InSAR Deformation Mapping and Modeling

Part I:
Introduction to Synthetic Aperture Radar

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Course Outline

- Principles of Imaging Radar
  – Resolution
  – What radar measures
  – Geometric distortion of radar image
  – Radar vs. optical imaging
- SAR satellites
- SAR applications
  – Geology
  – Snow, ice, glacier
  – Vegetation
  – Soil Moisture
  – Flooding
  – Ocean
  – Ship detection & fishery management
  – Environment protection & monitoring
- Summary

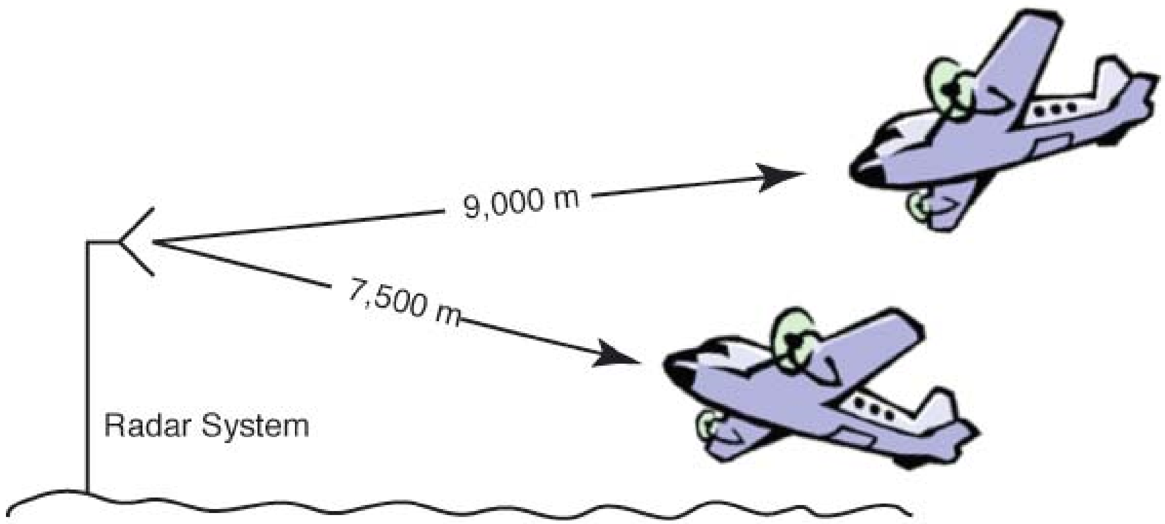
Principles of Imaging Radar

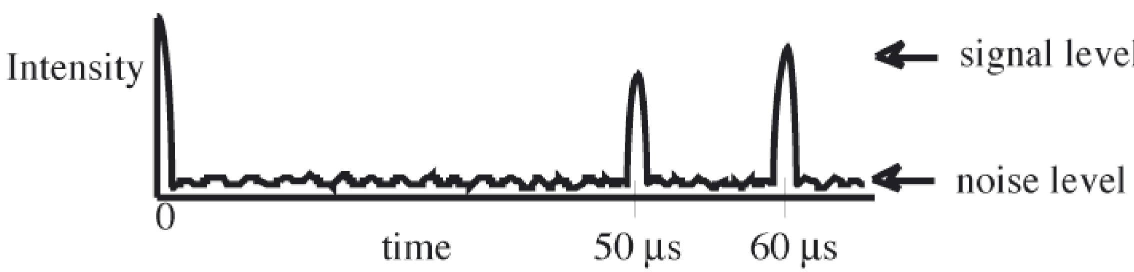
Radar - Radio Detection and Ranging

- In its simplest form, a radar operates by broadcasting a pulse of electromagnetic energy into space – if that pulse encounters an object then some of that energy is redirected back to the radar antenna.

- Precise timing of the echo delays allows determination of the distance, or “range”, while measuring the Doppler frequency tells the velocity of the target.

Distance measurements





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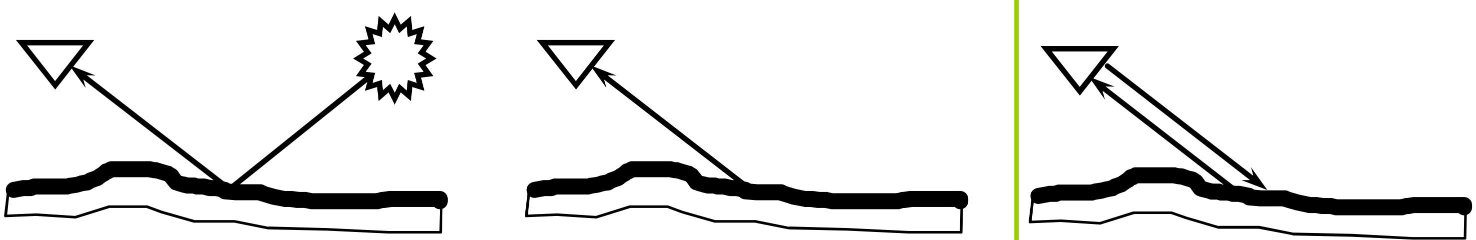
Synthetic Aperture Radar

- An advanced radar system that utilizes image processing techniques to synthesize a large antenna to achieve higher spatial resolution.

Remote Sensing: Optical vs. SAR

Sensor	Optical Sensor System		Radar System
Wavelength Region	Visible	Thermal infrared	Microwave

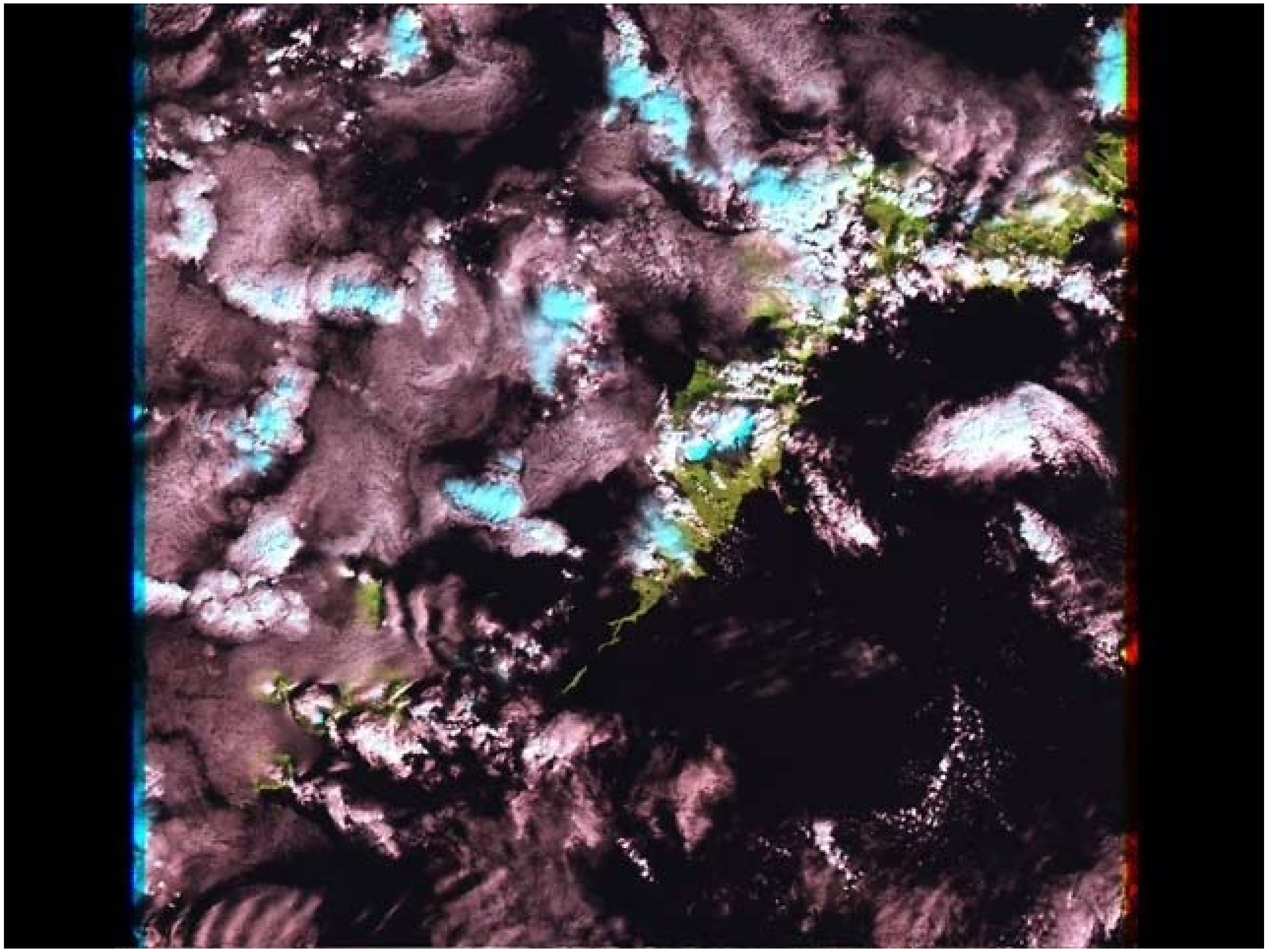


Source	Sun	Object	Transmitted by a sensor system
Object	Reflectance	Thermal radiation (temperature, emissivity)	Backscattering coefficient
Electro-magnetic Spectrum	Visible	Thermal infrared	Microwave

0.4 µm   0.7 µm   3.0 µm   10 µm   1 mm   1 m

Remote Sensing Over Cloud-prone and Rainy Areas

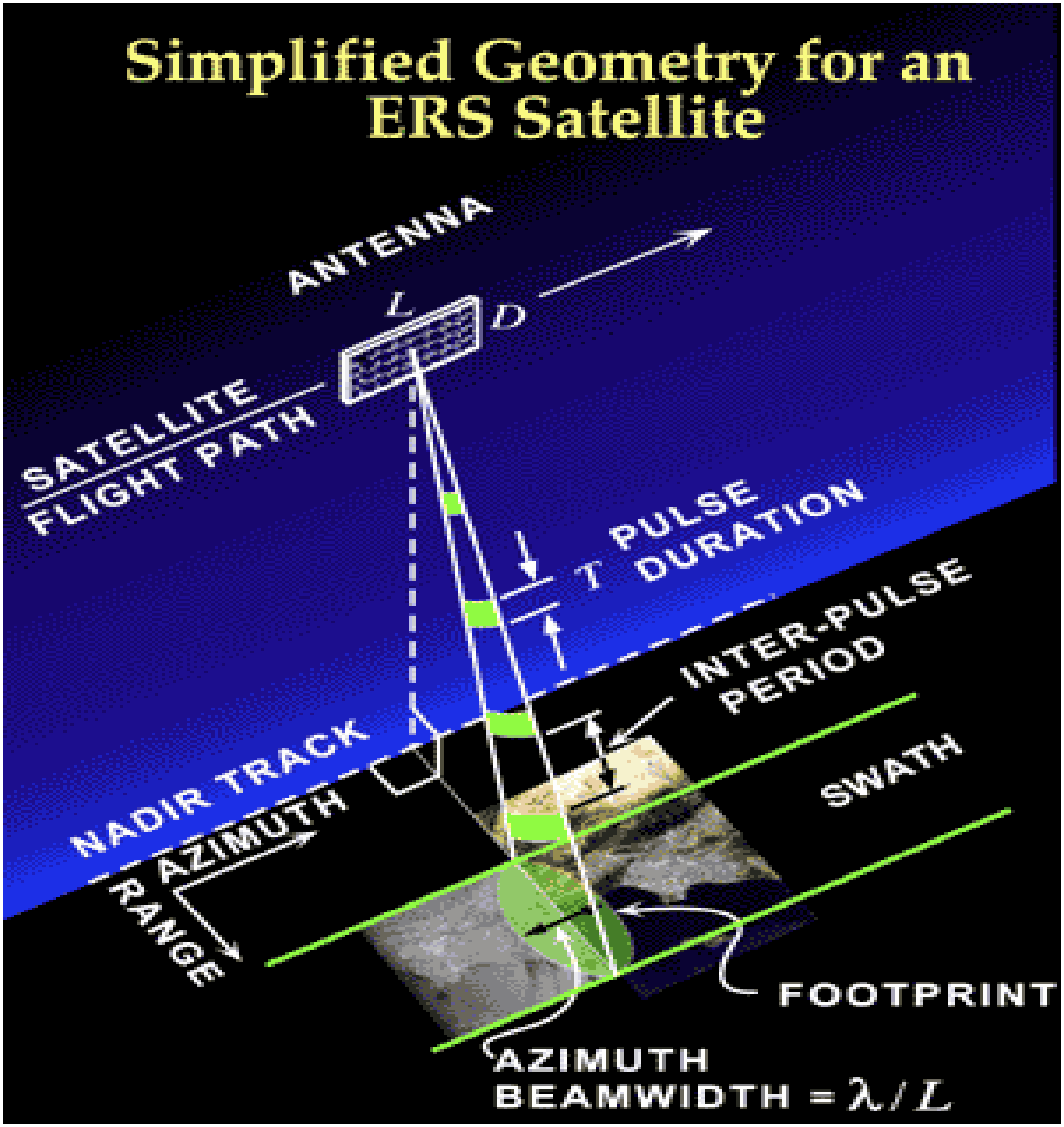
- Okmok Volcano, Alaska
  - 94 Landsat-7 images: 7/1999 – 9/2005
  - Less than 5% imagery is usable due to clouds!



Remote Sensing: Optical vs. SAR

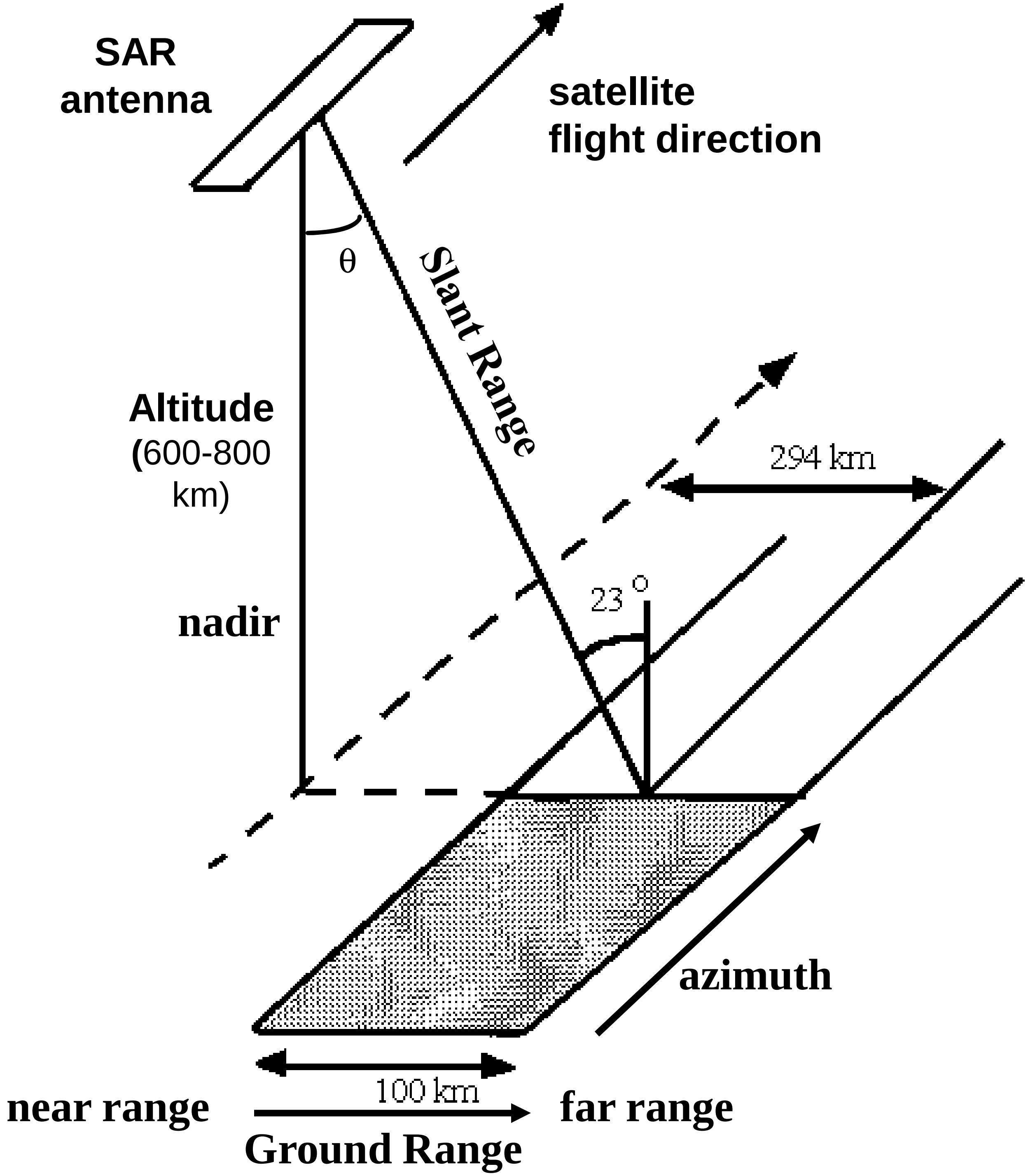
Optical	SAR
• passive sensor	• active sensor
• reflectance	• backscatter
• day time acquisition	• day and night
• cloud problem	• all weather
• usually nadir	• side looking geometry
• measure chemical composition and thermal properties	• measure target physical properties (roughness & dielectric constant)
	• coherent phase measurements allow for DEM and deformation mapping

Radar Imaging Geometry



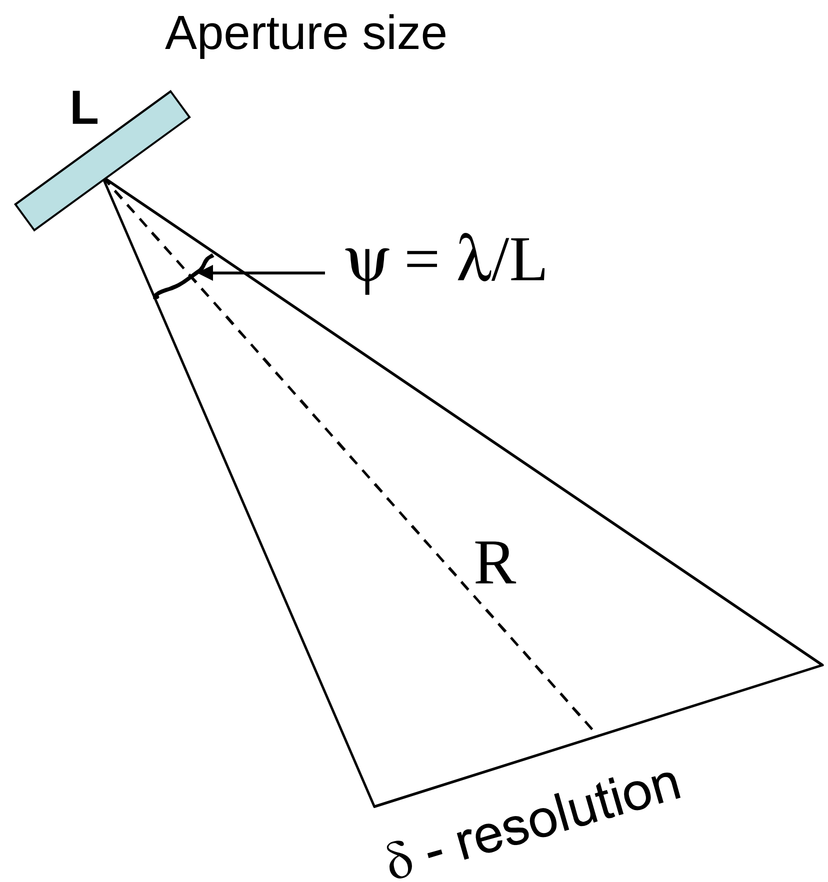
Terminology

- nadir
- azimuth direction
- look direction
- ground range (near and far)
- slant range
- look angle, incidence angle
- altitude



Landsat-7 Image Resolution

$$\delta = \mathbf{R}\lambda/\mathbf{L}$$



<u>Landsat-7</u>

$\lambda = 10^{-6}$m (wavelength)

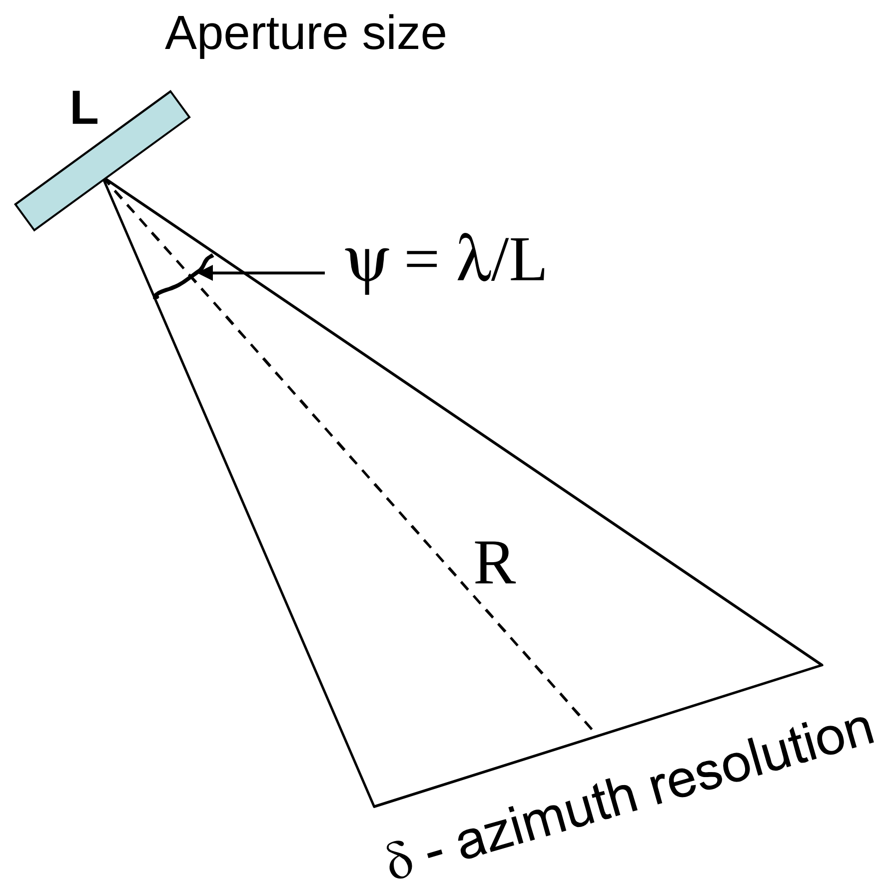
L = 0.1 m (aperture size)

R = 705 km (distance
from satellite to ground)

$\rightarrow \delta = \sim 10$ m

Azimuth Resolution: Real Aperture Radar

$$\delta = R\lambda/L$$



<u>ERS-1 Satellite Radar</u>

λ = 5.7 cm (wavelength)

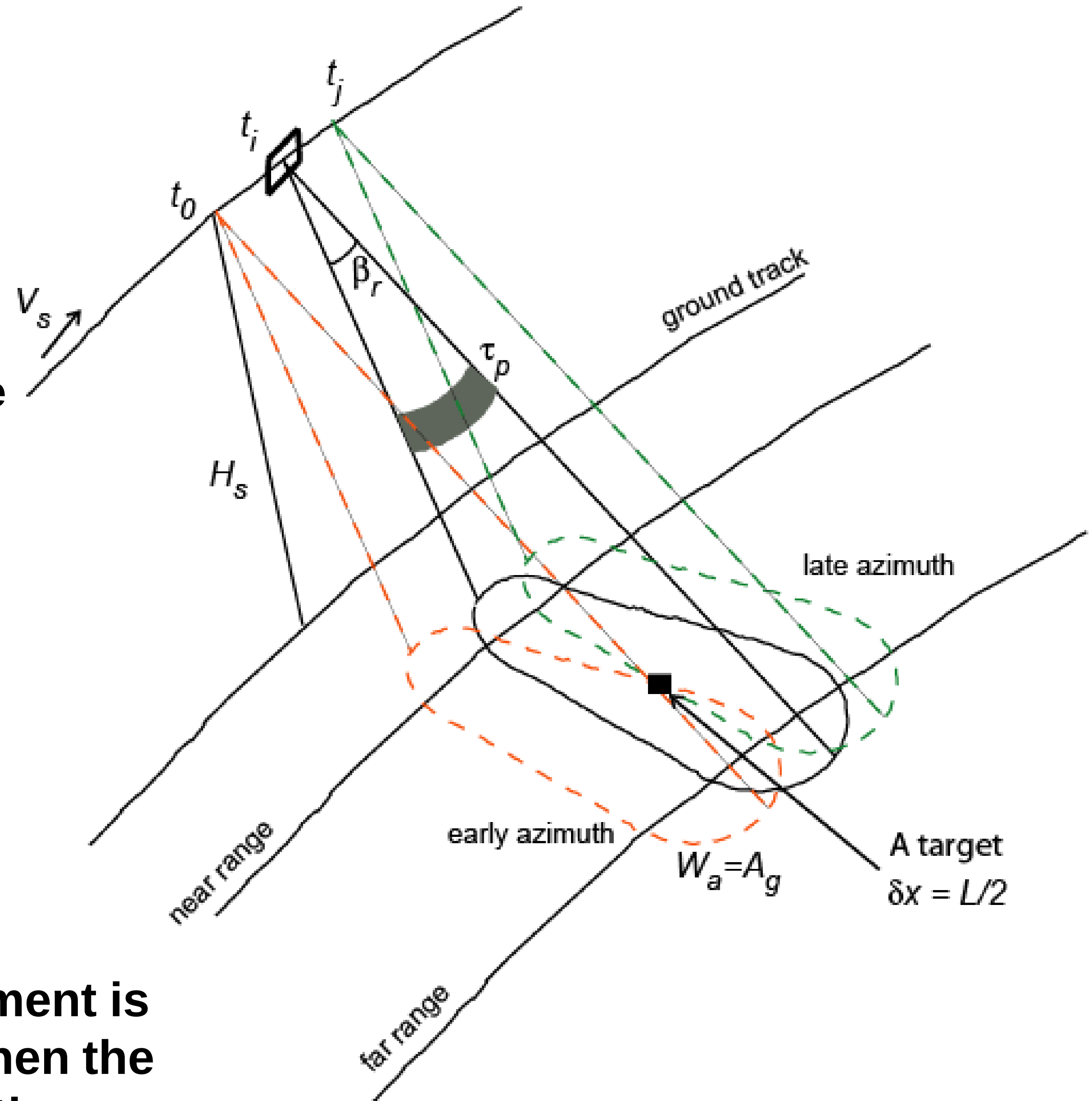
L = 10 m (aperture size)

R = 850 km (distance from satellite to ground)

$\rightarrow \delta$ = ~ 5 km (footprint)

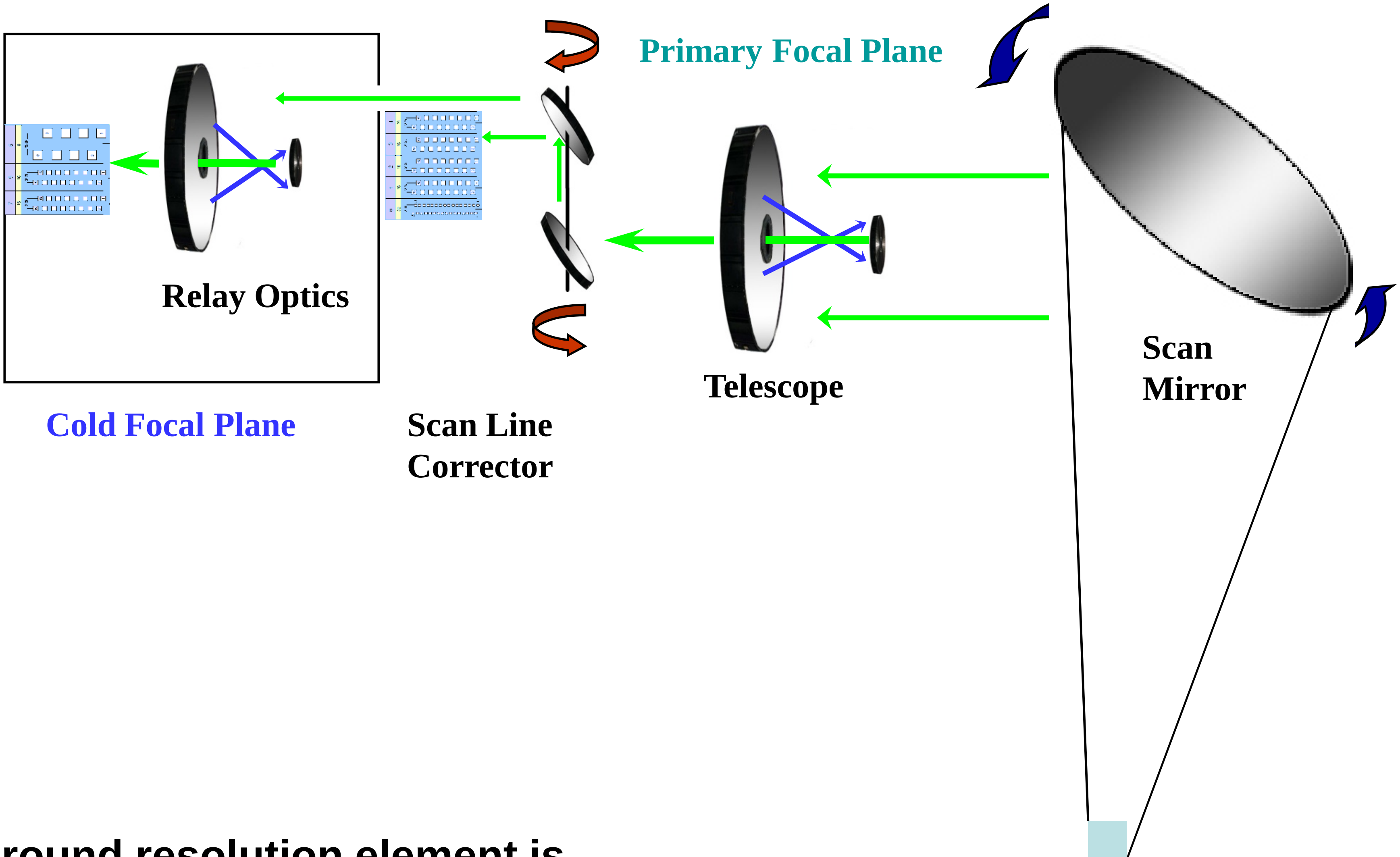
Synthetic Aperture Radar

- Pulse repetition: ~2000 s^{-1}
- Footprint width: ~5 km
- Ground speed: ~10km/s
- ΔT = ~0.5 second
- ~1000 pulses shall illuminate a single target on ground



A ground resolution element is "imaged" many times when the radar beam sweeps over the area

Landsat-7 Imaging Mechanism



A ground resolution element is "imaged" only ONCE when the Landsat-7 sweeps over the area

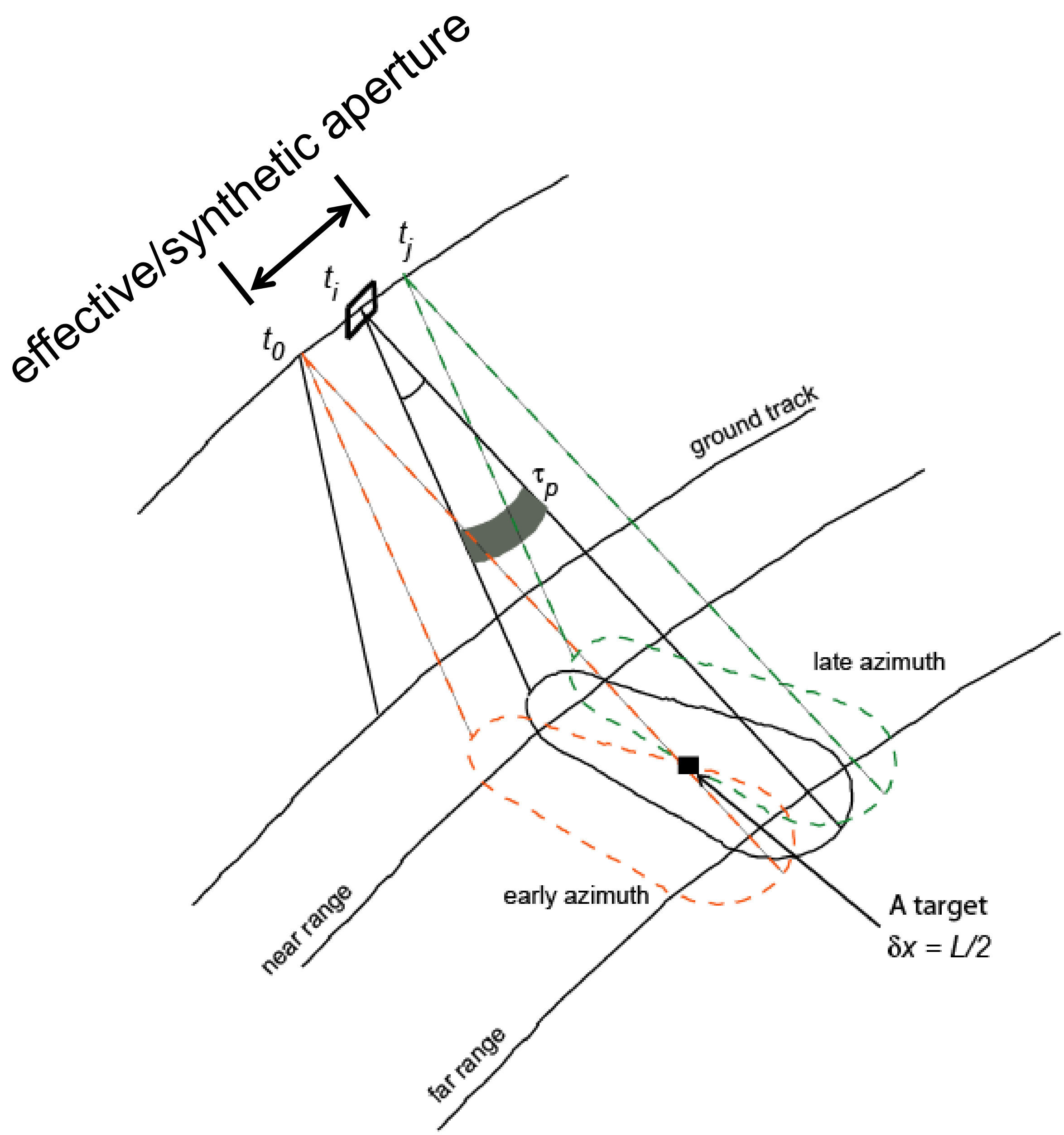
IFOV and Ground Resolution Cell

Azimuth Resolution: Synthetic Aperture Radar

$$\delta = \mathbf{R}\lambda/\mathbf{L}_{\mathbf{eff}}$$

$$\mathbf{L}_{\mathbf{eff}} = 2\mathbf{R}\lambda/\mathbf{L}$$

$$\delta = \mathbf{L}/2$$



Azimuth Resolution: Synthetic Aperture Radar

- For a real aperture radar, $\delta_{(real)} = R\lambda/L$
  - Depends on distance, wavelength, etc
- For a synthetic aperture radar, $\delta_{(SAR)} = L/2$
  - This result only depends on the length of the antenna, which is about a few meters for all SAR satellites.

SAR Image Formation

- The synthetic aperture approach uses the forward motion of the radar platform to synthesize a very long “synthetic” antenna
- A larger “synthetic” antenna gives higher resolution
- Objective of SAR processing is to focus a large “synthetic” antenna array for each point in the image
- The process of “synthesizing” the larger antenna by correlating the data with a point target model is the image formation process.

(Slant) Range Resolution

•Two objects can be distinguished in the range direction only if the leading edge of the pulse echo from the more distant object arrives at the antenna later than the trailing edge of the echo from the nearer object. The two slant ranges must differ by at least half of the pulse length for the objects to be resolvable.

•The quality of the radar image depends on the ratio of the return signal strength to the ambient system noise. To achieve meter-scale resolution over typical terrain, the pulse duration would have to be too short to generate enough energy to achieve an adequate signal-to-noise ratio. Engineering constraints and the principles of wave scattering preclude the realization of a short-duration pulse.

•SAR range resolution can be achieved by using a technique known as range compression together with a type of signal processing called matched filtering. The approach is based on transmitting and receiving not a single frequency but a spread of frequencies in the microwave range. In the auditory frequency range, such a pulse would sound like a chirp.

•When the returned echo of a linearly frequency modulated pulse (a chirp) is correlated with the known transmitted signal, the autocorrelation function is nearly zero except for a narrow spike that corresponds to the round trip travel time of the pulse.

•For ERS satellite radar:

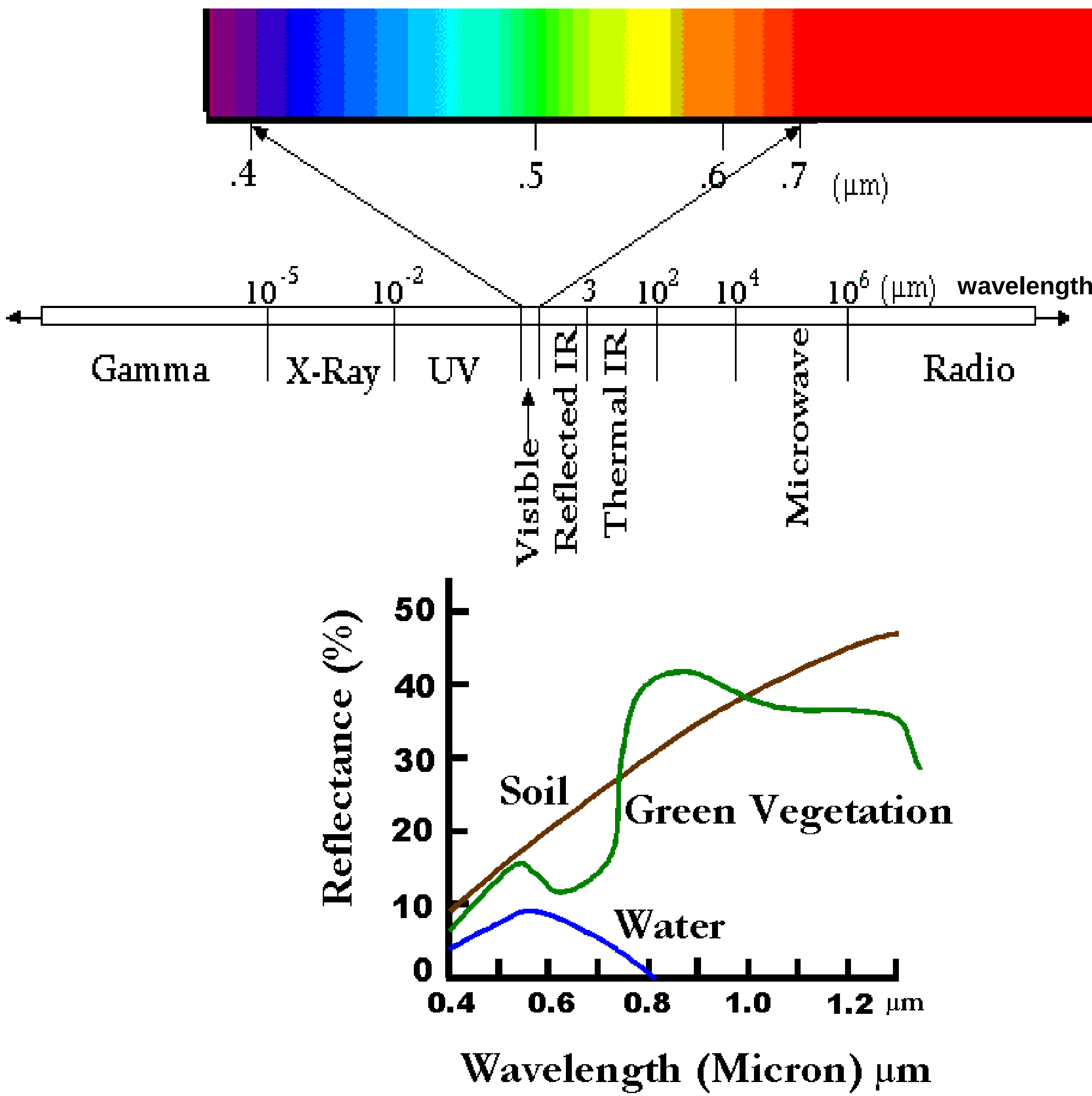
Chirp duration Tp **= 37.1 us => range resolution cTp/2 = 5 km (without matched filter)**

Chirp bandwidth B **= 15.5 MHz => range resolution c/2B = 10 m (with matched filter)**

(Slant) Range Resolution

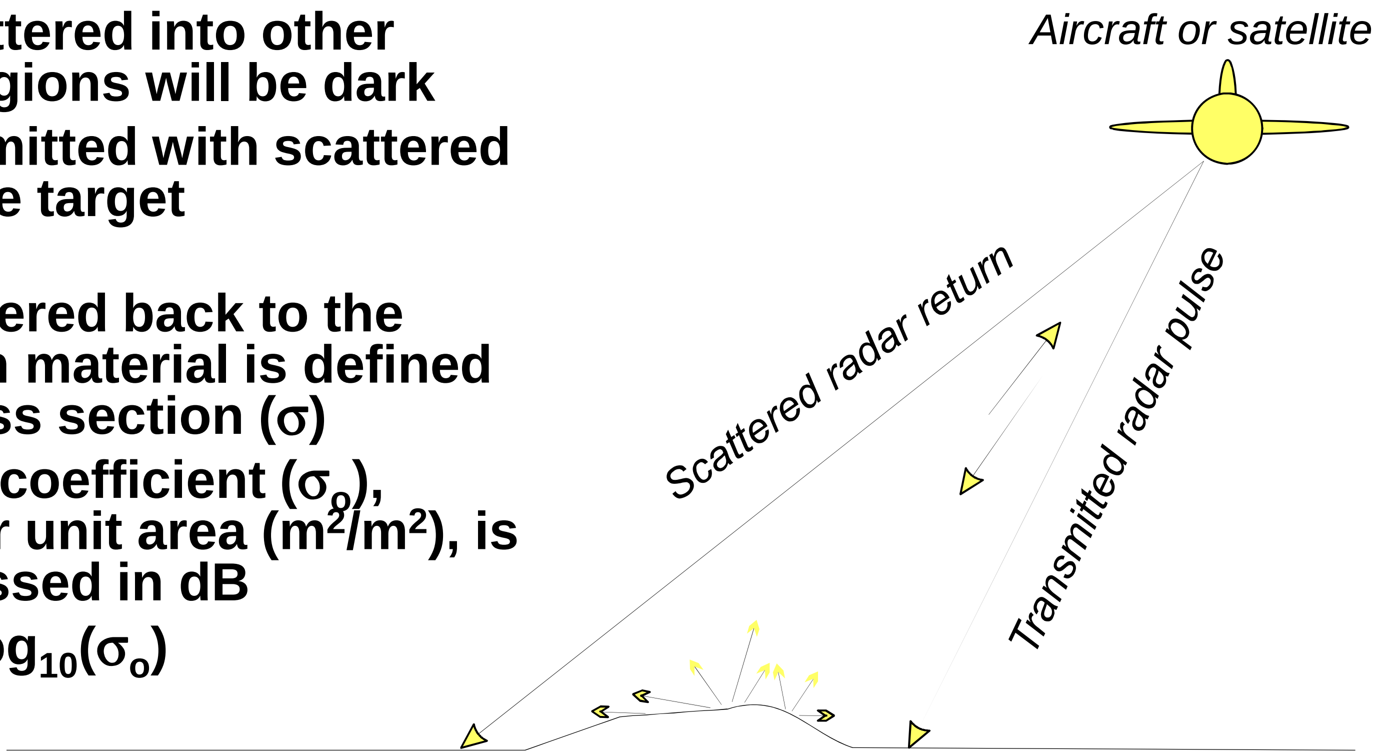
- Radar is a side-looking instrument
- Range (distance) is determined by precisely measuring the time from transmission of a pulse to receiving the echo from a target
- Range resolution is accomplished by transmitting large-bandwidth chirp waves
- The range resolution is independent of the height of the spacecraft
- The range resolution is about 10-20 m for current satellite SARs.

What Does Landsat-7 Measure?



What Does Radar Measure?

- **Radar is in side-viewing geometry**
- **Radar platform illuminates terrain and receives scattered signal**
- **Bright regions in radar image → more energy scattered back to the radar**
- **If energy is scattered into other directions → regions will be dark**
- **Compare transmitted with scattered signal to deduce target characteristics**
- **What gets scattered back to the radar by a given material is defined as its radar cross section (σ)**
- **Backscattering coefficient (σ_o), defined as σ per unit area (m^2/m^2), is normally expressed in dB**
- **σ_o (in dB) = $10\log_{10}(\sigma_o)$**



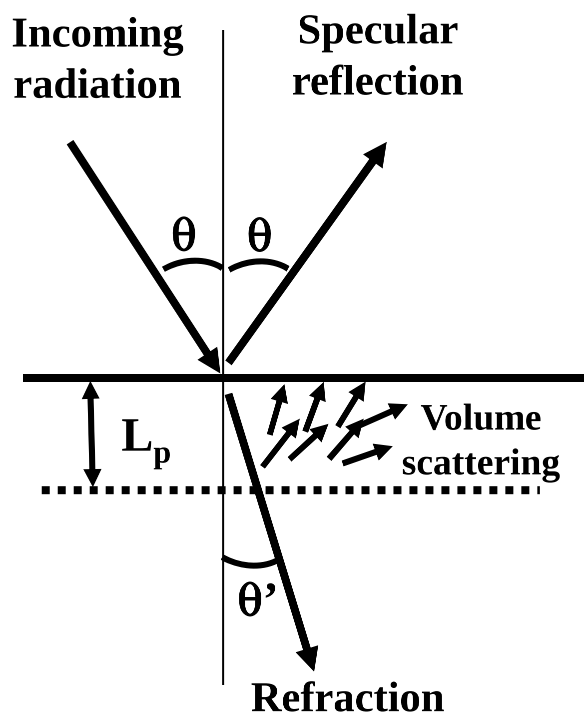
SAR backscattering is controlled by

- Dielectric constant
- Surface roughness
- Terrain slope (and radar look angle)
- Scattering mechanisms
- Polarization
- Radar wavelength

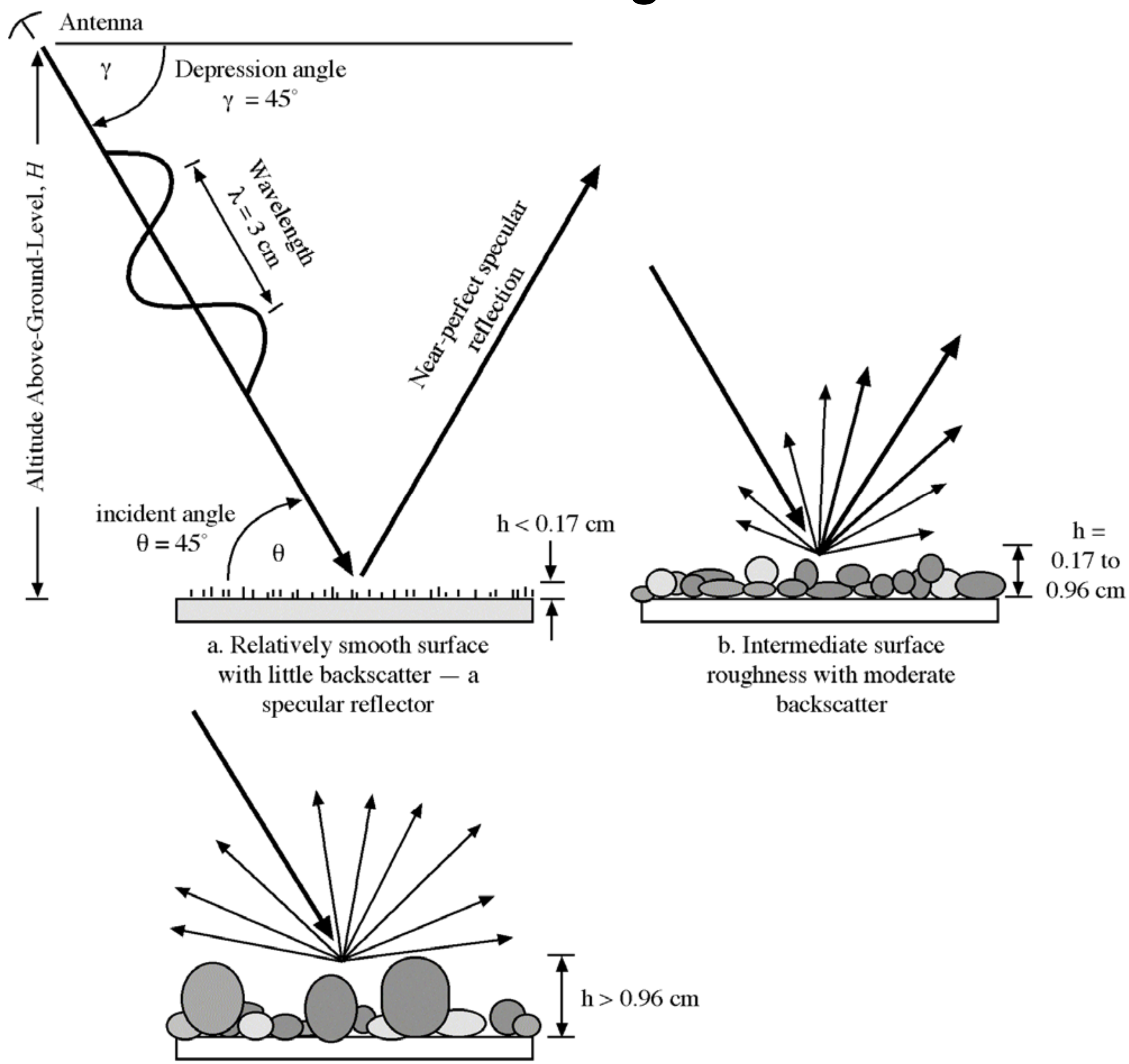
SAR backscattering is controlled by **Dielectric constant**

- **Dielectric constant characterizes a given medium's response to the presence of an electric field.**
- **Dielectric constant indicates how well radar signal propagates through the medium.**
- **The larger is the dielectric constant, the less is the penetration, the stronger is the backscattering, and the brighter is the feature in SAR image.**

Typical Value of Dielectric Constant	
Water	80
Dry soil	3
Moist Soil	10
Wet soil	20
Granite	4
Limestone	8
Ice	3



SAR backscattering is controlled by **Surface Roughness**



a. Relatively smooth surface with little backscatter — a specular reflector

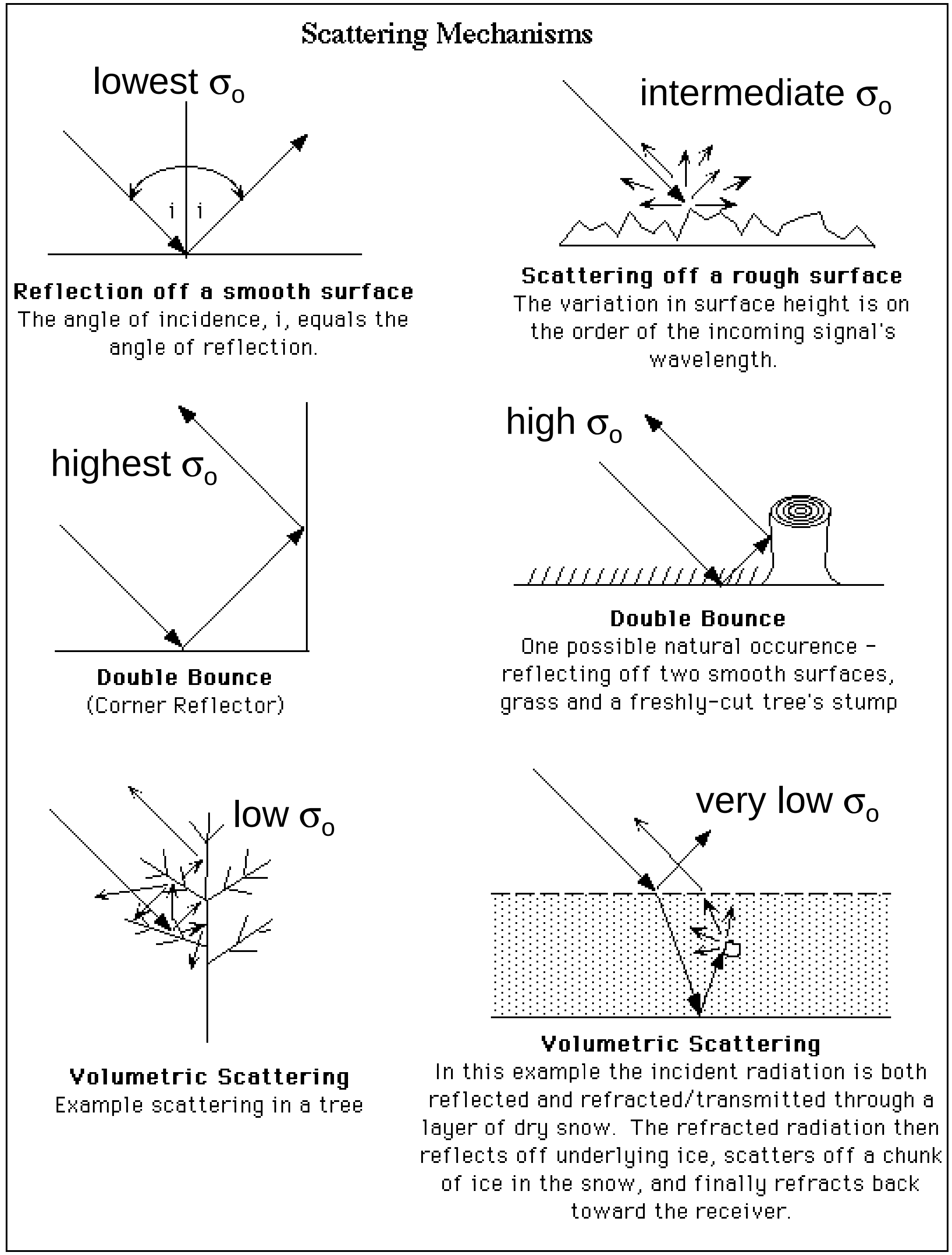
b. Intermediate surface roughness with moderate backscatter

c. Rough surface with diffuse backscatter

SAR backscattering is controlled by **Surface Roughness**

- The surface roughness is measured relative to the radar wavelength. For example, an ocean surface with capillary waves with 3 cm amplitude would be considered rough at C-band (λ = 5.6 cm) but smooth at L-band (λ = 24 cm).
- Smooth surface causes specular reflection and essentially no backscatter (dark feature)
- Slightly rough surface causes a small fraction of the incident energy scattered into a wide range of angles, including the direction back to the radar (intermediate dark feature).
- Rough surface causes the scattering pattern to spread out more and more, so the amount of energy scattered back to the radar increases (bright feature).
- Generally, the amount of backscatter is proportional to the roughness. Therefore, in a radar image, rougher features are brighter than smooth features.

SAR backscattering is controlled by **Scattering Mechanisms**



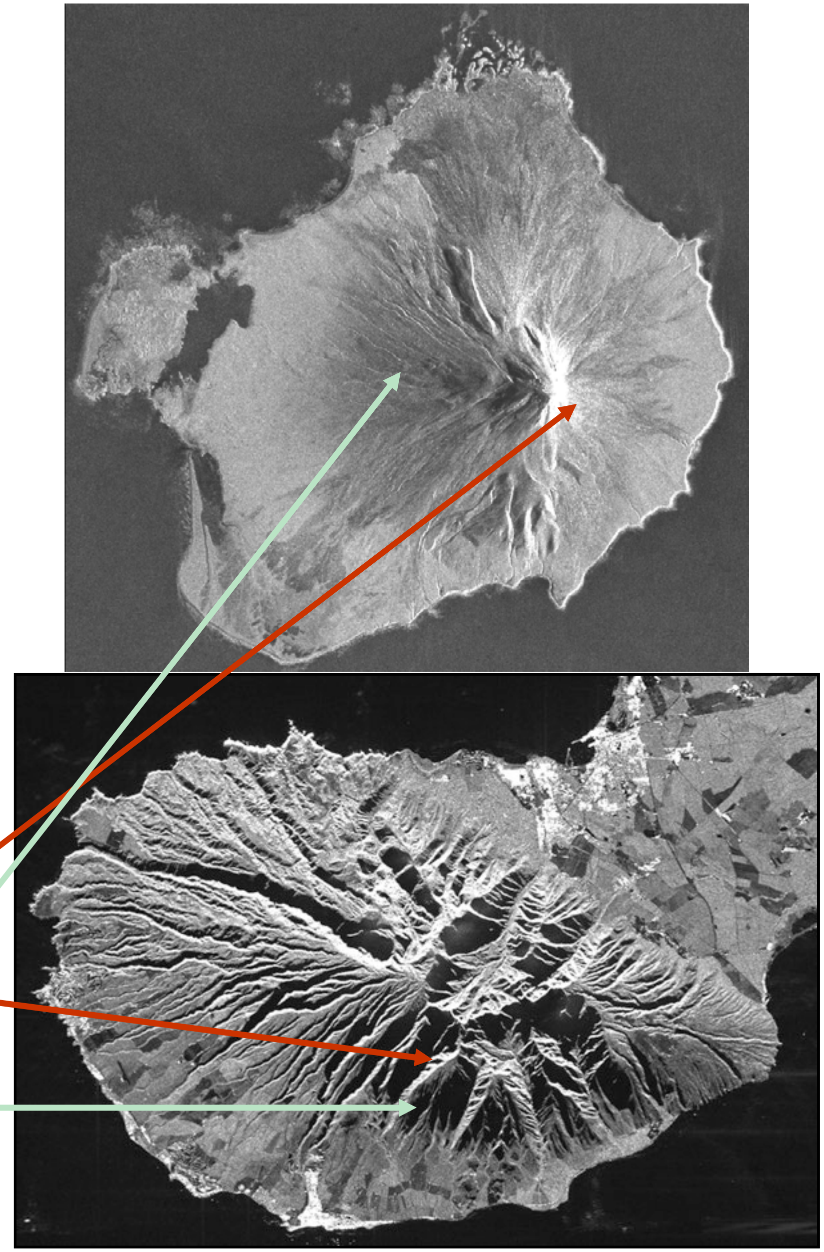
Appearance in radar image is governed by the physics of the scattering

SAR backscattering is controlled by **Terrain Slope (and Radar Look Angle)**

•A slope facing towards the radar wave results in large backscattering return (bright feature)

•A slope facing away from the radar wave has low backscattering return (dark feature)

•Radar backscattering essentially is determined by the local incidence angle (the angle between radar look direction and the local vertical).



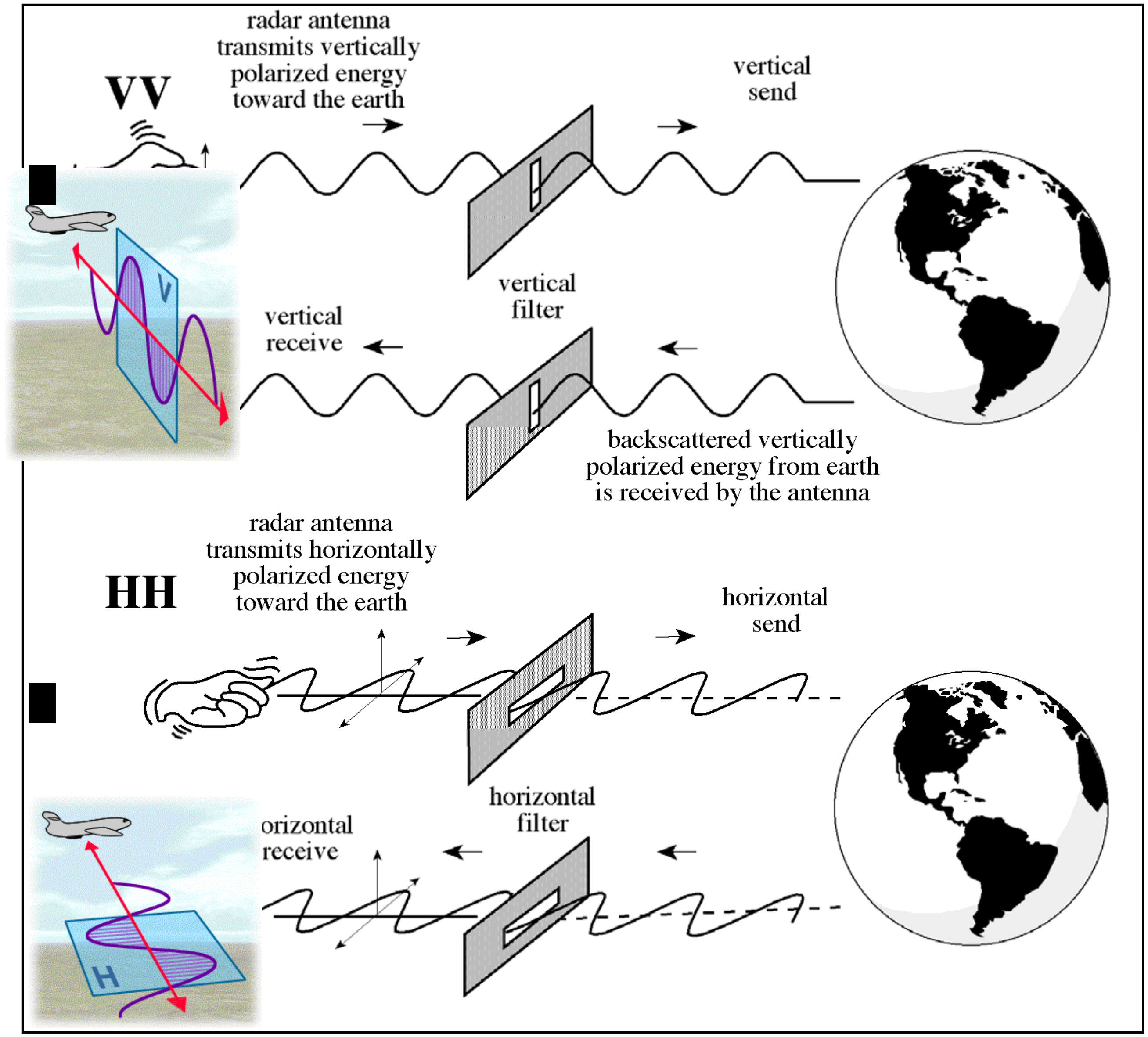
Slope facing towards radar wave

Slope facing away from radar wave

SAR data type: Polarization

- SAR backscattering is determined by both transmit and receive polarization; thus four possible polarization values HH, HV, VV, and VH

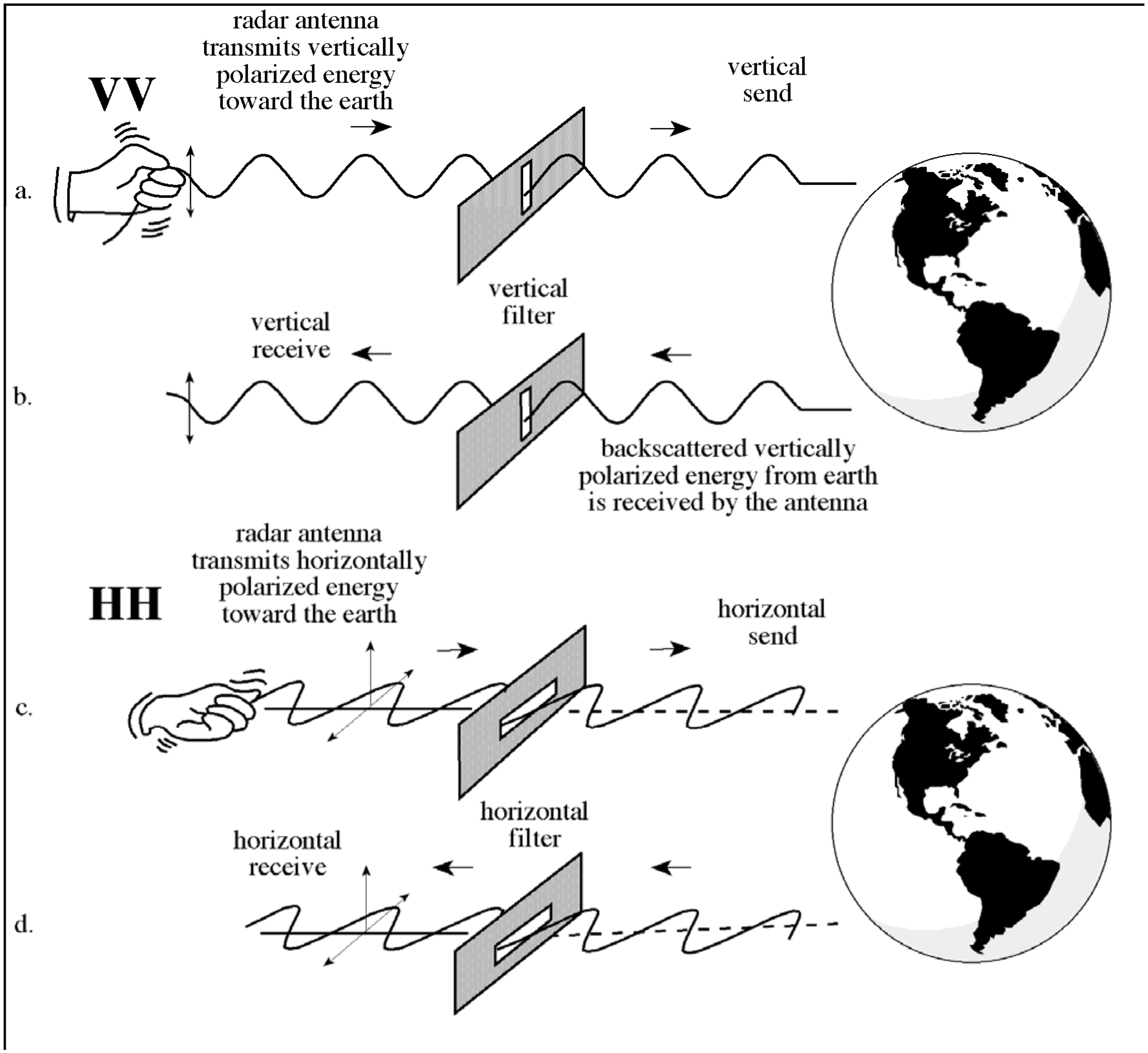
- **SAR backscattering is determined by physical structure of the target that tends to respond differently to different polarizations**



SAR backscattering is controlled by **Polarization**

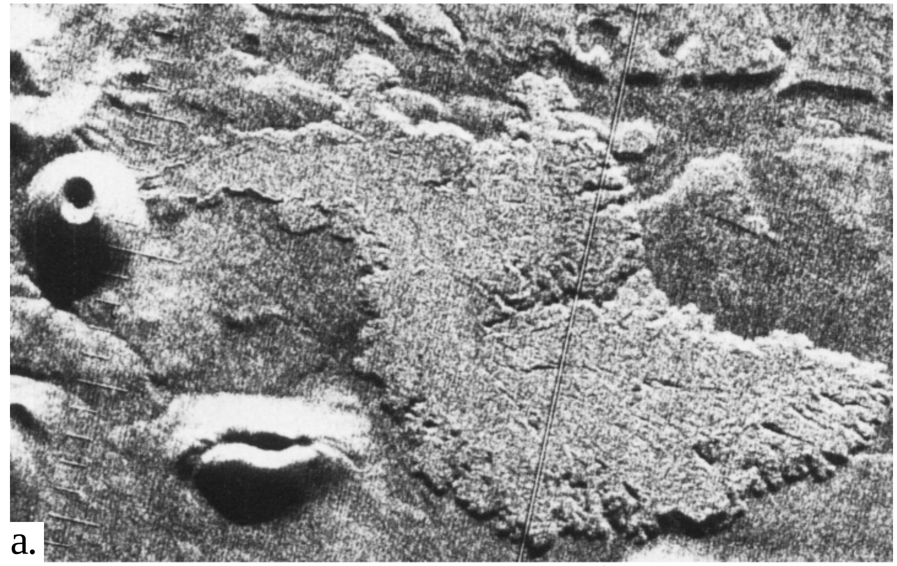
- SAR backscattering is determined by both transmit and receive polarization; thus four possible polarization values HH, HV, VV, and VH

- SAR backscattering is determined by physical structure of the target that tends to responds differently to different polarizations (e.g., wheat stalks attenuate VV but not HH)



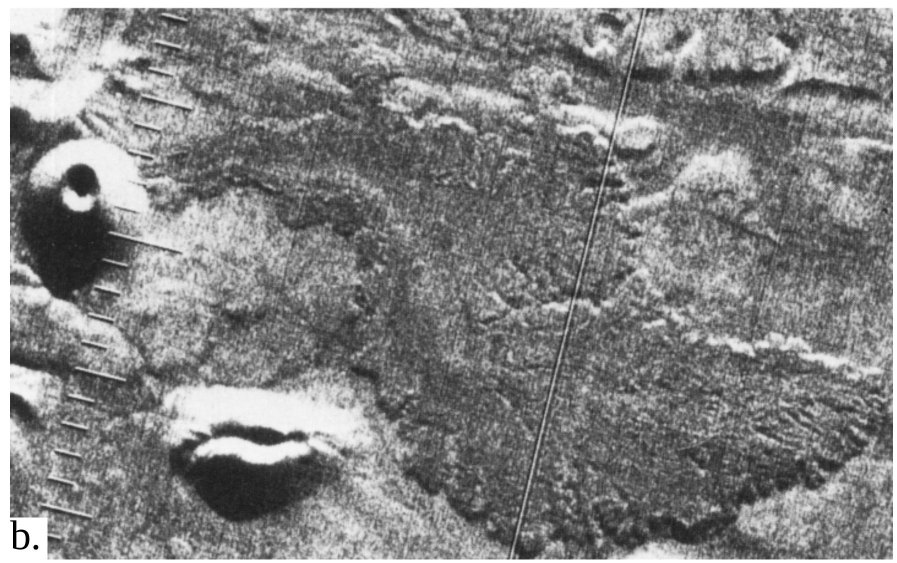
SAR backscattering is controlled by **Polarization**

Lava flow in north-center Arizona



K_a - band, HH polarization

look direction



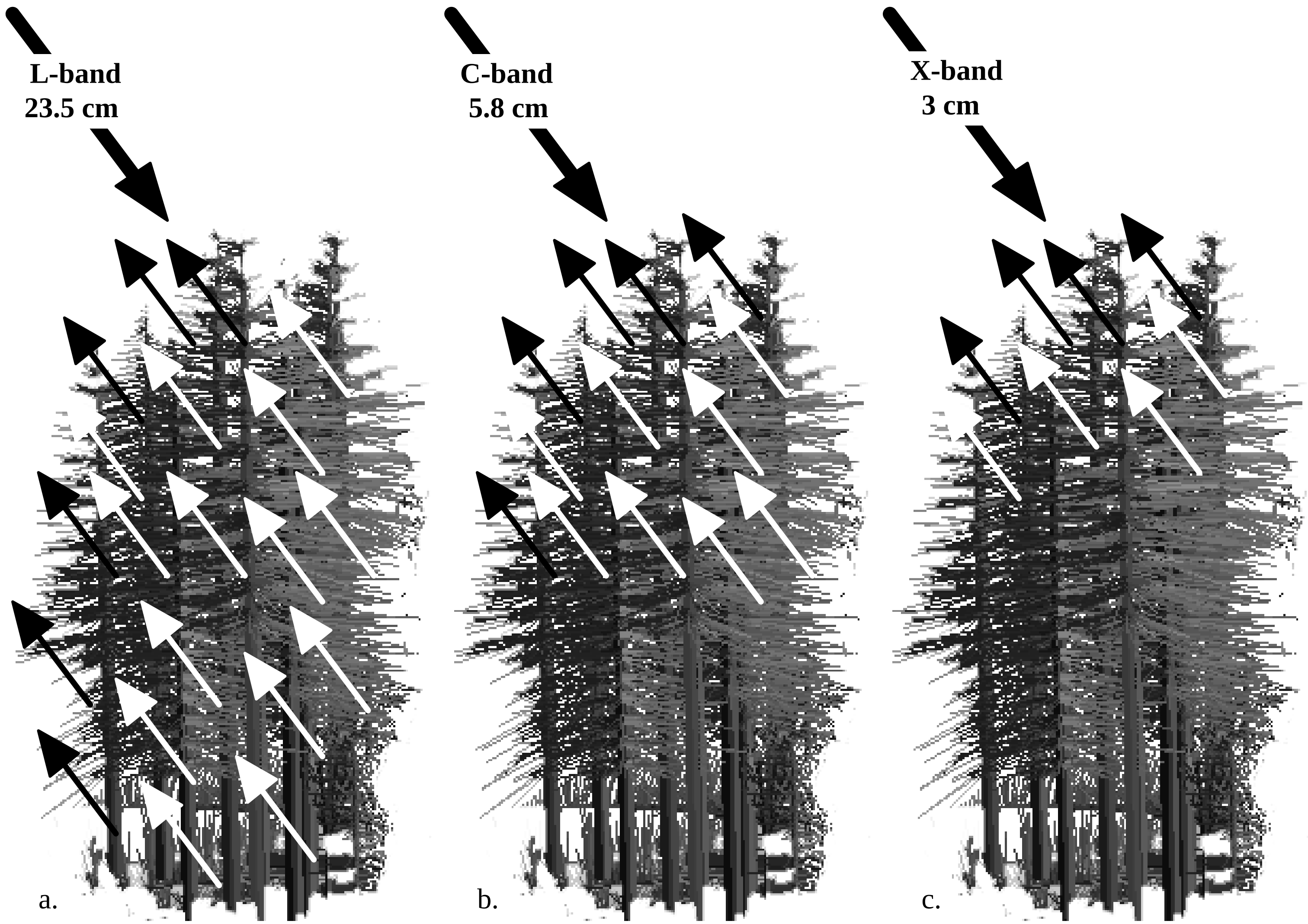
K_a - band, HV polarization

N

SAR backscattering is controlled by **Radar Wavelength**

Band	Wavelength, cm	Frequency, GHz
K_a	0.75-1.18	40.0-26.5
K	1.19-1.67	26.5-18.0
K_u	1.67-2.4	18.0-12.5
X	2.4-3.8	12.5-8.0
C	3.9-7.5	8.0-4.0
S	7.5-15.0	4.0-2.0
L	15.0-30.0	2.0-1.0
P	30.0-100	1.0-0.3

SAR backscattering is controlled by **Radar Wavelength**



Penetration ability to forest

SAR backscattering is controlled by **Radar Wavelength**

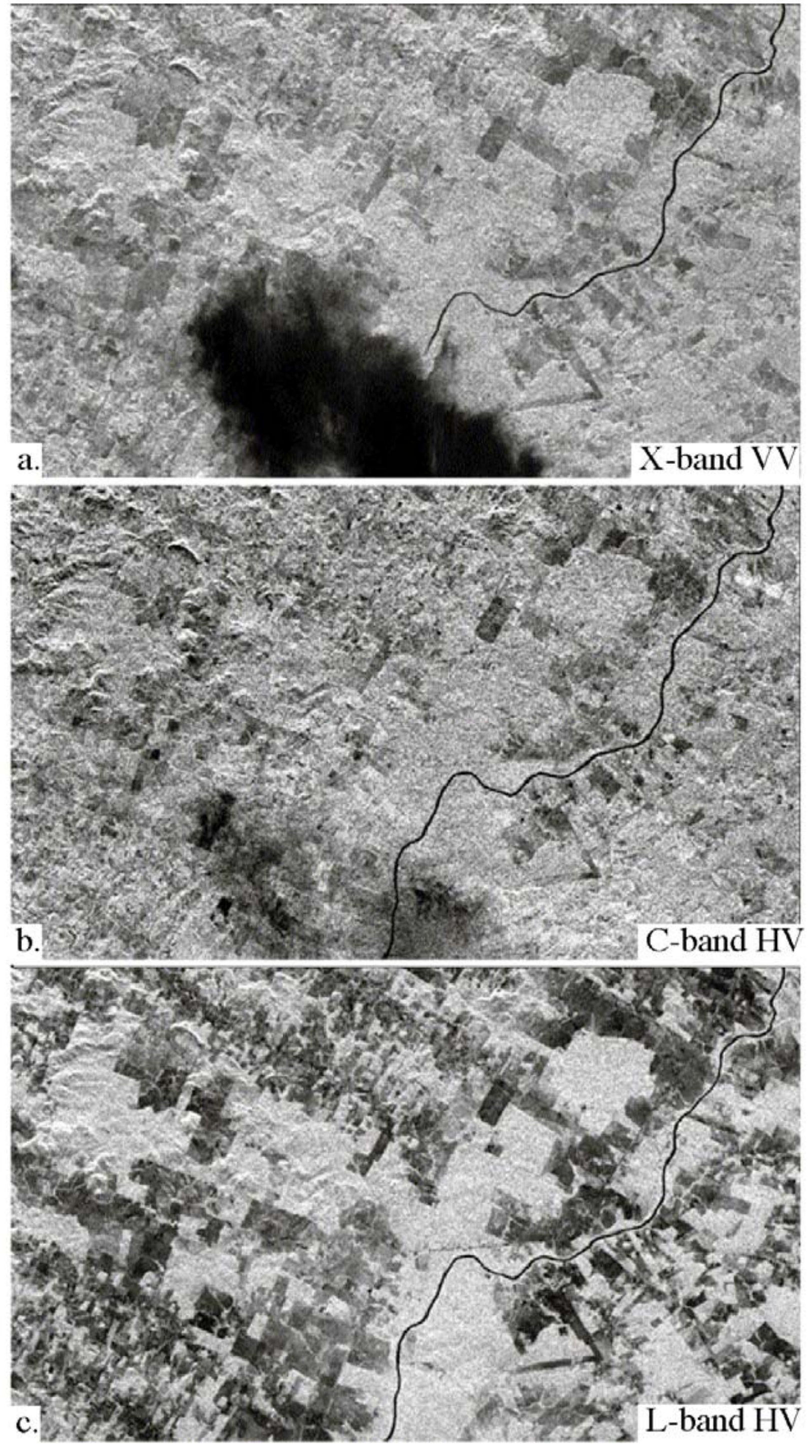
X-band (λ = 3 cm)

L-band (λ = 24 cm)

P-band (λ = ~70 cm)

SAR backscattering is controlled by **Radar Wavelength**

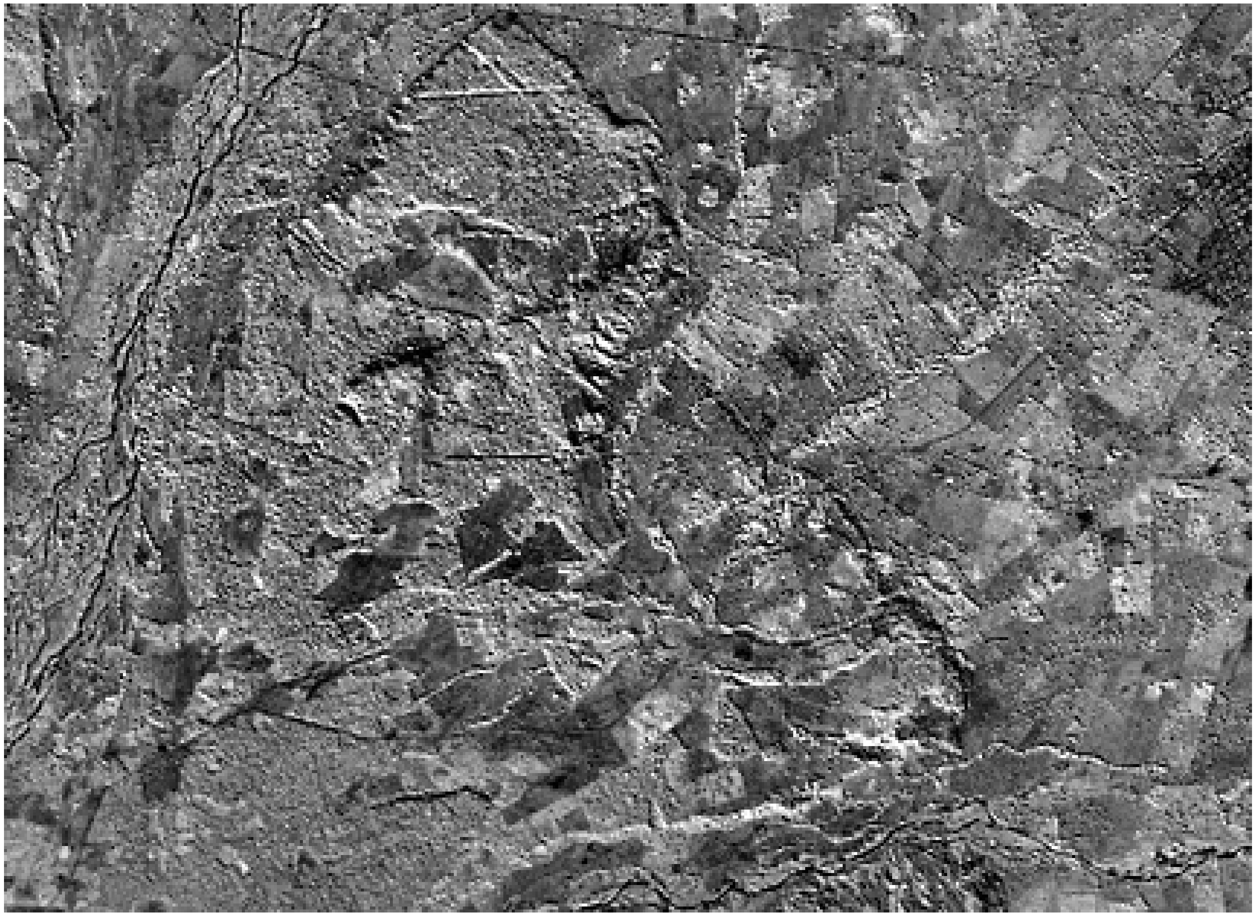
Penetration ability to heavy rainfall



SIR-C/X-SAR Images of a Portion of Rondonia, Brazil, April 10, 1994

X-band/P-band Comparison

X-band Image (λ = 3 cm)



A cloud-prone Colombian agricultural area

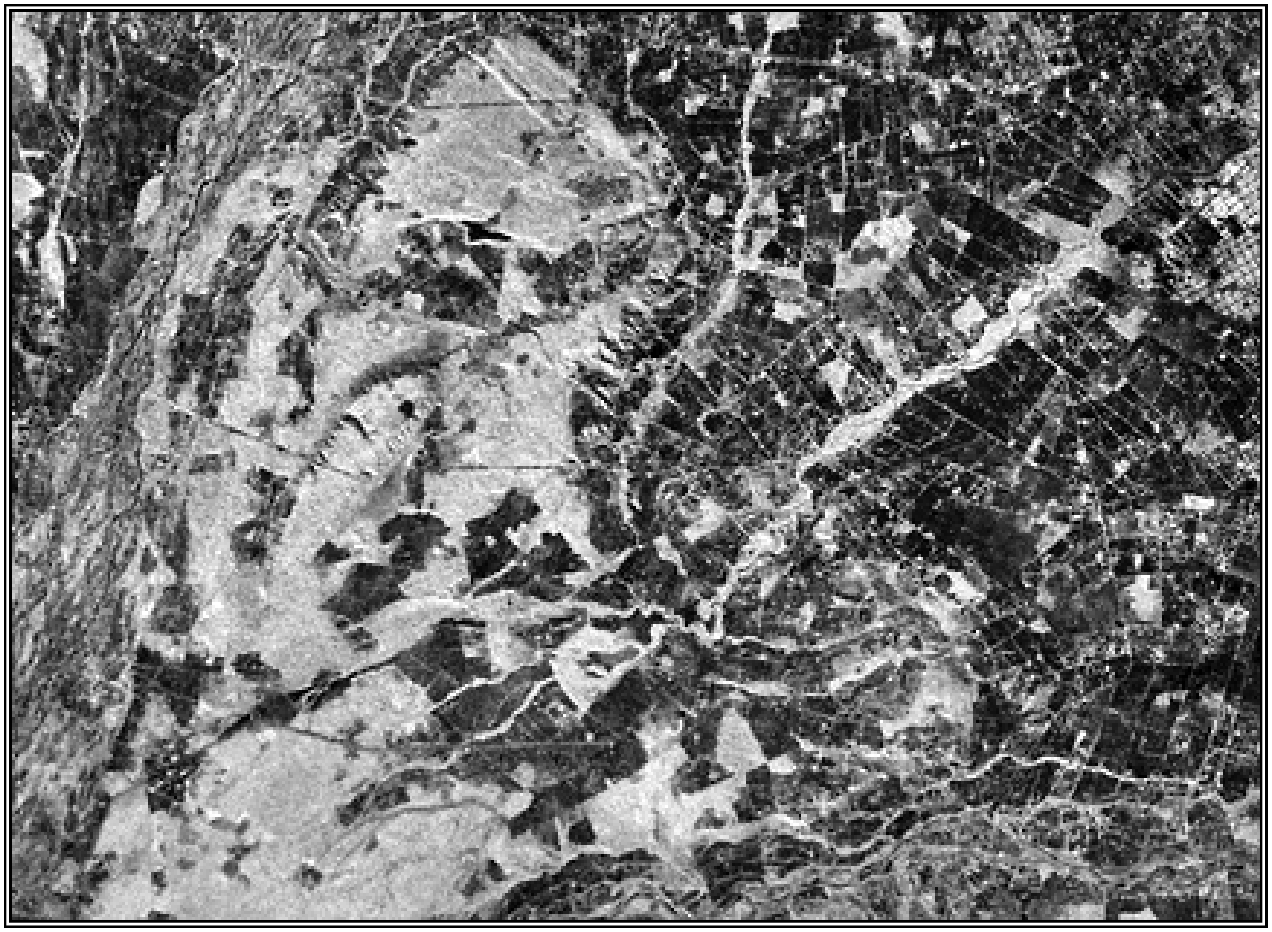
Courtesy of EarthData International

X-band/P-band Comparison

P-band Image (λ = 86 cm)

Small village otherwise obscured by trees

P-band shows fence lines, footpaths, and other subtle cultural effects on the soils and low lying vegetation



A cloud-prone Colombian agricultural area

Courtesy of EarthData International

What does Radar Measure?

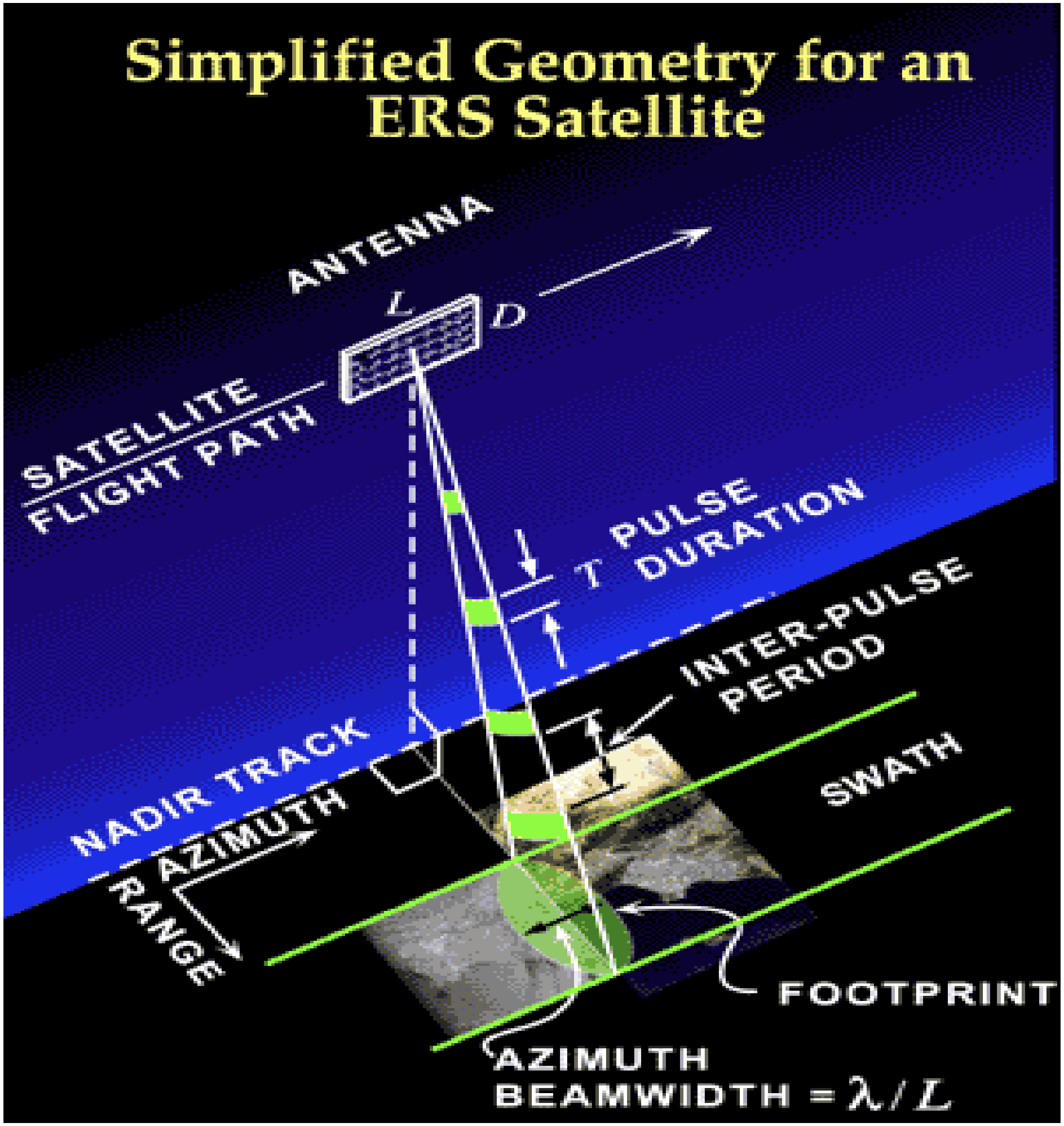
Radar parameters affecting radar brightness	*Target parameters affecting radar brightness*
Wavelength	Roughness
Polarization	Volume scattering
Look angle	Ground slope & azimuth
Flight orientation	Target geometry
	Dielectric constant

Radar brightness is due to a combination of all these factors!

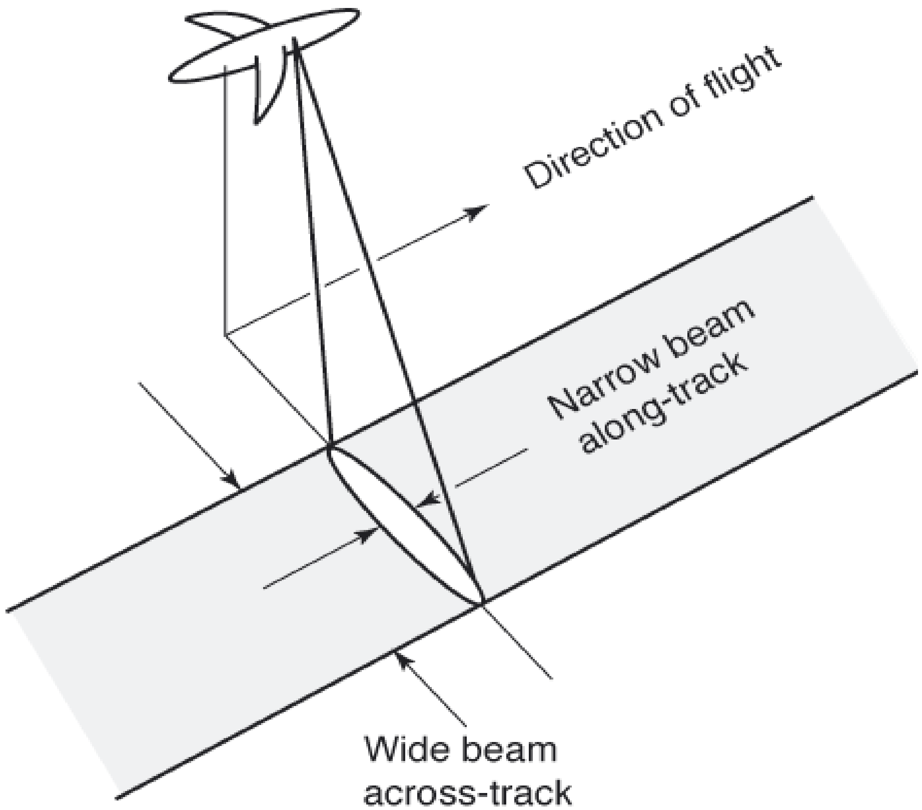
Geometric Distortions in SAR Image

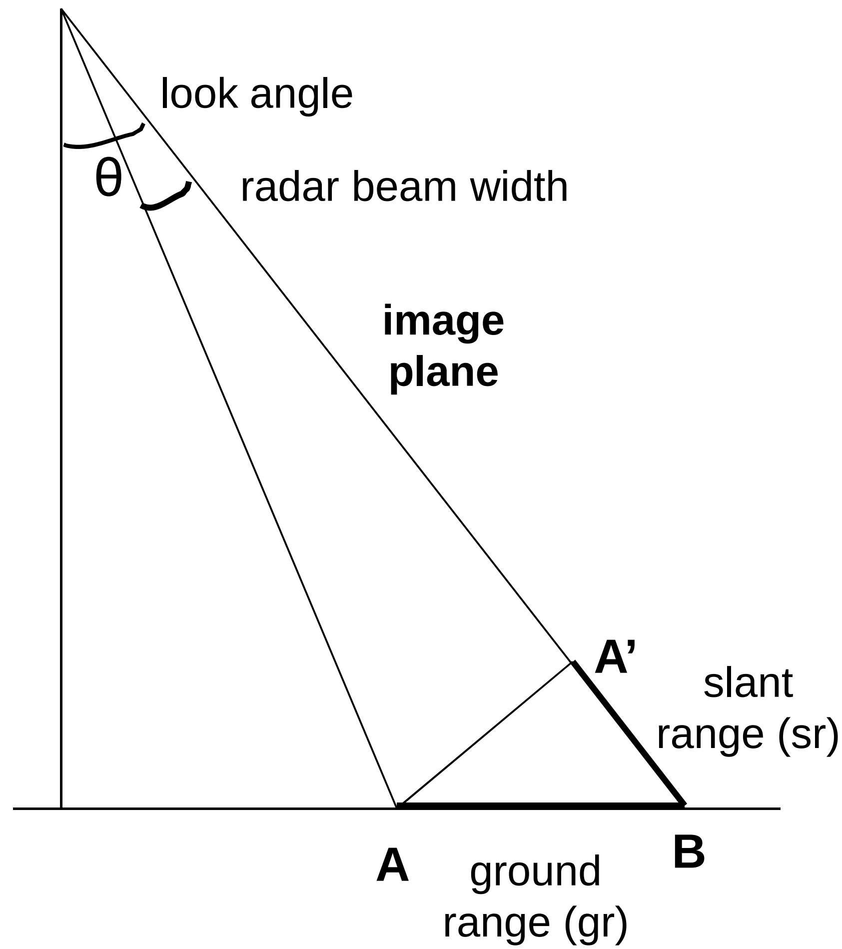
- Foreshortening
- Layover
- Shadow

Geometric distortions are due to inherent side-looking nature of radar



Side-looking Imaging geometry





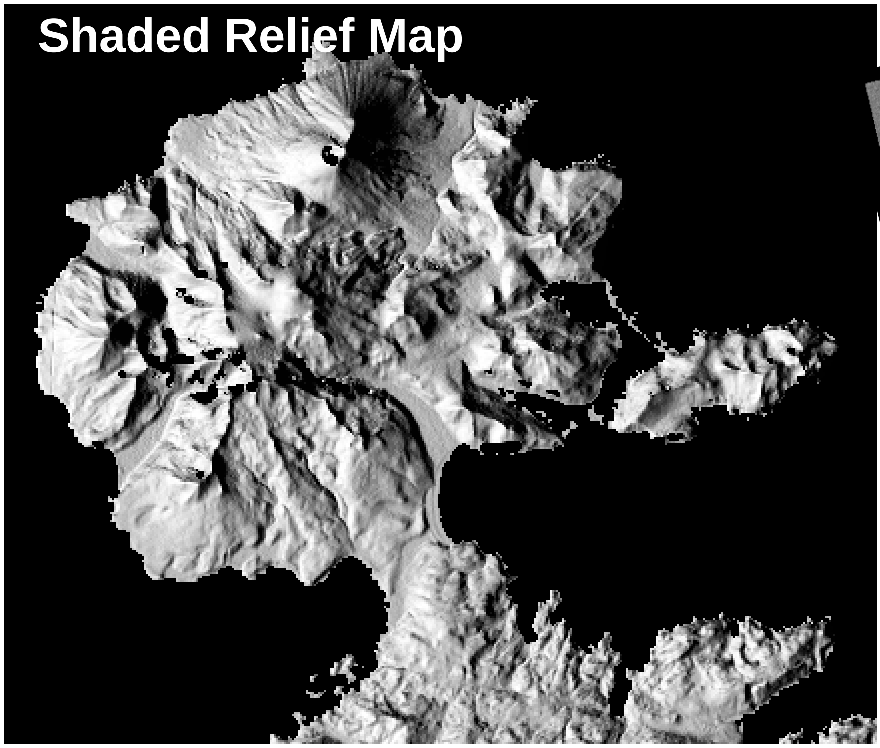
Radar signal data are sampled in the slant-range imaging plane

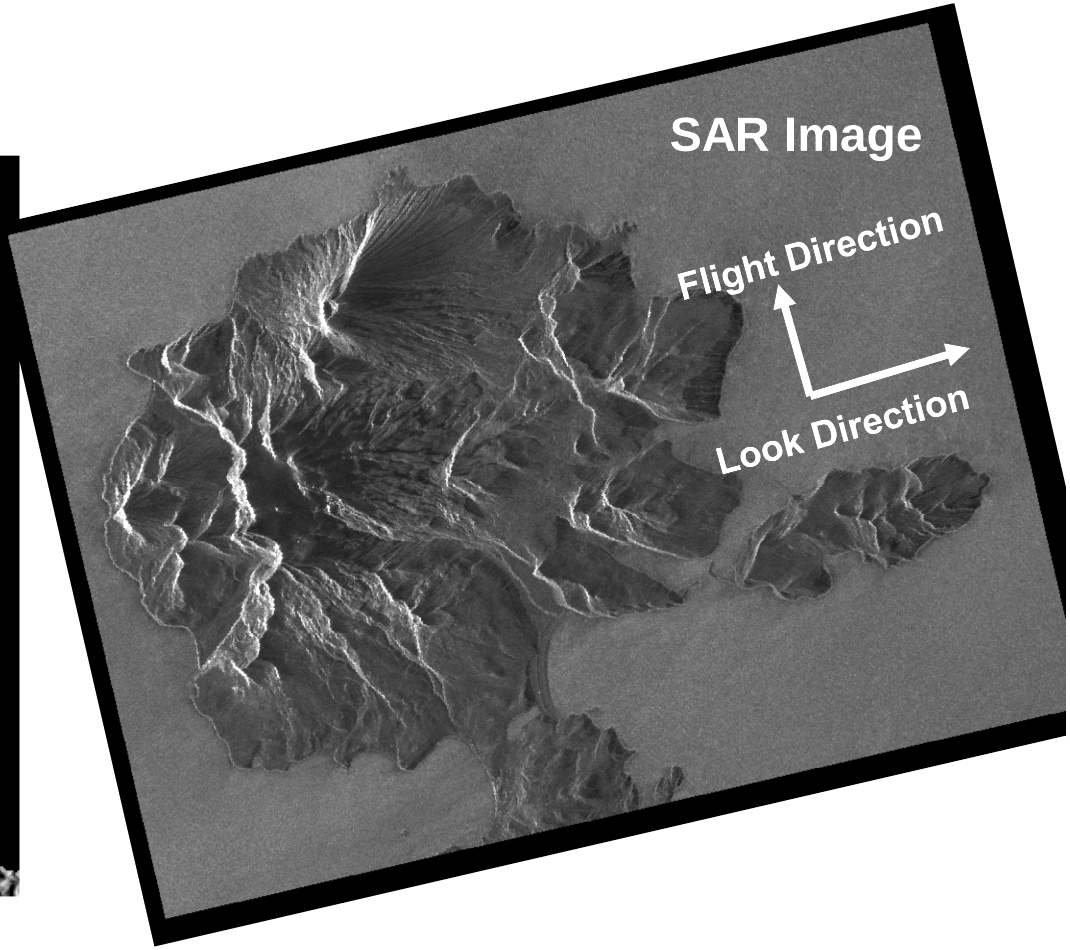
$$gr = sr/\sin(\theta)$$

Georeferenced vs. Geocoded Products

- **Georeferenced products**
  - geometrically corrected for an spheroid earth surface
  - not corrected for terrain heights
  - should not be used for mapping purposes.
- **Geocoded products**
  - geometrically corrected to conform to a map projection.
  - DEM is required.

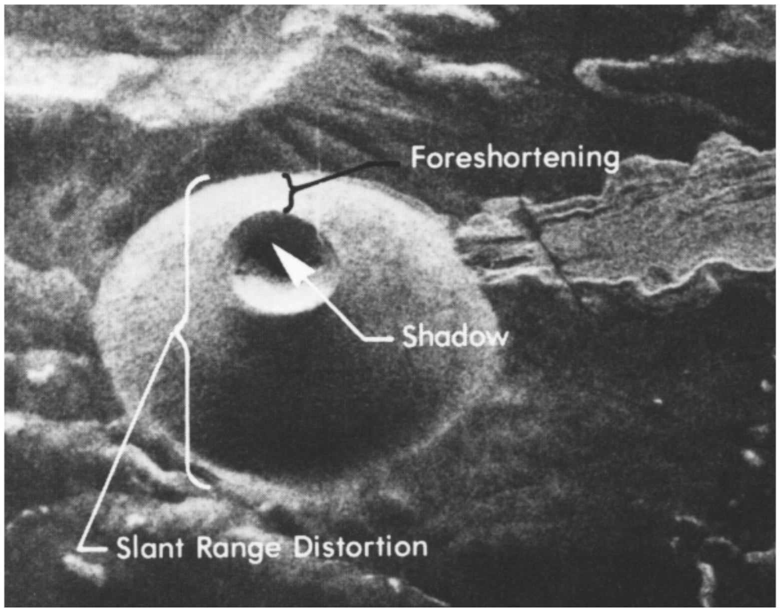
Geometric Distortions in SAR Image



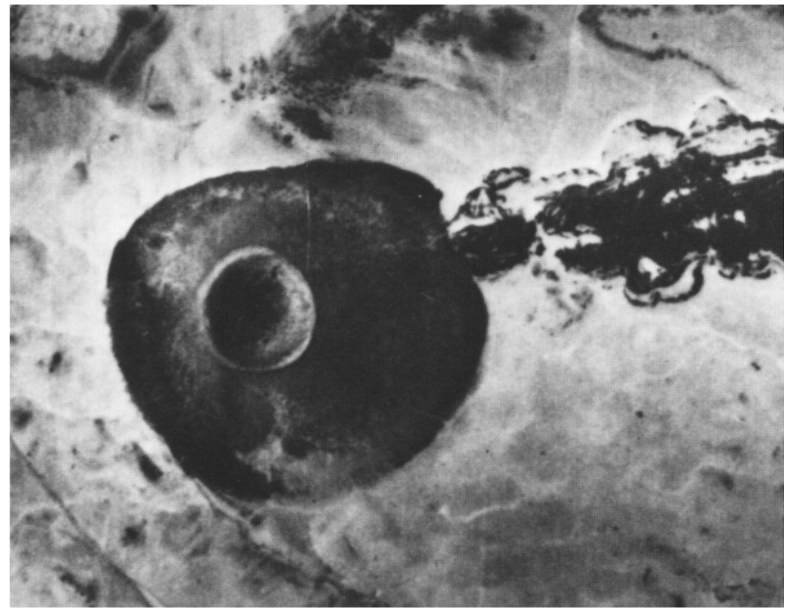


Korovin Volcano, AK

Geometric Distortions in SAR Images



X-band SAR image



Aerial Photograph

look direction

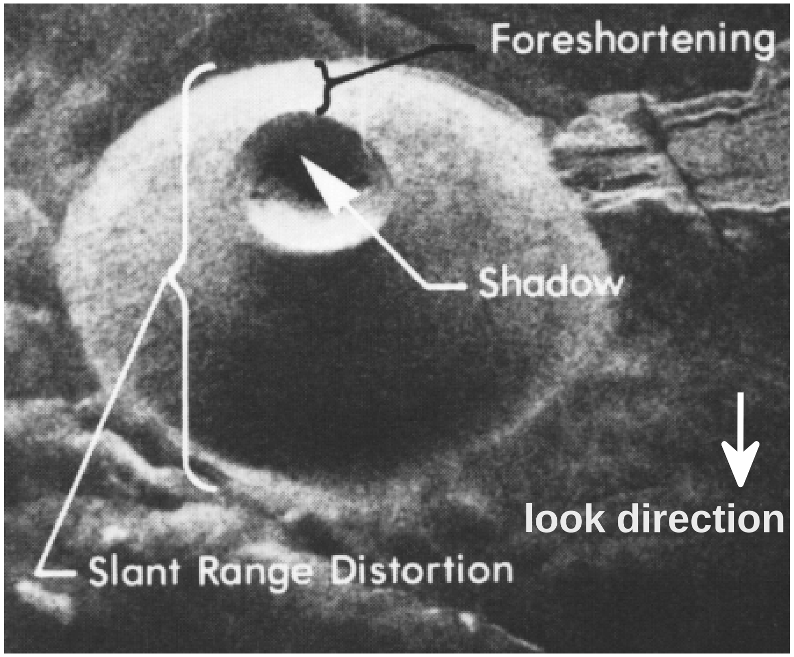
Foreshortening

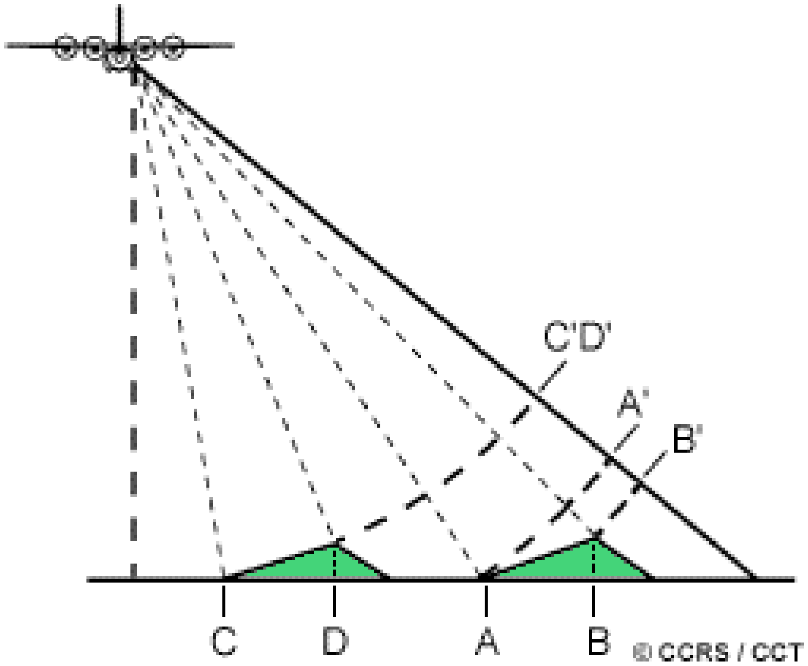
• When the radar beam reaches a slope facing towards the radar, foreshortening will occur. Because the radar measures distance in slant-range, the slope (A to B) will appear compressed and the length of the slope will be represented incorrectly (A' to B').

• Depending on the angle of the mountain slope in relation to the incidence angle of the radar beam, the severity of foreshortening will vary. Maximum foreshortening occurs when the radar beam is perpendicular to the slope such that the slope, the base, and the top are imaged simultaneously (C to D). The length of the slope will be reduced to an effective length of 0 in slant range (C'D').

• **The foreshortened slopes on the image appear as bright features on the image.**

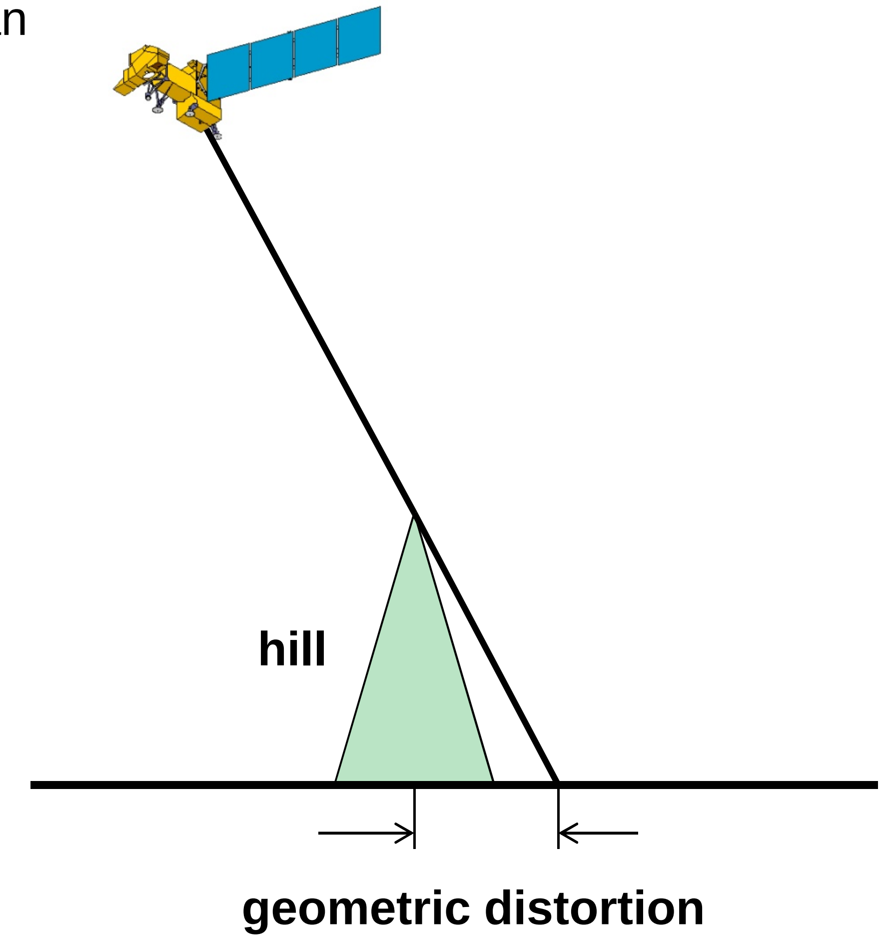
• Foreshortening distortion can be lessened by imaging at large incidence angles (say, 23° bad and 45° good). Image distortions can be rectified (geocoded) if a DEM is available.





Difference in geometric distortion between radar and Landsat-7 sensors

- In a radar image, the foreshortened slopes on the image appear as bright features and lean over toward the radar antenna.
- In an Landsat-7 image, the geometric distortion has the opposite effect. Mountain peaks appear further away from the sensor.

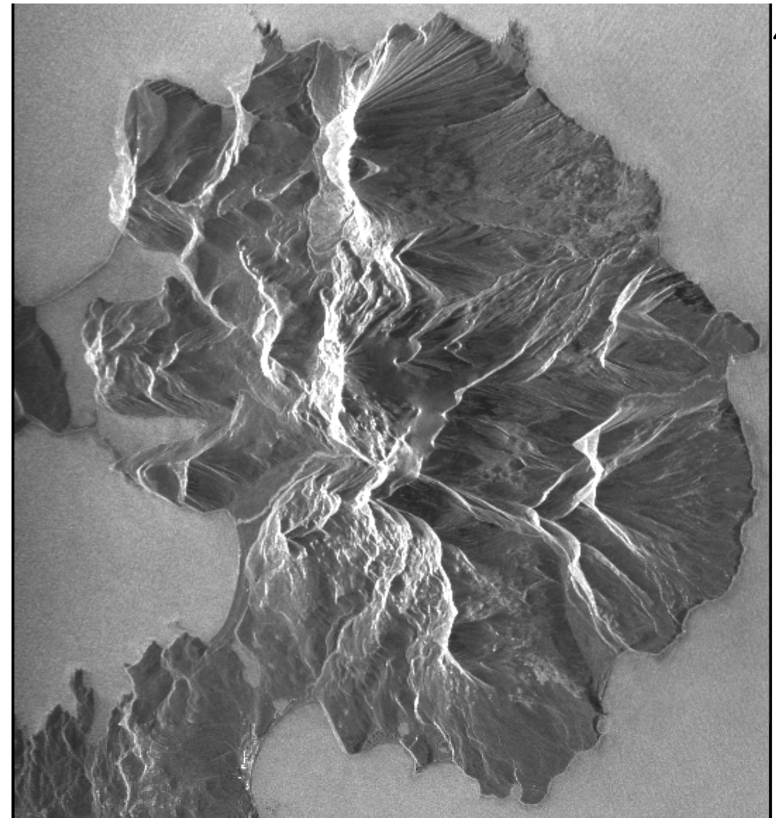


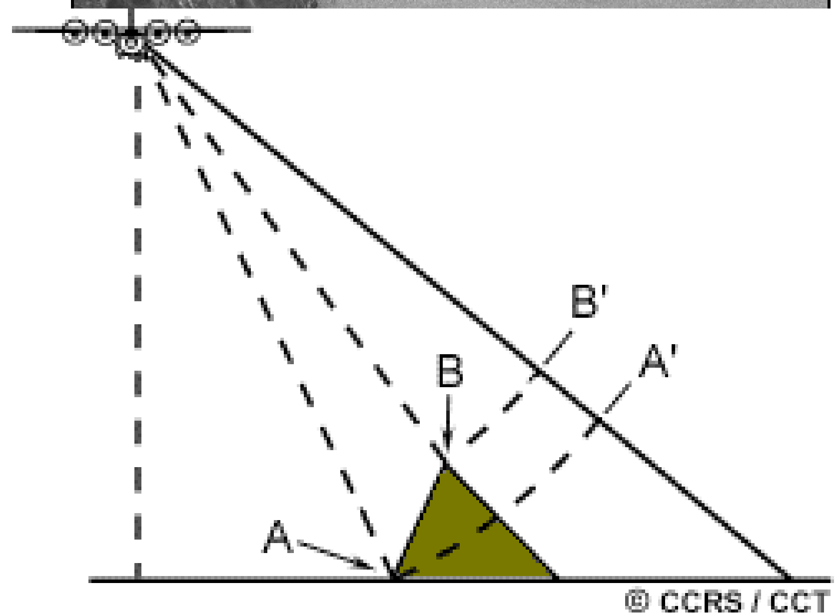
Layover

•Layover will occur when the return signal from the top of the feature will be received before the signal from the bottom. As a result, the top of the feature is displaced towards the radar from its true position on the ground, and "lays over" the base of the feature (B' to A').

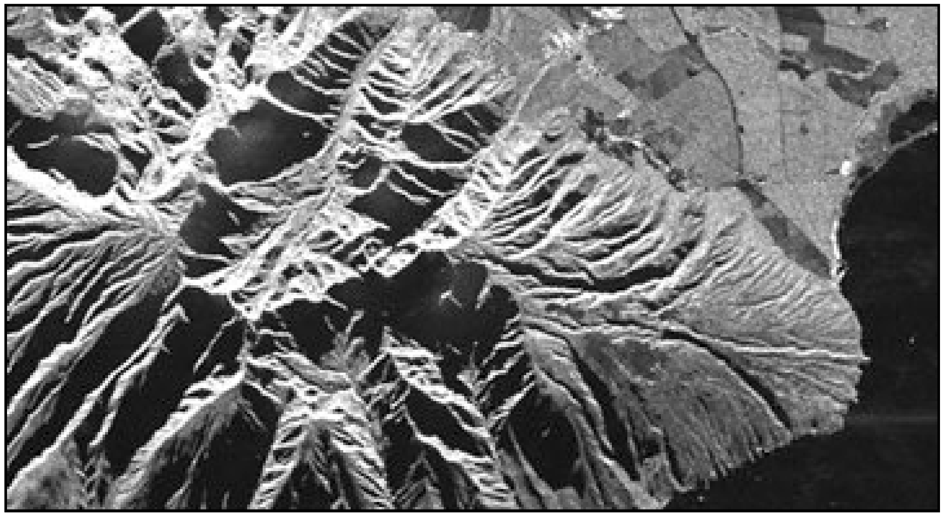
•**Layover effects on a radar image look very similar to effects due to foreshortening, resulting bright features in radar image. As with foreshortening, layover is most severe for small incidence angles, and in mountainous terrain**.

•Layover distortion can be lessened by imaging at large incidence angles (say, 23° bad and 45° good).





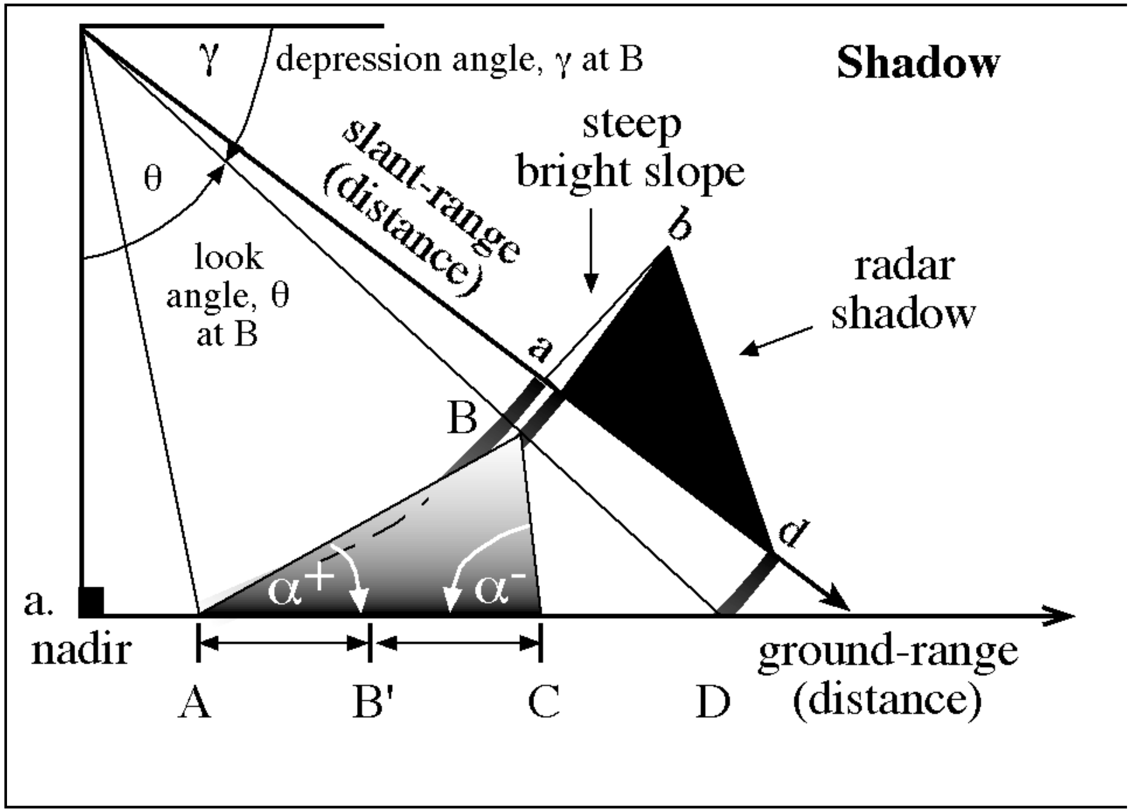
Shadow



•Because of side-looking geometry, shallow will occur when back slopes in mountainous terrain are obscured from view.

•**Radar shadow results in dark areas in image.**

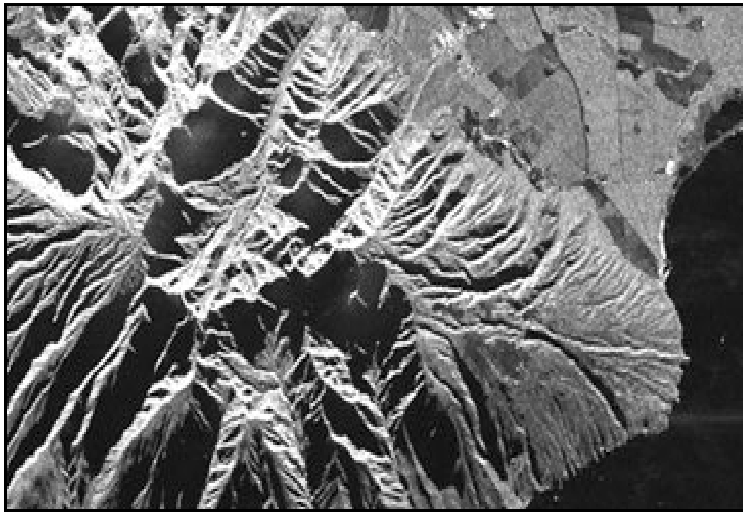
•Shadow areas can be imaged by looking the same area from the opposite side.



Difference in shadow between radar and Landsat-7 sensors

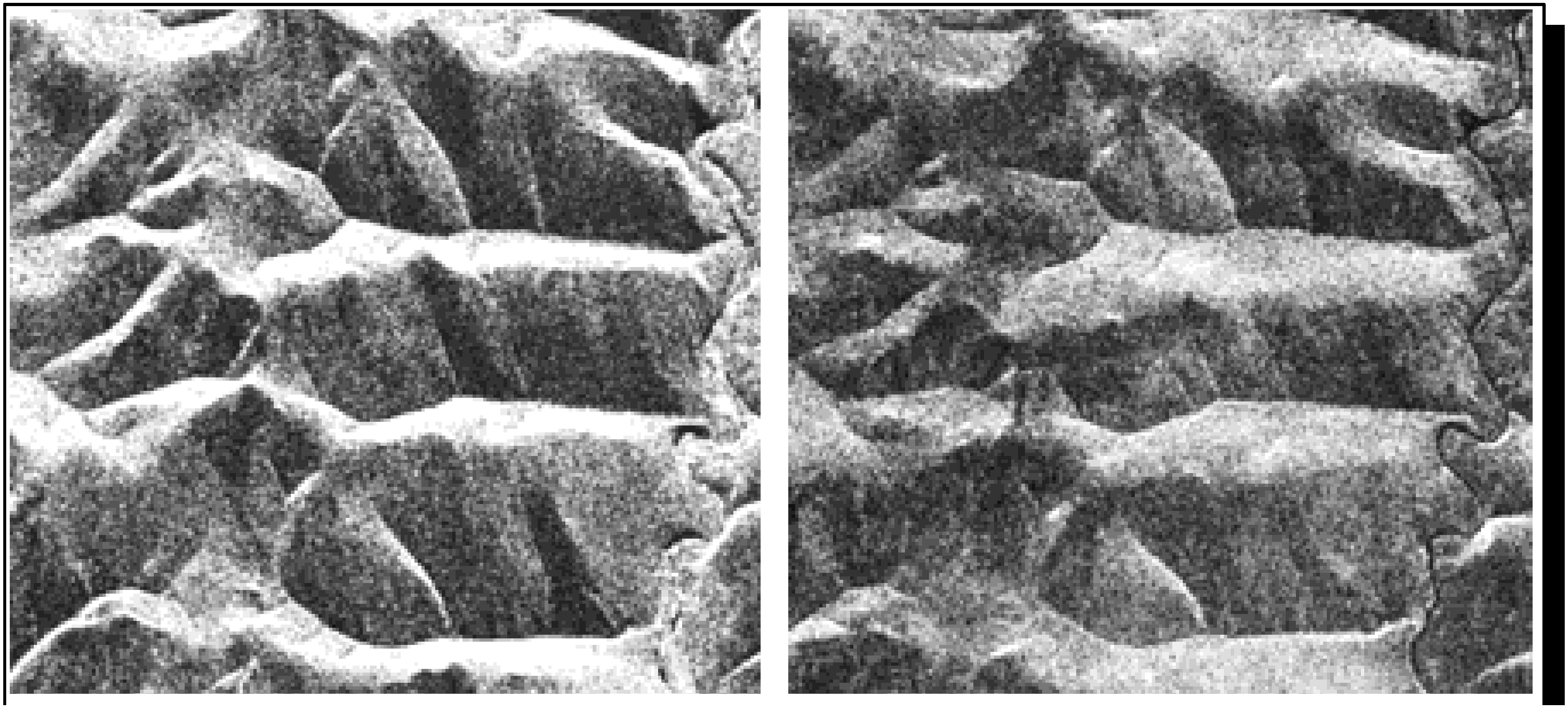
- Radar shallows are areas of a radar image where there is a complete lack of received information.
- Radar shadows correspond to regions that lie behind objects in the imaged scene and from which there is no return echo.
- Radar shallows should be regarded as radar “silence”.
- Landsat-7 image shadows are imaged regions that are weakly illuminated by the Sun.

Radar Shadows



Landsat-7 Image Shadows

Geometric Distortions in SAR Images



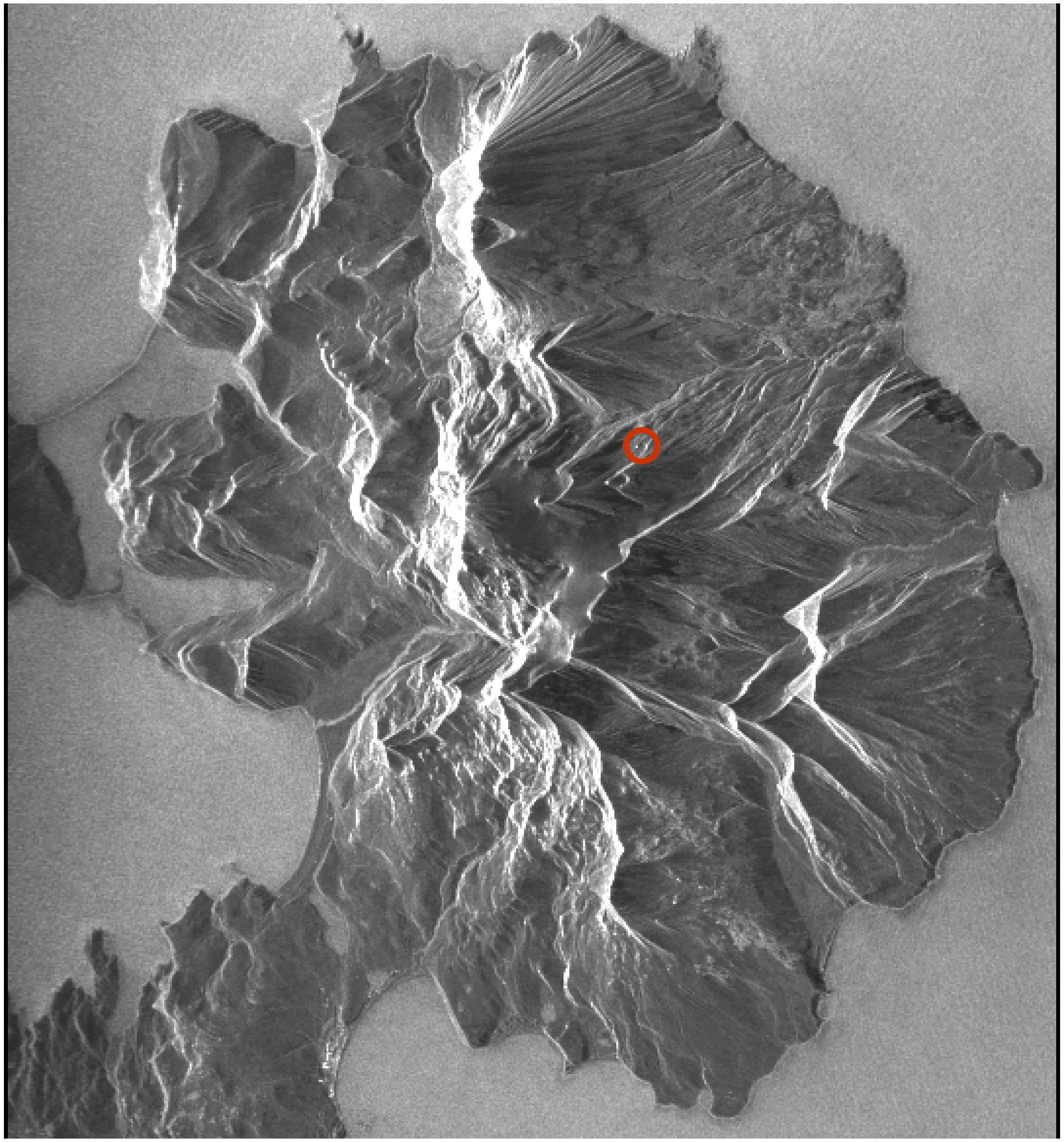
C-band ERS-1 image
look angle = 23°

L-band JERS-1 image
look angle = 39°

↓ **look direction**

$$\mathbf{gr = sr/sin(}\theta\mathbf{)}$$

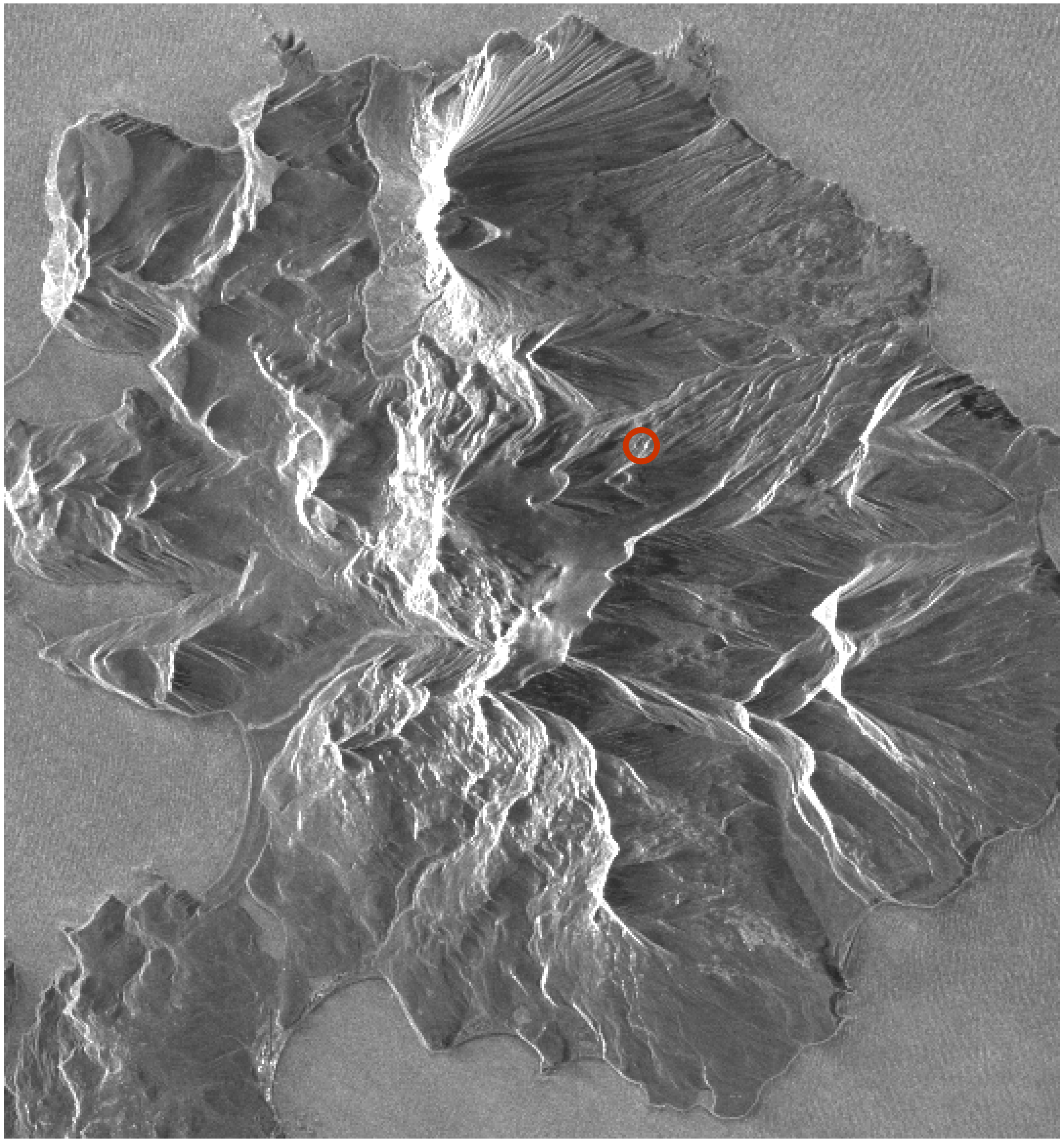
Geometric Distortions in SAR Images



Track 122: look angle = 20°

gr = sr/sin(θ**)**

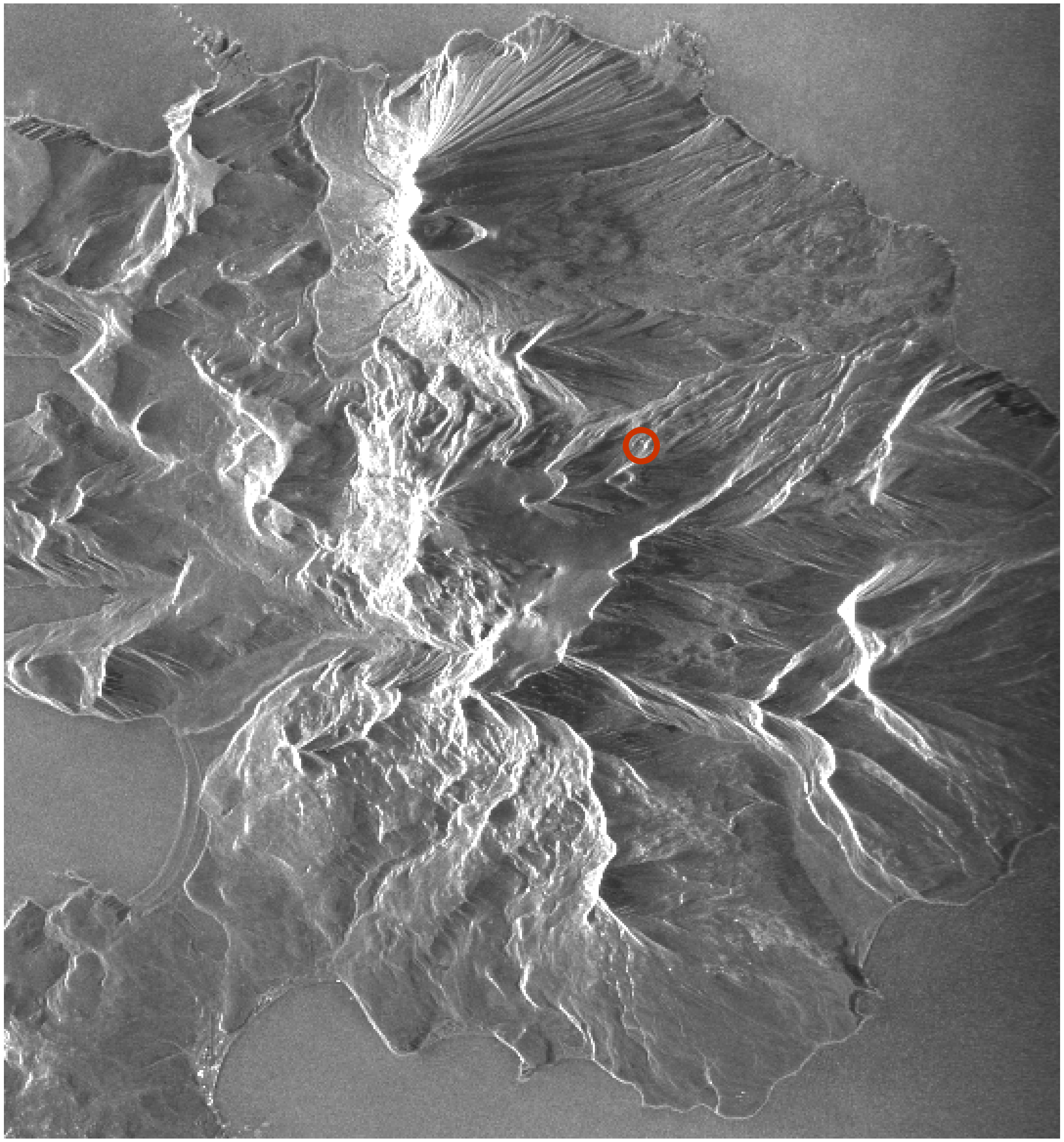
Geometric Distortions in SAR Images



Track 394: look angle = 23°

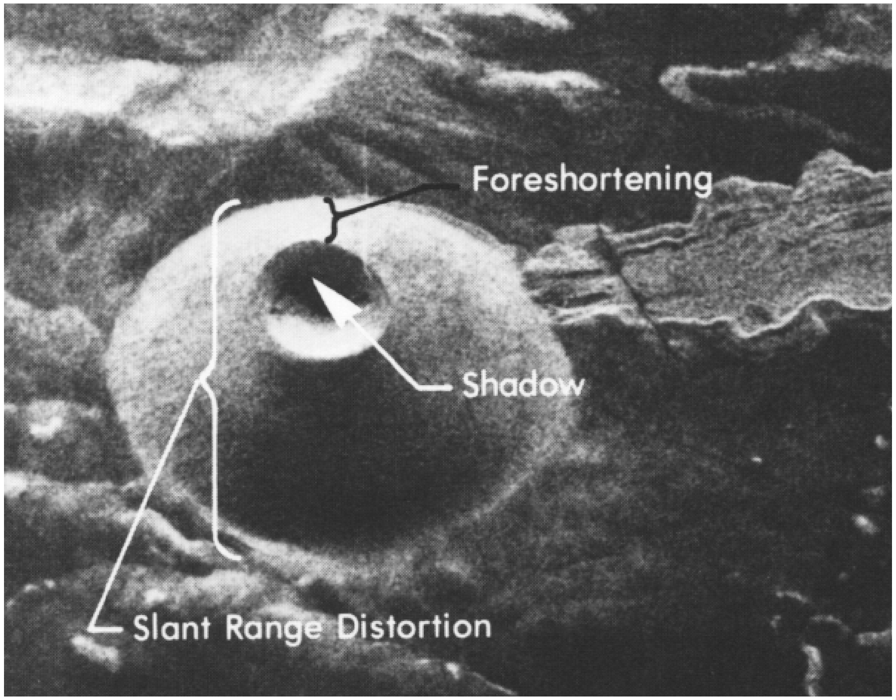
gr = sr/sin(θ)

Geometric Distortions in SAR Images



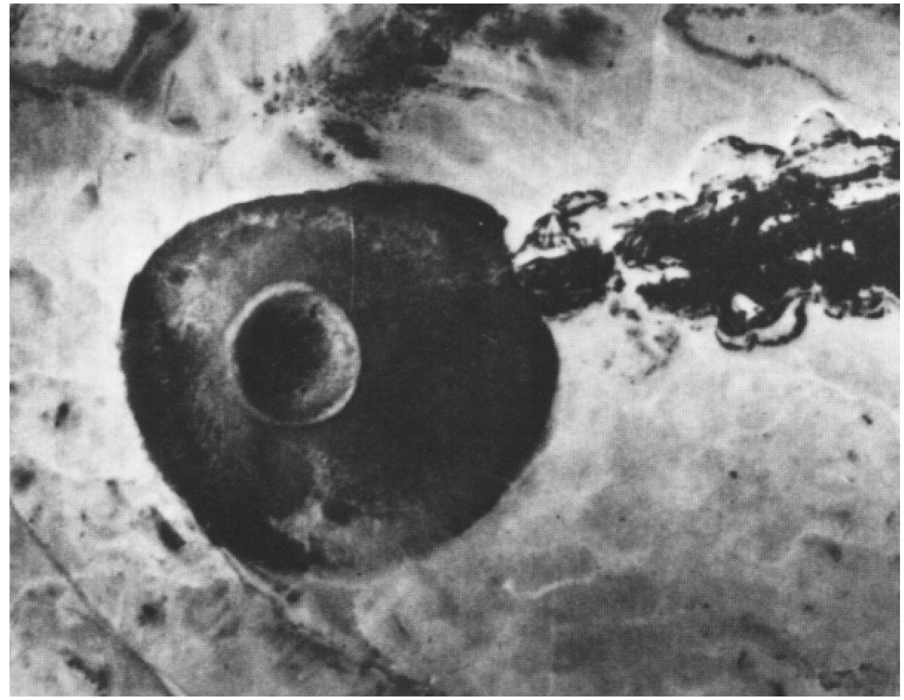
Track 165: look angle = 26°

Geometric Distortions in SAR Images



X-band SAR image

look direction



Aerial Photograph

Shadows?

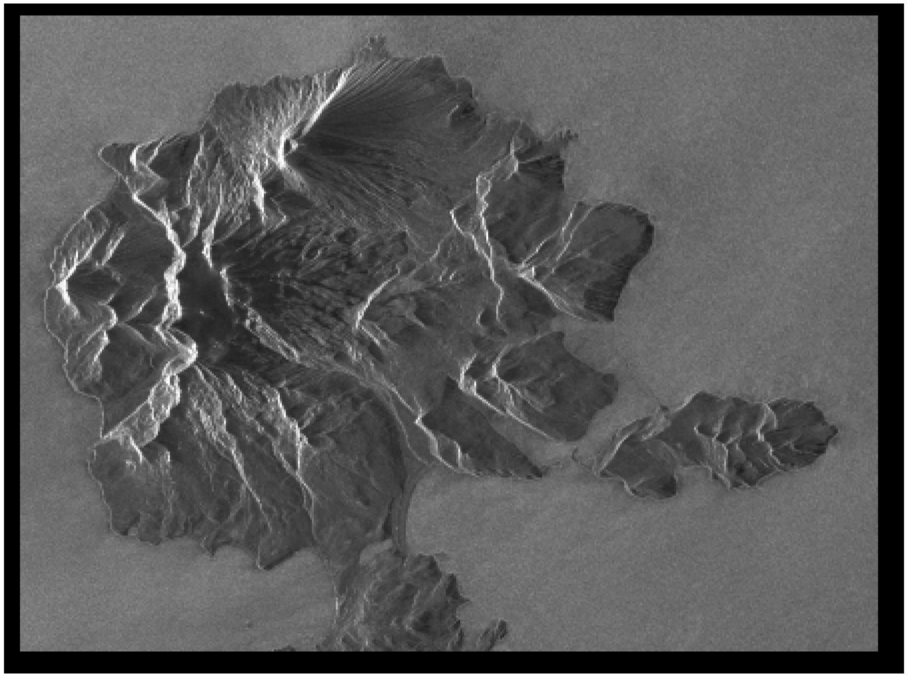
$$\mathbf{gr = sr/sin(\theta)}$$

Terrain Correction

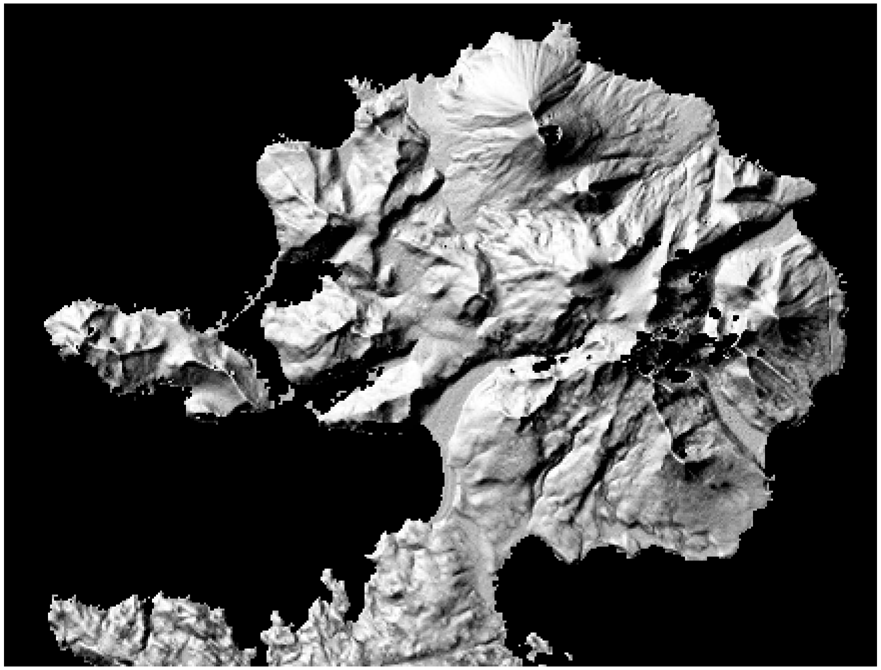
•The DEM needs to be resampled to project heights from a map coordinate into the appropriate radar geometry via geometric simulation of the imaging process (**lookup table**).

•The radar slant range and azimuth coordinates are calculated for each point in the DEM. This set of coordinates forms a non-uniformly sampled grid in the SAR coordinate space.

•The DEM height data are then resampled into a uniform grid in the radar coordinates using the values over the non-uniform grid.

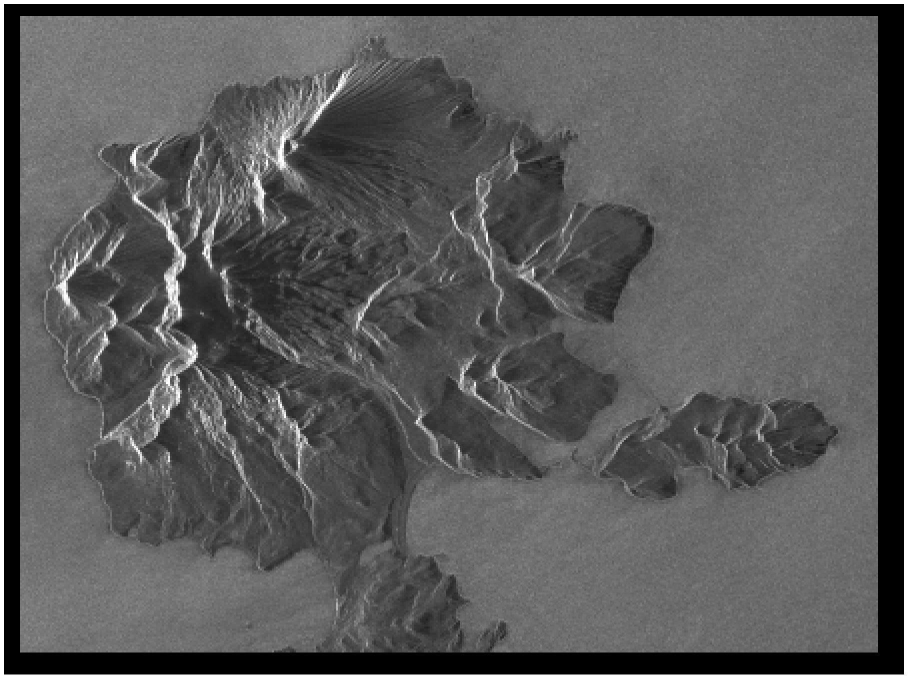


SAR image – SAR coordinate

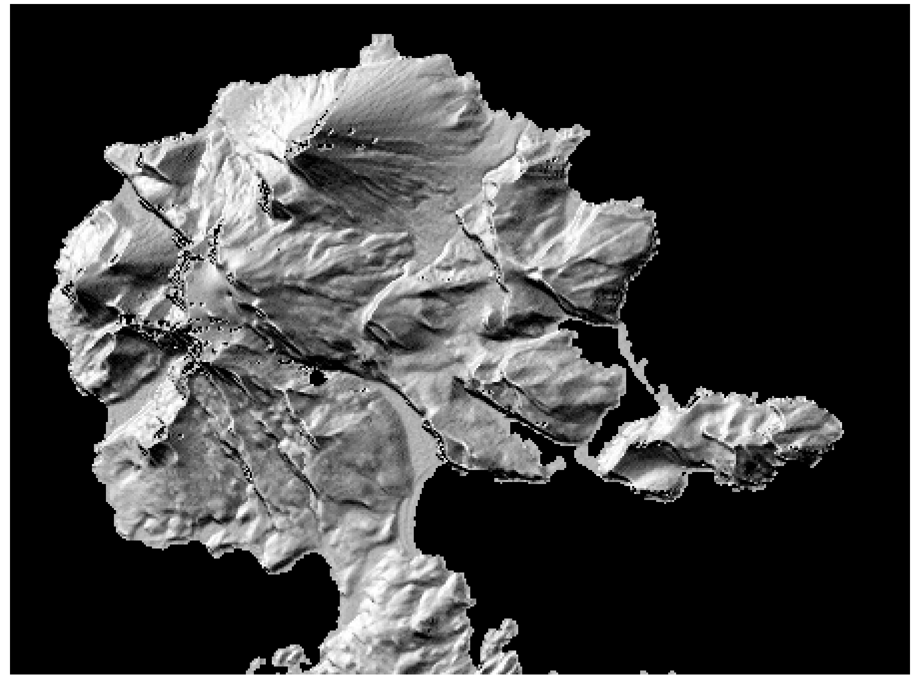


DEM covering about the SAR image

Terrain Correction



SAR image – SAR coordinate

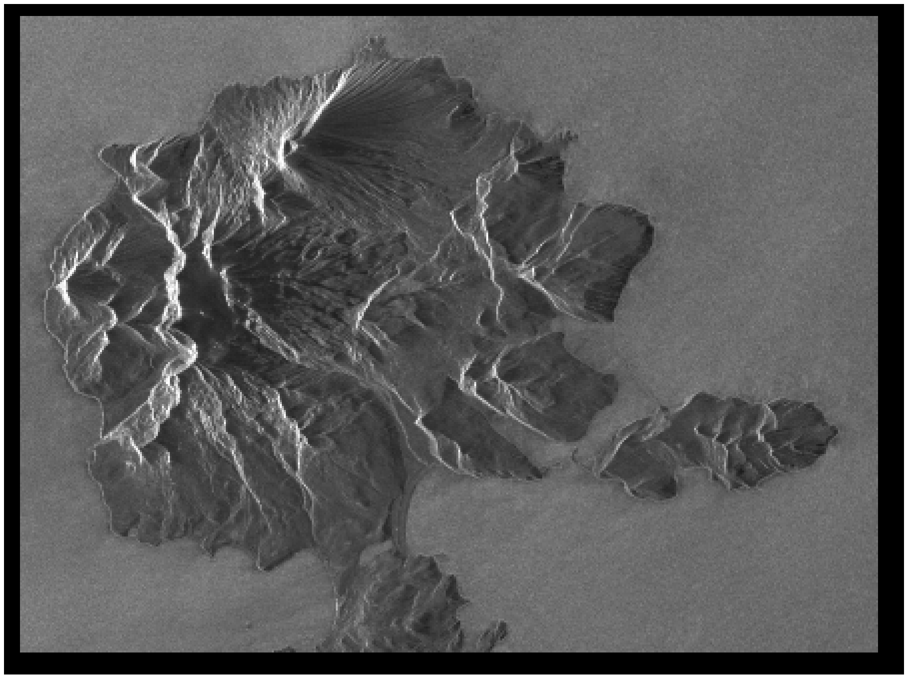


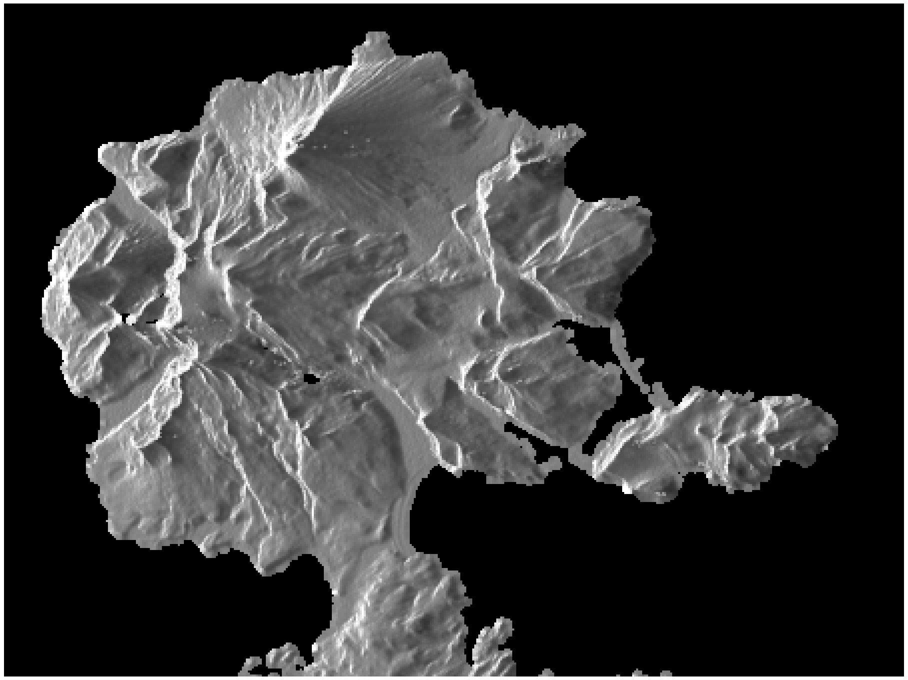
DEM (covering the SAR image)
in SAR coordinate

Terrain Correction

• Compare the simulated SAR image with the observed SAR image to **refine** the geometric simulation of the imaging process (**lookup table**).

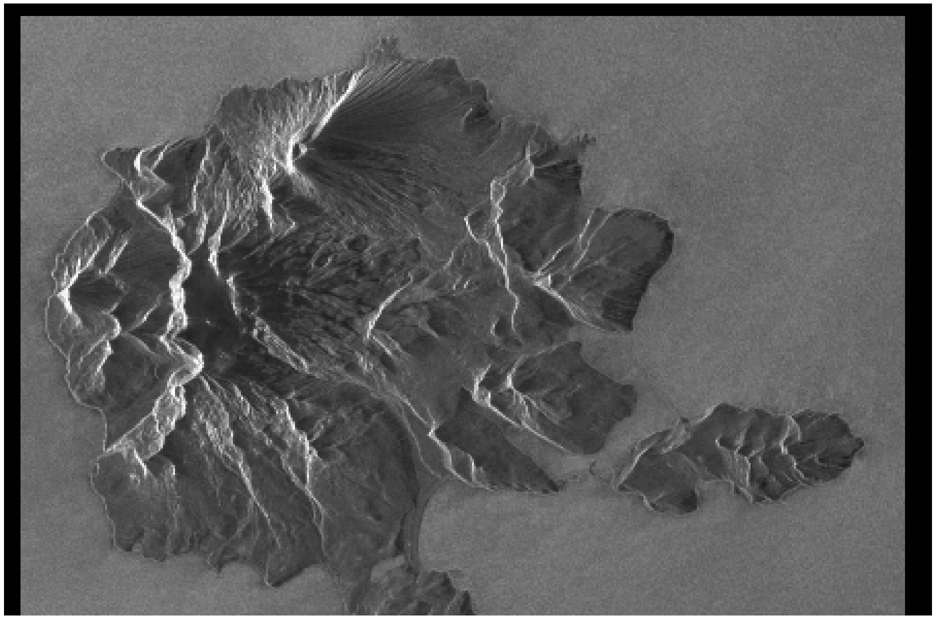
• The refined "**lookup table**" can then project SAR data into a map coordinate system.



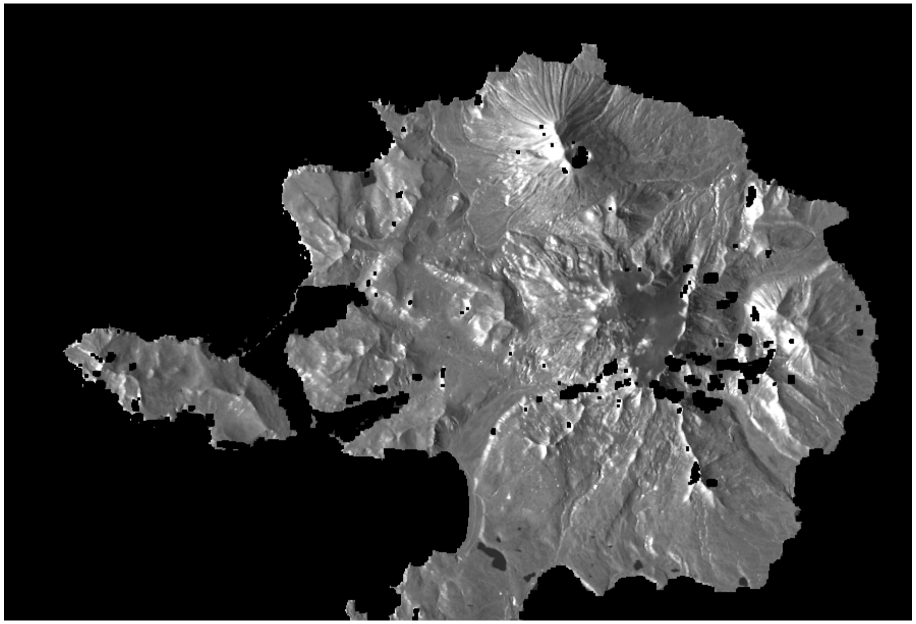


SAR image – SAR coordinate **Simulated SAR image in SAR coordinate**

Terrain Correction

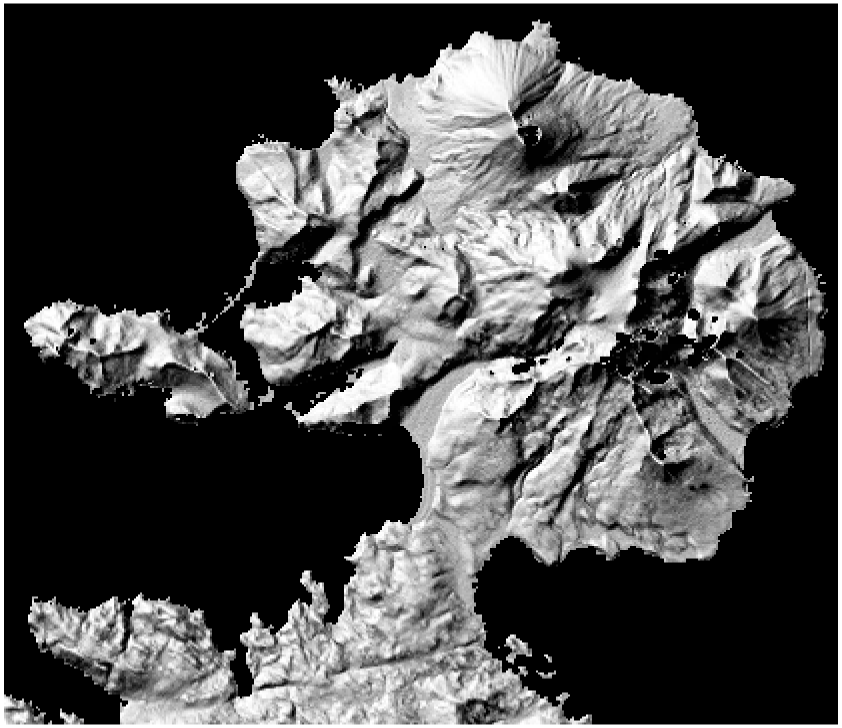


SAR image – SAR coordinate

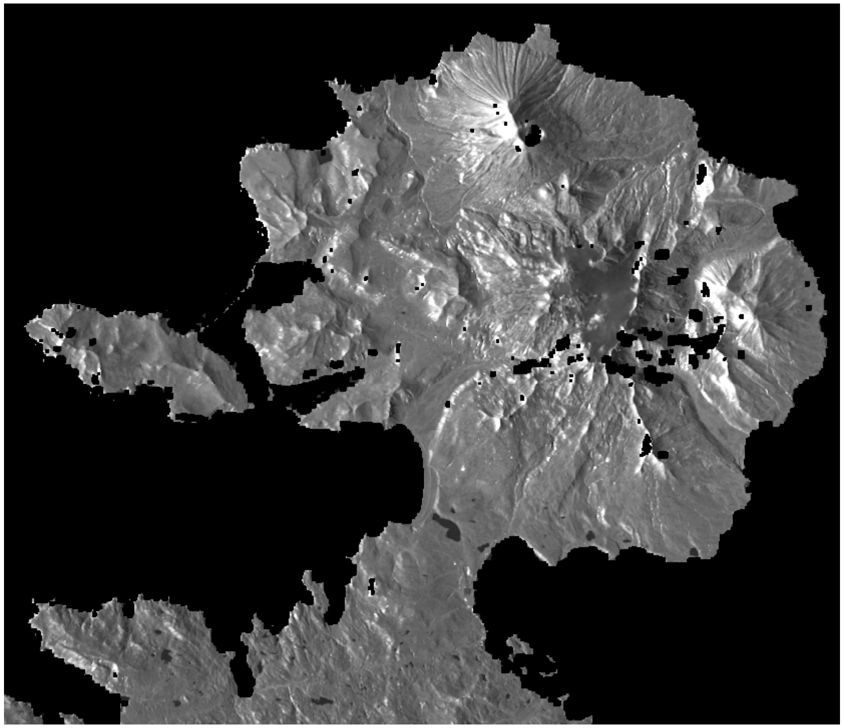


Terrain-corrected SAR image
in map coordinate

Terrain Correction



Shaded-relief DEM image



Terrain-corrected SAR image
in map coordinate

Radiometrically Calibrated Products

- Account for all the contributions in the radiometric values not due to the target characteristics, so that the backscatter values of targets can be compared to one another or a reference

- Calibration coefficients are normally provided by space agencies

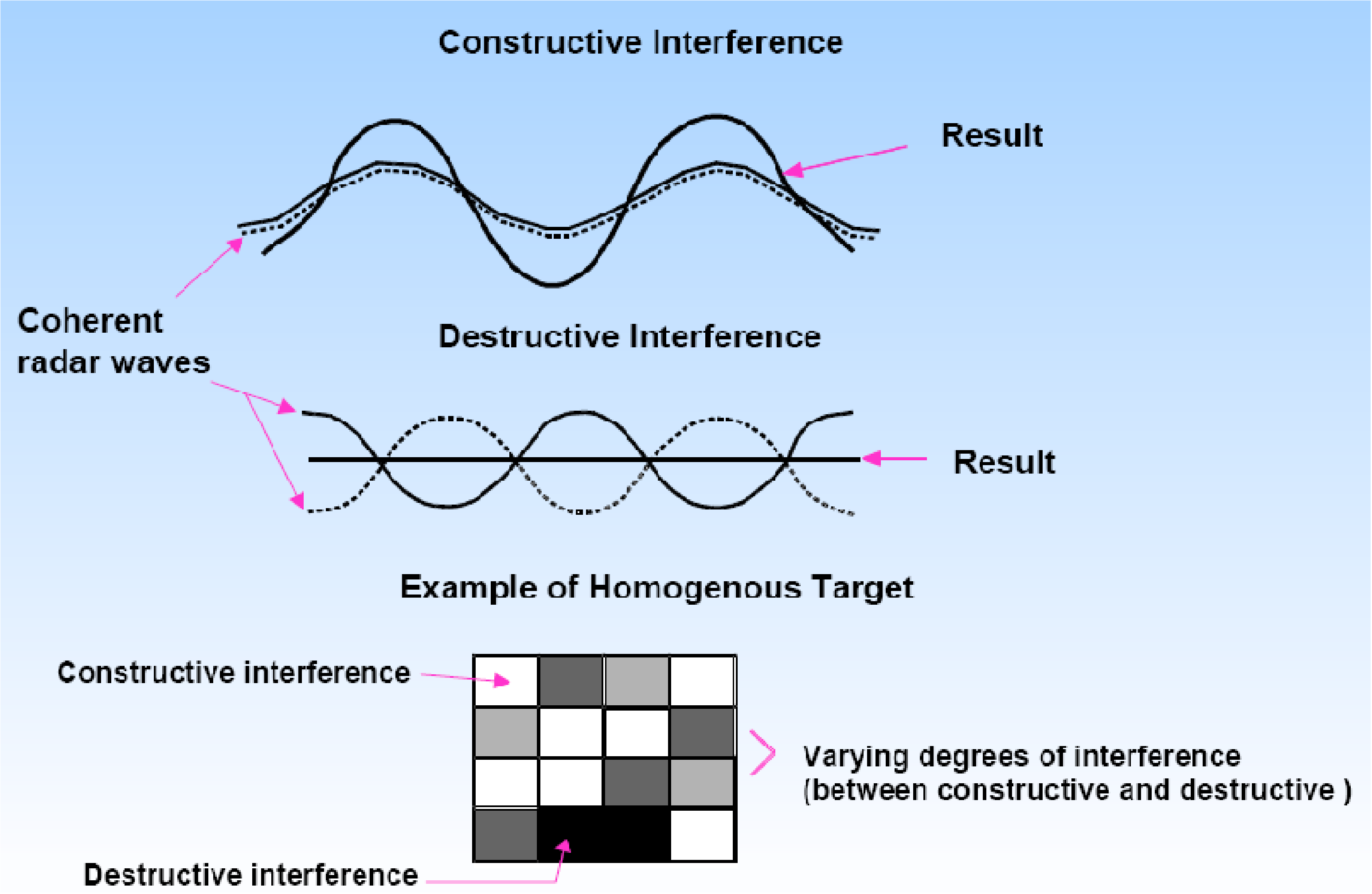
- Radiometric correction due to local terrain should be done during the terrain-correction processing

From CCRS

Radar Noise – Speckles

- Speckles are grainy salt-and-pepper patterns in radar imagery.
- Speckle is a scattering phenomenon which arises because the resolution of the sensor is not sufficient to resolve individual scatterers (size of radar wavelength).
- The total return from a resolution cell is a coherent sum of the returns from all the individual scatterers within it, which can be randomly distributed – essence of InSAR.
- **Speckles appear as random bright and dark areas in a radar image.**
- Speckles can be reduced by multiple looks.

Radar Noise – Speckles



From CCRS

Speckle Suppression

- Speckle can be reduced by incoherent (amplitude or power) processes.
- Speckle reduction (or smoothing) necessarily reduces the resolution of single channel SAR data.
- Two basic linear processes:
    - Multi-look - divides the signal into minimally overlapped frequency bands, processes each to a reduced resolution image, registers these, detects and adds the detected images.
    - Averaging - detects the full resolution image, performs local averaging and resampling processes to create reduced resolution, reduced speckle images.
    - For distributed targets both processes are equivalent.

From CCRS

Speckle Reduction Filters

- Reduce speckle with minimum loss of information
  - In homogeneous areas, the filter should preserve the radiometric information and edges between different areas
  - In textured areas, the filter should preserve the radiometric information and spatial signal variability (textural information)

- Non-adaptive filters
  - Do not take into account the local properties of the terrain backscatter or the nature of the sensor.
  - Not appropriate for filtering of non-stationary scene signal.
  - Examples are the FFT filters.

- Adaptive filters
  - Accommodate changes in local properties of the terrain backscatter.
  - Adaptive filter produces an accurate estimate of the backscattering coefficient inside homogeneous (stationary) areas while preserving edge and texture structure in nonstationary scenes.
  - Examples are the Frost, Lee, Map Gamma, local mean and local median filters.

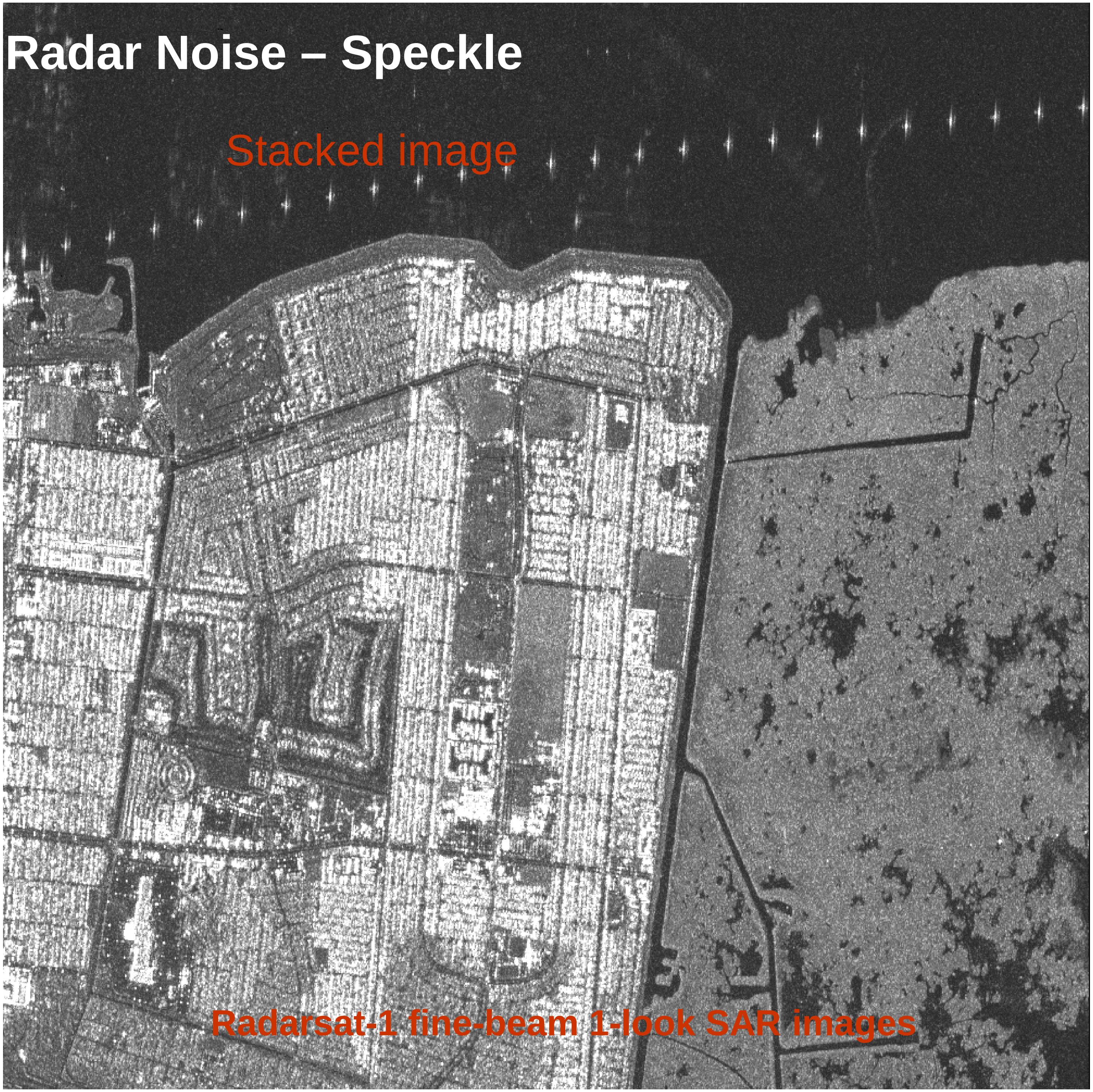
From CCRS

Radar Noise – Speckle

Radarsat-1 fine-beam 1-look SAR images

Radar Noise – Speckle

Radar Noise – Speckle



SAR Interpretation

- Two major types of brightness variations observable in a radar image:
  - variations in tone
  - variations in texture

- Computers are used to supplement and/or extend our visual interpretation of these brightness variations

From CCRS

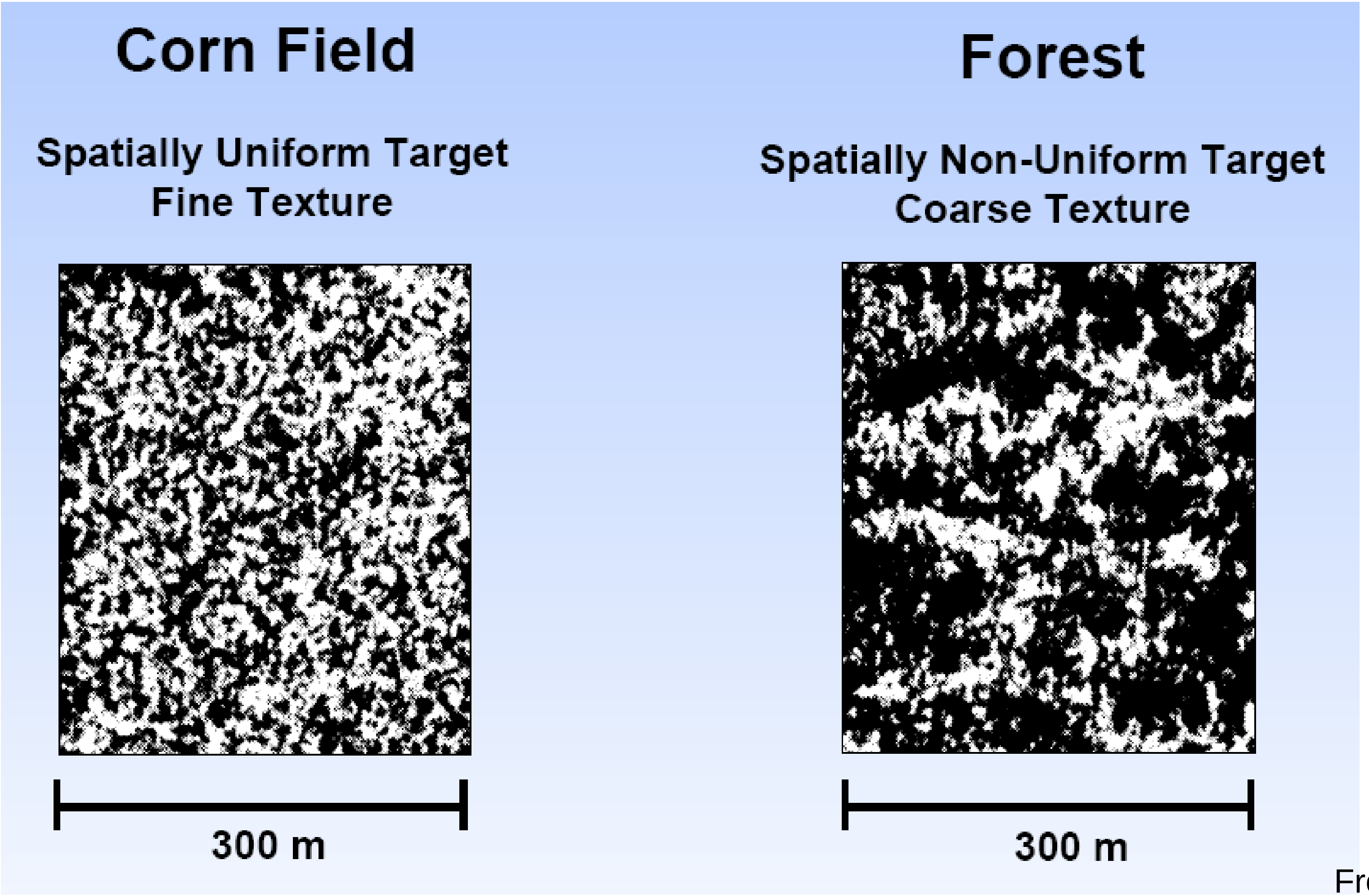
Image Tone

- Refer to each distinguishable grey level from black to white
- Proportional to strength of radar backscatter
- Used to infer backscattering mechanisms
  - relatively smooth targets like calm water appear as dark tones
  - diffuse targets like some vegetation appear as intermediate tones
  - man-made targets (buildings, ships) may produce bright tones, depending on their shape, orientation and/or constituent materials

From CCRS

Image Texture

- Refer to the pattern of spatial tone variations
- Function of spatial uniformity of scene targets
- SAR images texture consists of scene texture multiplied by speckle



From CCRS

Texture Analysis

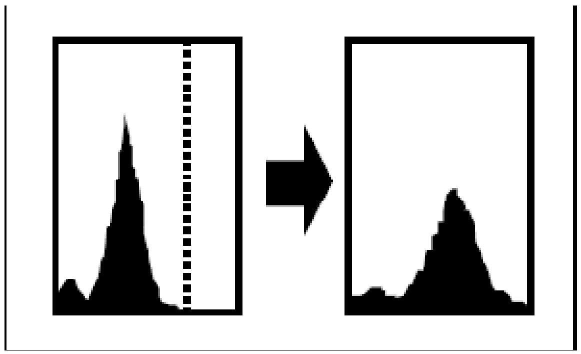
- Textural features contain information about the spatial distribution of tonal variations.

- Texture analysis methods include:
  - Co-occurrence matrix
  - Grey level difference vector
  - Lacunarity (gap analysis)
  - Neighbouring grey level dependence matrix
  - Spatial correlation function
  - Model-based approaches

From CCRS

Contrast Stretch

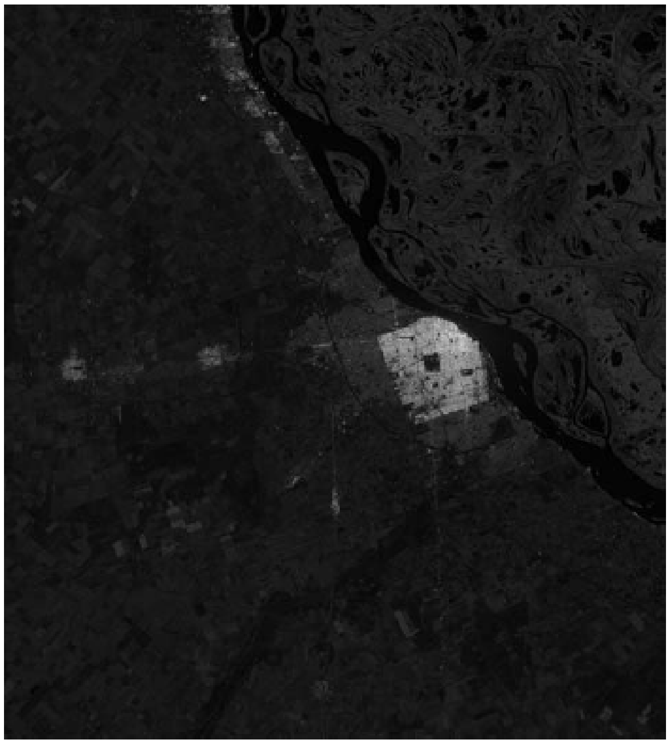
- Enhance visual interpretation
- Match data's dynamic range to dynamic range of display.
- Involve the construction of a look-up table (LUT).
- LUT is a graphical model of the mathematical function selected.



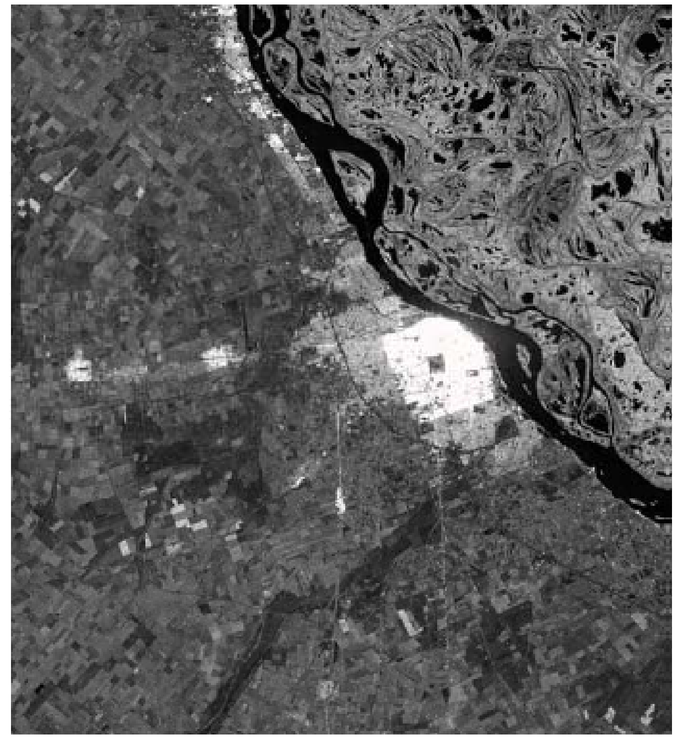
From CCRS

Contrast Stretch

Rosario, Argentina



Original image



Linear Stretched image

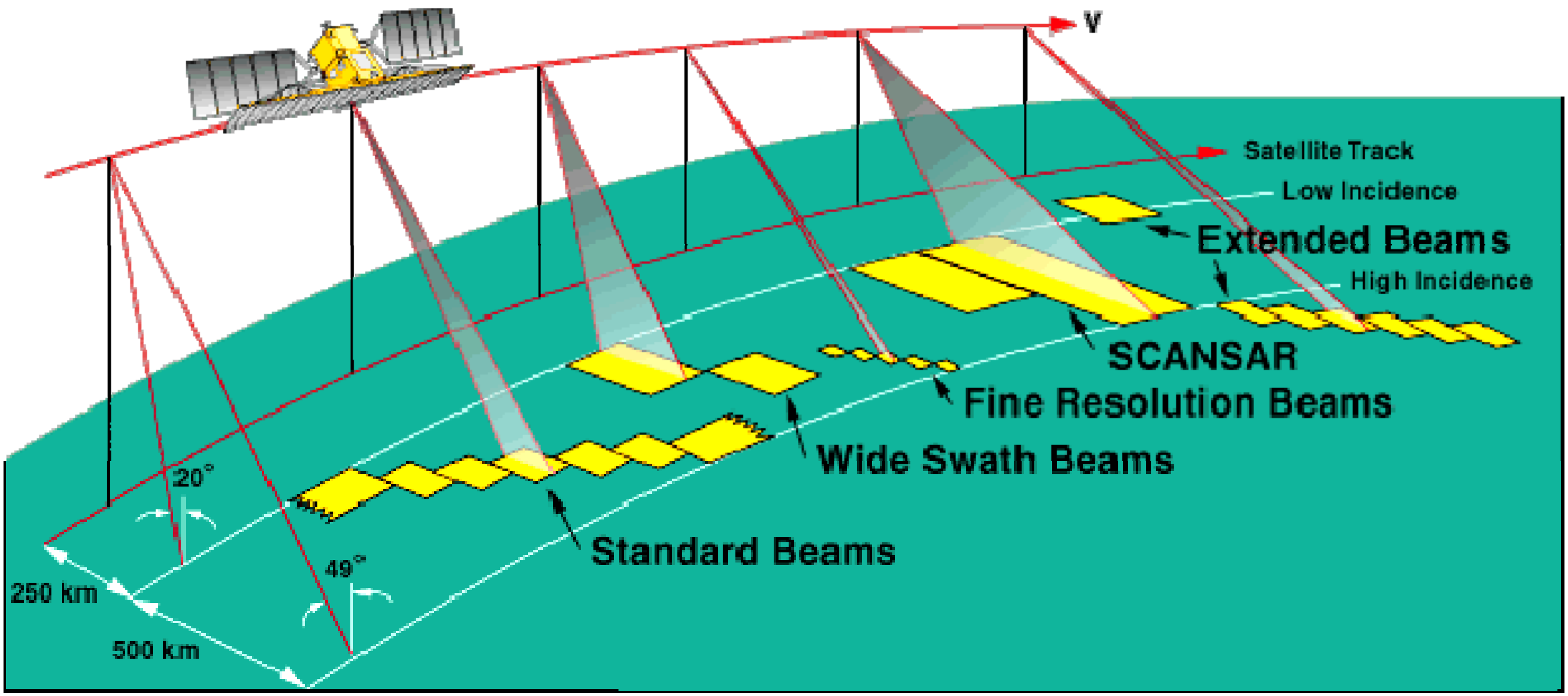
From CCRS

Advantages of Radar

- All weather, day or night - some areas of Earth are persistently cloud covered
- Penetrate clouds, vegetation, dry soil, dry snow – reveal features beneath
- Strongly affected by target physical properties (surface roughness and dielectric constant)
- Complimentary to visible/IR measurements
- Polarization capability to discover physical structure of targets
- Sensitive to water content for flood mapping and ocean imaging
- Interferometric SAR can generate high-resolution DEM and map surface deformation at mm-scale.

SAR Satellites

SAR Operation Modes



Courtesy of CCRS

SAR Satellites

European ERS-1,	**1991-2000,**	**C-band, VV polarized**
http://earth.esa.int/ers/		
Japanese JERS-1,	**1992-1998,**	**L-band, HH polarized**
http://www.eorc.nasda.go.jp/JERS-1/		
SIR-C,	**April, October 1994,**	**X/C/L, fully polarized**
http://southport.jpl.nasa.gov/sir-c/		
Canadian Radarsat-1,	**1995-now,**	**C-band, HH polarized**
http://www.space.gc.ca/asc/eng/satellites/radarsat1/		
European ERS-2,	**1995-now,**	**C-band, VV polarized**
(experienced malfunctions since early 2001)		
http://earth.esa.int/ers/		
European Envisat,	**2002-now,**	**C-band, dual polarizations**
http://envisat.esa.int/		
Japanese ALOS,	**2006-now,**	**L-band, fully polarized**
http://alos.nasda.go.jp/index-e.html		
Canadian Radarsat-2,	**2007-now,**	**C-band, fully polarized**
http://www.mda.ca/radarsat-2/overview.shtml		
German TerraSAR-X,	**2007-now,**	**X-band, fully polarized**
http://www.caf.dlr.de/tsx/main/mission_en.htm		
Italian COSMO-SkyMed Constellation,	**2007-now,**	**X-band**
http://www.cosmo-skymed.it/en/index.htm		
German Tandem-X	**2019 – now,**	**X-band, fully polarized**
http://www.terrasar.de/en/prod/tandem/index.php		

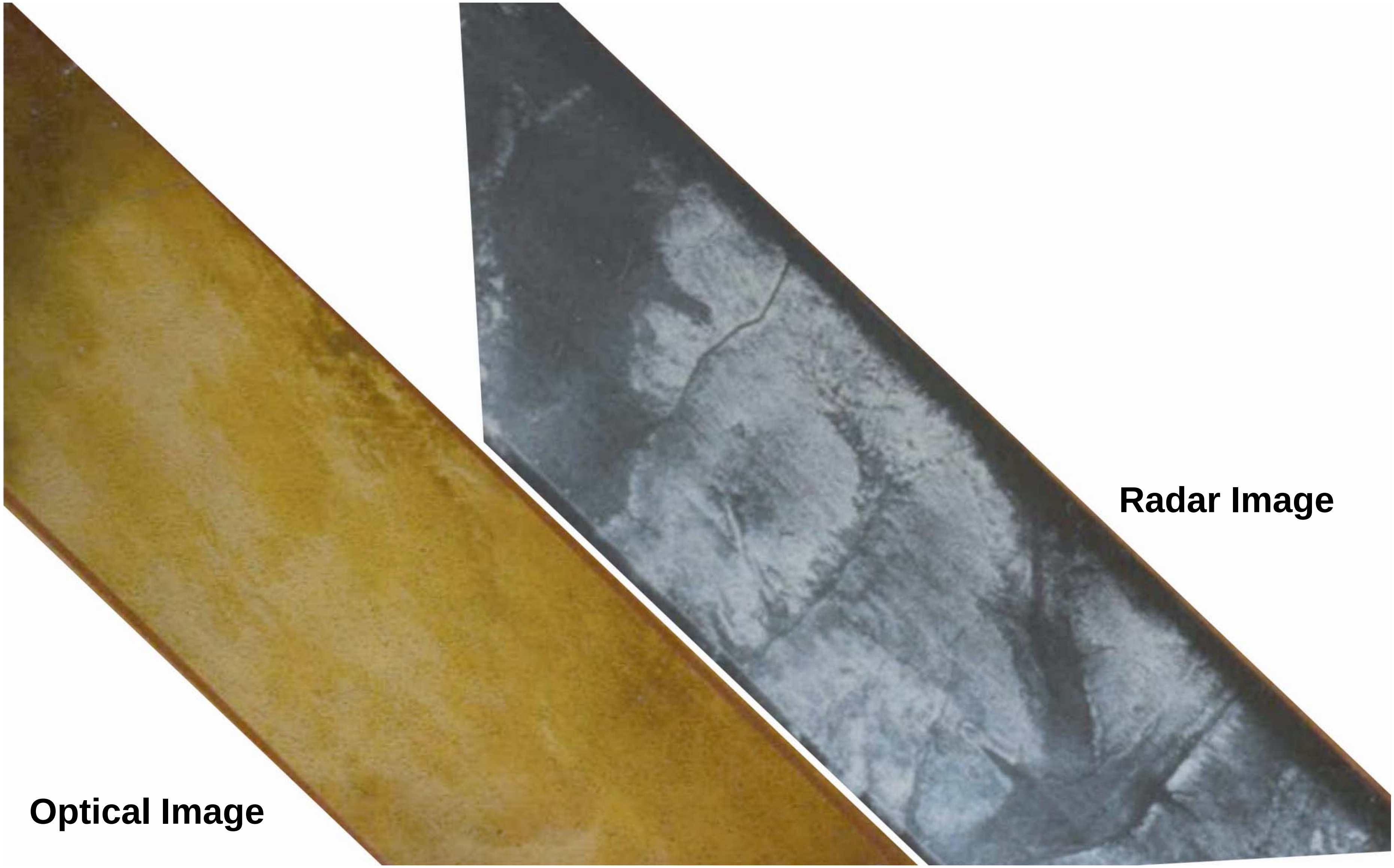
Summary: SAR Image Interpretation

- SAR can transmit its energy source
- SAR can only measure part of radar energy reflected back towards the antenna (backscattering)
- SAR backscatter strength depends on
  - Radar wavelength
  - Radar polarization
  - Viewing geometry (incidence angle and terrain slope)
  - Surface roughness
  - Structure of surface or objects being imaged
  - Surface dielectric constant

SAR Applications: Geology

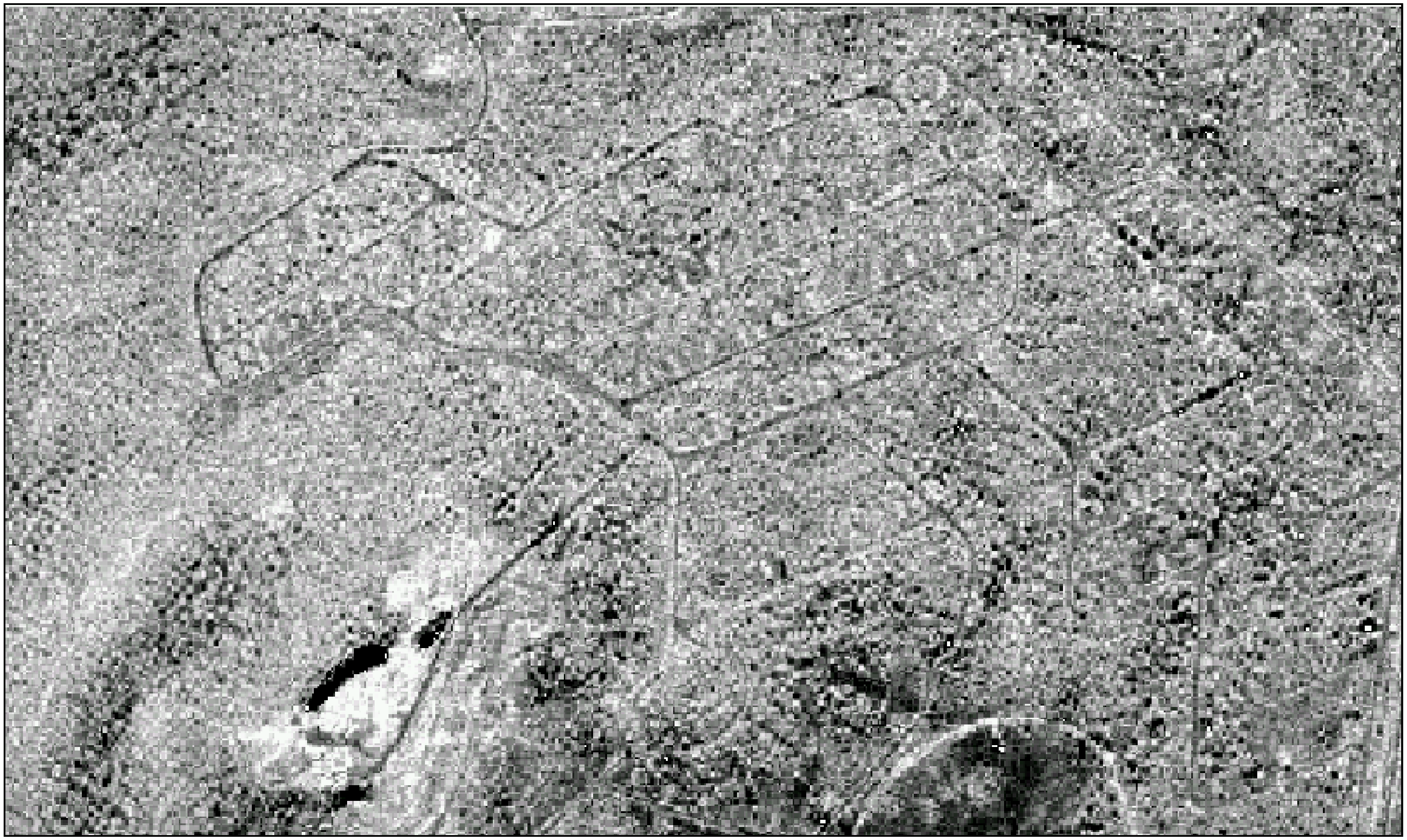
- Locate fault lines, map rock types, and structural features such as salt domes
- Estimate surface roughness, alluvia fans
- Archeology – subsurface imaging
- Natural hazards monitoring with interferometric SAR
  - Volcano
  - Earthquake
  - Landslide
  - Mining
  - Land subsidence

Archeology



North Africa's Sahara Desert near Kufra Oasis in southeast Libya

Revealing structure beneath vegetation



X-band shows tops of trees and locations of cuts in trees.

Courtesy of EarthData International

Revealing structure beneath vegetation

P-band penetrates vegetation to reveal structures beneath tress.

Courtesy of EarthData International

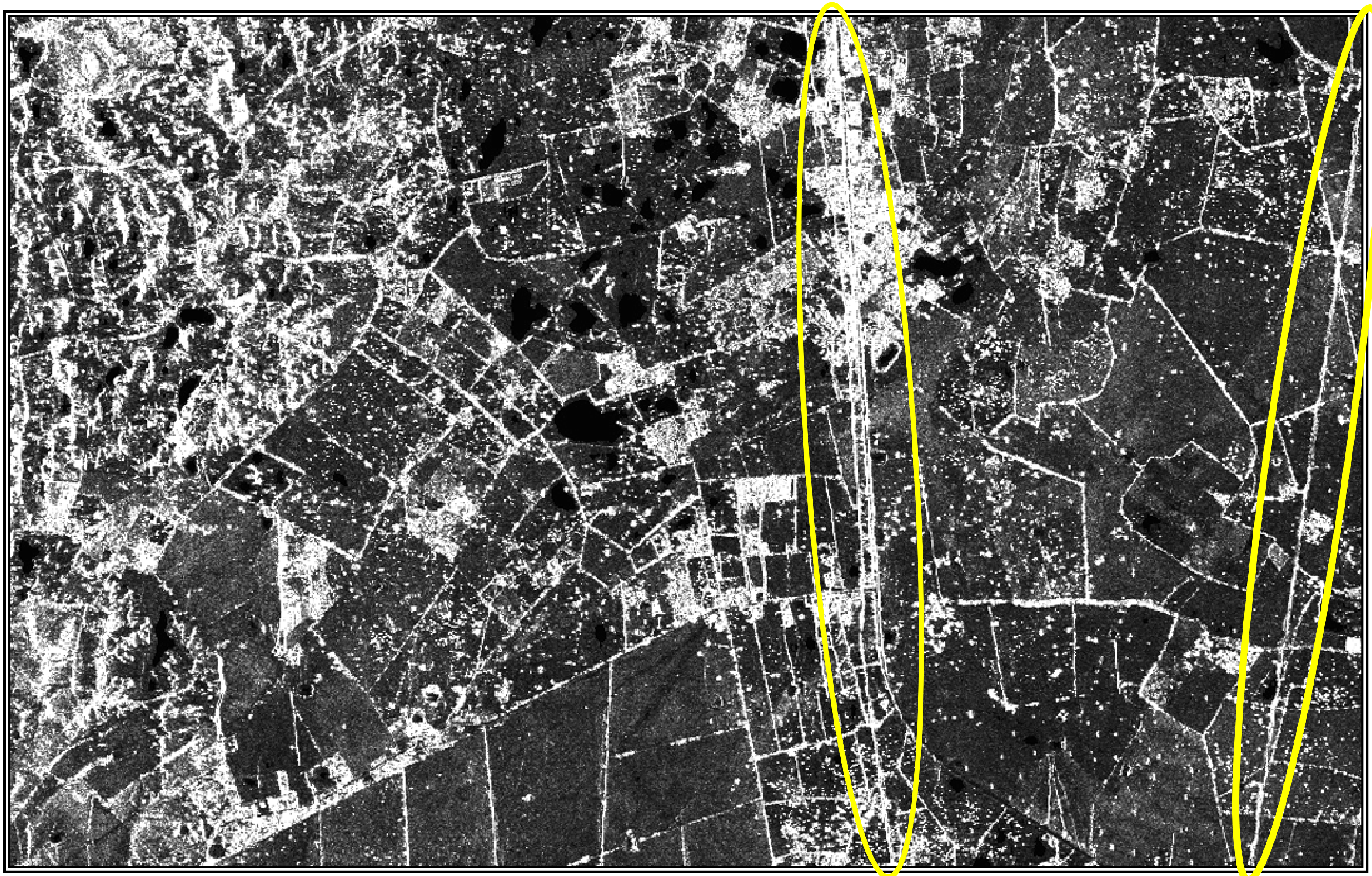
Revealing structure beneath vegetation

X-band Image (λ = 3 cm)

Courtesy of EarthData International

Revealing structure beneath vegetation

P-band Image (λ = 86 cm)



Fence lines, trails, power lines, and disturbed soils show up in the P-band

Courtesy of EarthData International

Okmok Volcano, Alaska

Interferometric SAR (InSAR)

• Synthetic Aperture Radar (SAR) – all-weather, day-and-night imaging sensor: the amplitude image is sensitive to terrain slope, surface roughness and dielectric constant, while the phase image is related to the distance from satellite to ground.

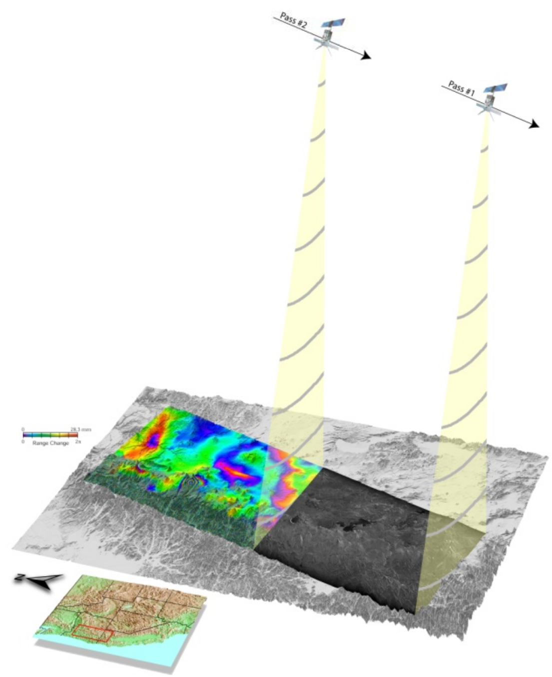
• **InSAR** combines two or more SAR images of the same area acquired from similar vantage points at different times to produce an **interferogram**.

• The **interferogram**, depicting the changes in distance between the radar and the ground, can be further processed to

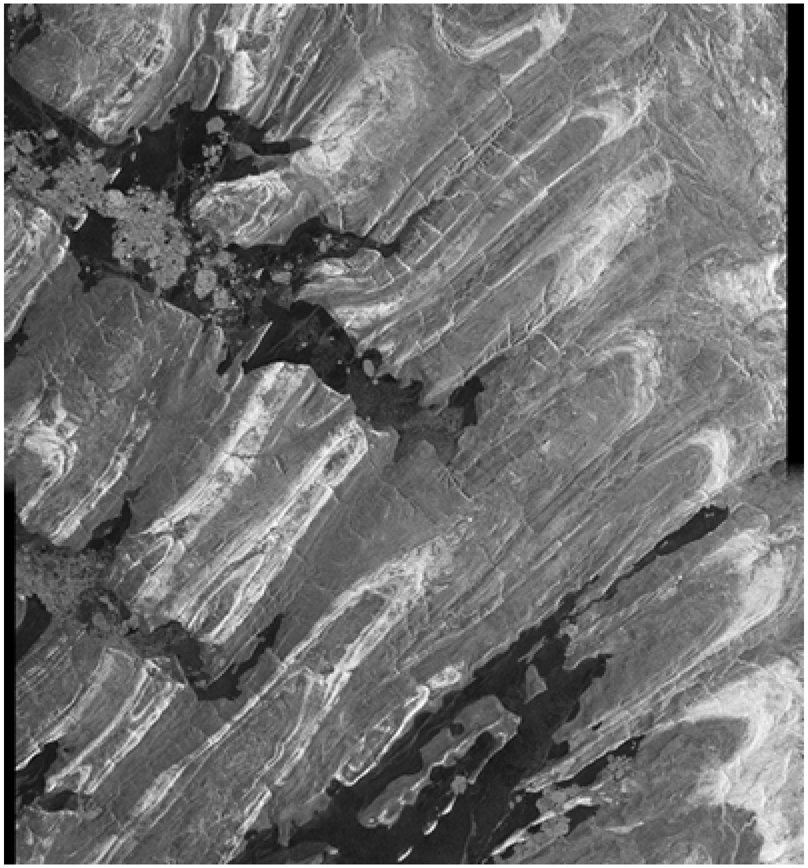
i) **image ground deformation** at a horizontal resolution of tens of meters over large areas with centimeter to sub-centimeter precision under favorable conditions.

or

ii) **generate DEM** at horizontal resolution of tens of meters with a few meters precision.



Faults, Folds, Rocks



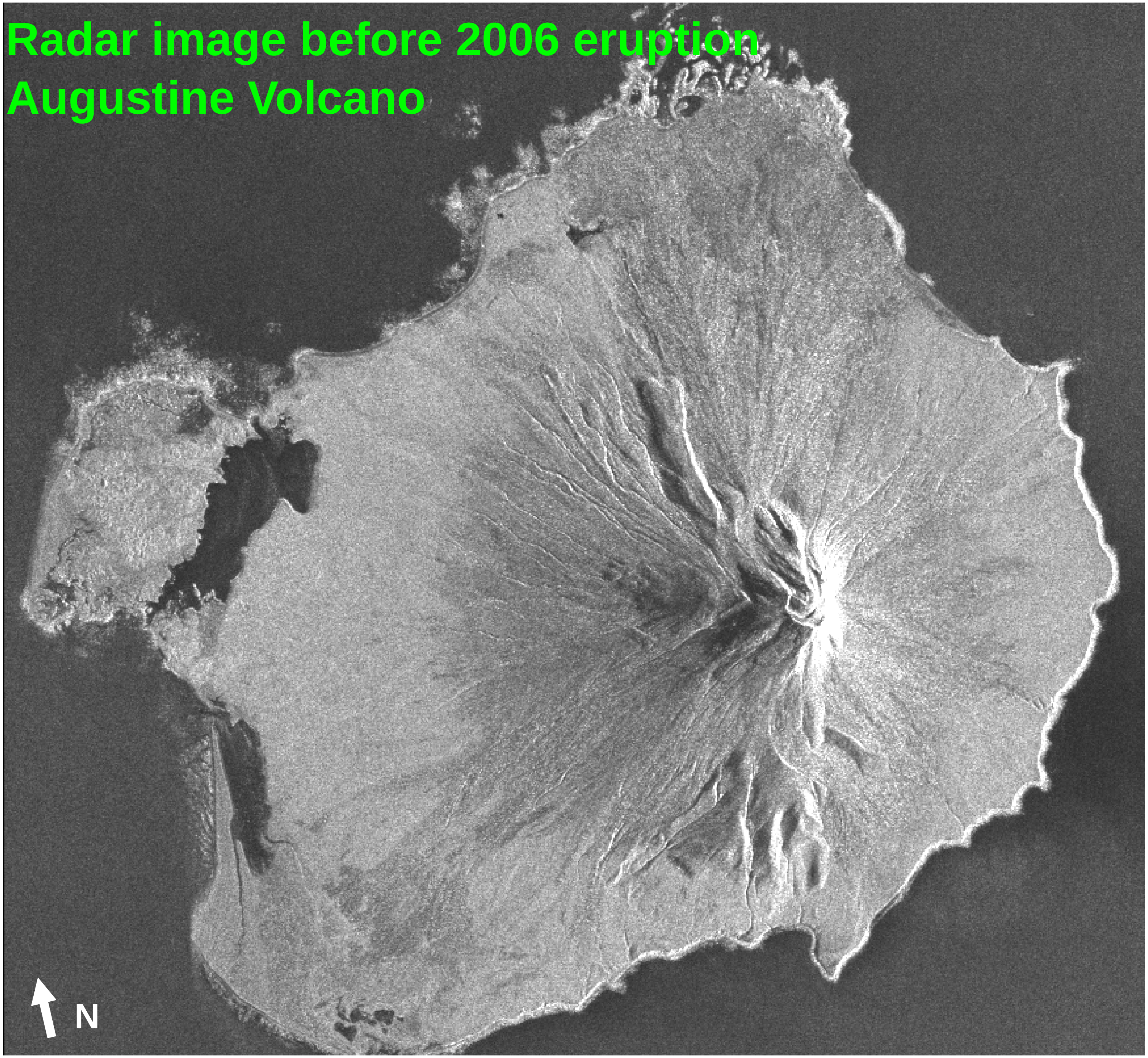
Envisat ASAR Image of Bathurst Island, Canada.

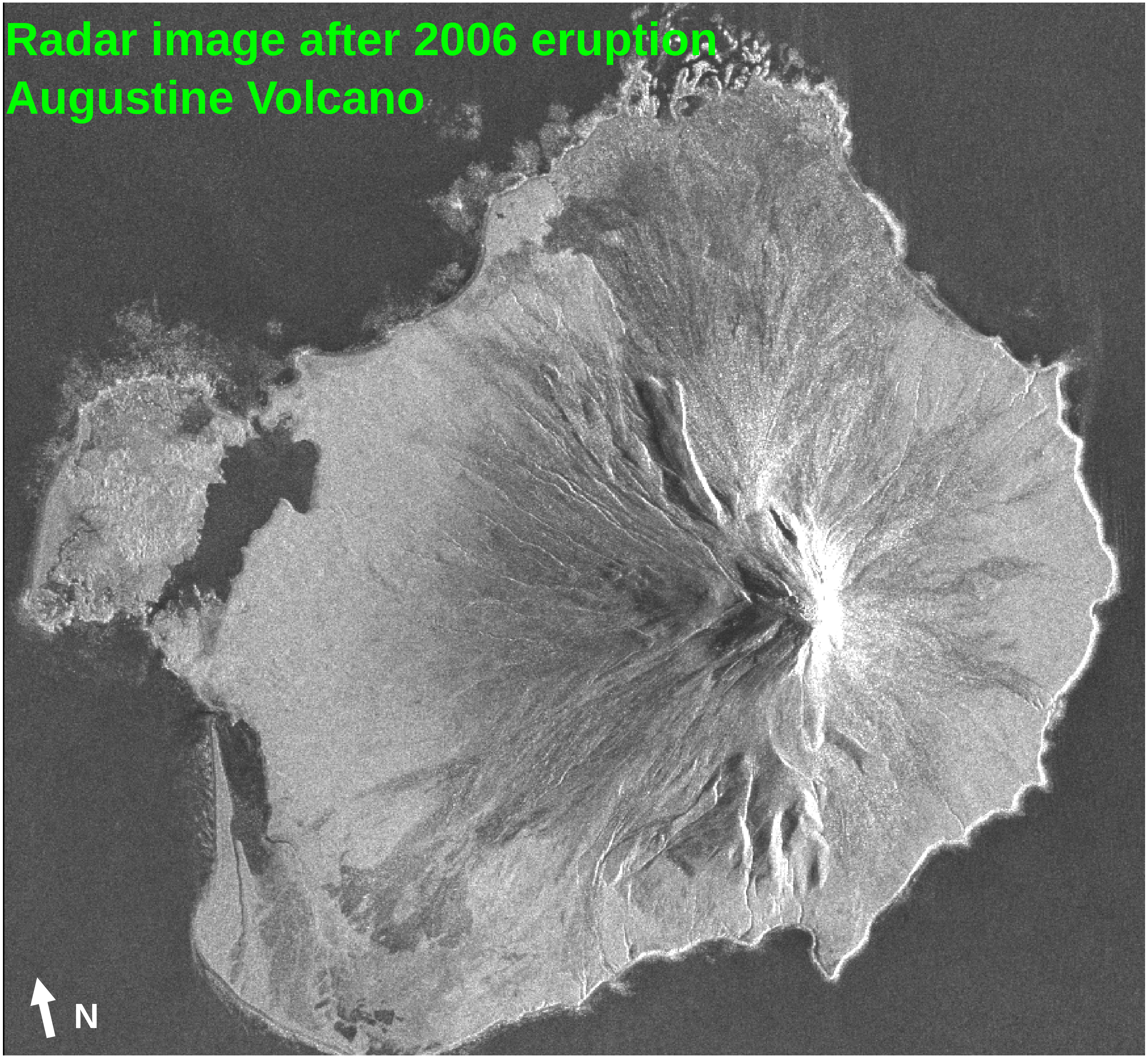
Impact Crater Imaged From SIR-C Images

red: L-HH, green: C-HH, blue: C-HV

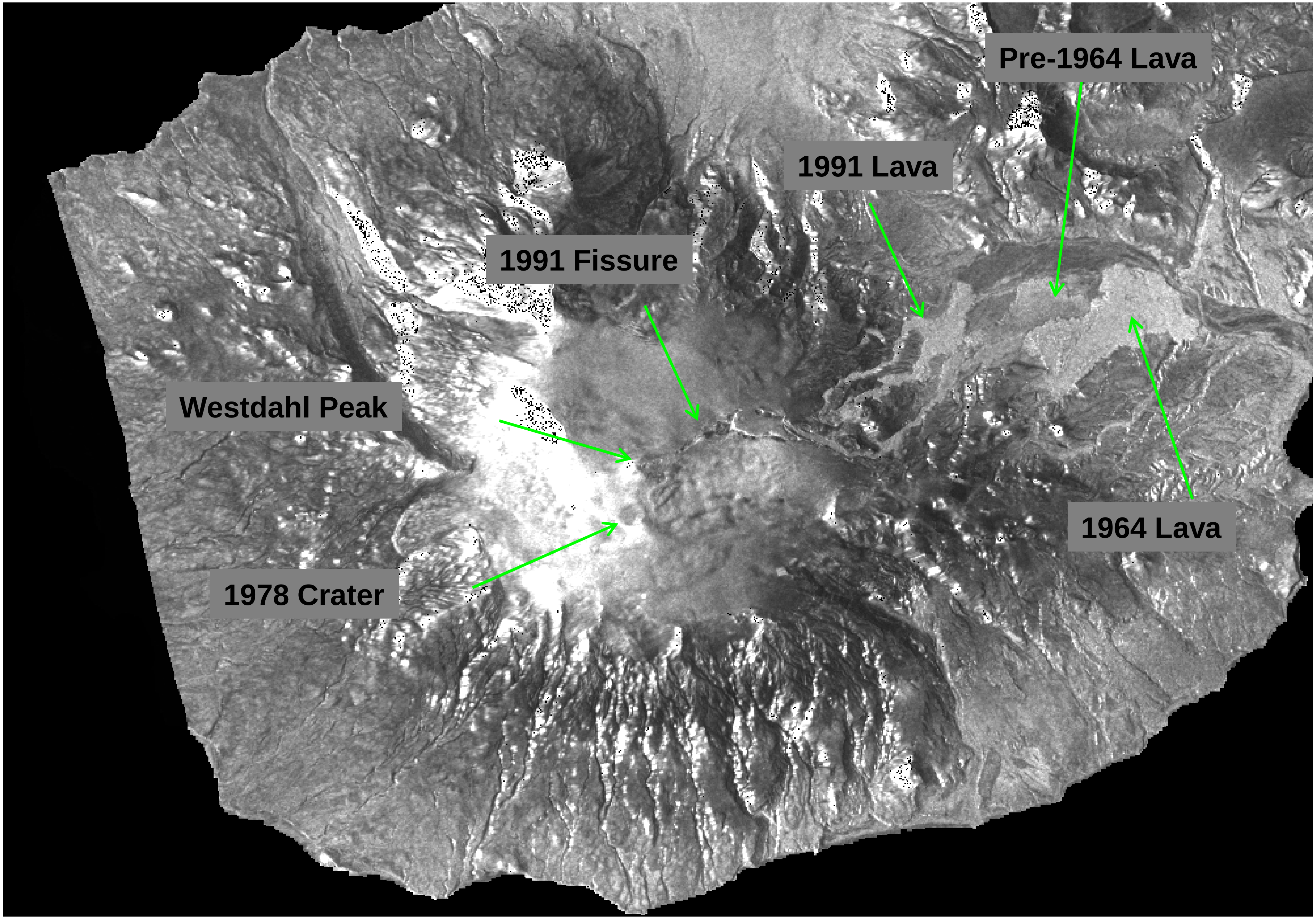
Impact crater structures, Mauritania

TerraSAR-X @ DLR

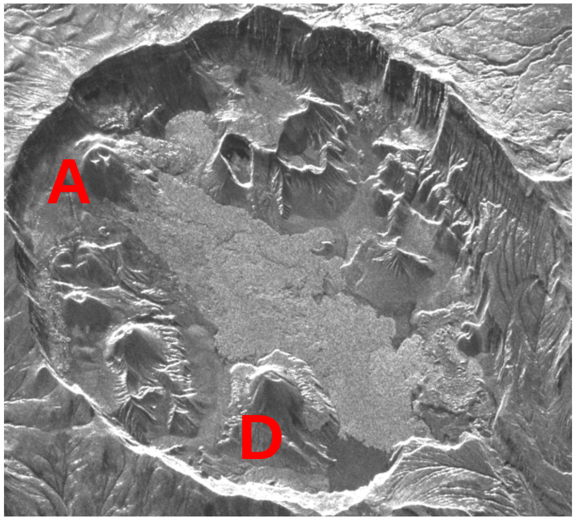

Radar image before 2006 eruption
Augustine Volcano
N


Radar image after 2006 eruption
Augustine Volcano
N

Lava flow from Nov 1991 eruption, Westdahl Volcano



Caldera Changes During 2008 Eruption at Okmok volcano, AK

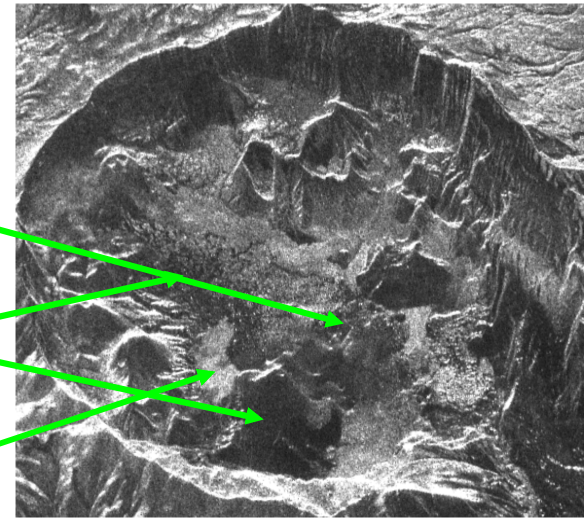


Pre-2008 C-band

New cones(?), fallouts(?)

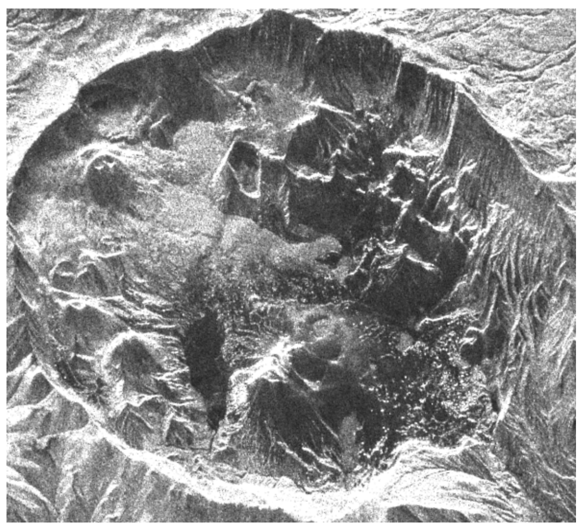
Ash deposits

Lahar deposits

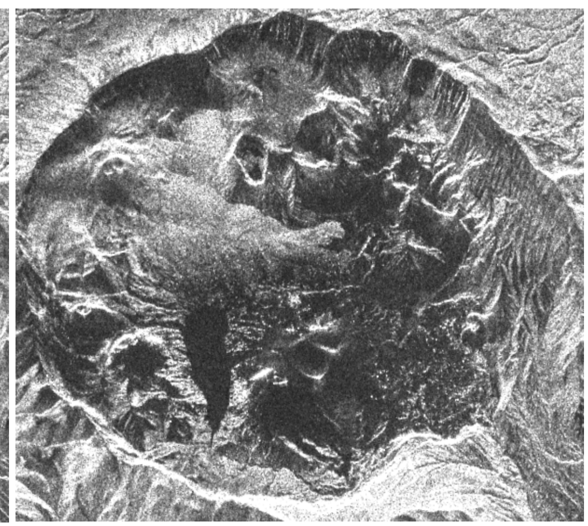


V179: 7-13

V179: 7-16



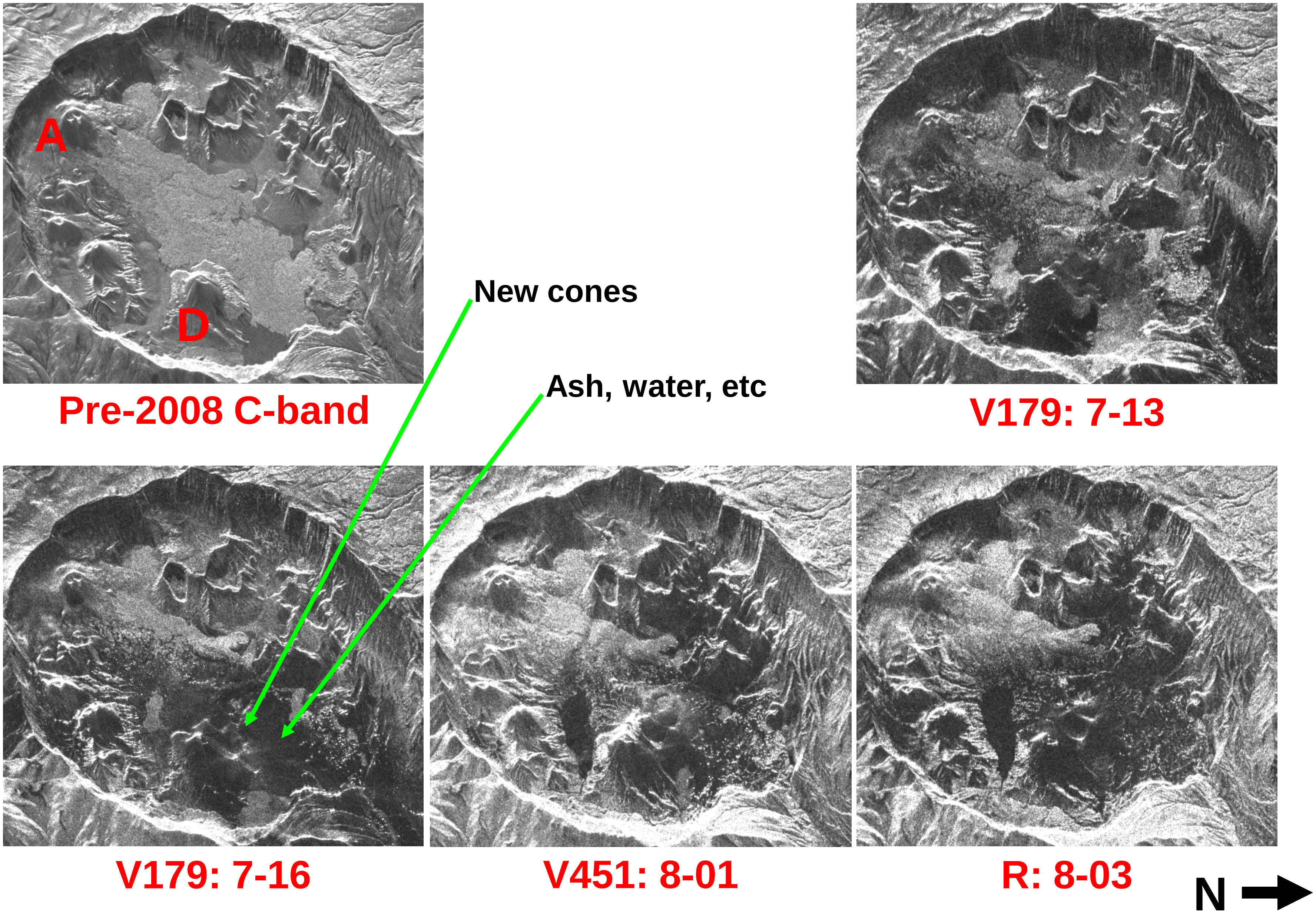
V451: 8-01



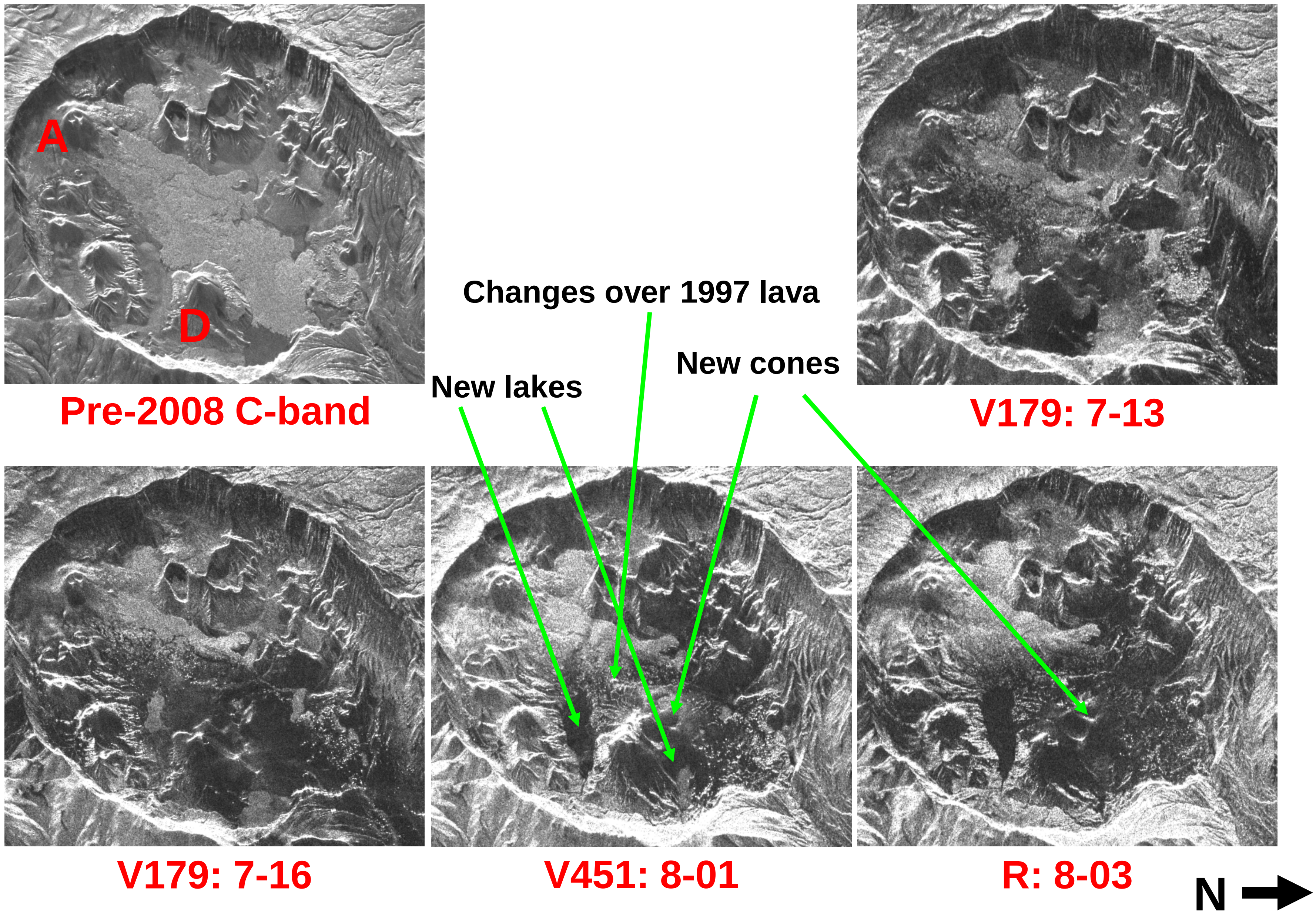
R: 8-03

N

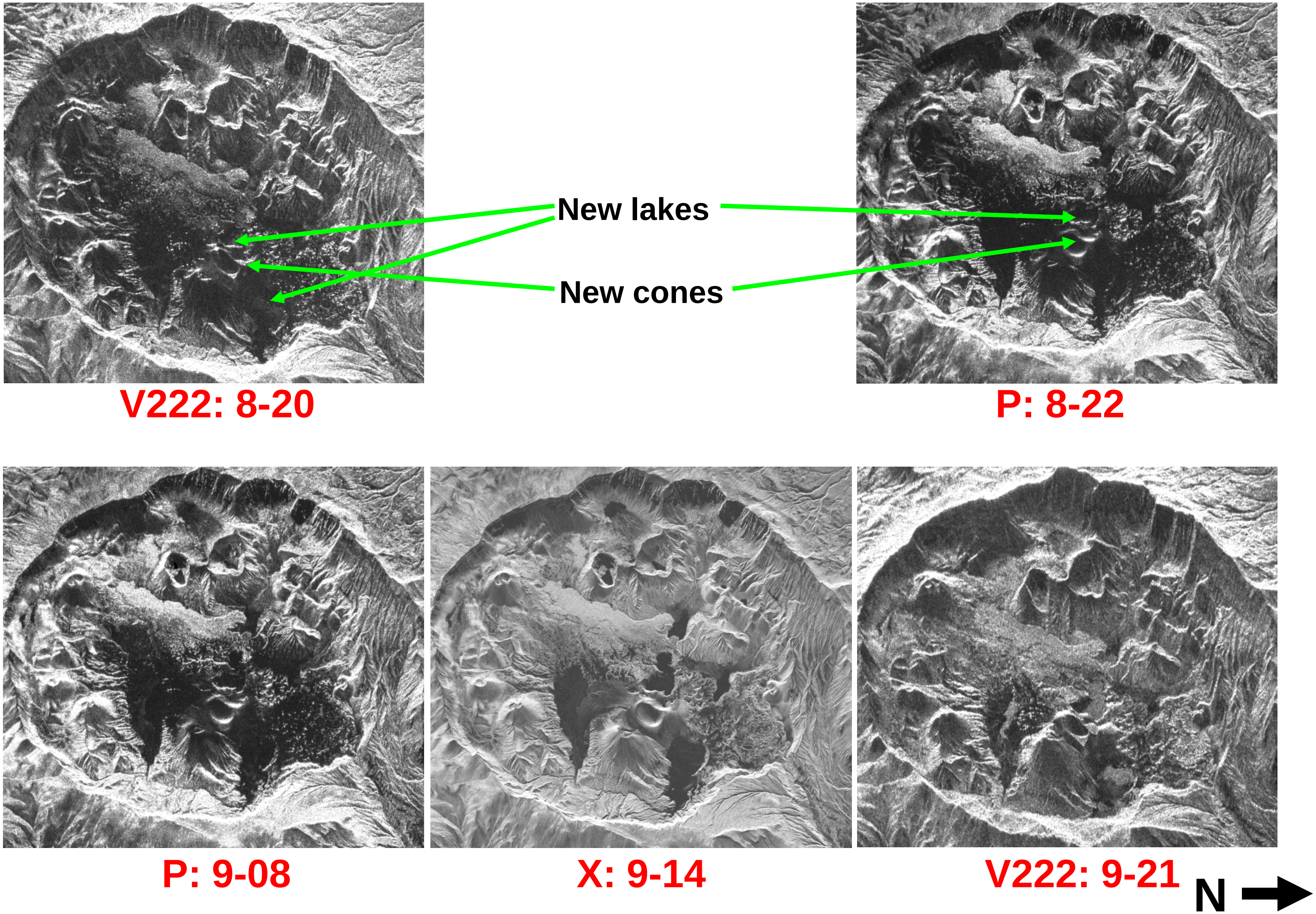
Caldera Changes During 2008 Eruption



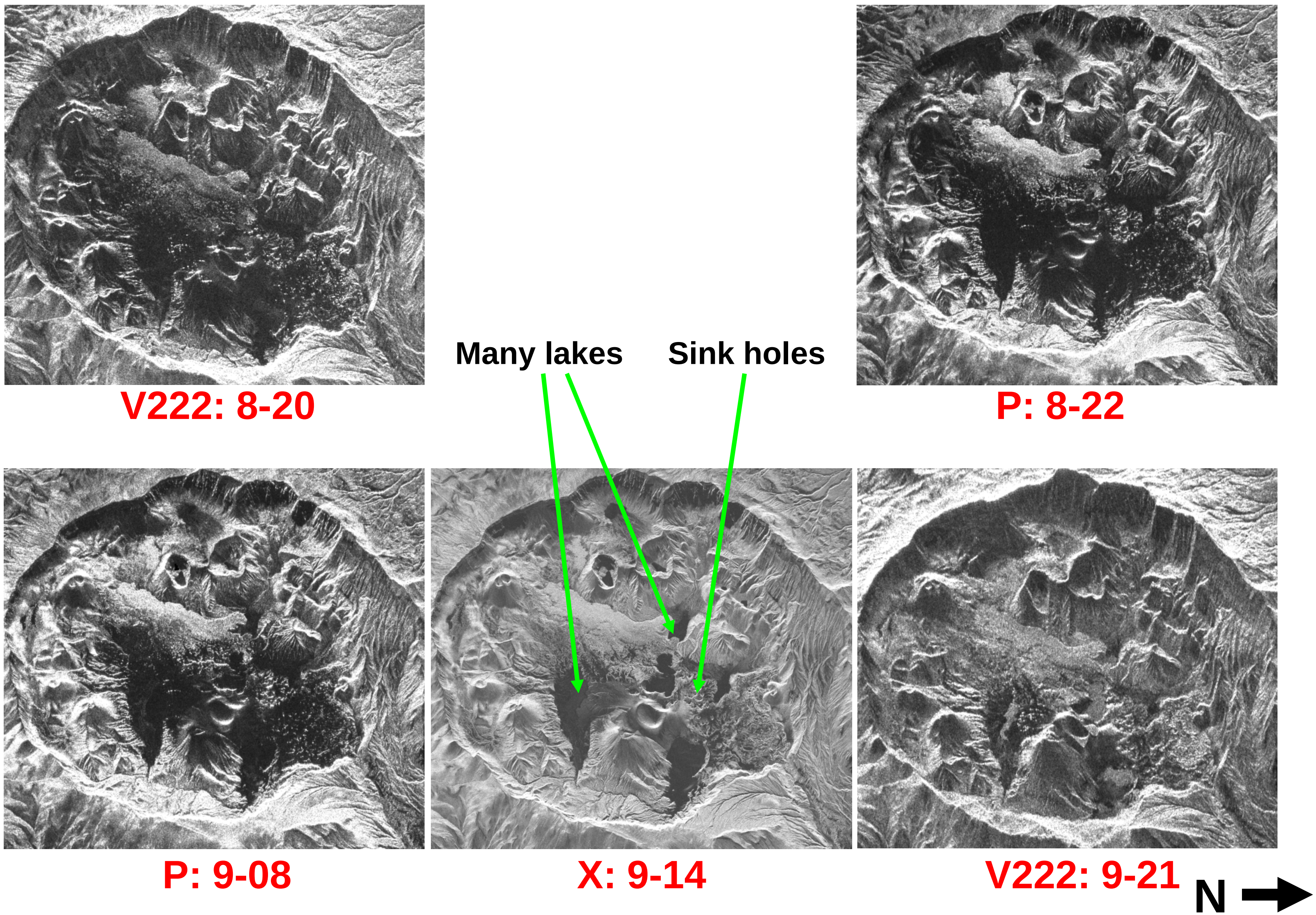
Caldera Changes During 2008 Eruption



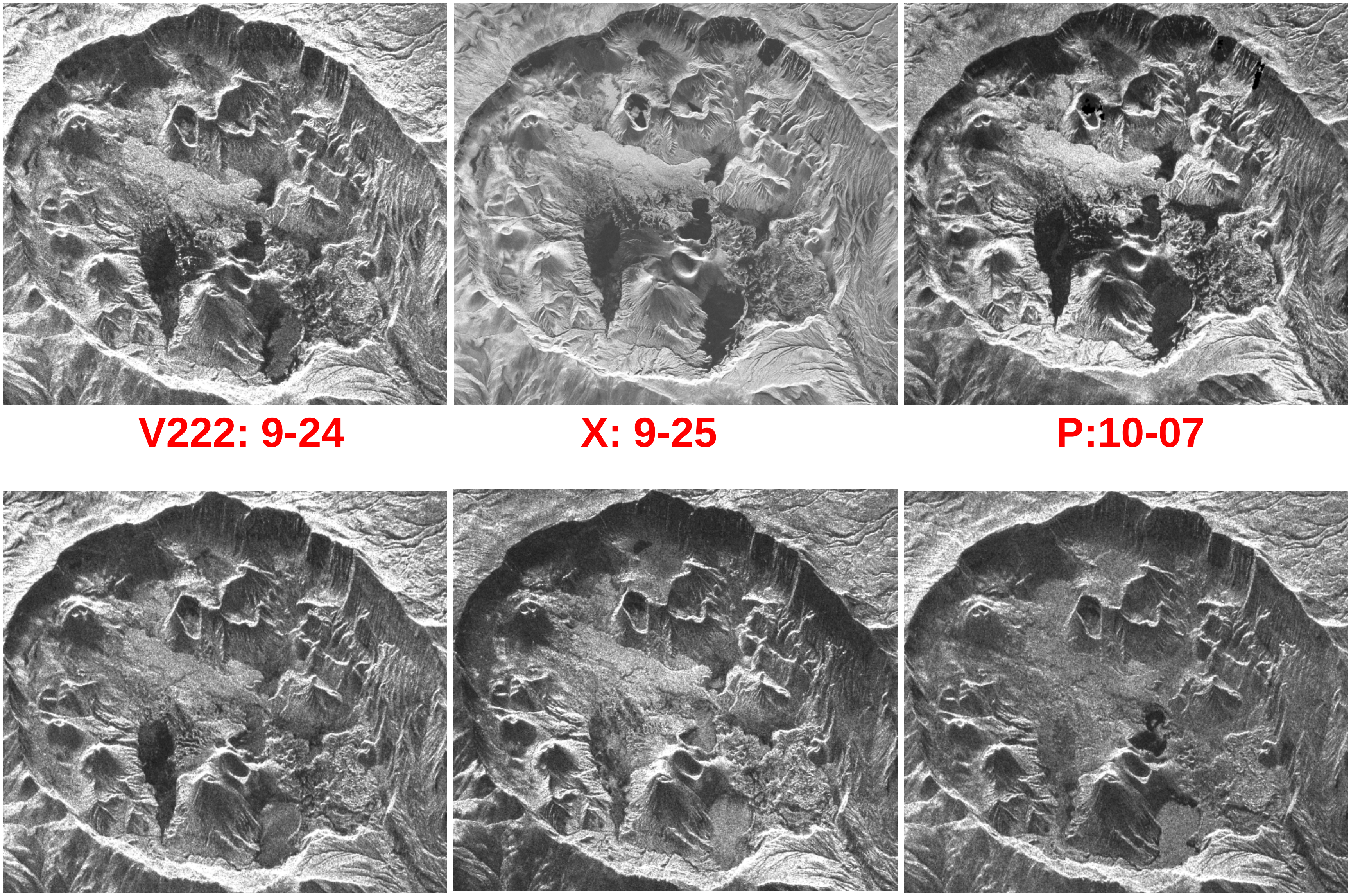
Caldera Changes During 2008 Eruption



Caldera Changes During 2008 Eruption



Caldera Changes During 2008 Eruption



V222: 9-24

X: 9-25

P:10-07

V451:10-10

V222:10-29

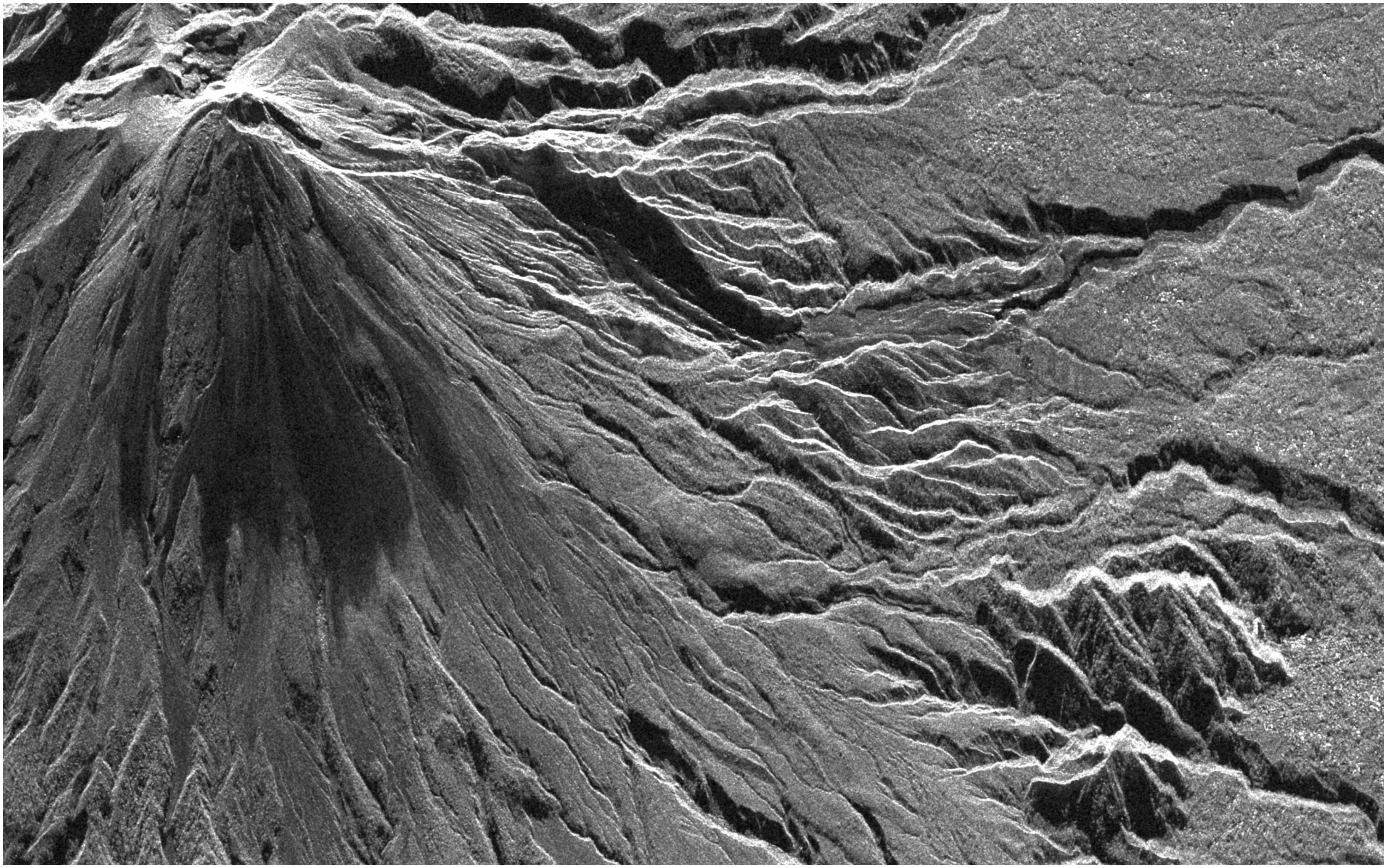
V451:11-14

N →

2010 Eruption at Merapi

2010/10/26

N

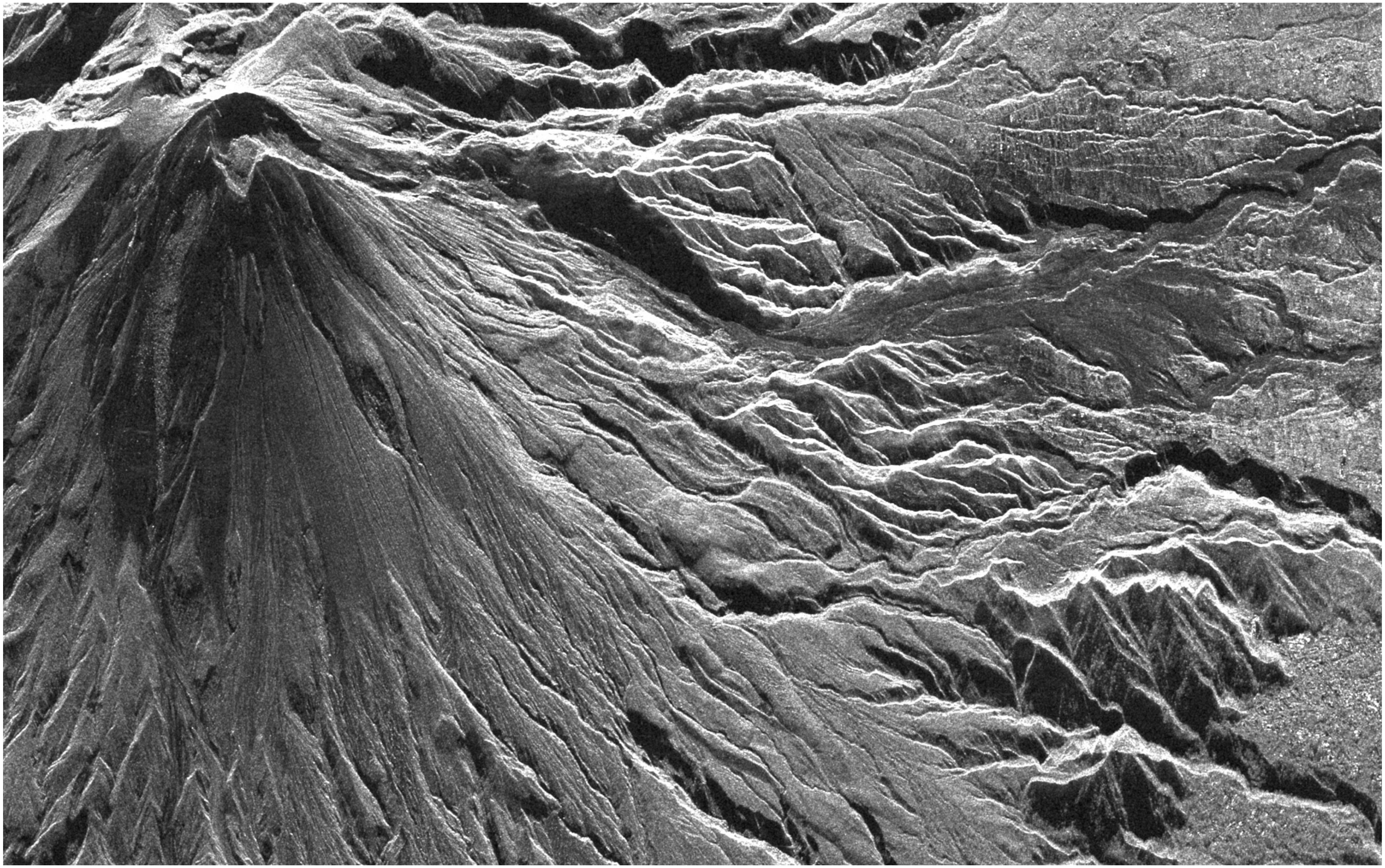


@DLR

2010 Eruption at Merapi

2010/11/06

← **N**



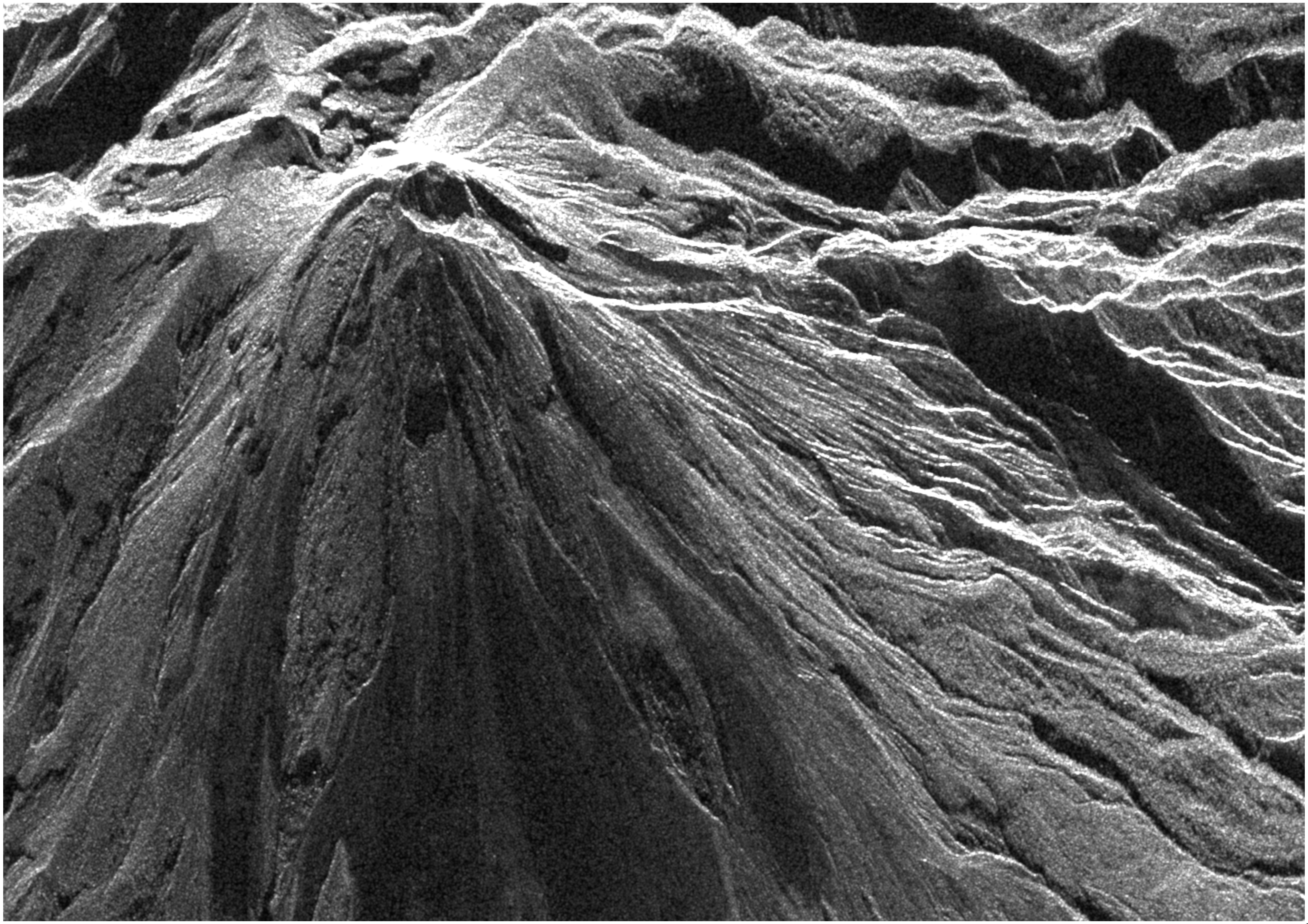
@DLR

USGS

2010 Eruption at Merapi

2010/10/26

← N

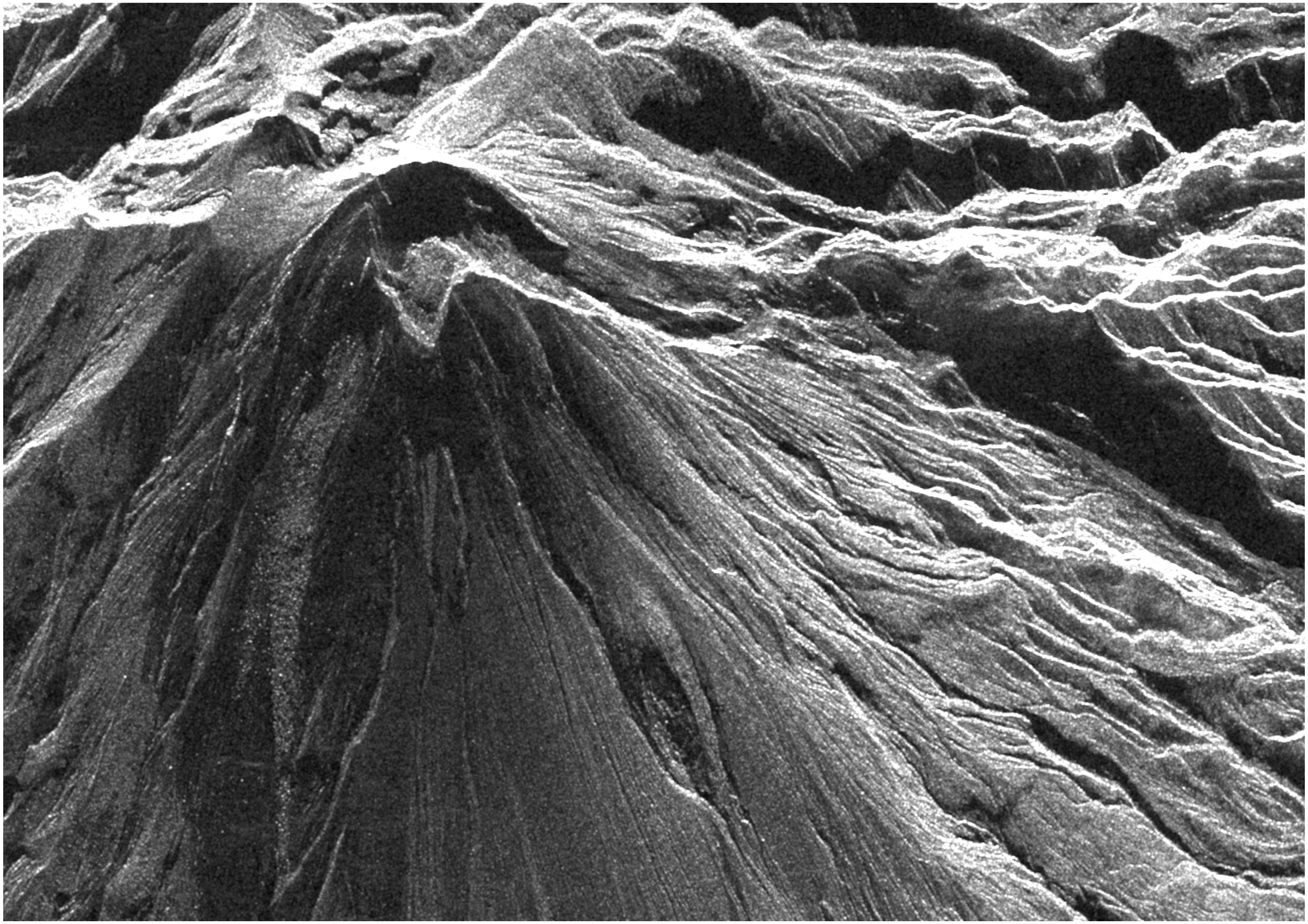


@DLR

2010 Eruption at Merapi

2010/11/06

N



@DLR

Useful Online Radar Courses

- http://earth.esa.int/applications/data_util/SARDOCS/spaceborne/Radar_Courses/
- http://www.ccrs.nrcan.gc.ca/resource/index_e.php#tutor
- http://southport.jpl.nasa.gov/
- ……