Modes:**
  - **ScanSAR Mode**:
    - Lowest resolution – largest coverage
  - **Stripmap Mode** (standard mode)
    - Intermediate resolution
  - **Spotlight Mode**
    - Highest resolution – limited coverage



Recently Developed SAR Modes

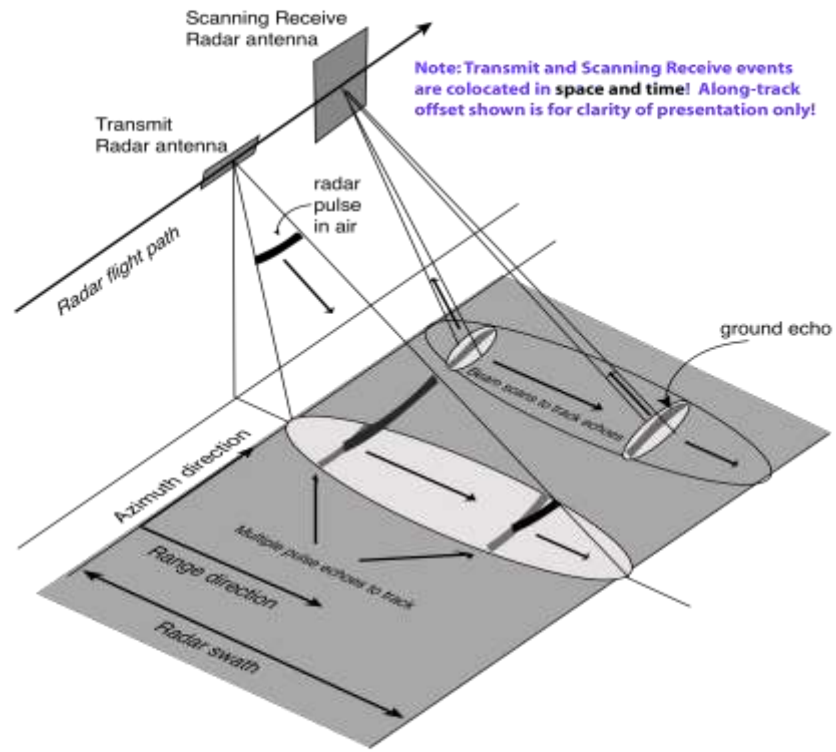
Toward Full Resolution and Wide Swath SARs

Terrain Observation by Progressive Scan (TOPS)



- Time-share synthetic aperture among elevation beams to increase swath
- Scan beam forward in azimuth within burst to improve radiometry
- Degraded azimuth resolution

Scan on Receive SAR (SweepSAR)

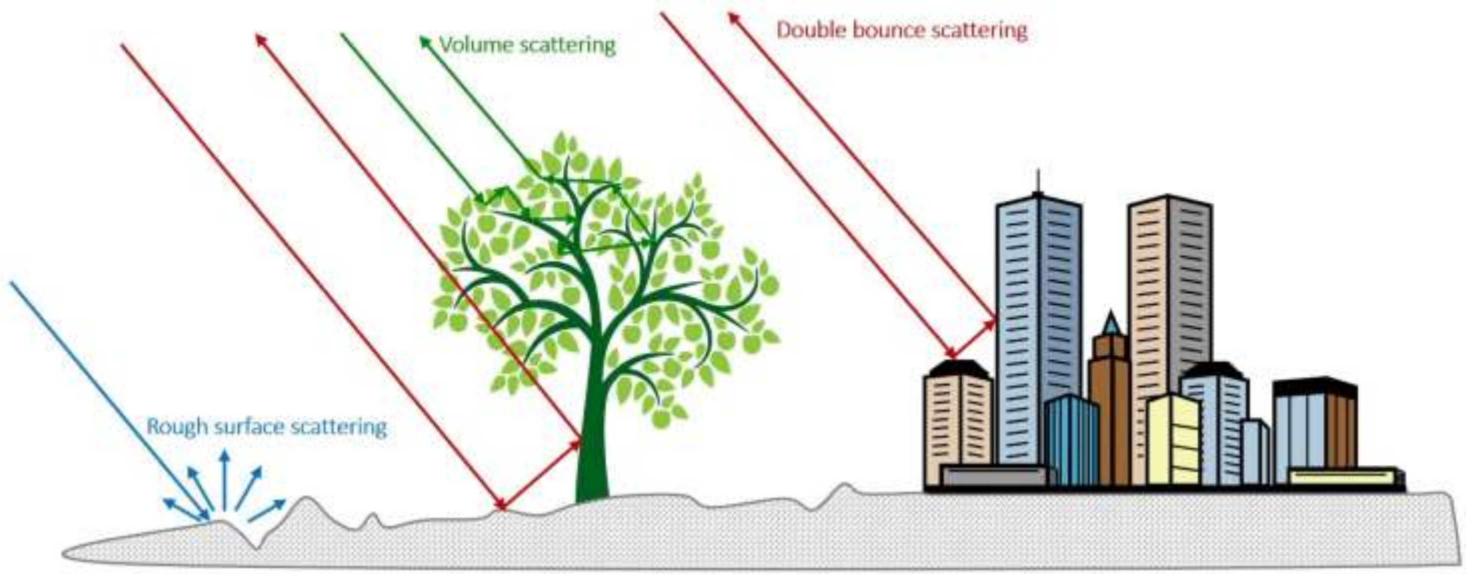


- Time-share pulse returns on receive with multiple receive beams to increase swath
- Track receive echoes as they propagate across the swath
- Narrow receive beam controls ambiguities

WHAT SAR IMAGES LOOK LIKE

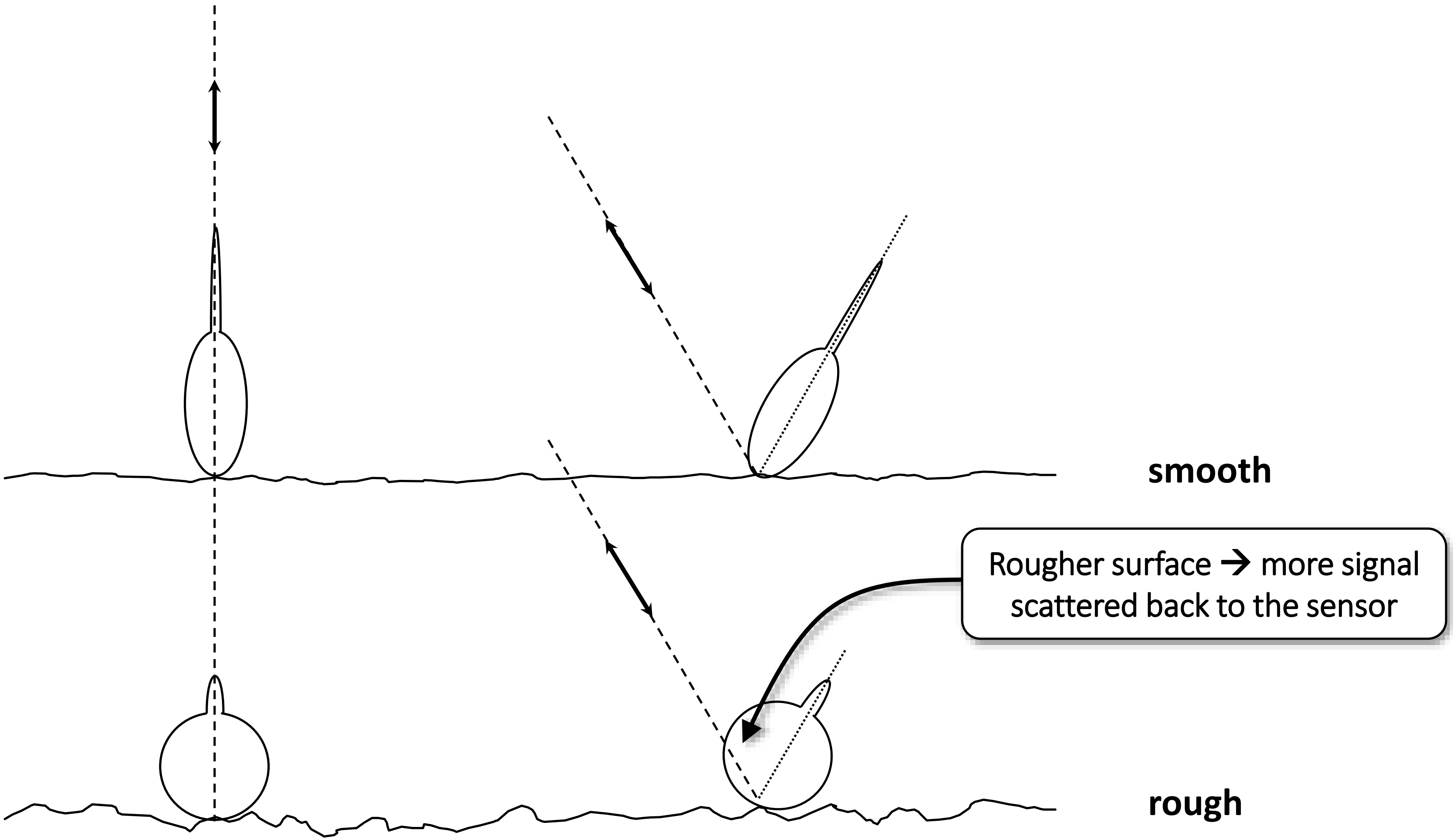
What Does SAR See?

- **At Radar wavelength, scattering is very physical and can be described as a series of bounces on scattering interfaces**
- **Three main scattering mechanisms dominate**:
  - **Scattering on (rough) surfaces**: Water, bare soils, roads – Scattering strongly dependent on surface roughness and sensor wavelength (see Slide #36)
  - **Double-bounce scattering**: Buildings, tree trunks, light poles – little wavelength dependence
  - **Volume Scattering**: Vegetation; dry soils with high penetration – strongly dependent on sensor wavelength and dielectric properties of medium



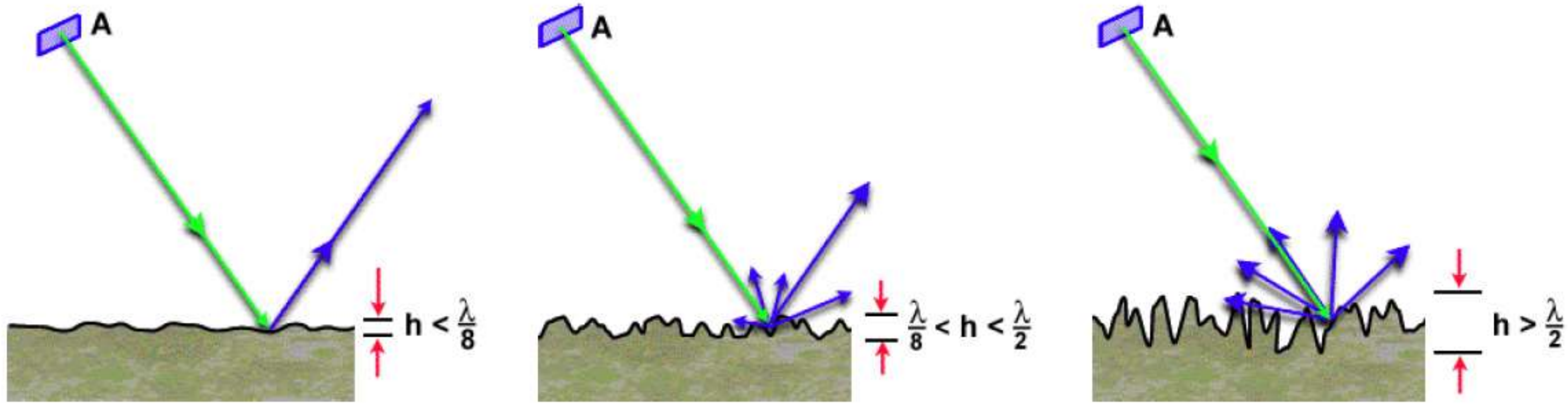
Scattering on Rough Surfaces

Rougher Surfaces → Brighter in SAR Images



Scattering on Rough Surfaces

The Apparent Roughness of a Surface is Strongly Wavelength Dependent



Smooth surface
Specular reflection
No return

Intermediate roughness
Moderate return

Rough surface
Diffuse scattering
Strong return

- **When is a surface rough?** The Fraunhofer criterion (a strict criterion) states:

$$h_{rough} > \frac{\lambda}{32 cos\theta_i}$$

Wavelength Dependence of Roughness

- **Wavelength dependence of radar brightness for given surface roughness h_{rough}:**

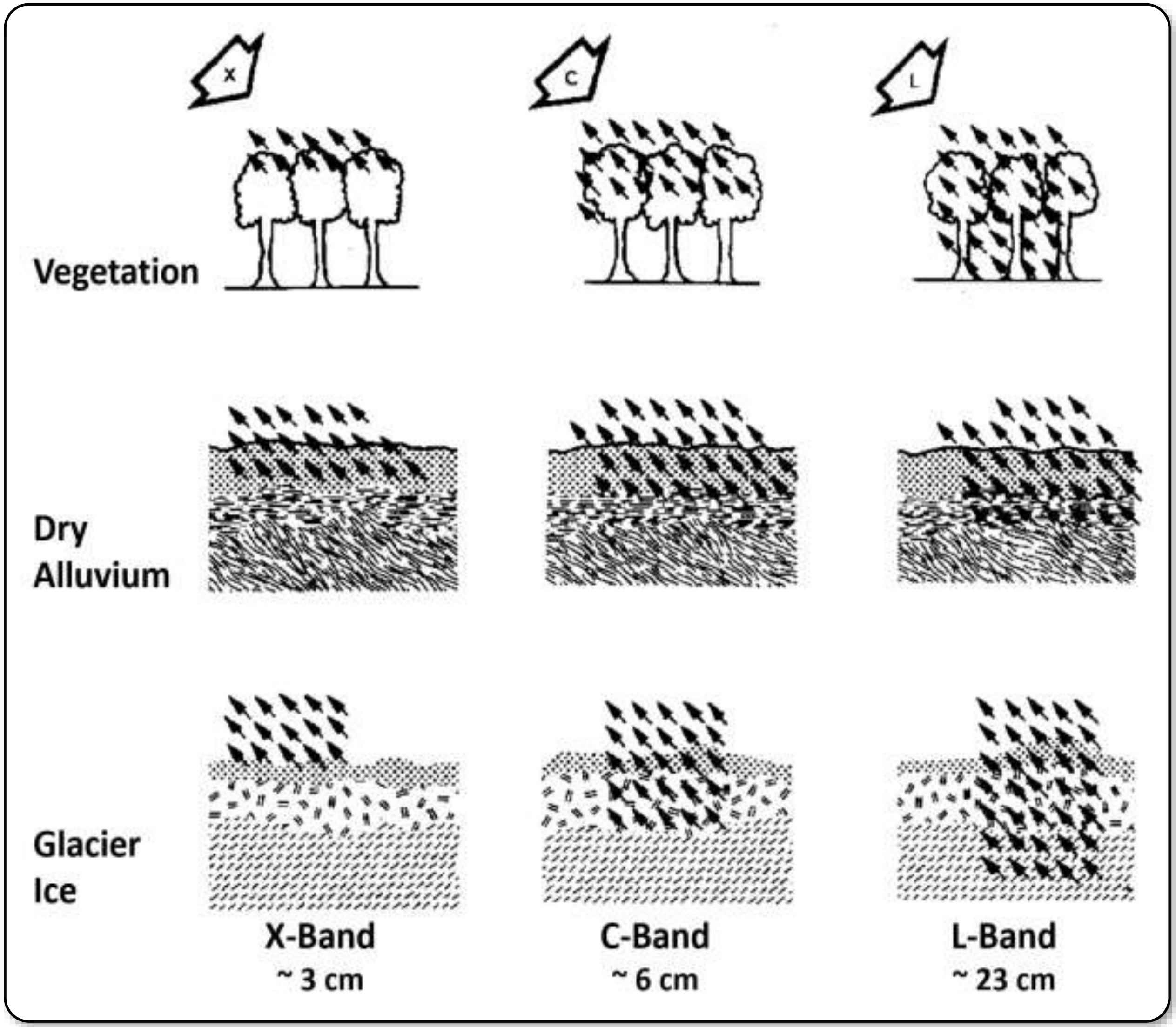
Sensor Wavelength	X-band [[$\lambda \approx 3.5cm$]]	C-band [[$\lambda \approx 5.6cm$]]	L-band [[$\lambda \approx 25cm$]]
Radar Brightness			

Volume Scattering

Penetration into Volumes is Strongly Wavelength Dependent

- **Penetration into vegetation and soils increases with sensor wavelength**
  - L-band penetration > C-band penetration > X-band penetration

- **Penetration into soils also strongly dependent on soil moisture content (see next slide)**



Volume Scattering

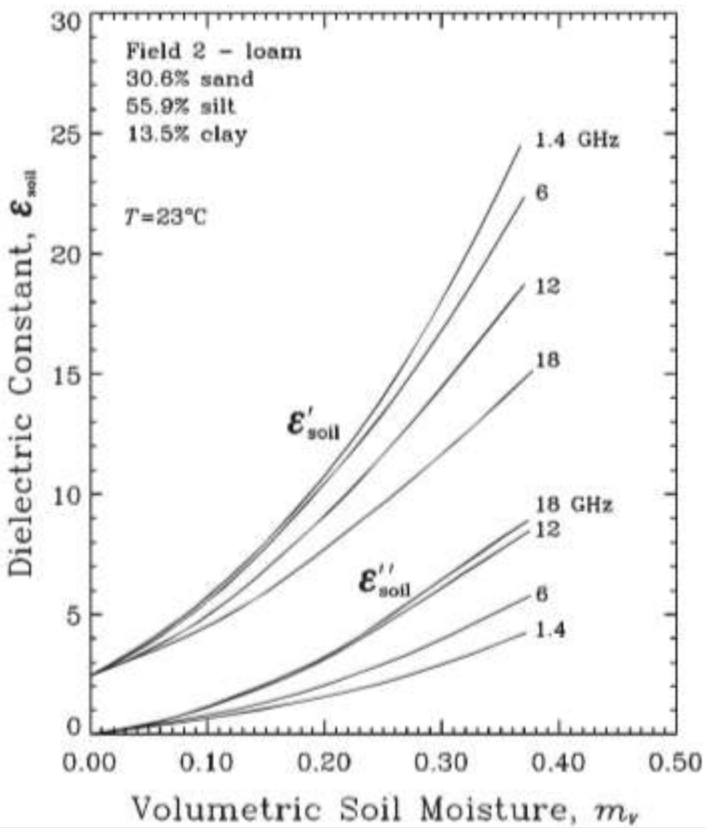
The Role Of Soil Moisture

- **Penetration depth $\boldsymbol{\delta_p}$** into soils **depends on wavelength & complex dielectric constant** $\varepsilon_r = \varepsilon_r' - j\varepsilon_r''$

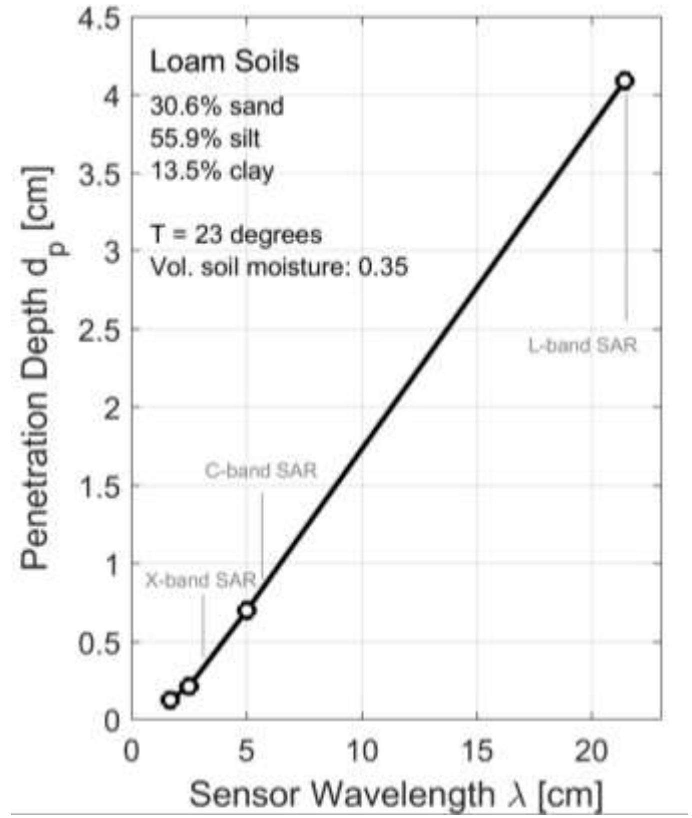
$$\delta_p \approx \frac{\lambda\sqrt{\varepsilon_r'}}{2\pi\varepsilon_r''}$$

- **Dielectric constant is a function of soil moisture:**

Dependence of Dielectric Constant on Soil Moisture

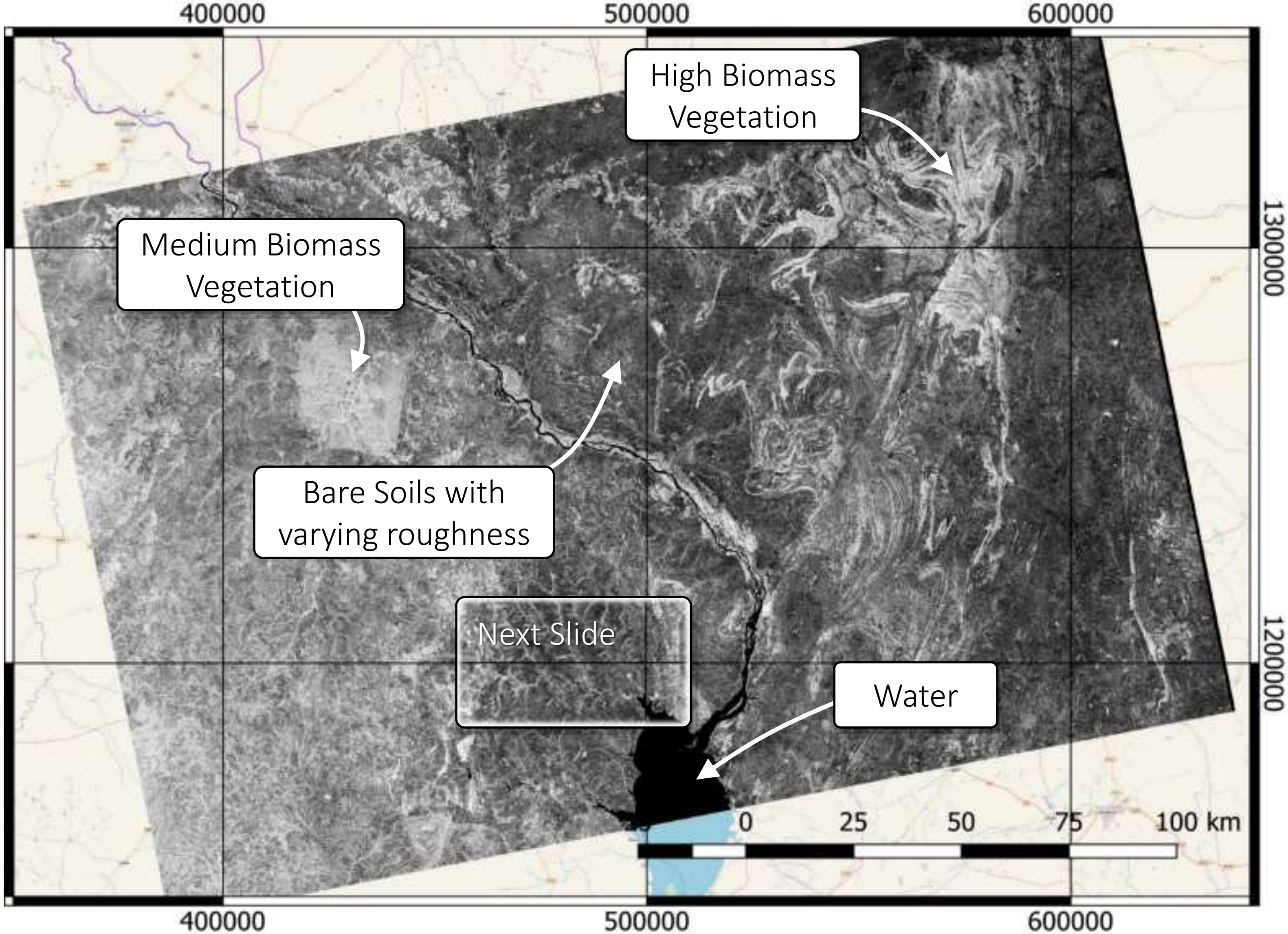


For a Given Soil Moisture, penetration increases with wavelength λ



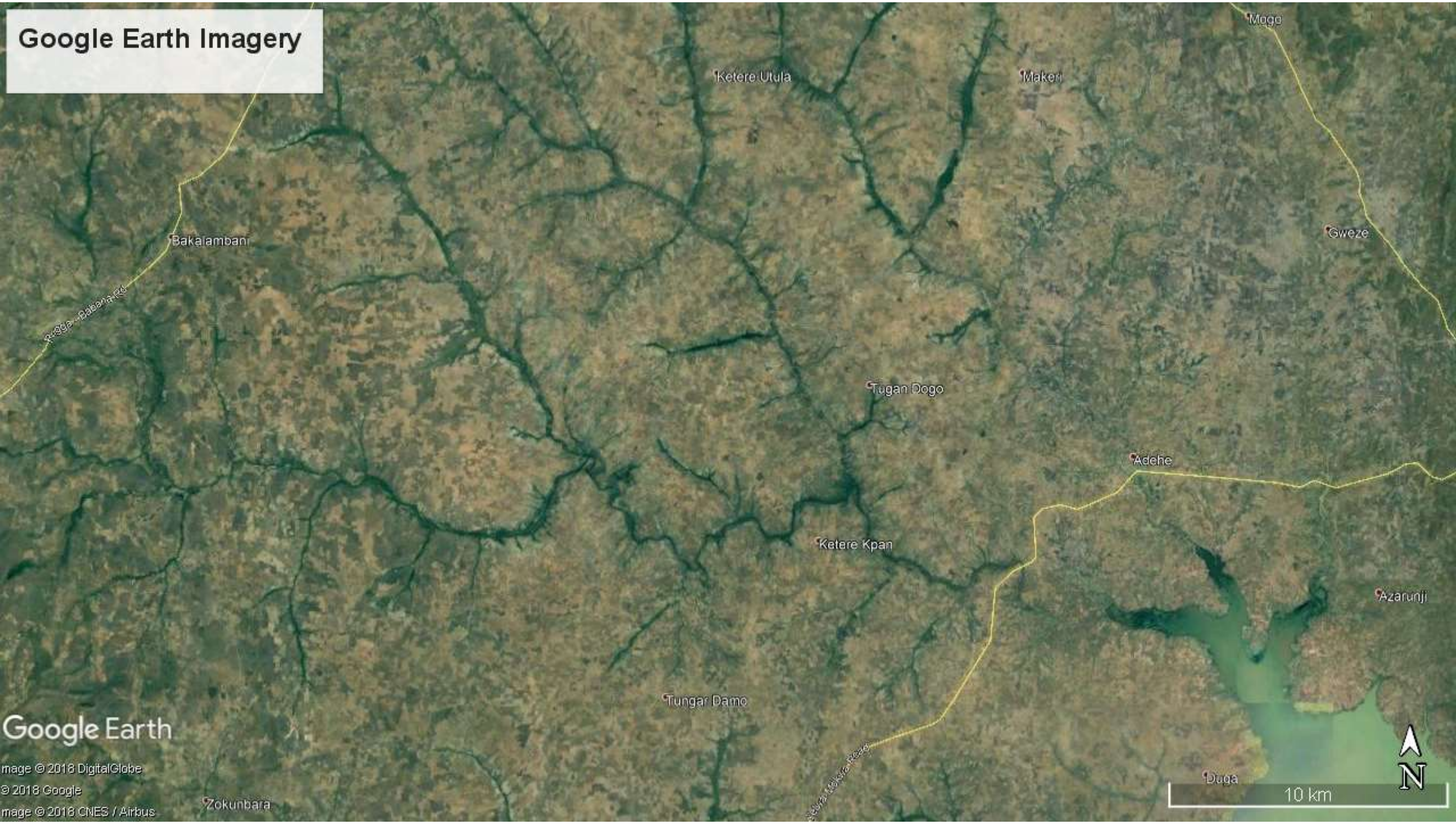
SAR Data Example

Southern Niger – Sentinel-1 [C-band; VV polarization]



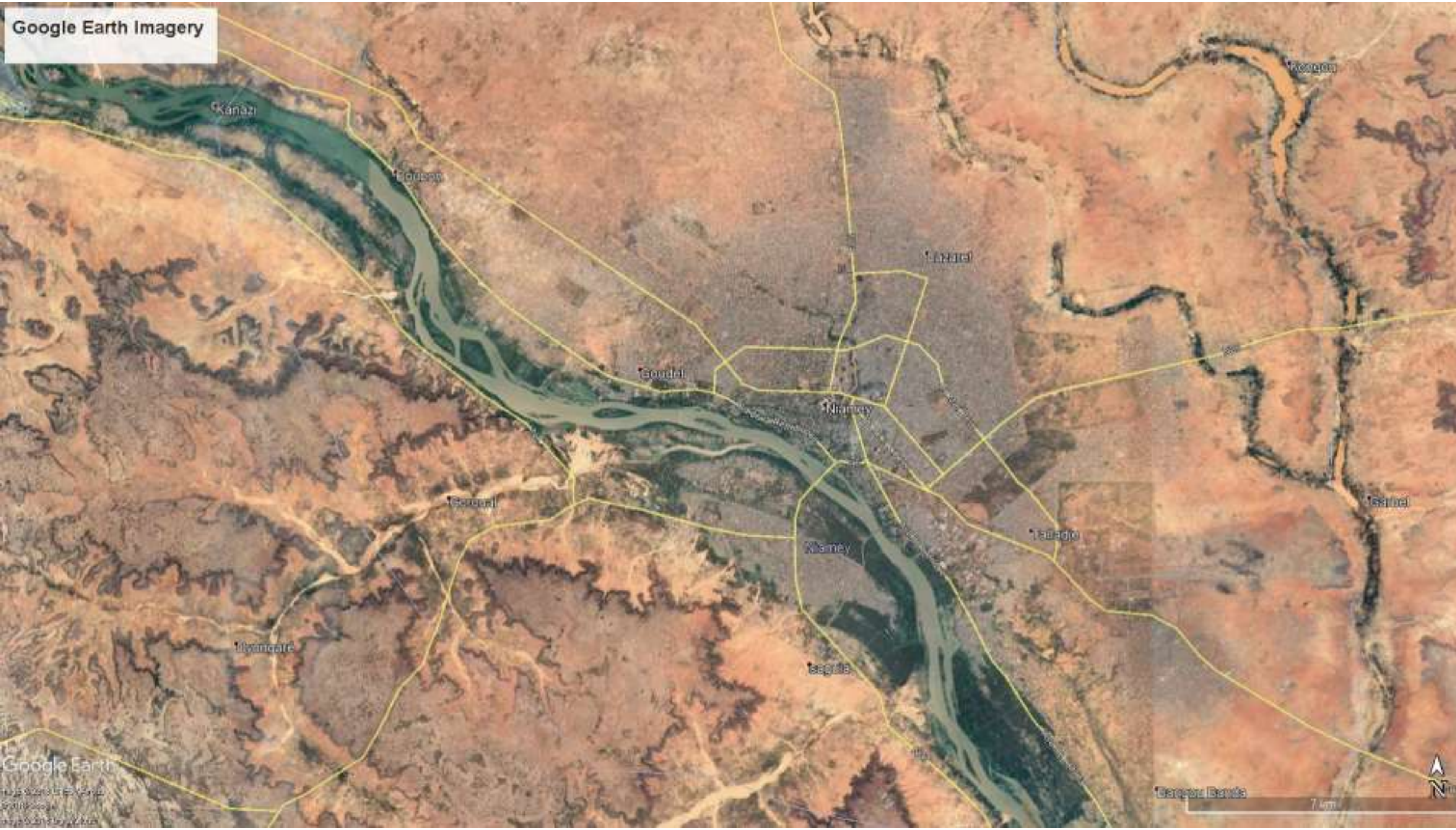
SAR Data Example

Southern Niger – Sentinel-1 [C-band; VV polarization] - subset



SAR Data Example

Niamey, Niger – Sentinel-1 [C-band; VV polarization] - subset



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SUMMARY

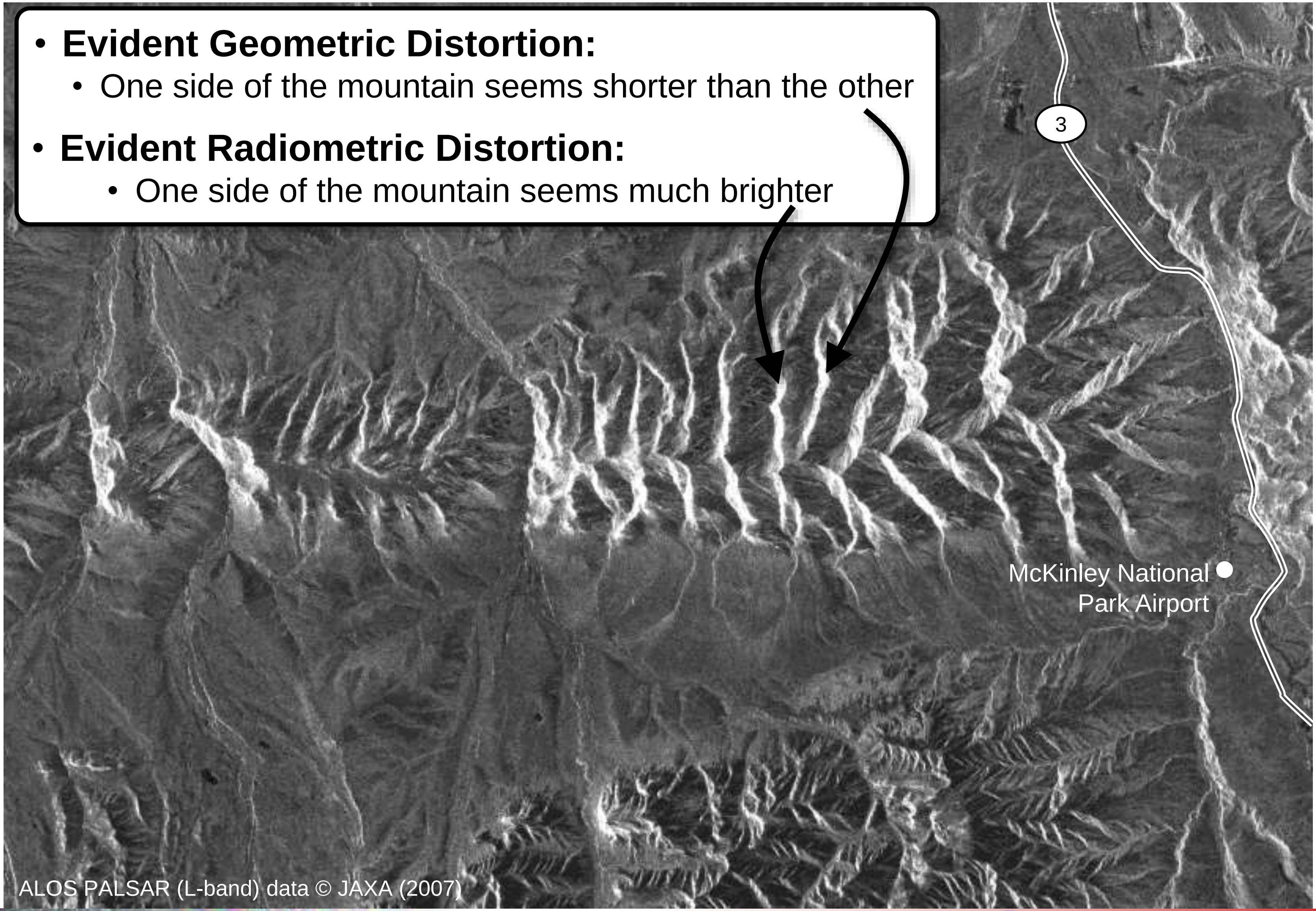
Problems to Solve when Trying to Use SAR Data for Geophysical Analysis

- **Problem 1:** SAR data suffers from geometric distortions owing to the side-looking observation geometry
- **Solution:** We will identify distortions and look for ways to remove them

- **Problem 2:** SAR images appear noisy, making interpretation harder
- **Solution:** We will describe the noise and talk about filtering methods

- **Problem 3:** SAR data is in the acquisition coordinate system defined by the Azimuth and Slant Range directions
- **Solution:** We will talk about Geocoding

Example of a Geometric and Radiometric Distortions in SAR Imagery

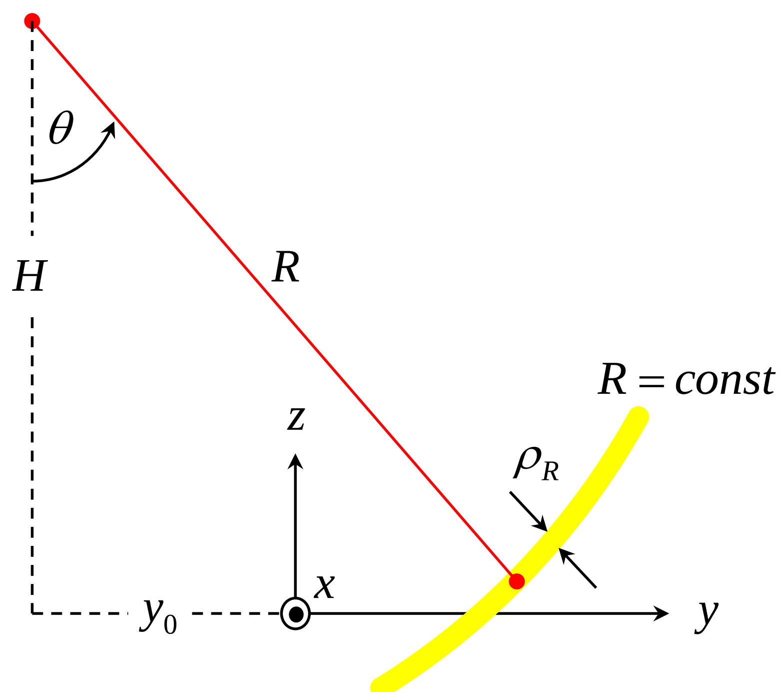


GEOMETRIC DISTORTIONS

Geometric Distortions are Caused by the Slant Observation Geometry of SAR Systems

For SAR images processed to 'zero-Doppler' geometry: $\begin{pmatrix} x \\ y \\ z \end{pmatrix} \rightarrow \begin{pmatrix} x \\ R \end{pmatrix}$

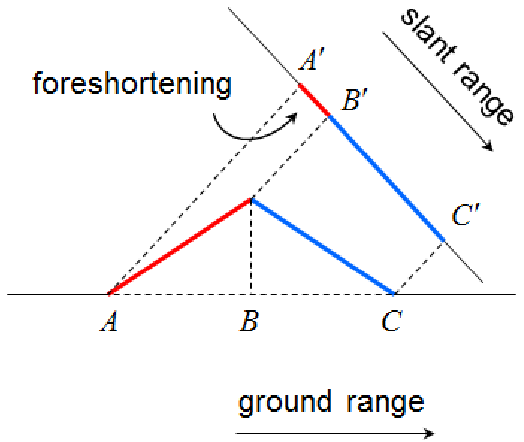
where $R = \sqrt{(y_0 + y)^2 + (H - z)^2}$



Three Types of Geometric Distortions Occur As a Consequence of Oblique Look Angle

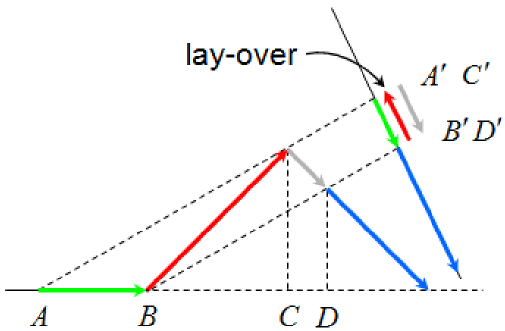
Foreshortening

- Sensor-facing slope forshortened in image
- Foreshortening effects *decrease* with increasing look angle



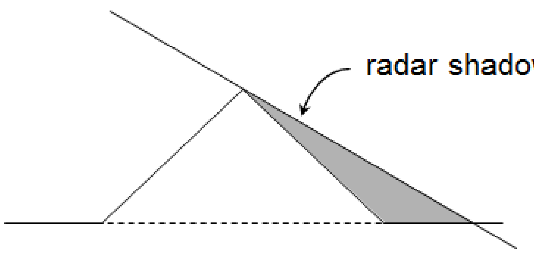
Layover

- Mountain top overlain on ground ahead of mountain
- Layover effects *decrease* with increasing look angle



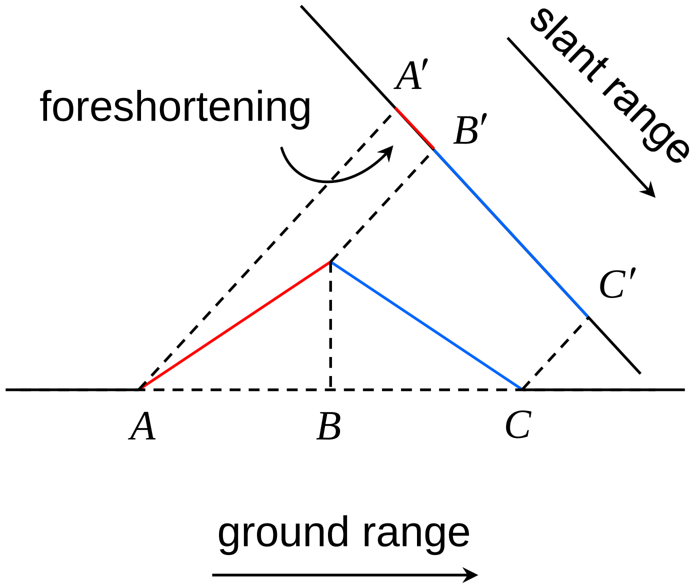
Shadow

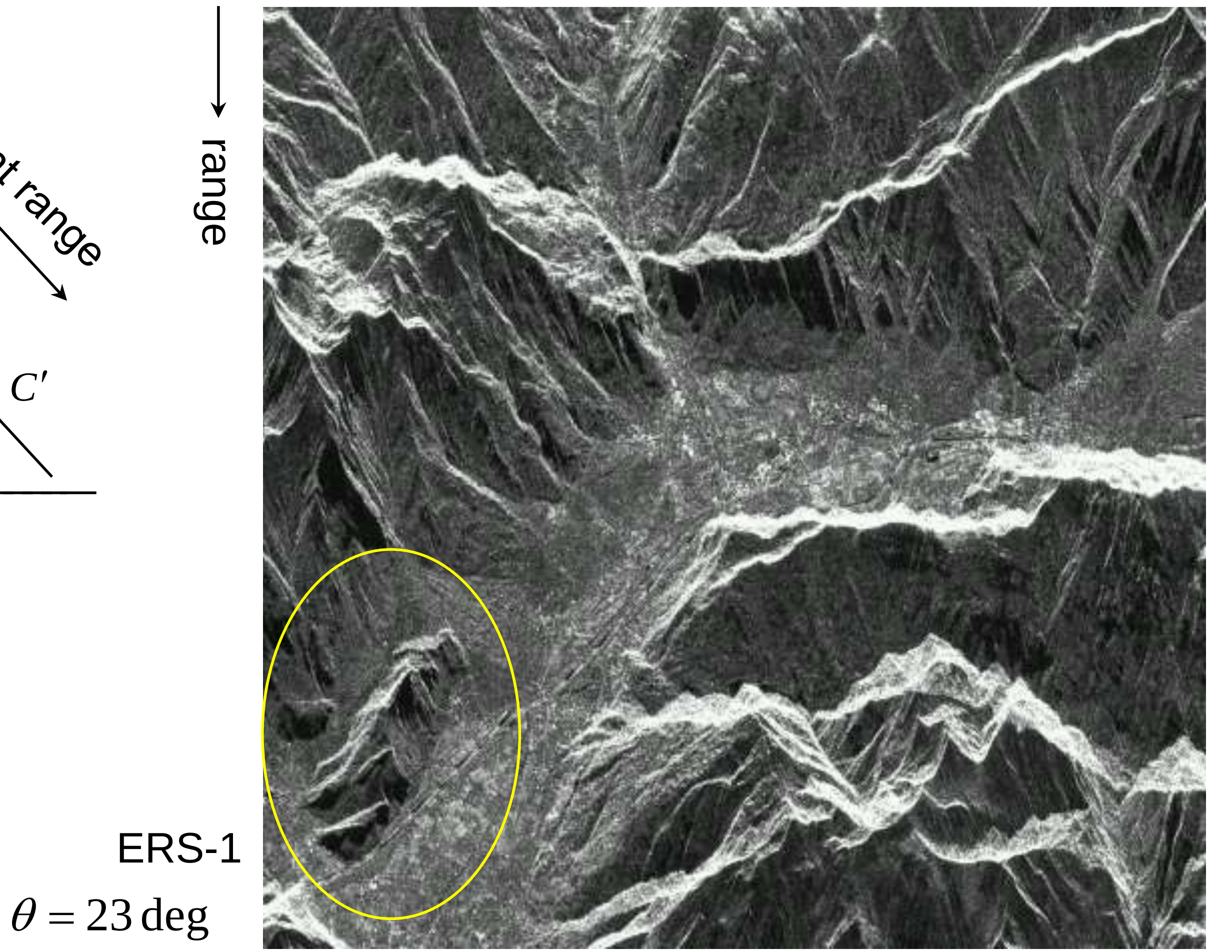
- Area behind mountain cannot be seen by sensor
- Shadow effects *increase* with increasing look angle



Geometric Distortions of SAR Images

1. Foreshortening

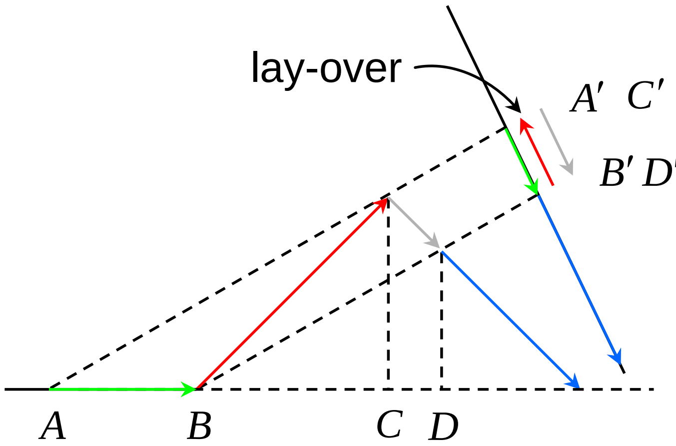


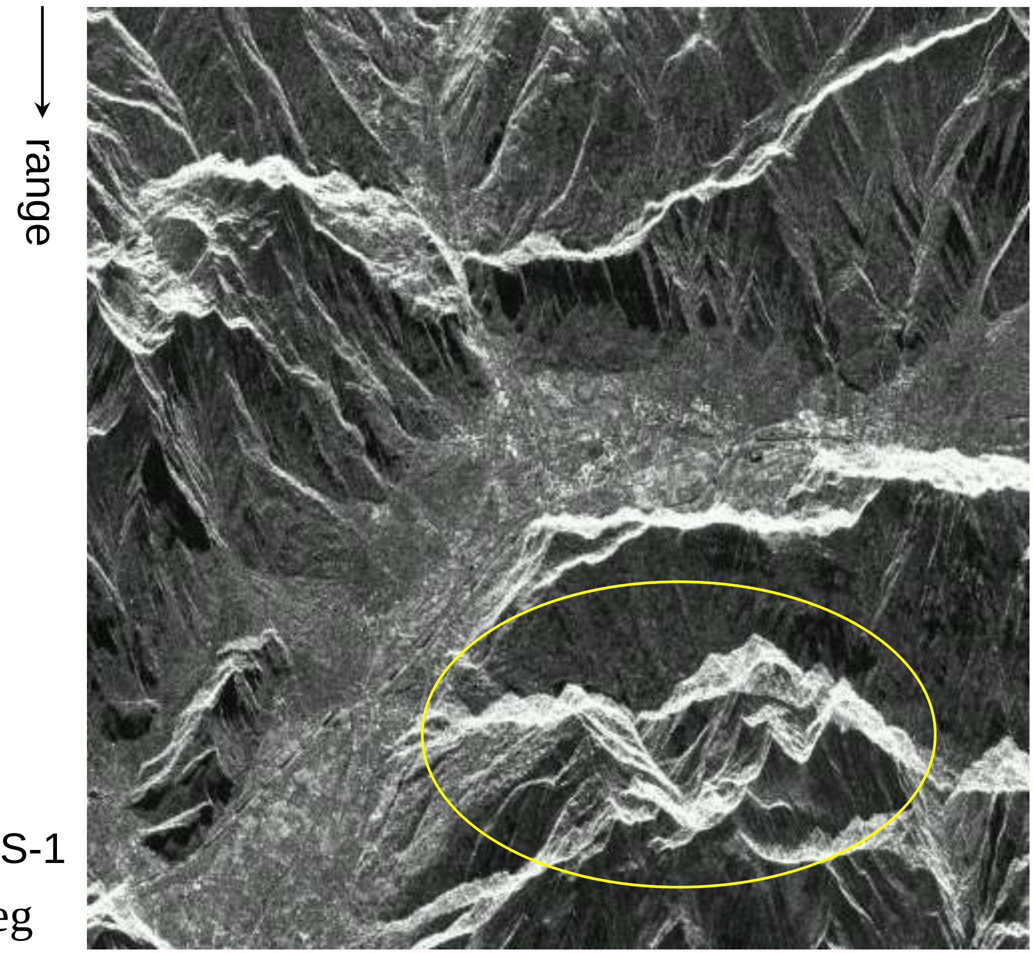


data © ESA

Geometric Distortions of SAR Images

2. Layover





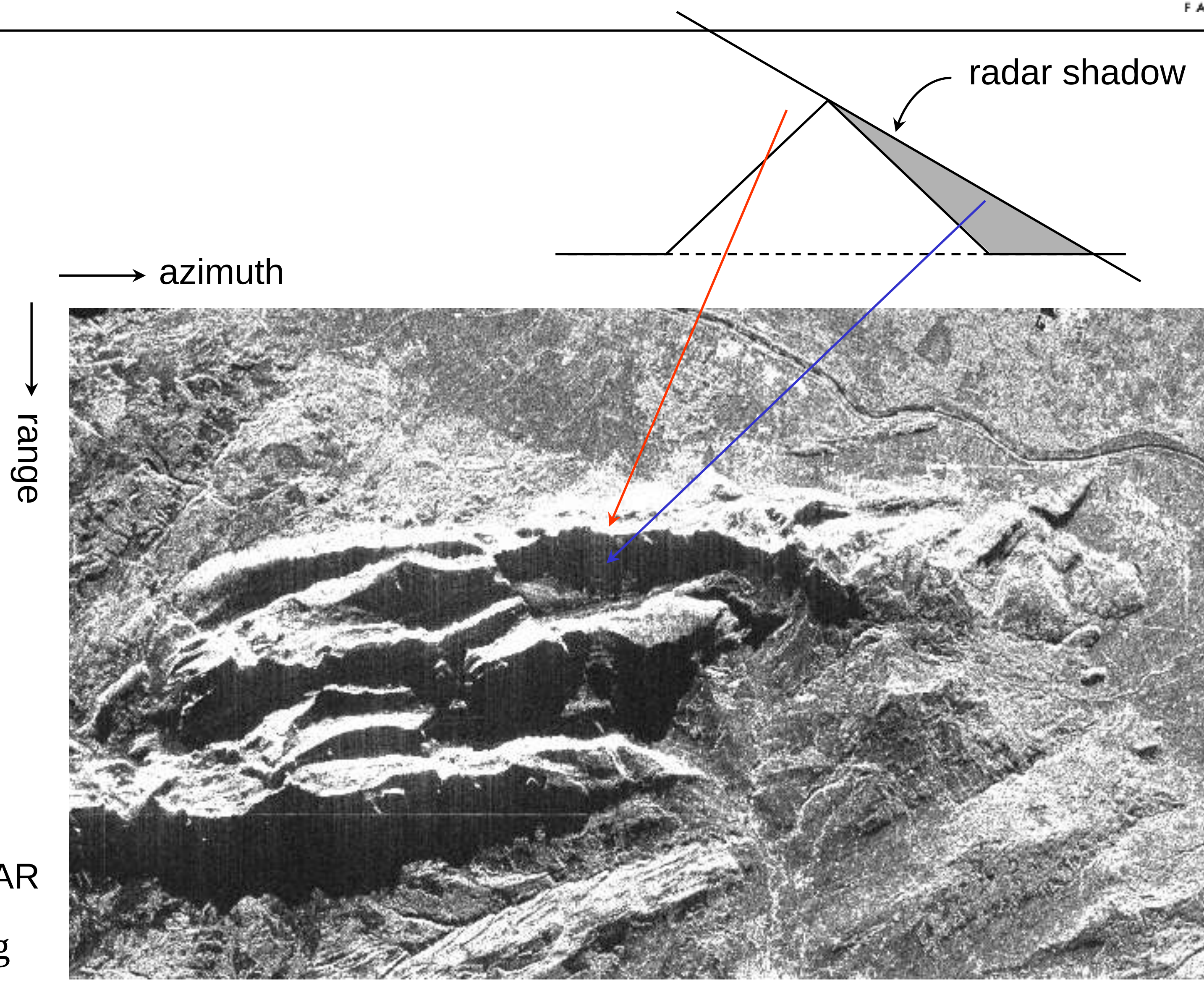
ERS-1

$\theta = 23\,\mathrm{deg}$

data © ESA

Geometric Distortions of SAR Images

3. Shadow

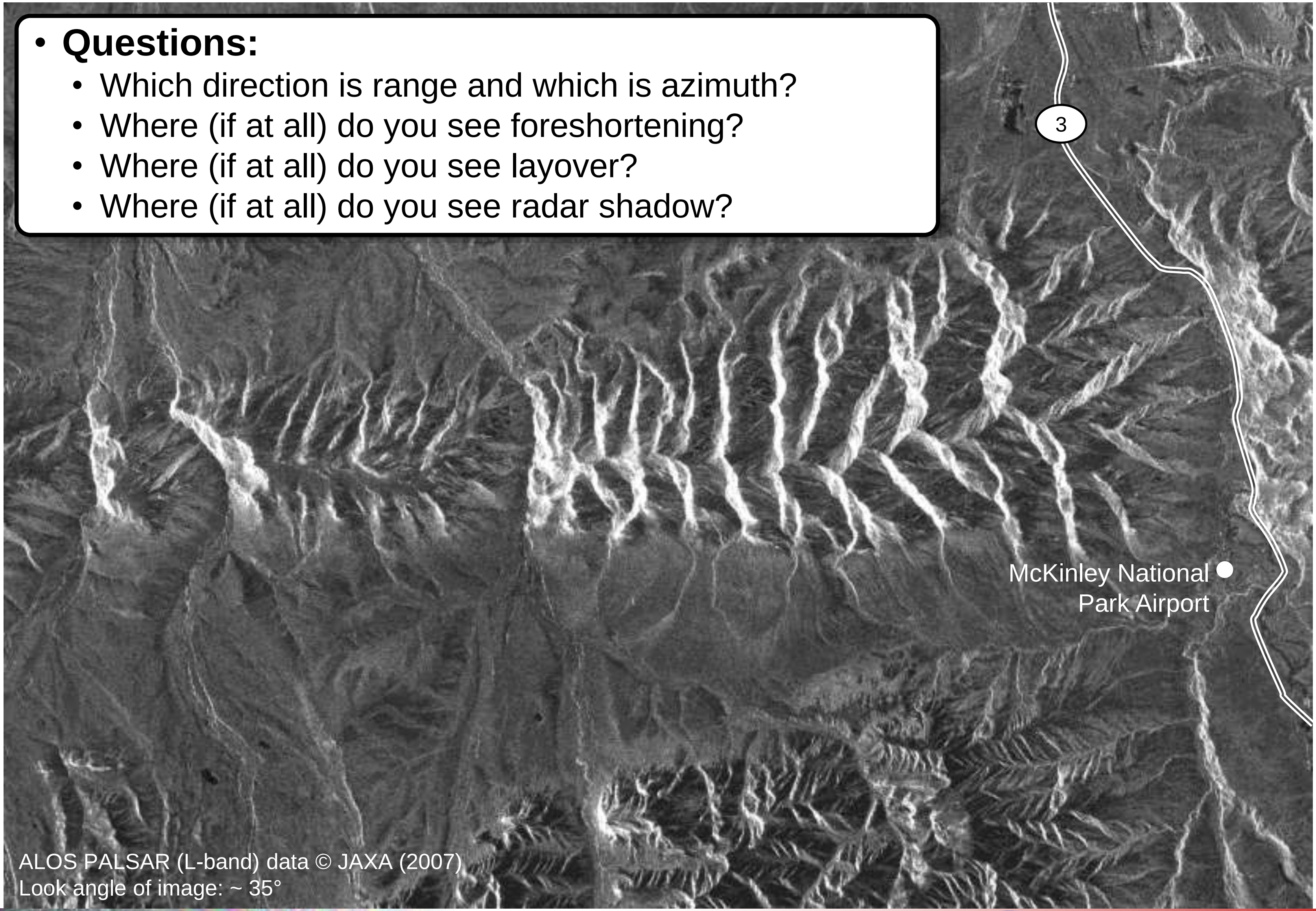


SRTM/X-SAR

$\theta = 54 \text{ deg}$

Example of a Geometric and Radiometric Distortions in SAR Imagery

- **Questions:**
  - Which direction is range and which is azimuth?
  - Where (if at all) do you see foreshortening?
  - Where (if at all) do you see layover?
  - Where (if at all) do you see radar shadow?



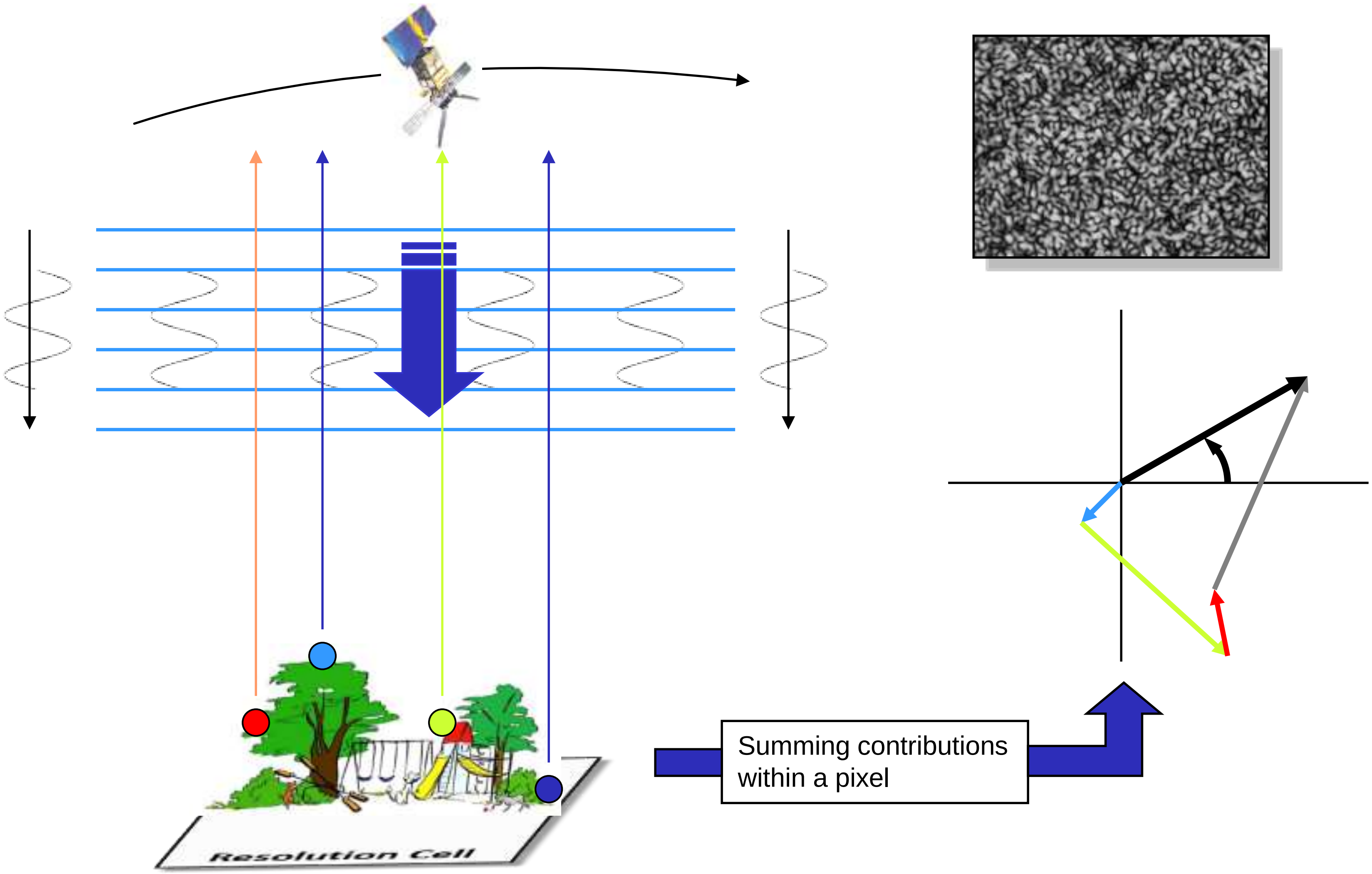
RADIOMETRIC DISTORTIONS

SAR Images Often Appear a Bit Noisy

- **Do you see the noise?**
- **This noise is caused "Speckle" and is an inherent property of all coherent imaging systems**
- **Technically speaking, it is not noise but an interference pattern**

  http://www.astronomy.com/news/2015/02/a-new-way-to-view-titan-despeckle-it

Coherent Waves and Speckle

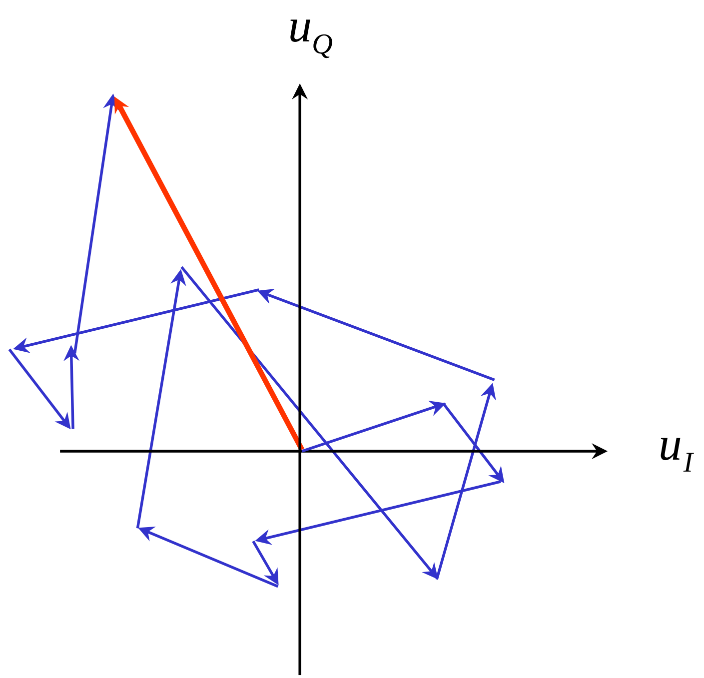


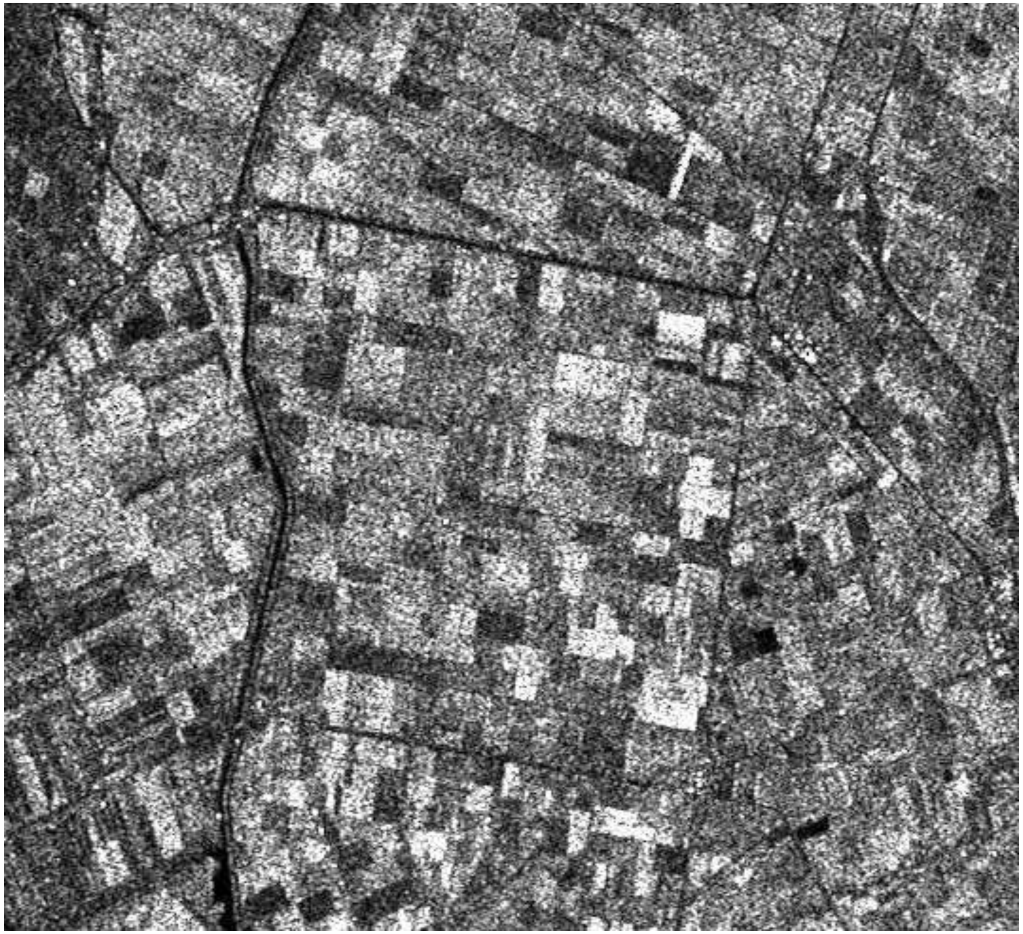
Speckle

Random positive and negative interference of wave contributions from the many individual scatterers within one resolution cell

→ varying brightness from pixel to pixel even for constant σ^0

→ granular appearance

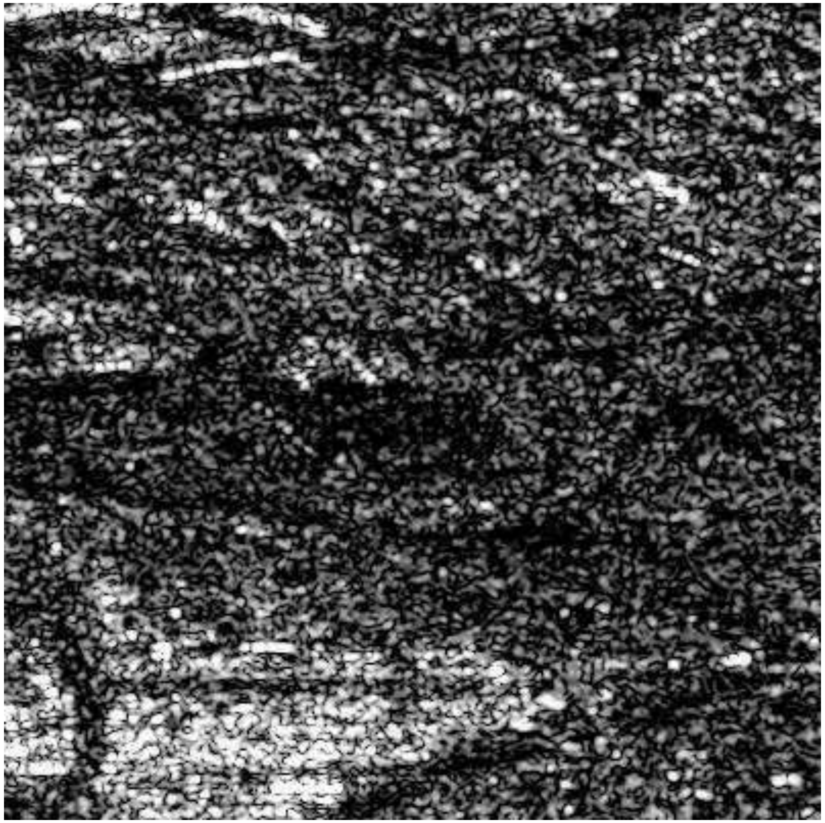




Speckle Example

Time Series of SAR Images

incoherent average of 70 ERS SAR images



individual images (9 years)

- **Right image** shows how speckle can vary over time and in space
- **Left image** shows that *on average*, the backscatter from an area is equal to its radar cross section σ^0

Speckle Reduction

- ***SPECKLE is a scattering phenomenon and not noise. However, speckle can be modeled as multiplicative noise for distributed targets (Lee, IGARSS-98)***

- Speckle “masks” underlying image

- **Speckle filtering:**
  - **GOAL: Reduction of the speckle noise without sacrificing information content (including the spatial resolution)**
  - **PRINCIPLE:** ***Select homogeneous neighboring pixels and then average***

- **Simplest form of speckle reduction:** averaging of adjacent pixels (box filter) or **multi-looking → loss of resolution**

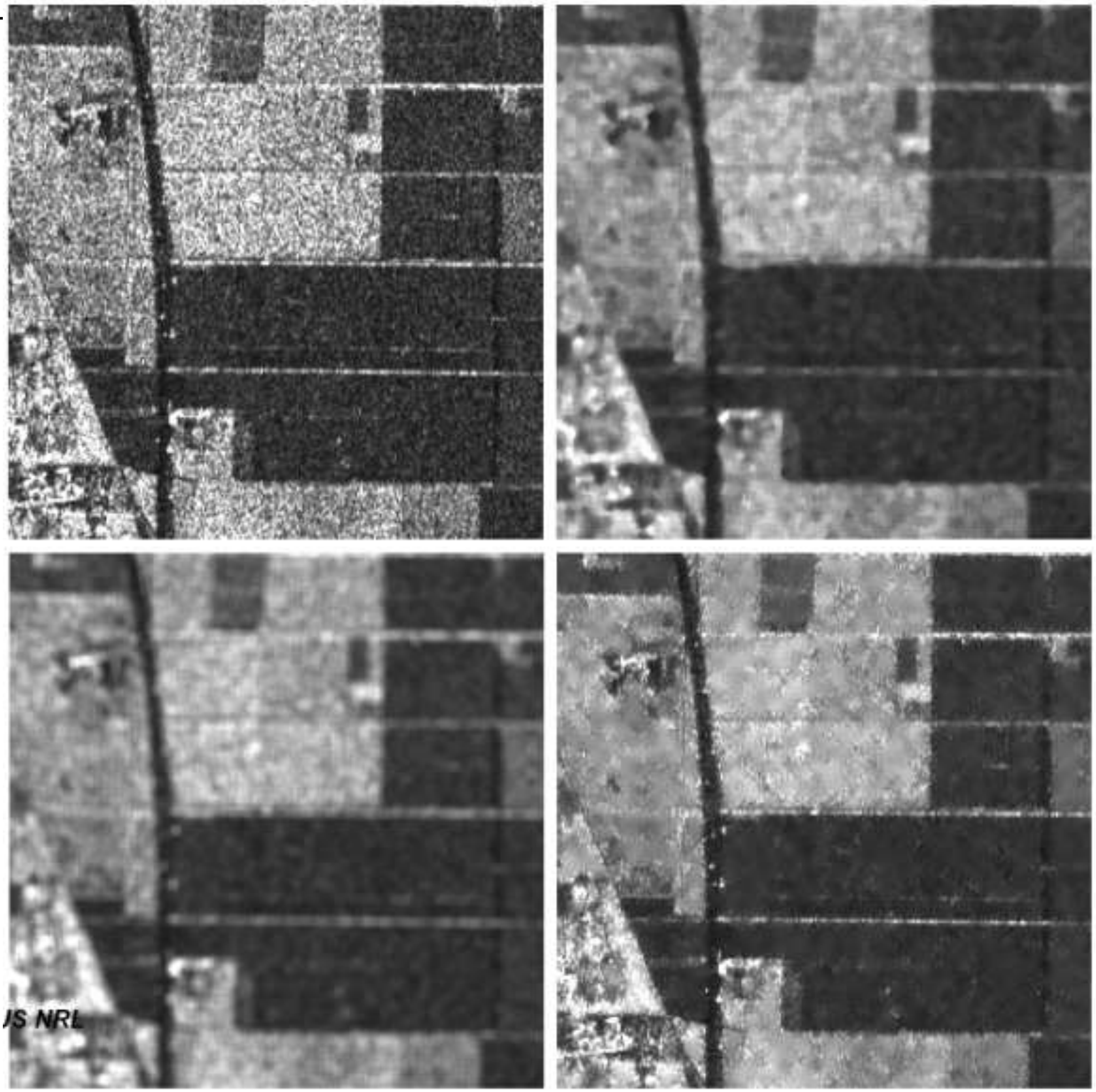
- More complex models (try to limit resolution degradation)

Speckle Reduction

Example

Original
4-look
amplitude

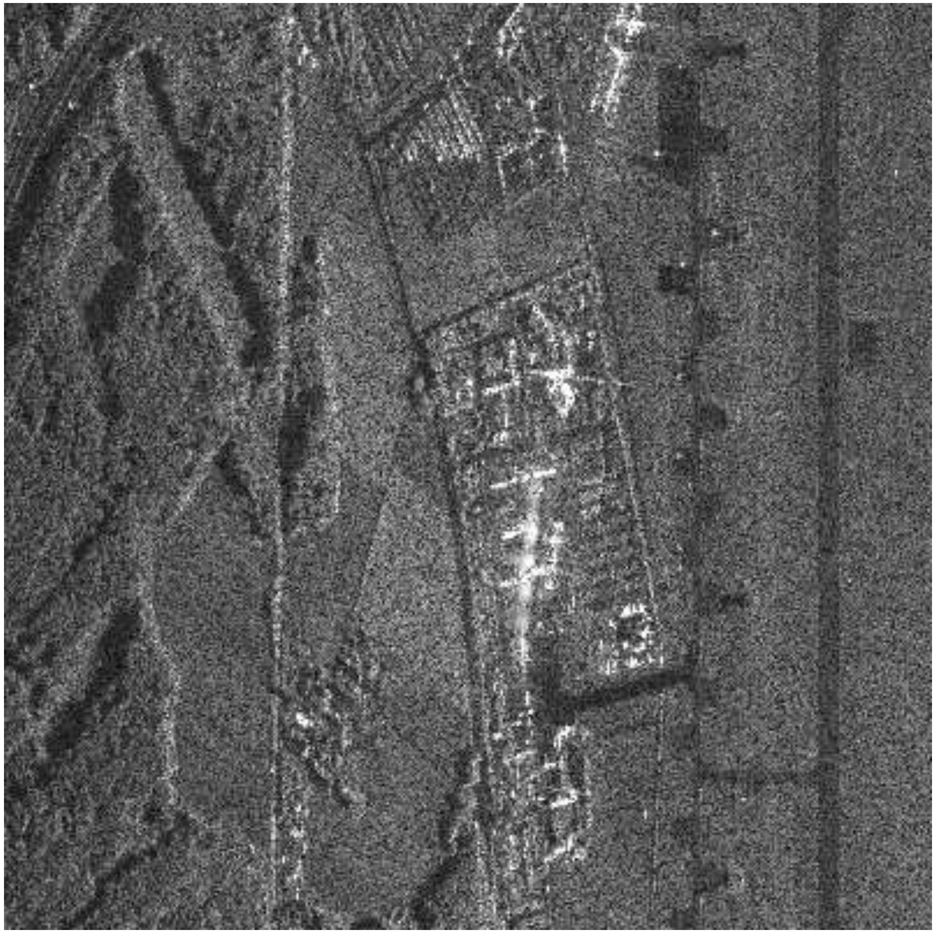
5x5 Median



5x5 Boxcar

Lee refined
(7x7)

Example for Bayesian Speckle Reduction



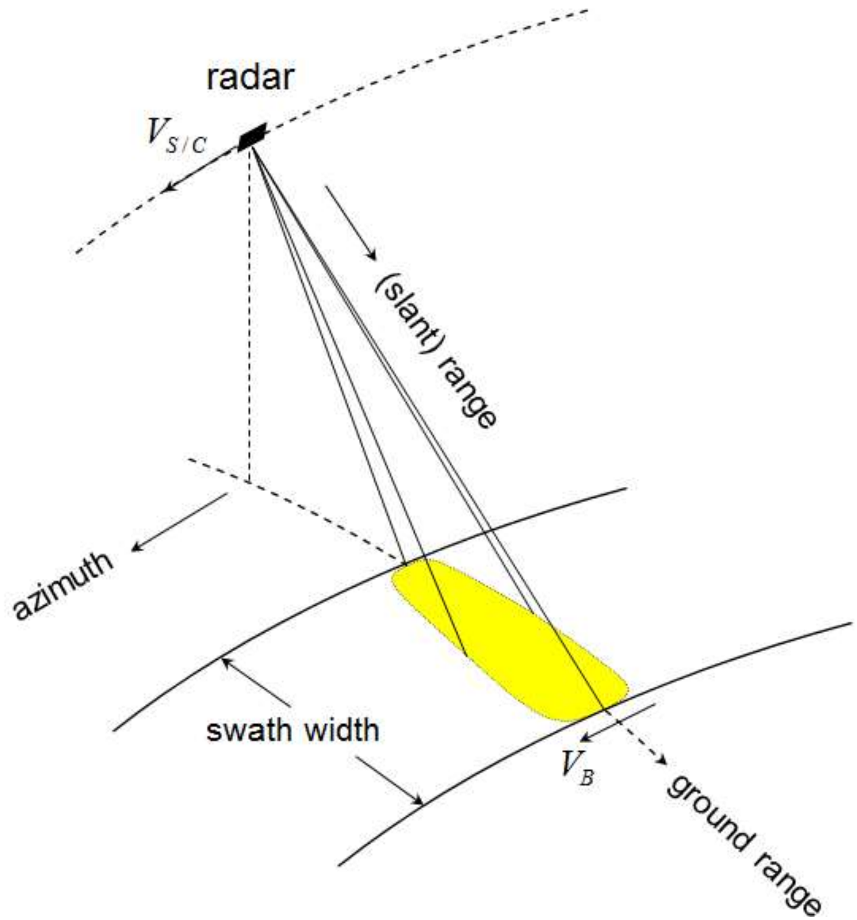
Original SAR Image
SAR data © AeroSensing GmbH

Speckle Filtered
Bayesian Algorithm

GEOCODING AS WELL AS GEOMETRIC & RADIOMETRIC CORRECTION

Geocoding Using a Sensor Model

- **Sensor model**
  - sensor specific
  - analytical reconstruction of image formation using orbit and sensor parameters
  - Digital Elevation Model (DEM) required to correct image globally



Geocoding Steps

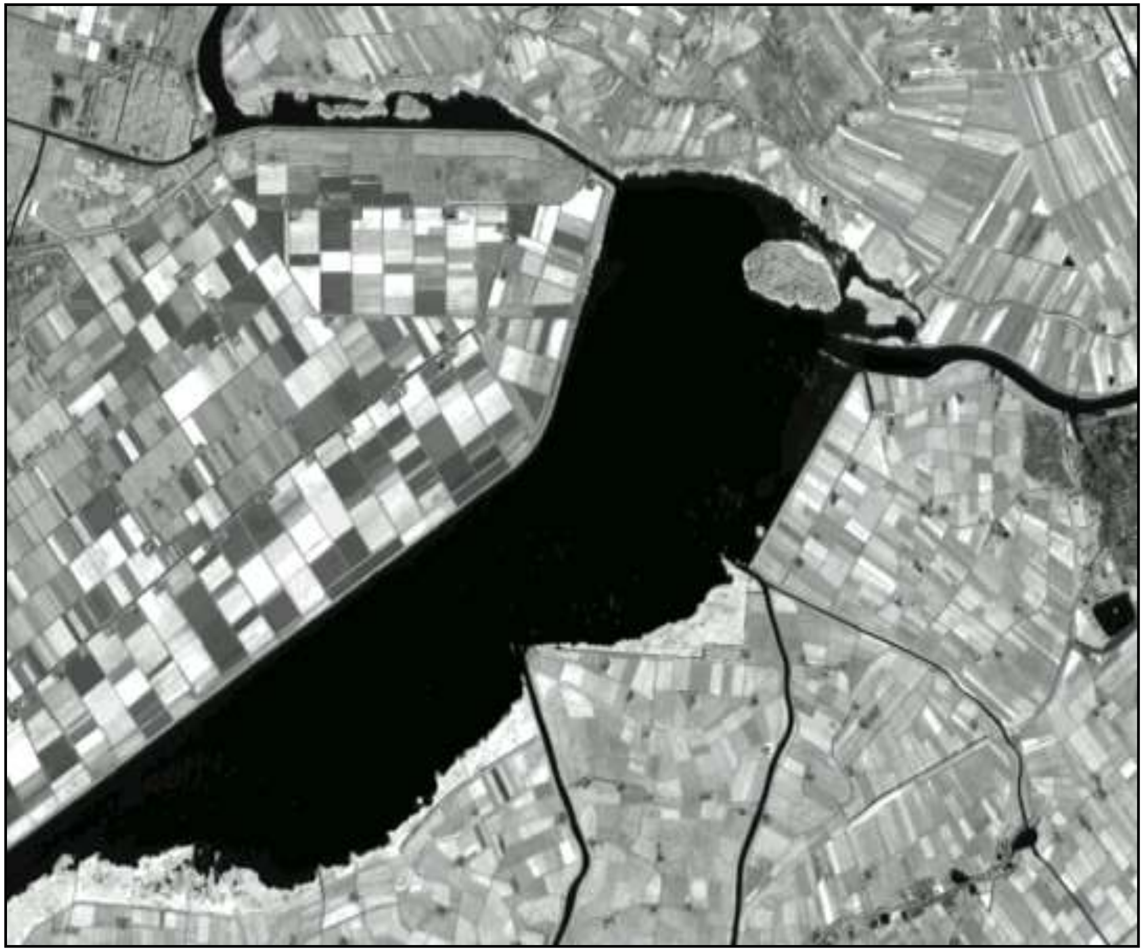
1. **Relation between image coordinates and geographic coordinates using image and sensor geometry and DEM information**
   - line / sample → latitude / longitude

2. **Conversion of geographic coordinates into map-projected coordinates**
   - latitude / longitude → x_{map} / y_{map}
   - choice of map projection and datum

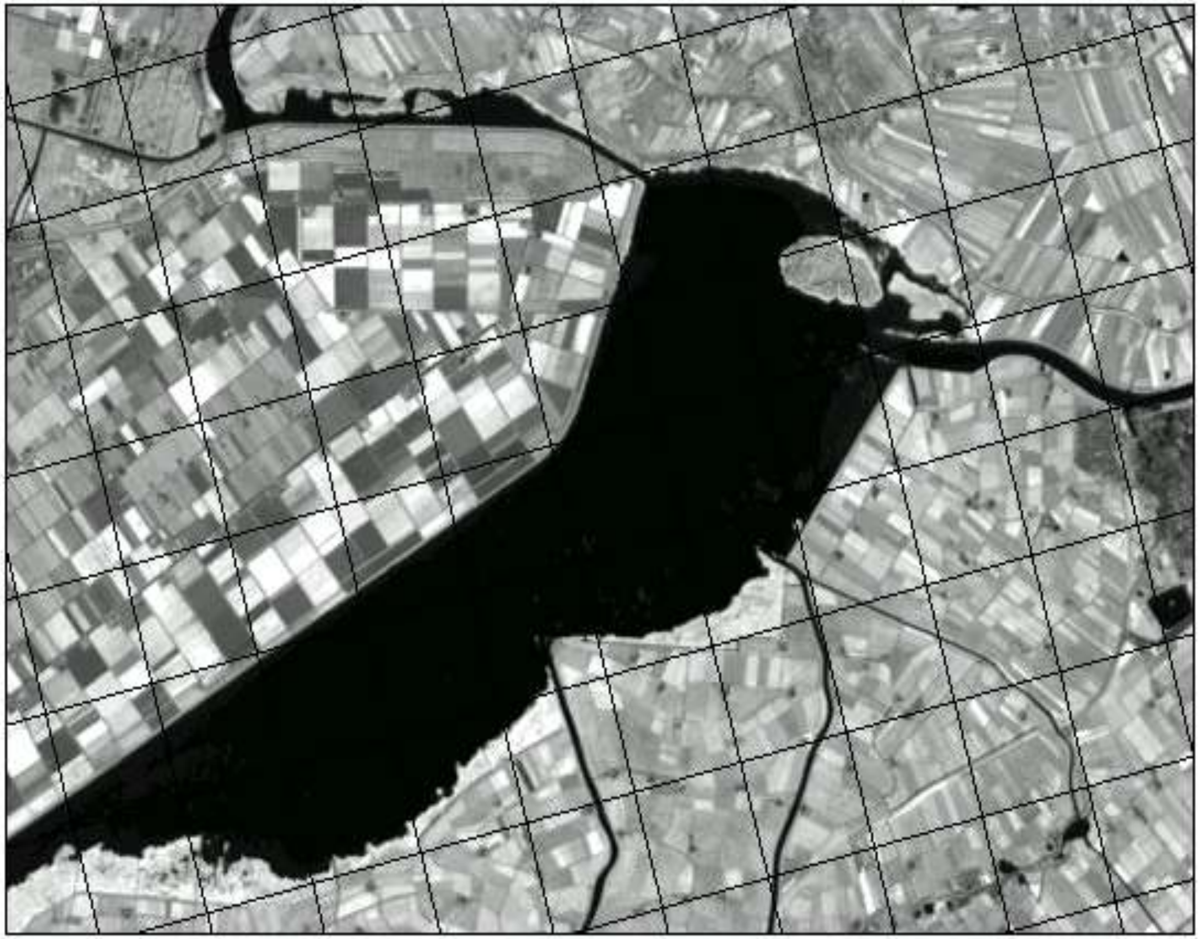
3. **Determination of a transformation function to map image coordinates into projection coordinates**

4. **Resampling using mapping function**
   - determination of pixel value in the map projected using one of the interpolation methods

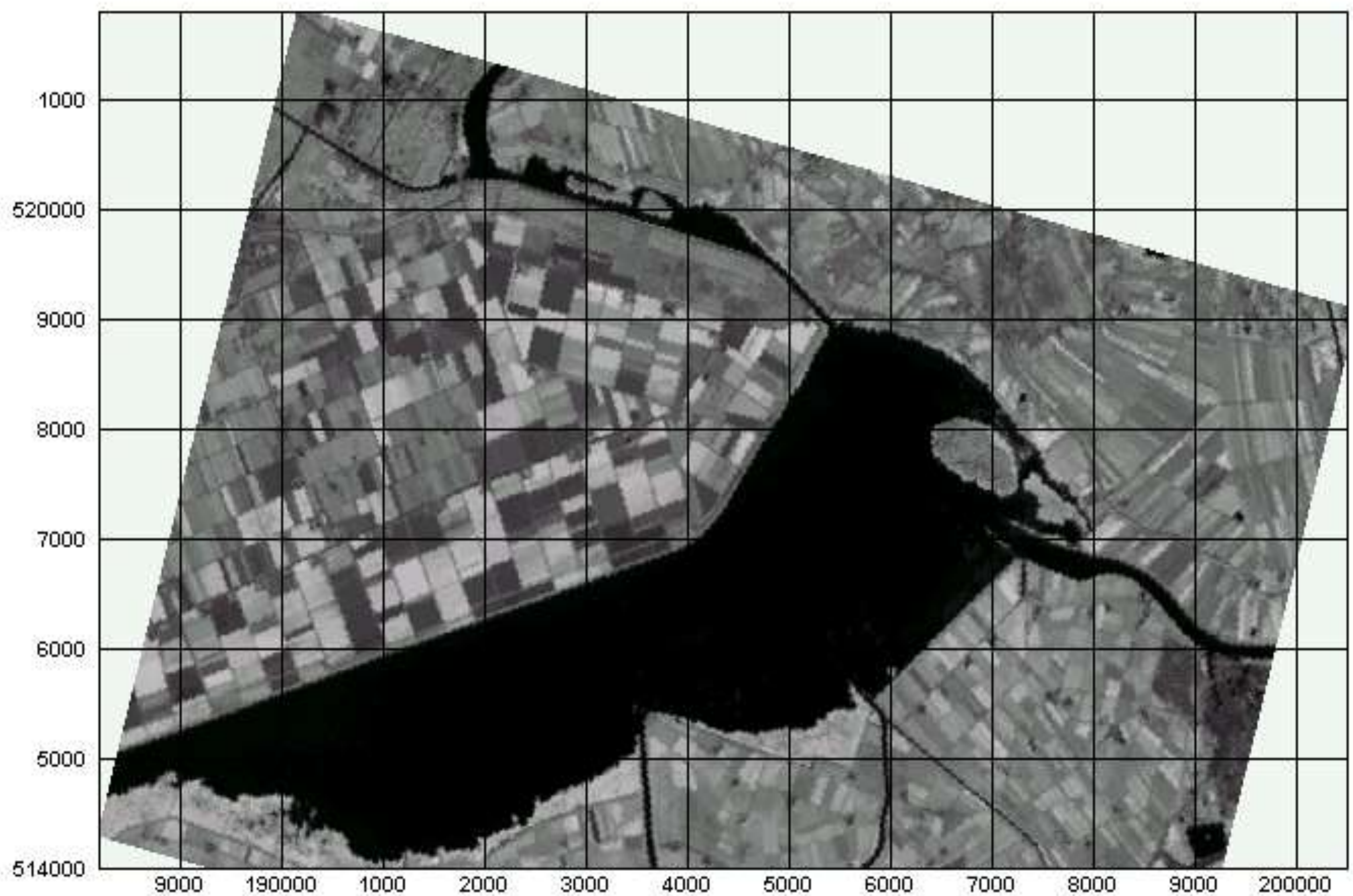
Example: Original Image



Example: Transformed Image
(After Steps 1-3)



Example: Geocoded Image
(After Steps 1-4)



Geometric Terrain Correction

- **Geometric terrain correction (GTC) describes how to remove geometric distortions by using a DEM in the geocoding process:**
  - To make sure that ALL pixels appear at their proper geographic location.
  - To allow for overlaying SAR data onto remote-sensing data from different sensors

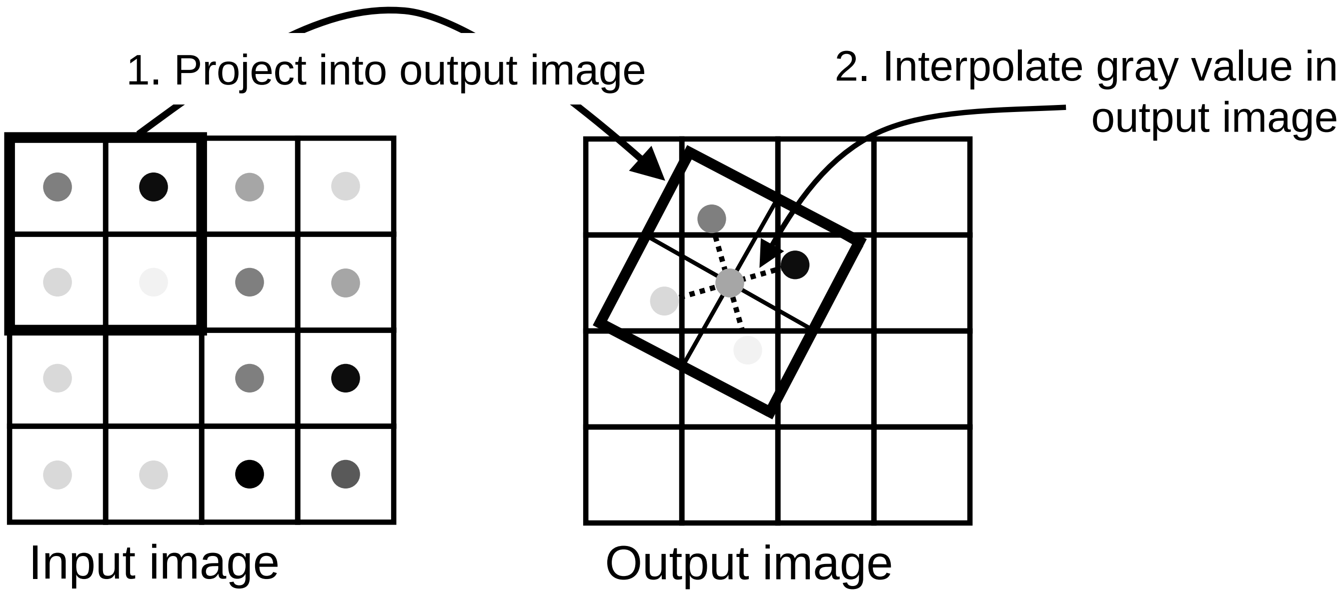
- **GTC problem:** What are the image gray values in every pixel of the output (geocoded) image given the input image and the DEM?

- **Two main approaches for geocoding *including GTC* are shown in the following:**
  - Backward Geocoding
  - Forward Geocoding

A Look At Forward Geocoding

1. Forward Geocoding:

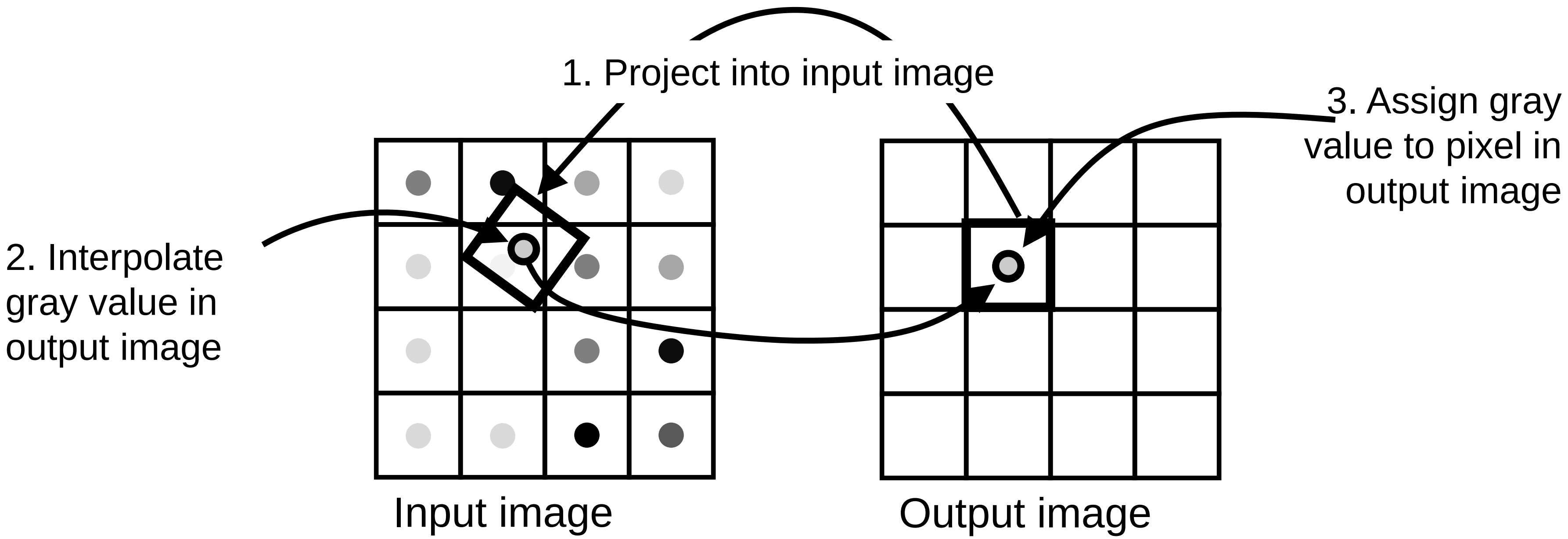
- **Step 1:** Project pixels (x_i, y_i) into output image g_o using DEM
- **Step 2:** Determine gray values in output image by interpolation between projected pixels



A Look at Backward Geocoding

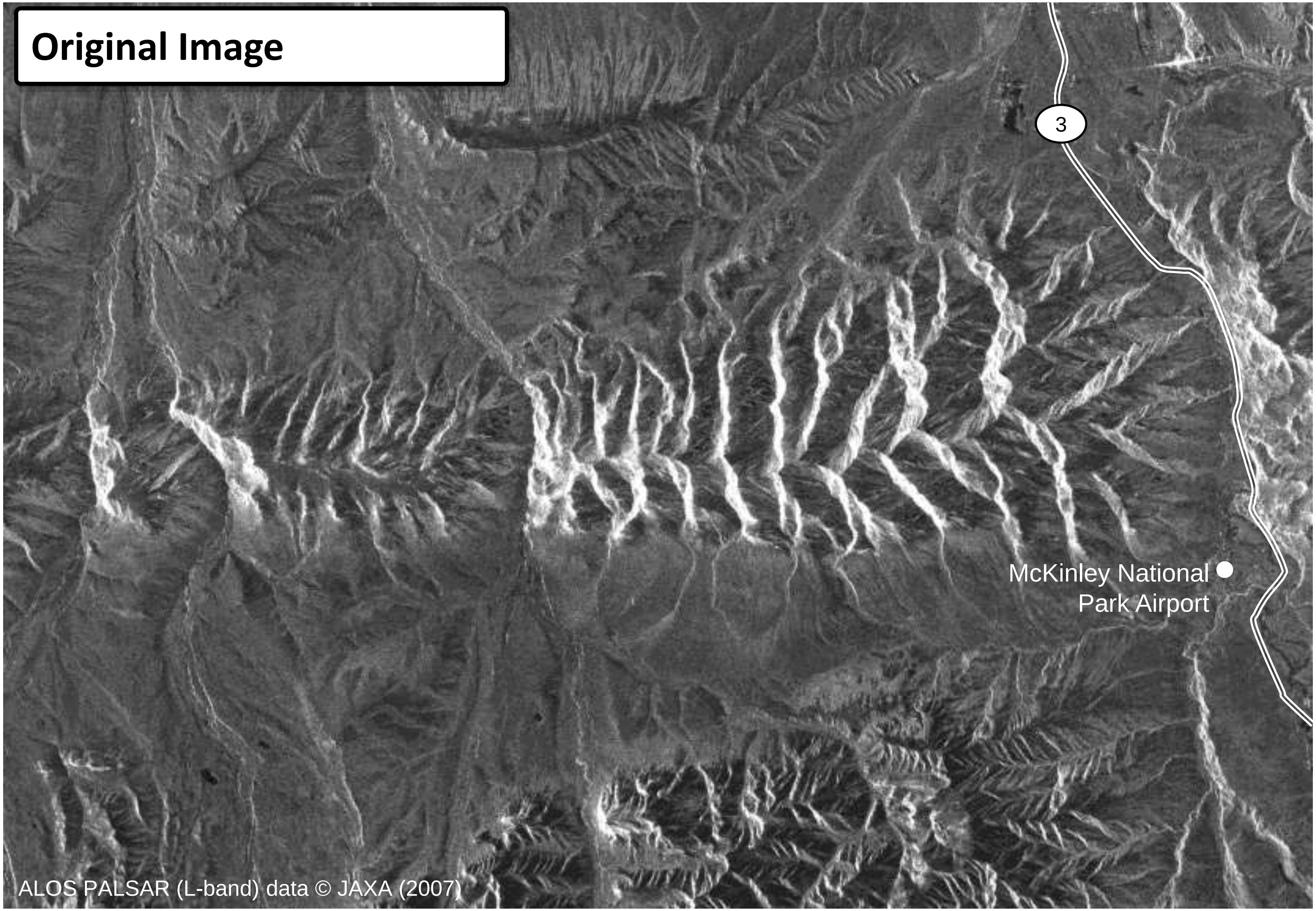
2. Backward Geocoding:

- **Step 1:** Project output image pixels (x_o, y_o) into input image g_i using DEM
- **Step 2:** Step 2: calculated gray value of projected pixel by interpolation and assign to (x_o, y_o) in output image

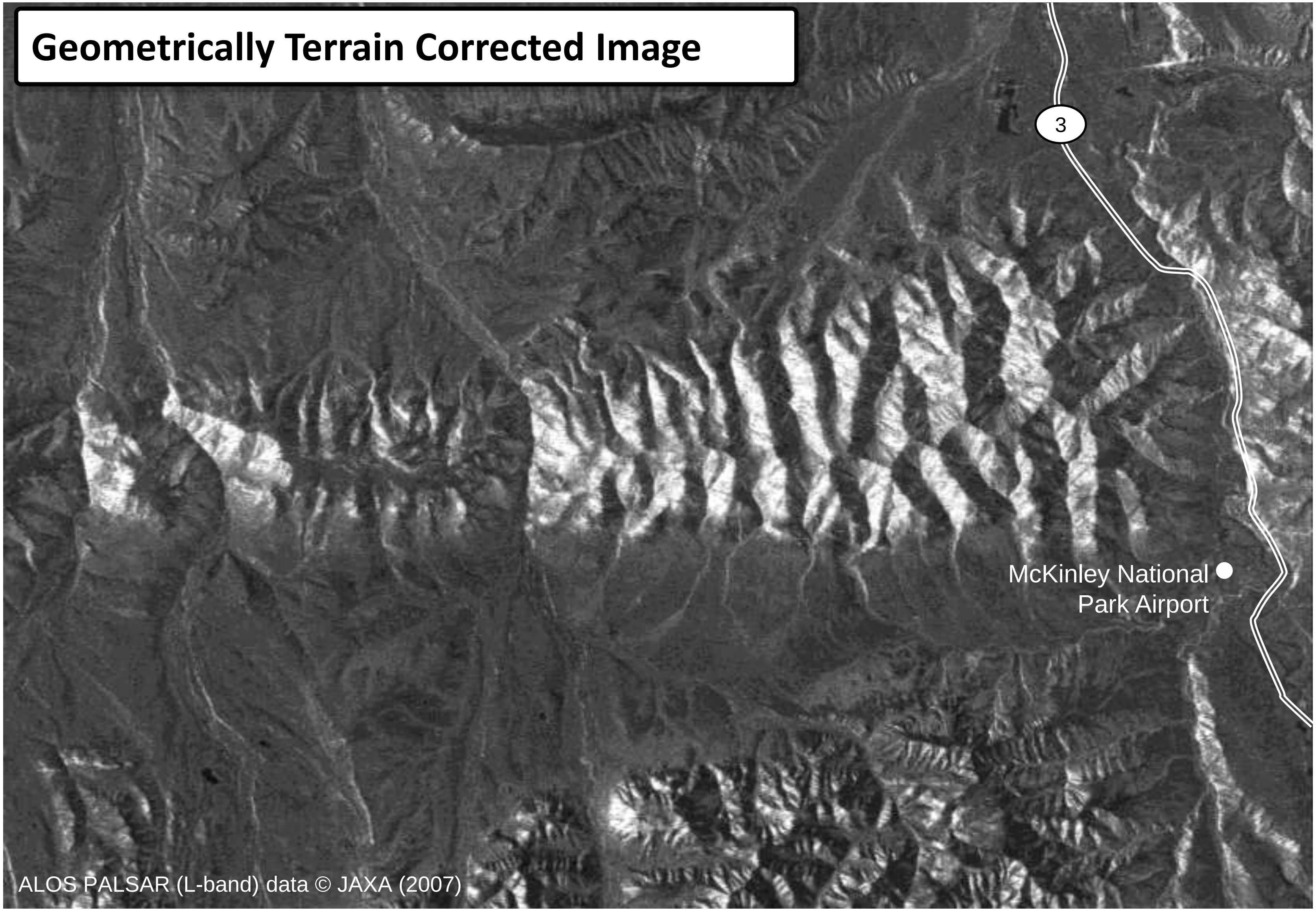


Only Inverse Mapping guarantees that ALL pixels in the output image receives a gray value (no holes) → inverse mapping is standard approach

Geometric Terrain Correction Example (I)



Geometric Terrain Correction Example (II)

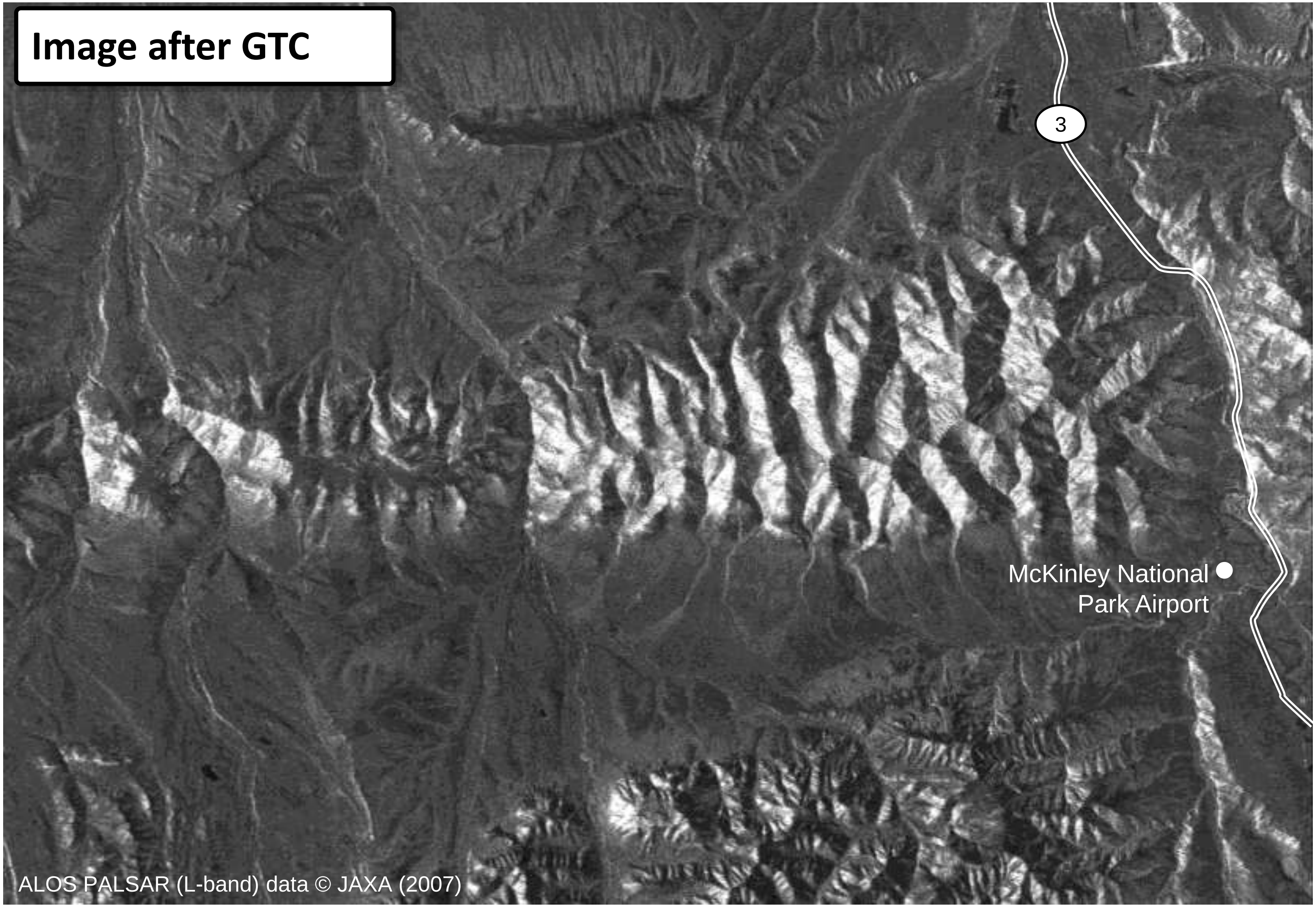


Radiometric Terrain Correction

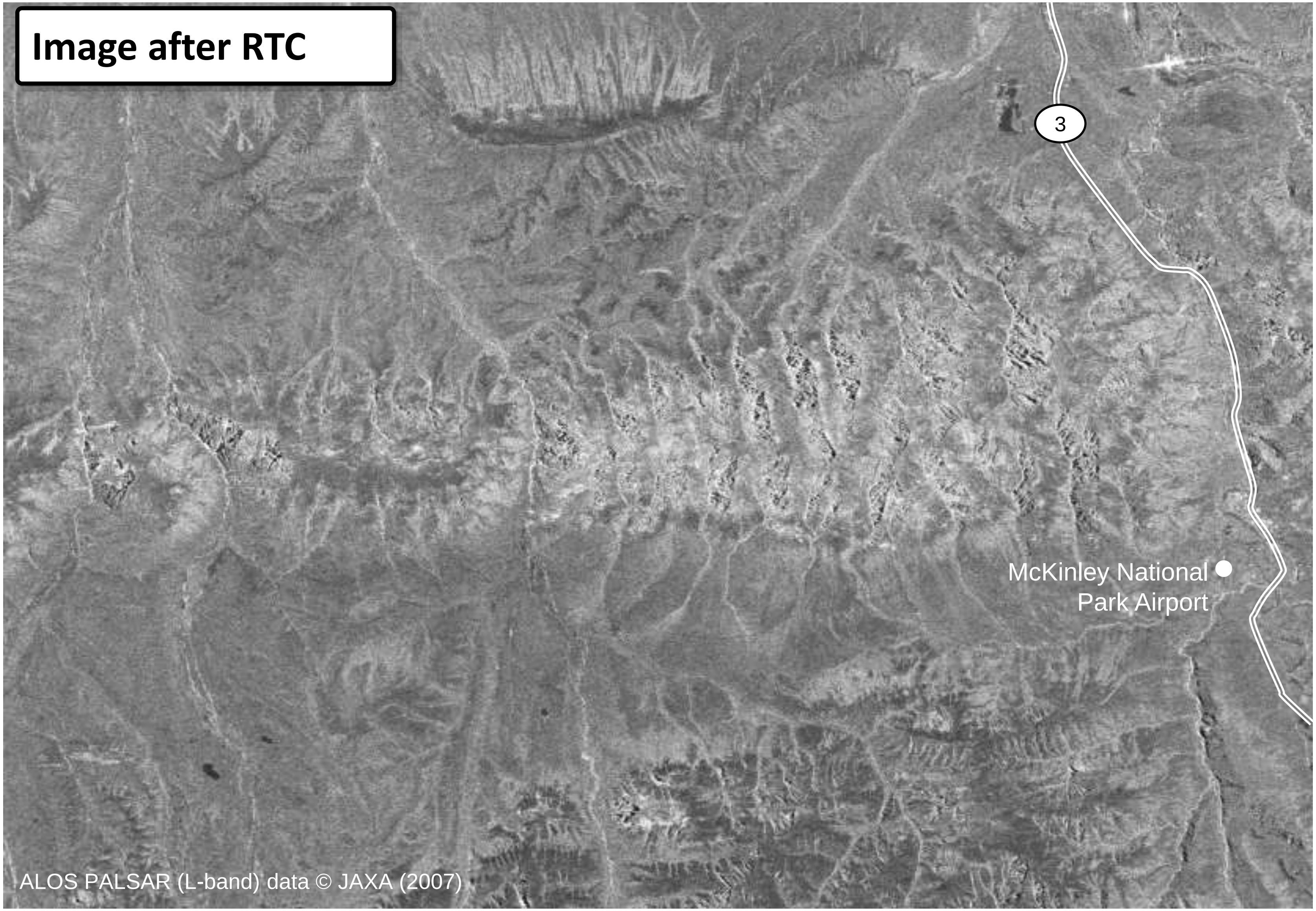
- **Problem:** Sensor facing slopes appear overly bright in radar images.
- **Cause:** Pixel Size on sensor-facing slopes is larger → more ground is integrated into pixel → brightness goes up

- **Solution:** **Radiometric Terrain Correction (RTC)**
  1. Using DEM and observation geometry, calculate *exact equivalent area* A_σ covered by each pixel
  2. Normalize radar cross section by A_σ to arrive at terrain normalized data σ_T^0

Radiometric Terrain Correction Example (I)



Radiometric Terrain Correction Example (II)

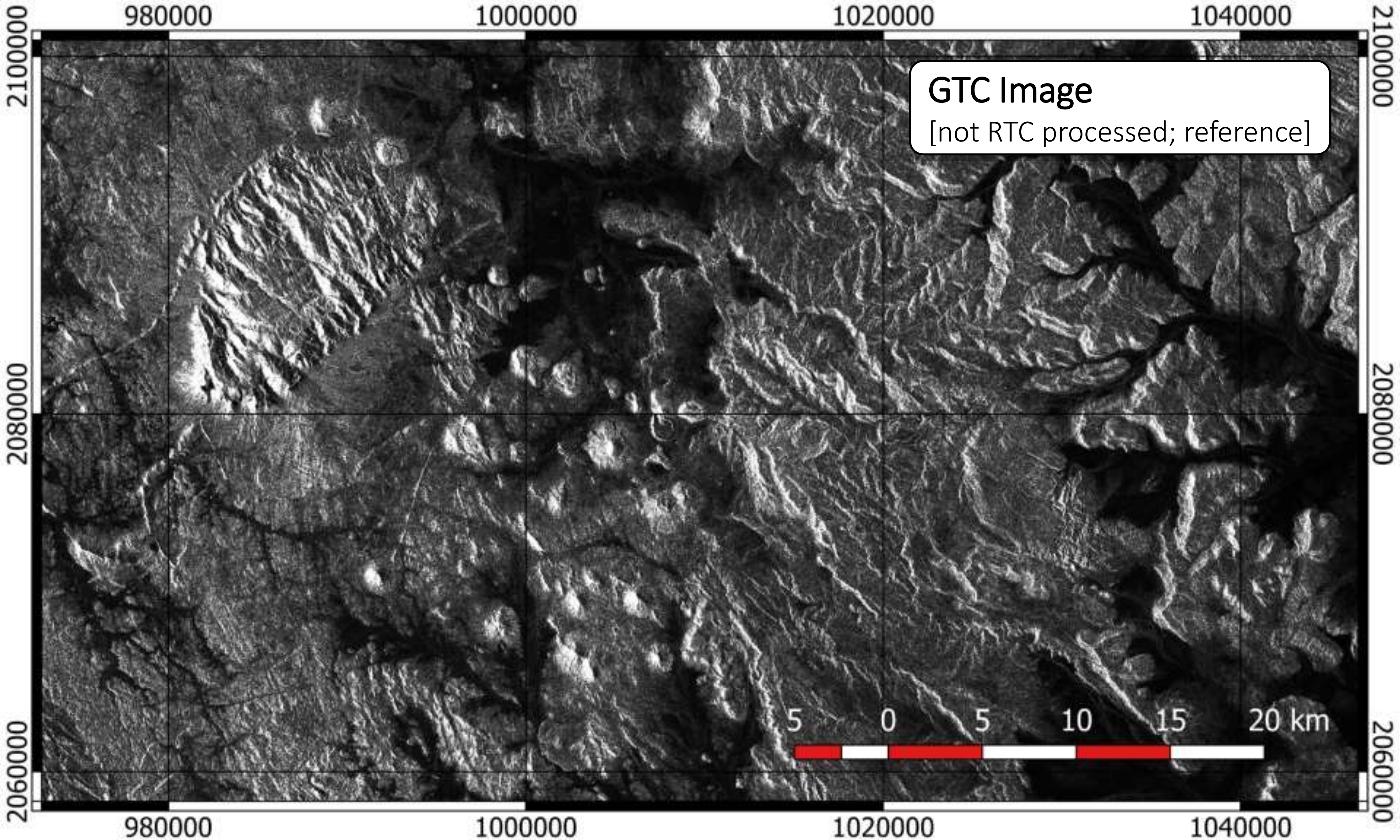


Example of RTC Normalization for an Area in Arkansas, USA

VV/VH/Ratio RGB composite **after** pixel scattering area normalization

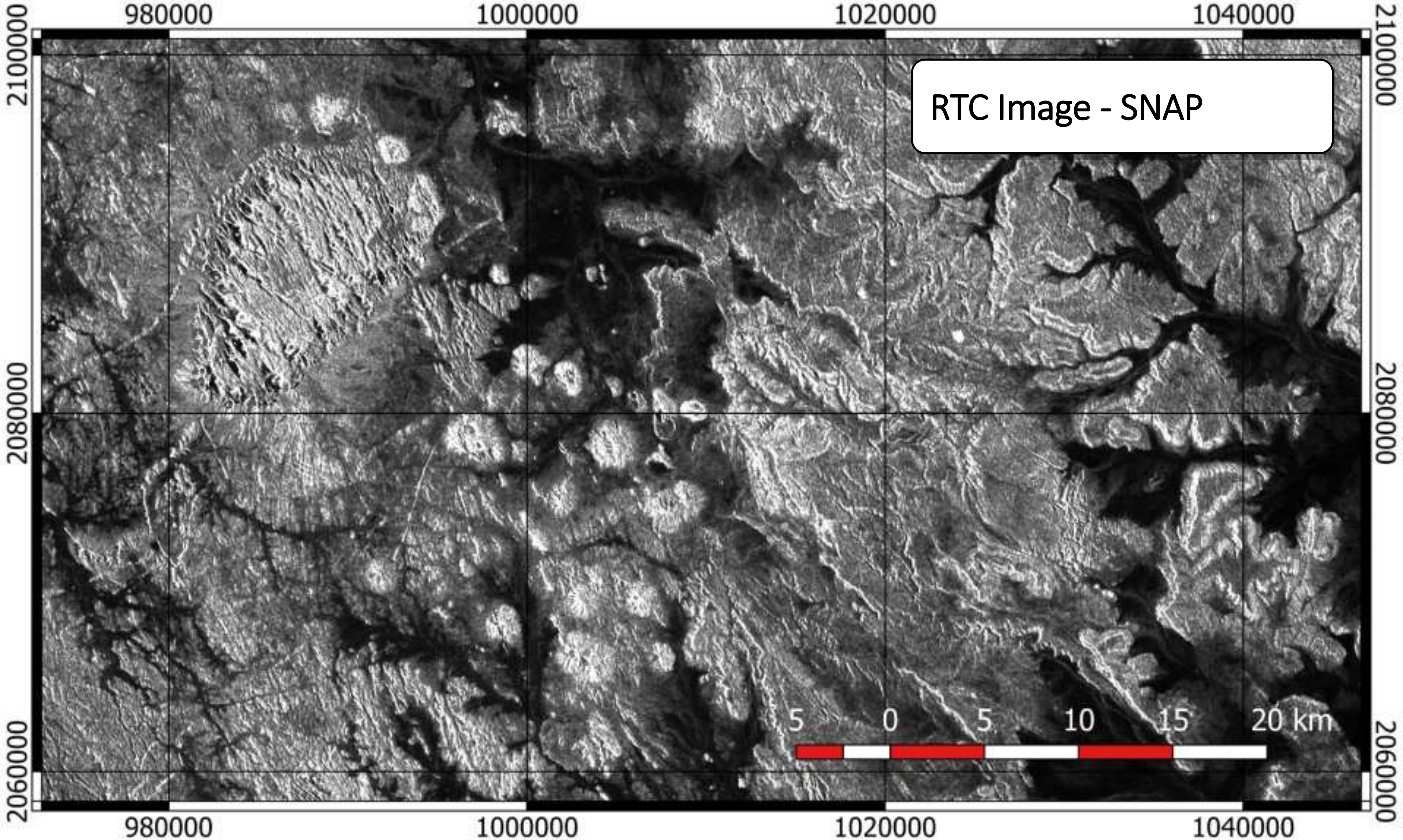
RTC Example

Comparison of Processing Techniques [SNAP vs GAMMA]



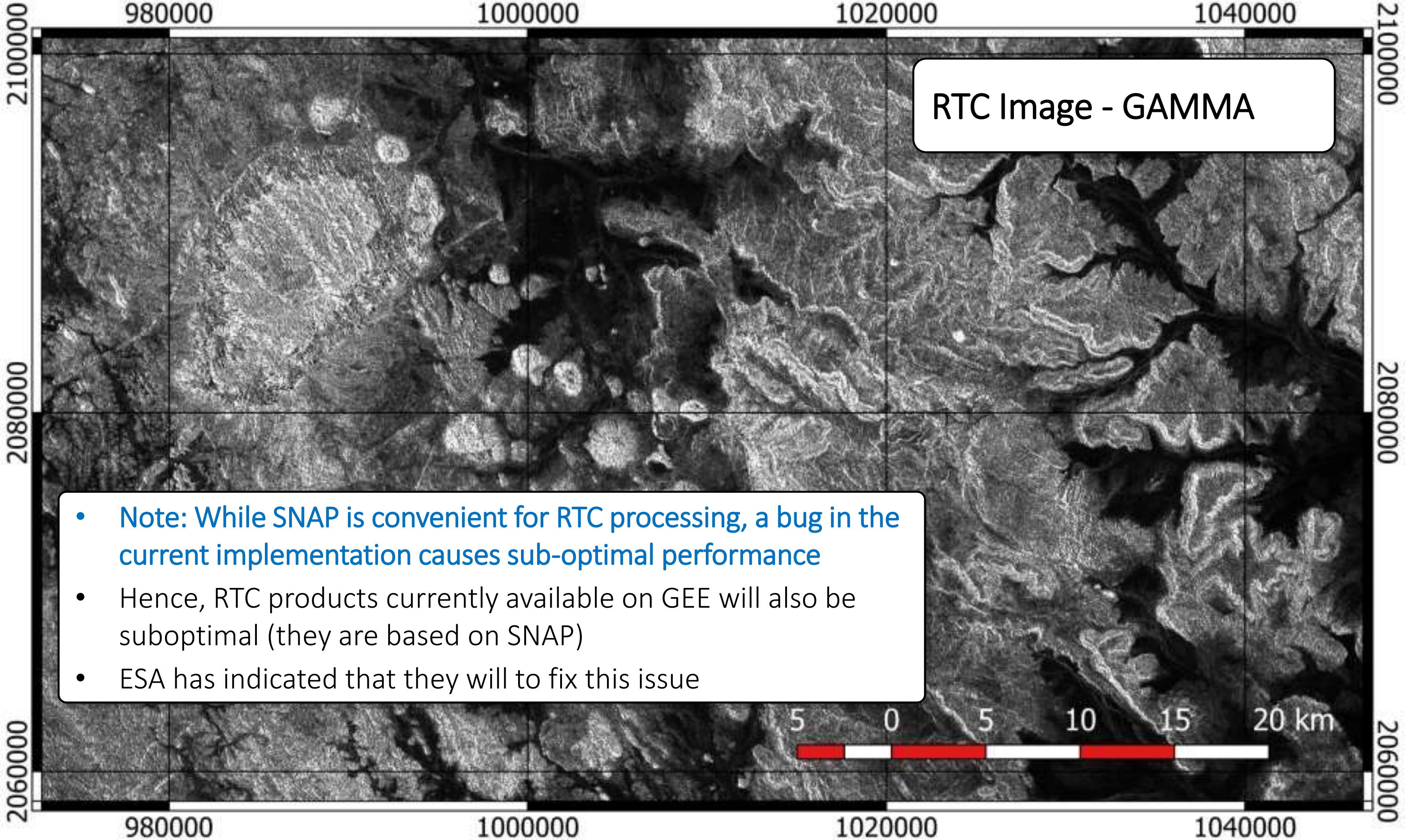
RTC Example

Comparison of Processing Techniques [SNAP vs GAMMA]



RTC Example

Comparison of Processing Techniques [SNAP vs GAMMA]



- Note: While SNAP is convenient for RTC processing, a bug in the current implementation causes sub-optimal performance
- Hence, RTC products currently available on GEE will also be suboptimal (they are based on SNAP)
- ESA has indicated that they will to fix this issue

Currently Available RTC Processing Services

- **Fully geocoded and radiometrically corrected RTC products are available on Google Earth Engine (<u>Warning</u>: based on SNAP → suboptimal products)**

- **Optimally processed RTC data are available through:**

http://hyp3.asf.alaska.edu/

Available Services:
- RTC Processing to UTM and Lat/Lon
- Full-frame processing
- 30m and 10m resolution options

Earth Big Data
Where Solutions Begin.

http://earthbigdata.com

Available Services:
- RTC Processing to UTM and Lat/Lon
- Full-frame or Sentinel-2 tiling
- Custom processing (e.g., user DEM)
- Time Series Processing
- Client Algorithm

QUESTIONS?

UP NEXT: INTERFEROMETRIC SAR