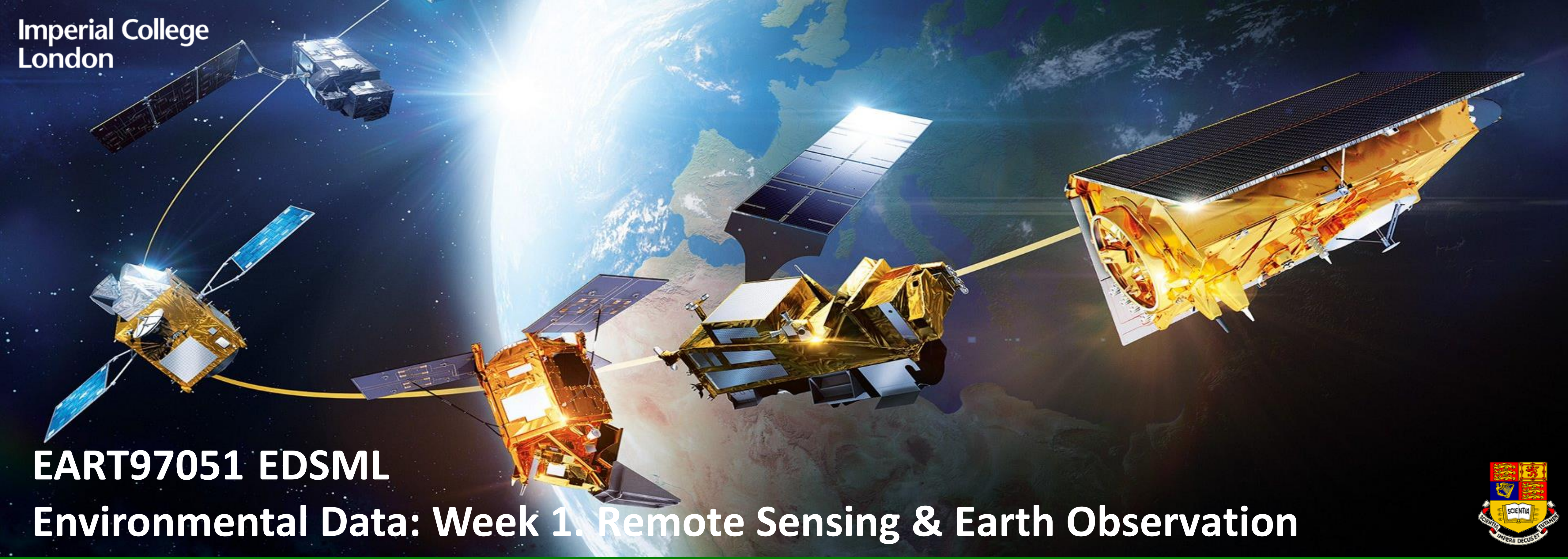
Imperial College London



EART97051 EDSML
Environmental Data: Week 1. Remote Sensing & Earth Observation

4. Introduction to radar remote sensing & InSAR

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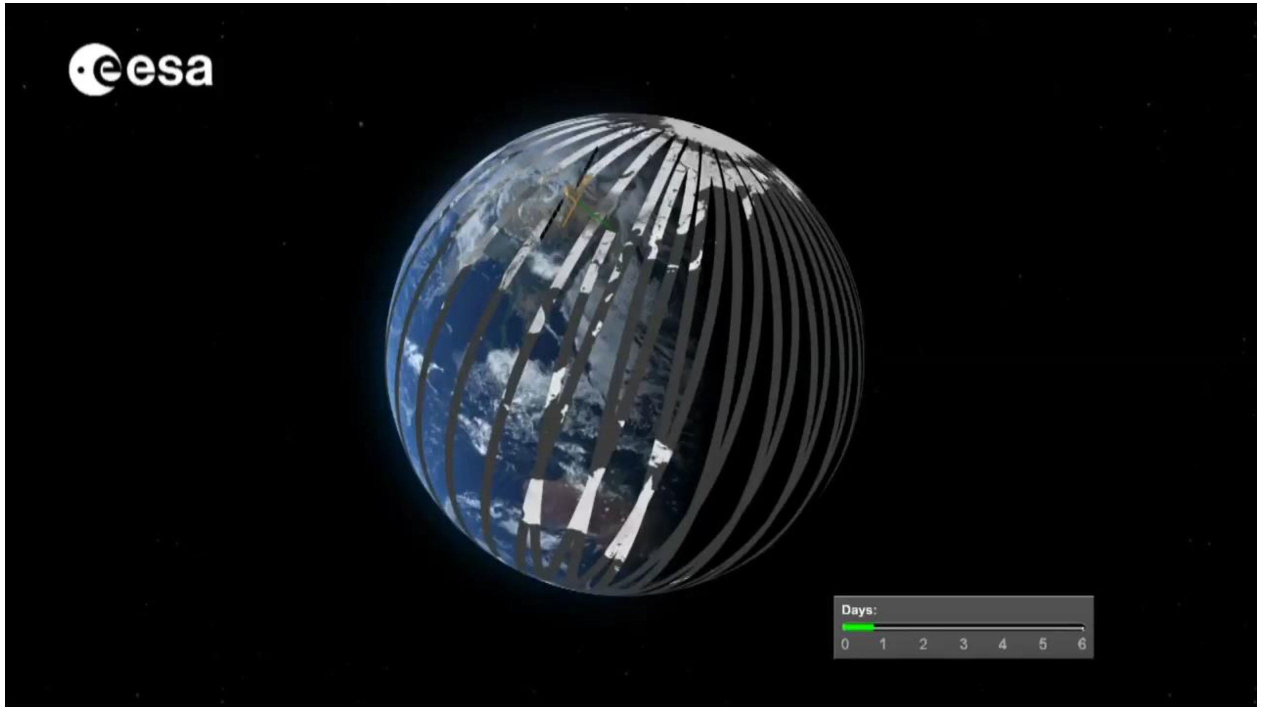
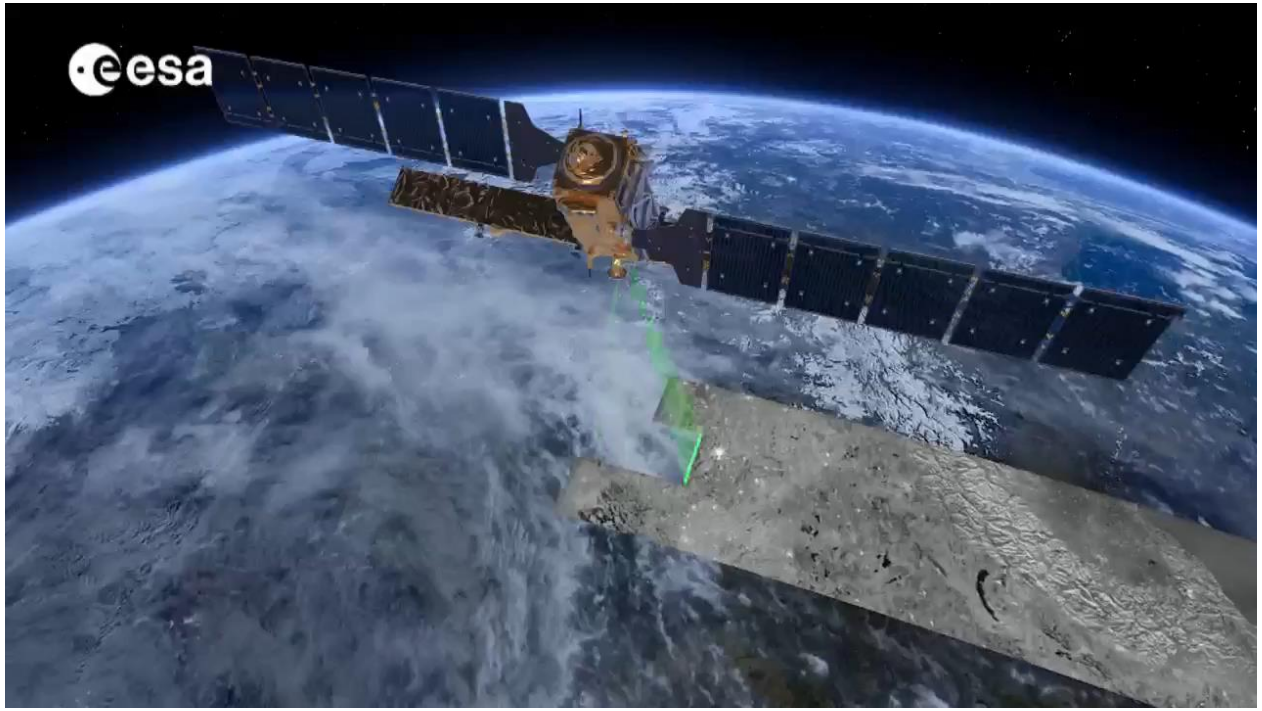
Lesson plan

1. What is radar imaging?
2. Real and Synthetic Aperture Radar
3. Image resolution in SAR images
4. Characteristics of SAR images
5. Applications for SAR imaging
6. Whistle-stop introduction of InSAR & time-series analysis

5. Radar Remote Sensing

Repeated measurements & global archives	From polar-orbiting SAR imaging satellites
	

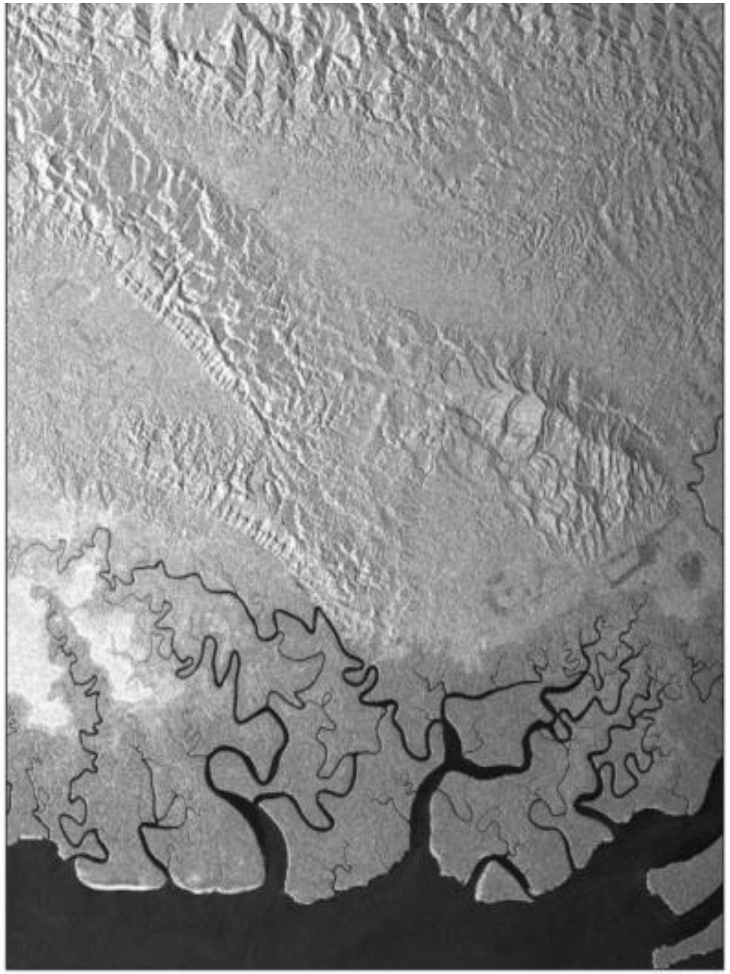
From Sentinel-1 and many others

Animation credit: European Space Agency

What is radar imaging?

An imaging radar is an active sensor system: **RADAR = RA**dio **D**etection **A**nd **R**anging

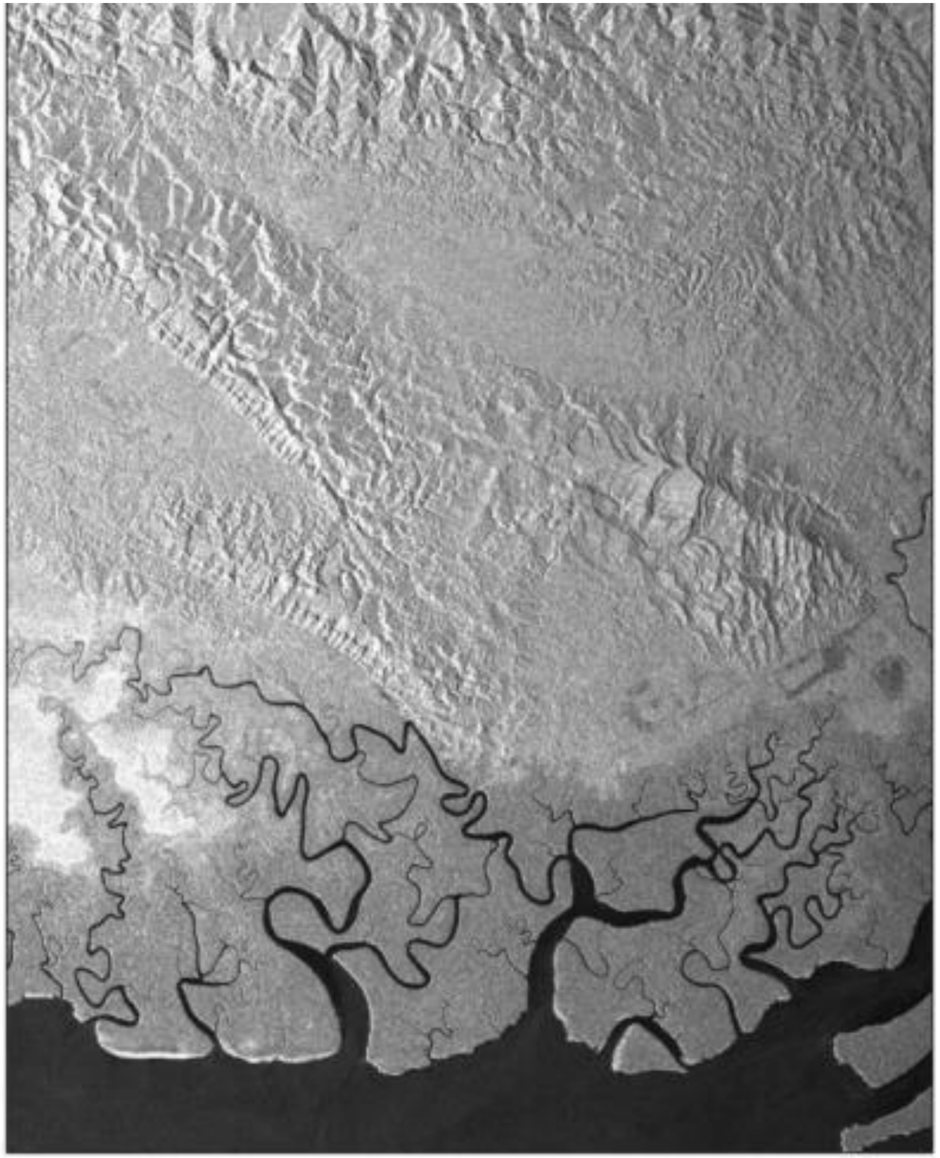
- Sends **microwave radiation pulses** to illuminate a ground target area and receives the **returned signals to produce an image**
  - In contrast to the most commonly used panchromatic and multi-spectral optical sensors which are **passive sensors**
- Operates at much longer EMR wavelengths, usually from **1 cm to 100 cm**, so is not subject to any atmospheric scattering and absorption effects
- Radar beam can penetrate thick clouds because the size of water droplets in clouds is much smaller than the radar wavelength
- As an active sensor, radar can operate in **day and night, and in all weather** mean that imaging radar is widely used in EO remote sensing



Radar

Optical

Advantages & disadvantages of radar



Radar

Advantages with respect to optical:

1. Day/night imaging - Active system, independent of solar illumination - no need for external illumination
2. All-weather - Penetrates clouds, rain, dry sand and, in some cases, vegetation
3. Coherent - Travel path changes can be measured with the accuracy of a fraction of the wavelength
4. Very sensitive to water, roughness, soil moisture and dielectric constant
5. Sensitivity to man made objects (& use of polarimetry)
6. Subsurface penetration

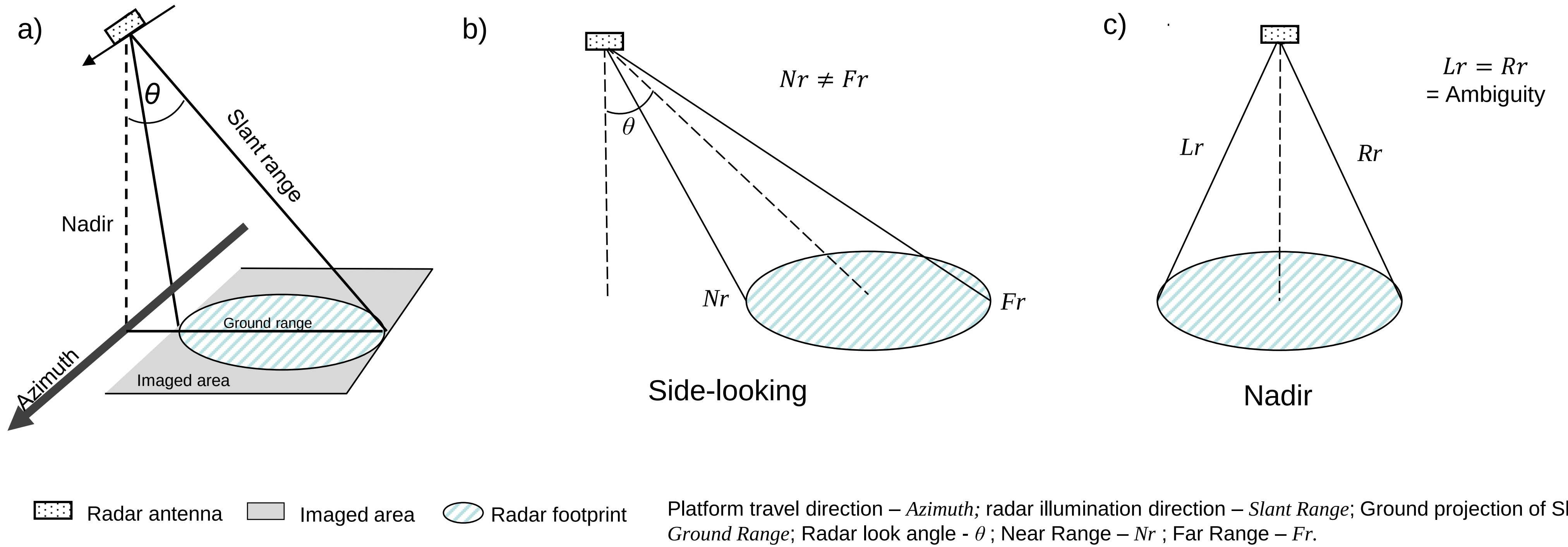
Disadvantages:

1. Complex interactions (difficulty in understanding, complex processing) „
2. Speckle effec difficulty in visual interpretation) „
3. Geometric distortions„
4. Complex effect of surfac oughness

5.1 Imaging Radar System

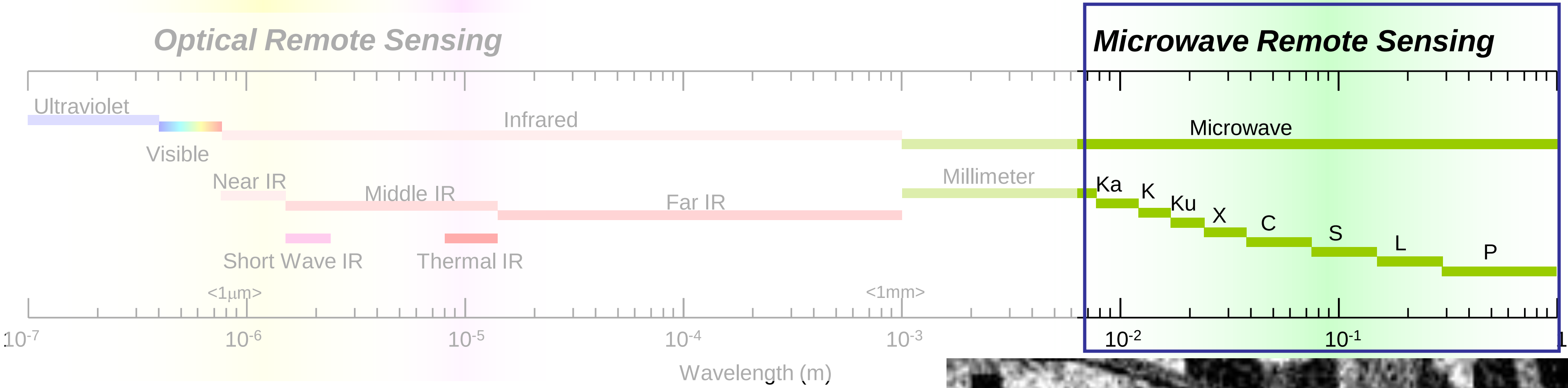
Side Looking Radar (SLR)

- Nearly all imaging radar systems are **side looking** – hence Side Looking Radar (**SLR**).
- = ranging system which forms an image by recording the position of return signals based on time.
- If a radar system is configured to view the both sides of the platform (aircraft or satellite) symmetrically, the return signals from both sides in an equal distance will be received at the same time causing ambiguity.



Platform travel direction – *Azimuth;* radar illumination direction – *Slant Range*; Ground projection of Slant Range – *Ground Range*; Radar look angle - θ ; Near Range – *Nr* ; Far Range – *Fr*.

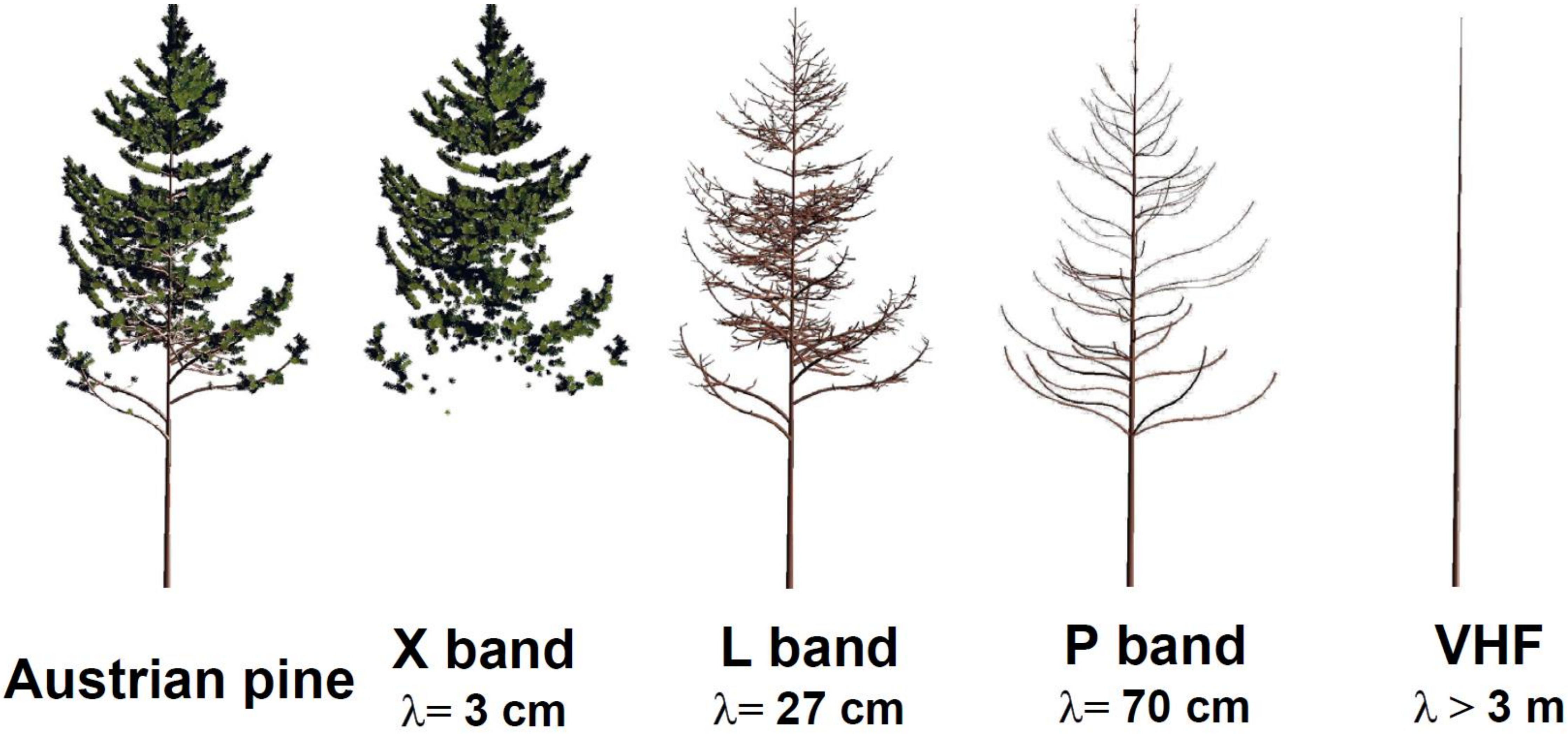
Radar wave bands & frequencies



Band	Wavelength λ (cm)	Frequency MH_z (10^6 cycles sec^{-1})
K_a	0.75 - 1.1	40,000 - 26,500
K	1.1 - 1.67	26,500 - 18,000
K_u	1.67 - 2.4	18,000 - 12,500
X	2.4 - 3.75	12,500 - 8,000
C	3.75 - 7.5	8,000 - 4,000
S	7.5 – 15	4,000 - 2,000
L	15 – 30	2,000 - 1,000
P	30 - 100	1,000 - 300

These commonly used code letters for radar bands were given during World War II, and remain to this day.

What different SAR wavelengths 'see'



Comparing optical and SAR images

Multi-look SAR amplitude image

Radar amplitude is a measure of the **strength of a signal**, and, in particular, the strength or height of an electromagnetic wave (units of voltage).

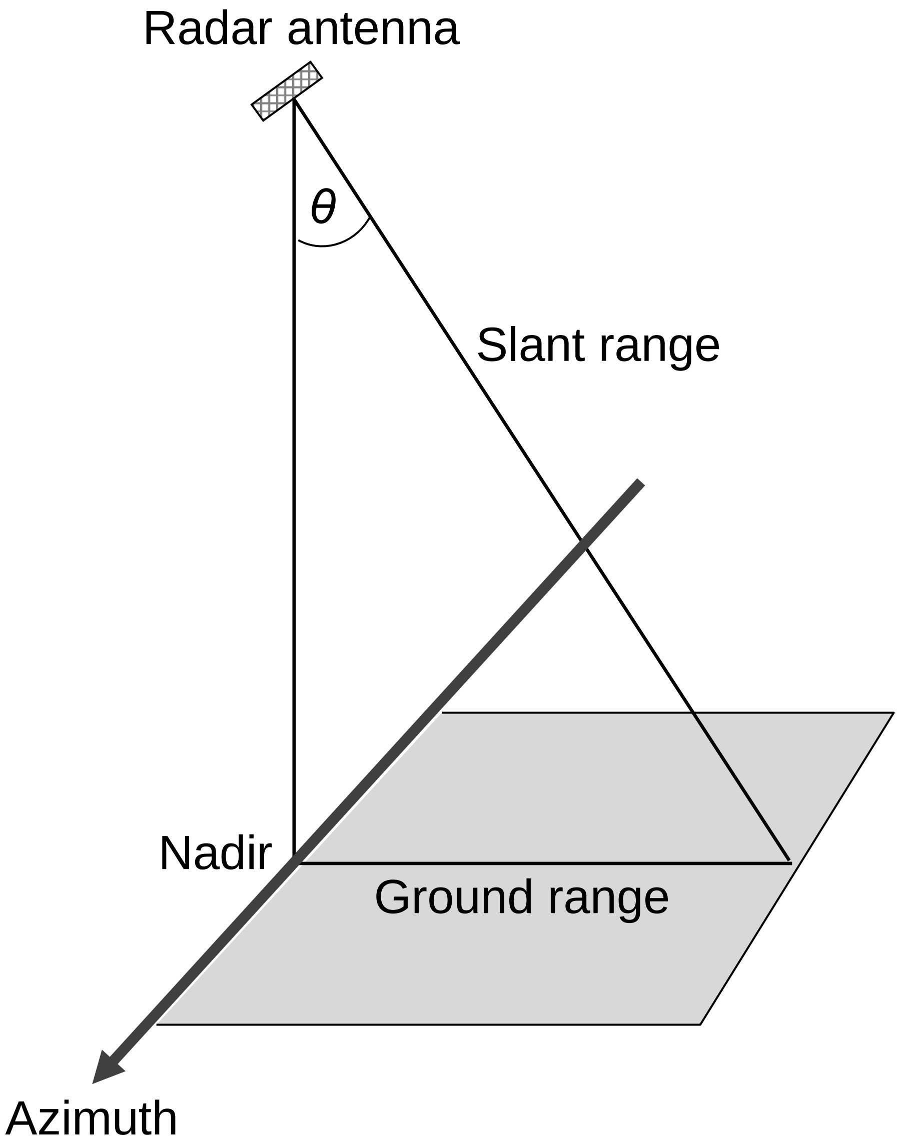
Amplitude is a complex signal, including magnitude & phase
Used to quantify the Intensity of radar backscatter ($I = A^2$)

Amplitude signal (backscattered energy) is not influenced by solar radiation or weather conditions

Optical (panchromatic) image

An optical image is a measure of the reflectance or absorption of solar energy from a target object or material, during day-time. The image information & quality may be affected by cloud shadow, haze and other scattering effects etc

Radar imaging geometry

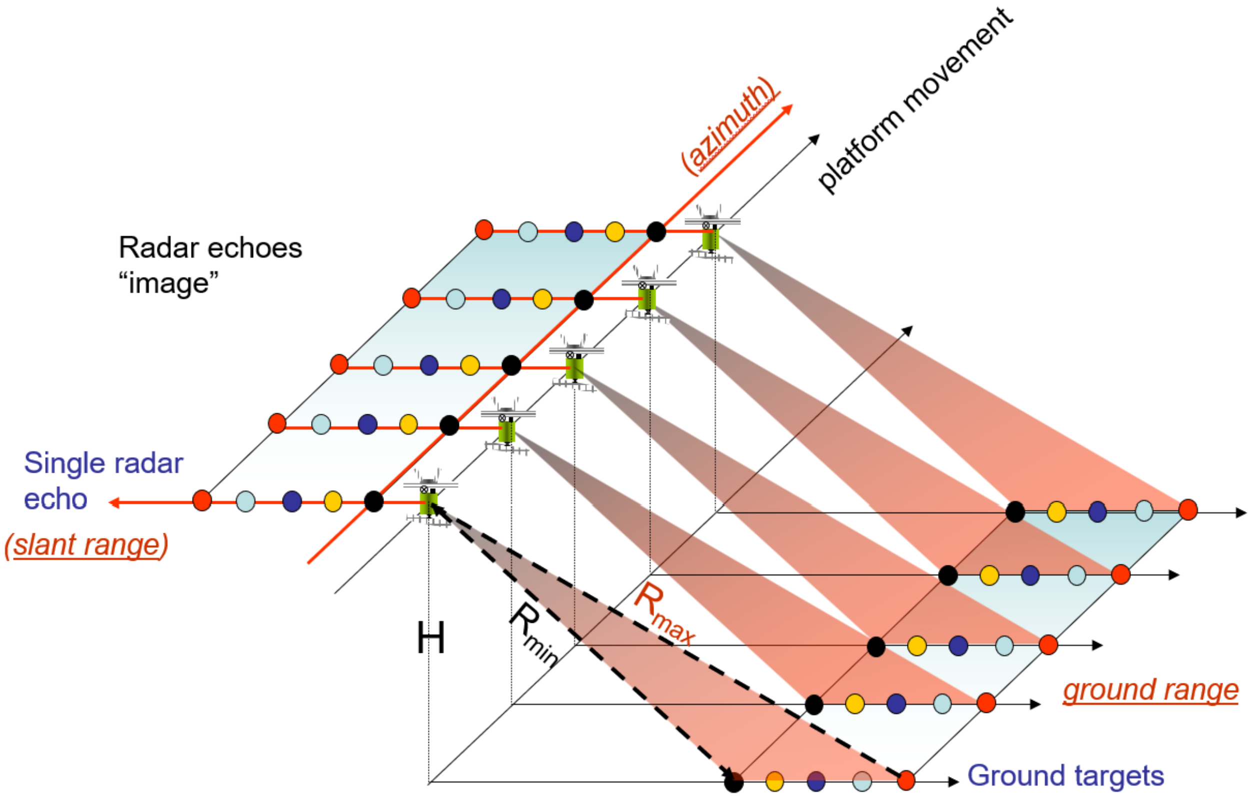


- Given a radar look angle θ, the radar imagery data is configured in relation to two co-ordinates: **range** and **azimuth**.

- **Slant range** is the distance between the radar antenna and the imaged ground object, corresponding to the two-way signal delay time of this object.
- **Ground range** is the distance between the imaged point and the radar nadir which is the projection of slant range on the ground.
- **Azimuth** is the **direction** parallel to the flight path of the platform

a) Real Aperture Radar, RAR (or Real aperture SLR)

- In the **azimuth** direction, the image is built in strips corresponding to the pulse number sequence.
  - As the platform moves forward, the radar antenna transmits microwave pulse beams to scan on one side of the flight path strip-by-strip and meanwhile records the backscattered signals.
- Thus a two-dimensional radar image is built in **ground range** and **azimuth**.
- Unlike optical imagery, **spatial resolution in range and azimuth directions is different**
- The azimuth resolution R_a of a **real aperture** SLR is a function of radar wavelength λ, the slant range S and the radar antenna length D_r:



$$R_a = \frac{S\lambda}{D_r}$$

Therefore, for RAR to achieve high azimuth resolution, the radar antenna has to be **very large to produce a very narrow footprint (or better focused).**

b) Synthetic Aperture Radar (SAR)

Principle of SAR:

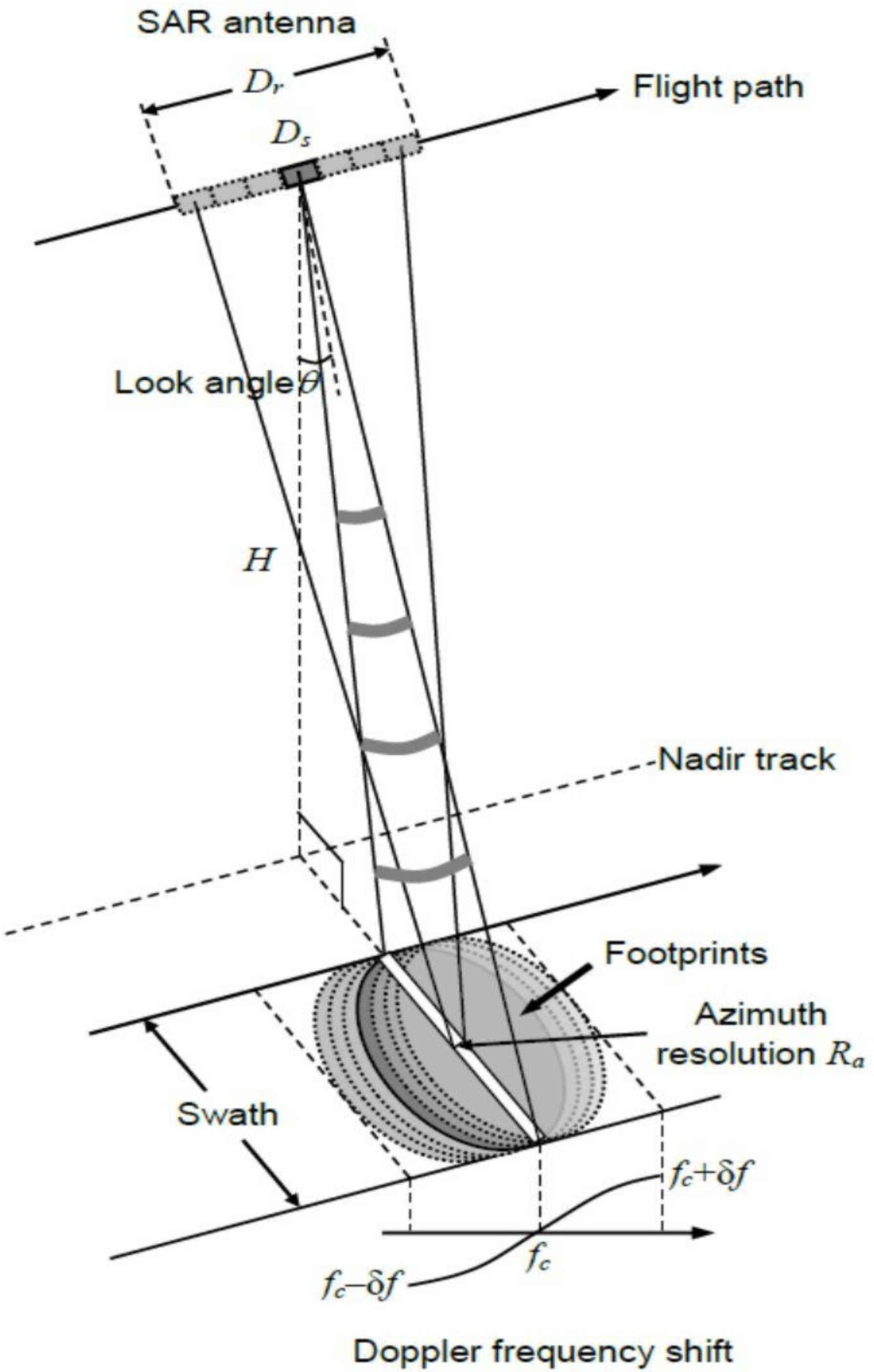
- The motion of SAR antenna with a small length of D_s along its flight path simulates a virtual long antenna D_r
- This enables to achieve a high azimuth resolution R_a much smaller than the SAR footprint width via a digital signal processing procedure called matched filtering on the overlapped footprints based on Doppler frequency shift δf from the SAR carrier frequency f_c.

Azimuth resolution of SAR (R_a)

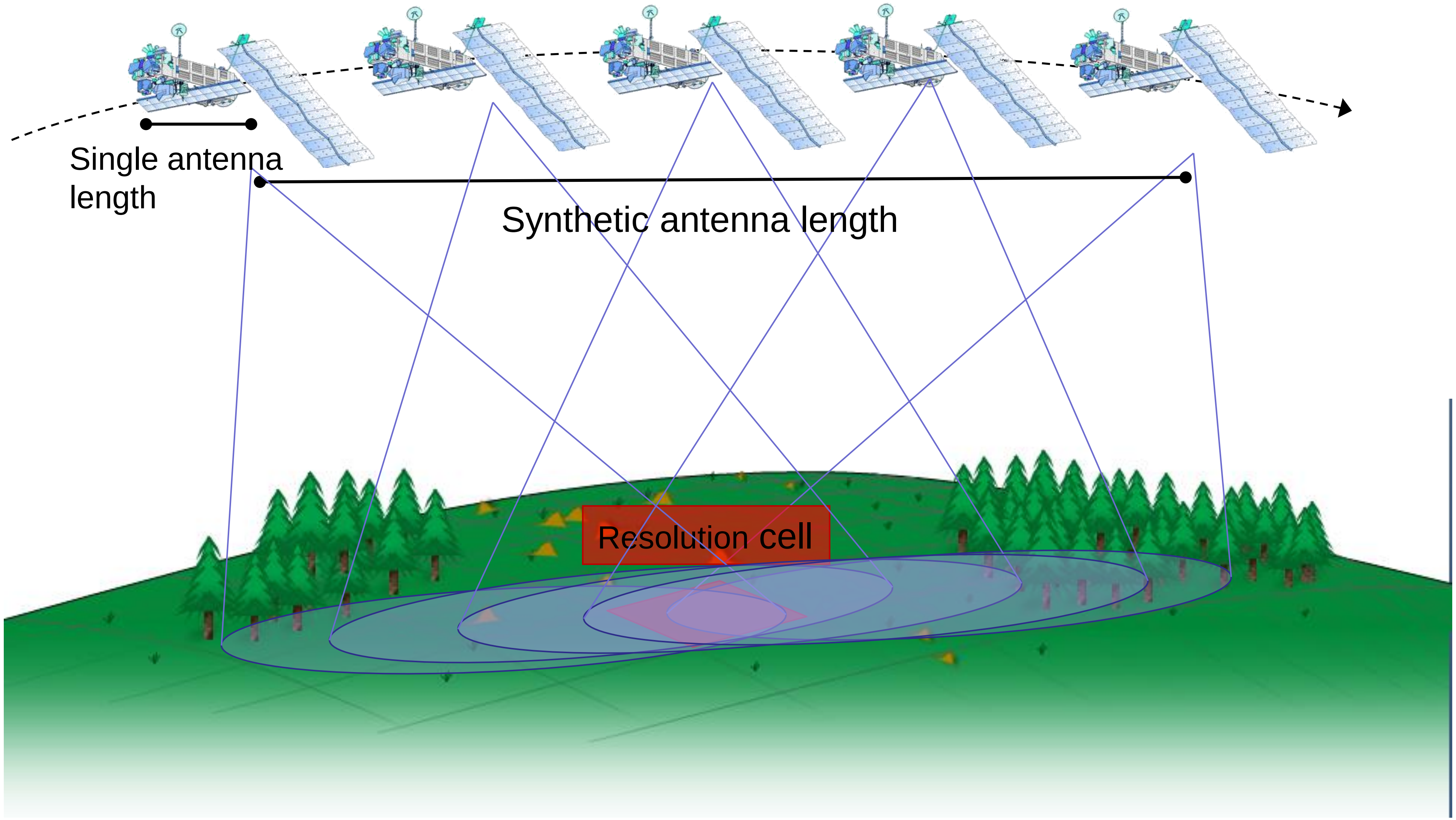
- Equivalent to half of the length of its real antenna. This means that the shorter antenna diameter of SAR achieves higher azimuth resolution.

$$R_a = \frac{D_s}{2}$$

(Curlander and McDonogh, 1991)



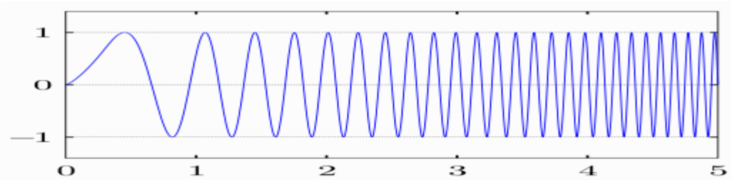
SAR image acquisition

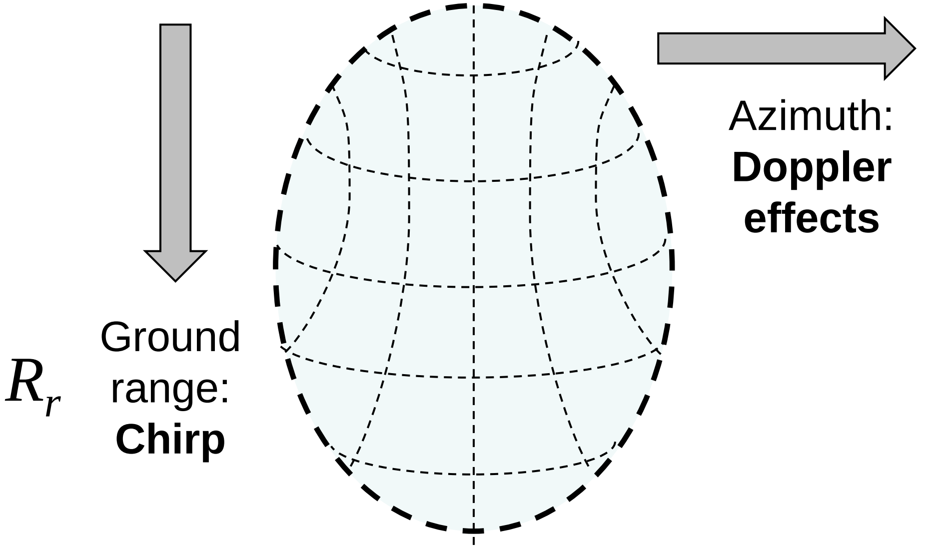


Ground range (GR) resolution of SAR (R_r)

- GR resolution is extracted from the **return time** of radar echo signal: far range signal returns later than near range signal. Resolution in range (R_r) is generally lower than in azimuth (R_a) directions
- But the precision of recording time differences is limited so to achieve a high ground range resolution, SAR emits a **chirp** pulse with a bandwidth of tens of MHz modulating a carrier wave frequency f_c (the nominal frequency of the SAR).
- Depending on the increasing or decreasing of the chirp frequencies, there are ascending and descending chirps.
  - For ascending chirp, the exact frequency of a radar pulse reaching the ground is higher in far range than in near range and so are the echoes from different ranges. The opposite applies to a descending chirp.
- The returned signal is then demodulated with the chirp form and sampled based on the chirp frequency shift from the nominal frequency of the SAR via matched filtering signal processing.

- High spatial resolution in a SAR image is achieved in azimuth direction by Doppler effects and in range direction by chirp.

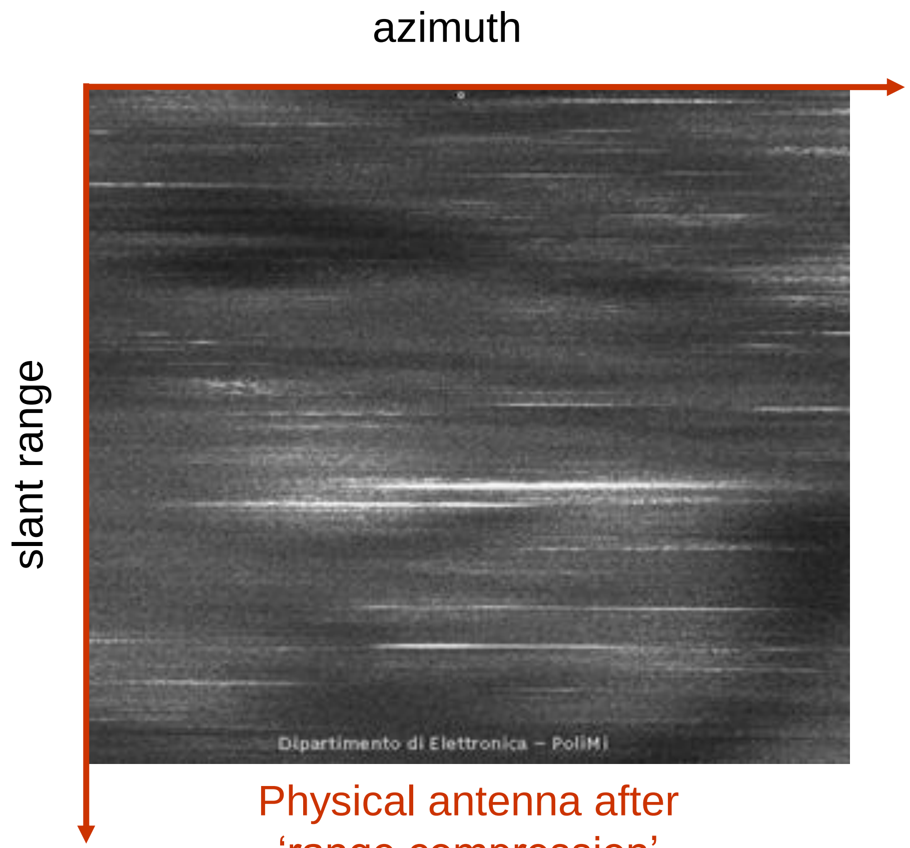




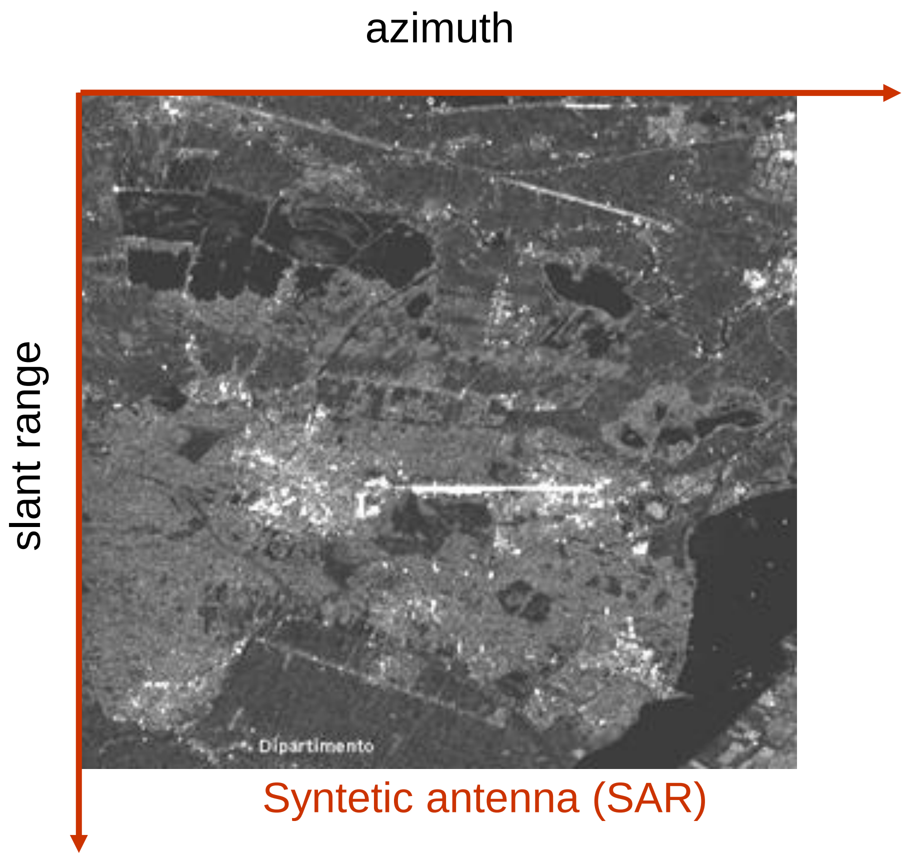
$$R_a = \frac{D_s}{2}$$

SAR images

1. In general the bigger the antenna, the better is azimuth resolution
2. For **metre-scale resolution** in the image, you would need a real antenna with a **length of several km**!!
3. In SAR, a metre-scale real antenna is used on board, while a longer antenna is ‘synthesized’ by computation, combining hundreds of echoes of the same target acquired from different positions along the satellite path



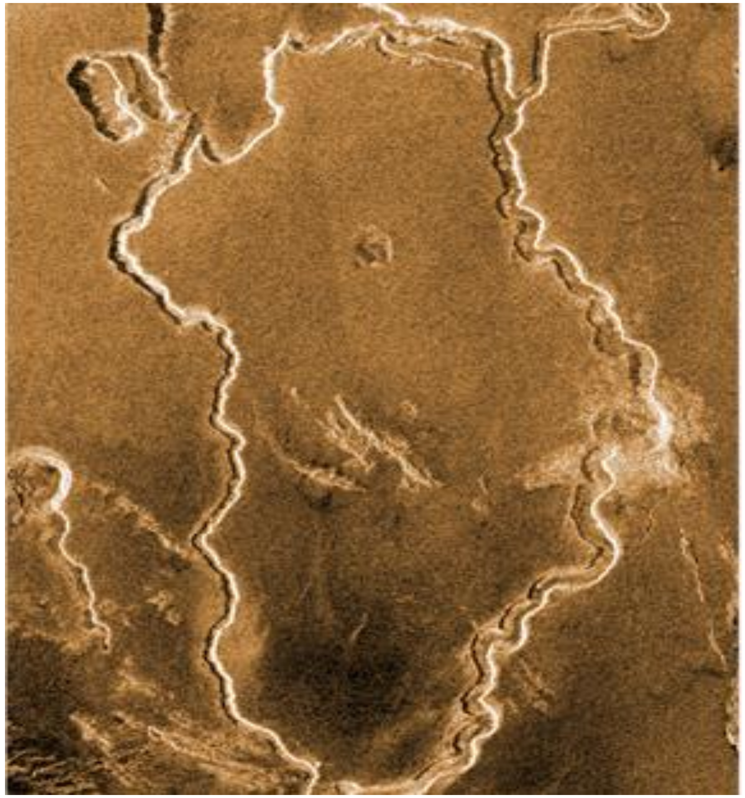
Physical antenna after ‘range compression’



Syntetic antenna (SAR)

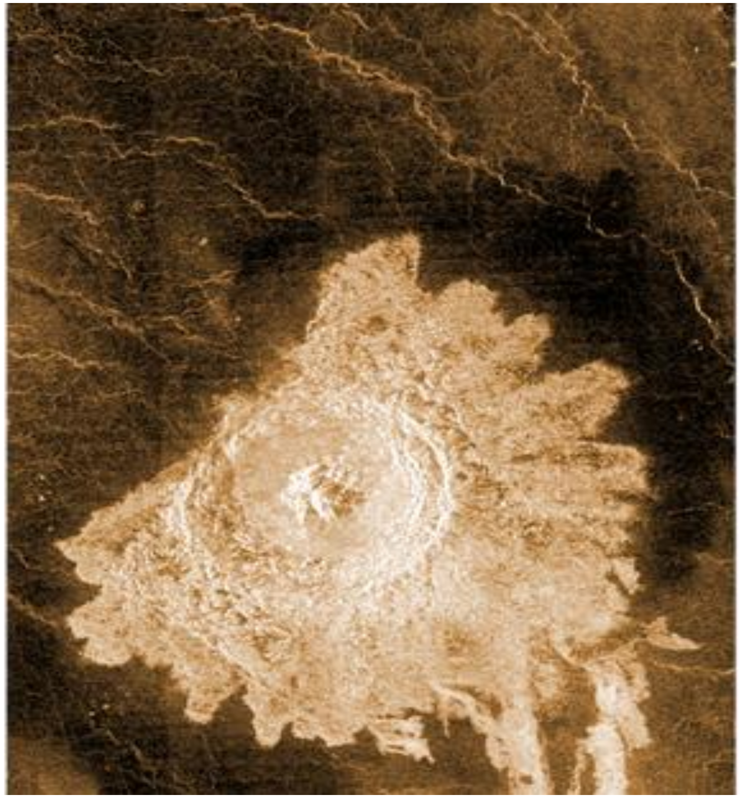
5.2 Characteristics of SAR Images

SAR is sensitive to slope, roughness and electrical properties of the surface



a. Slope

Radar-facing slopes are bright (determined by geomorphology, slope and tectonics etc)



b. Roughness

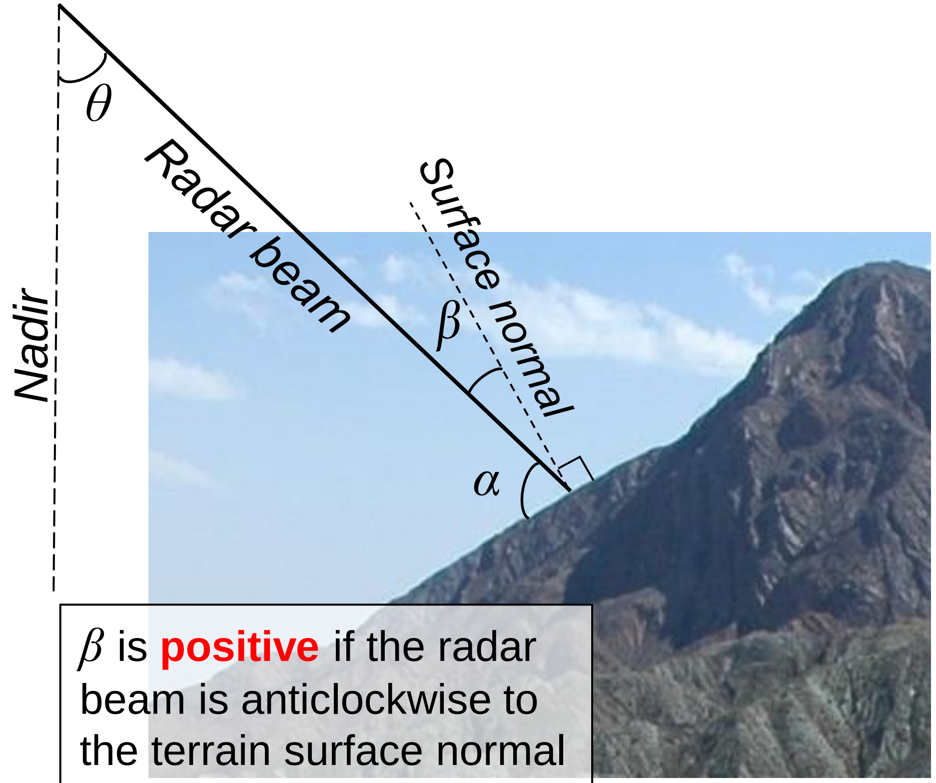
Blocky irregular surfaces are bright (a function of **grain size, fragmentation, material composition**)

c. Dielectric

This affects surface brightness and is determined by **moisture content & chemistry** of materials)

a. Distortions caused by imaging geometry with respect to slope

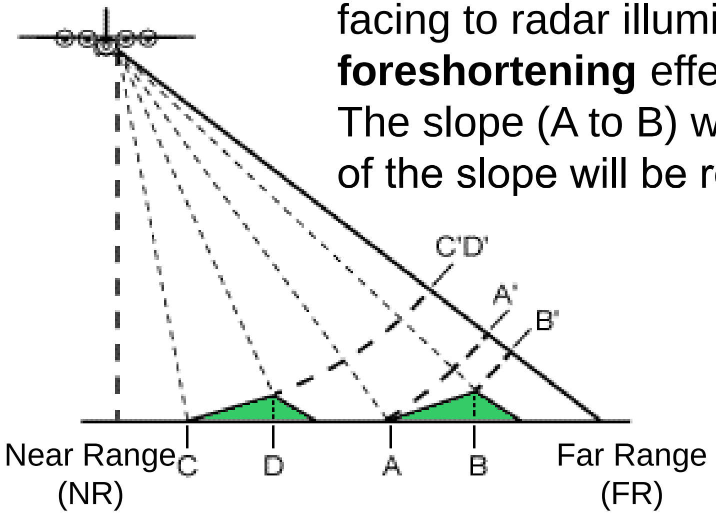
The relationship between radar look angle θ and local incidence angle β, $\alpha = 90° - \beta$



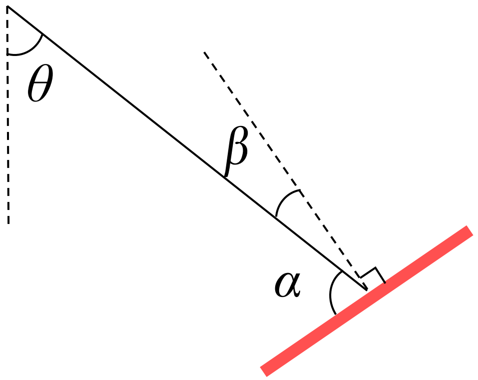
β is **positive** if the radar beam is anticlockwise to the terrain surface normal and **negative** otherwise.

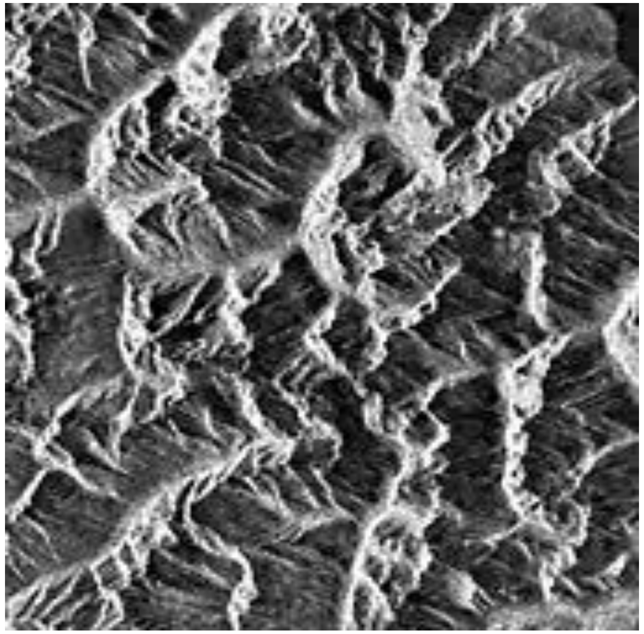
1. Foreshortening

When the local incident angle is **positive**, all terrain slopes facing to radar illumination will exhibit various degrees of **foreshortening** effects.
The slope (A to B) will appear compressed, and the length of the slope will be represented incorrectly (A' to B').

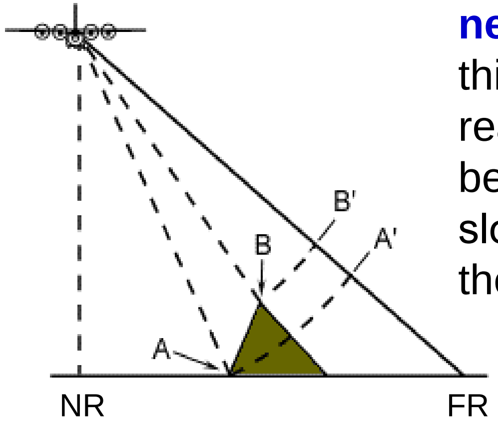


Foreshortening effects are sensitive to look angle, elevation (slope) and to ground range position (between NR and FR)

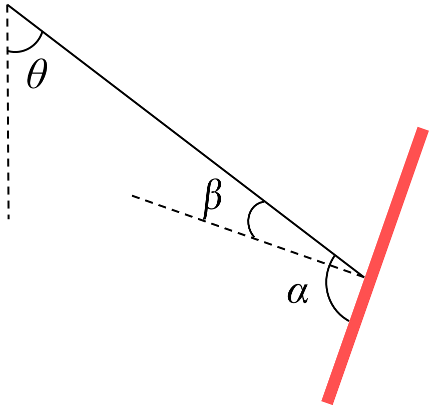




2. Layover

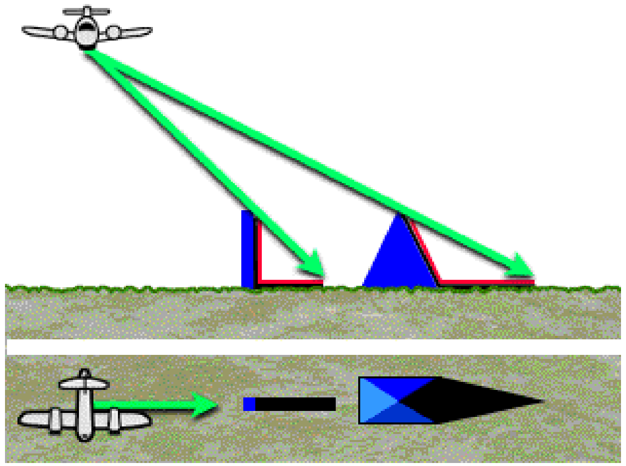


When the local incident angle is **negative Layover** effects appear. In this case (above) the radar beam reaches the top of a tall feature (B) before it reaches the base (A) and the slope AB is recorded inversely as B'A' in the SAR image.



Layover effects are sensitive to look angle, elevation (slope) and to ground range position (between NR and FR)

3. Shadow

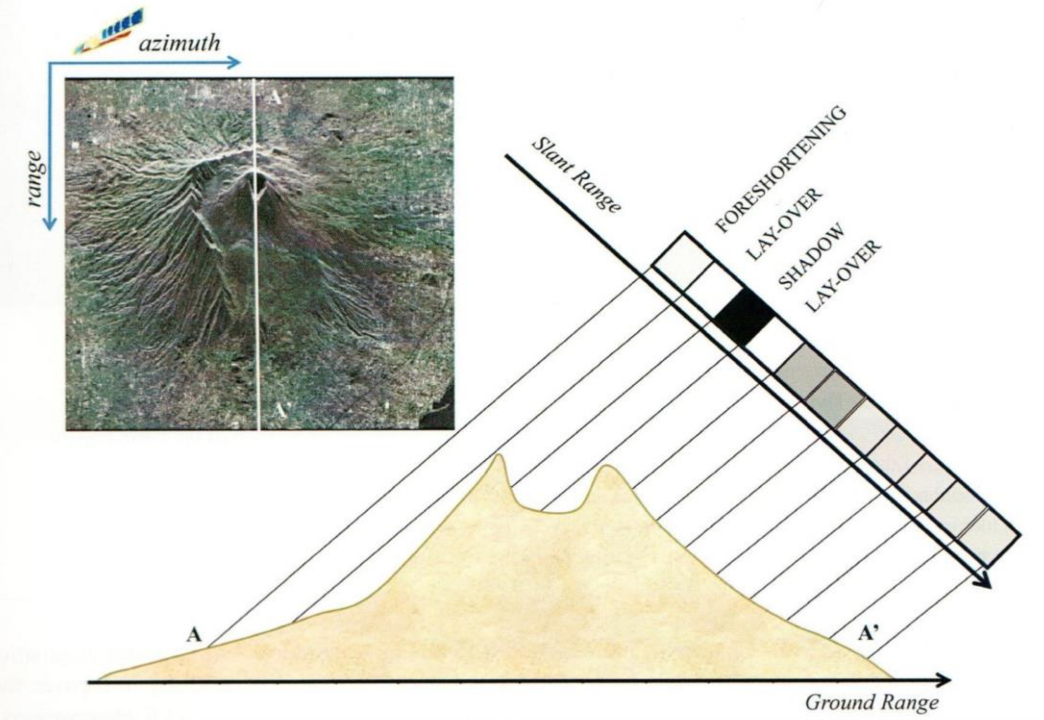


Radar shadows occur increasingly in the down-range direction towards the far range, behind vertical features or steep slopes.

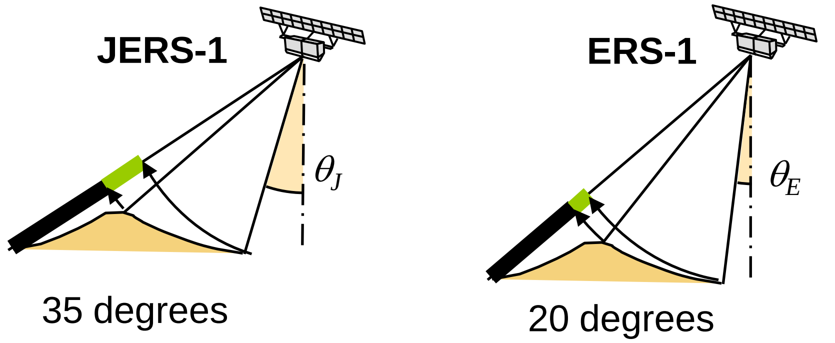
Shadowed areas will appear dark on a SAR image as no energy is available to be backscattered. Radar shadow is particularly dark because atmosphere does not scatter micro-wave EMR!

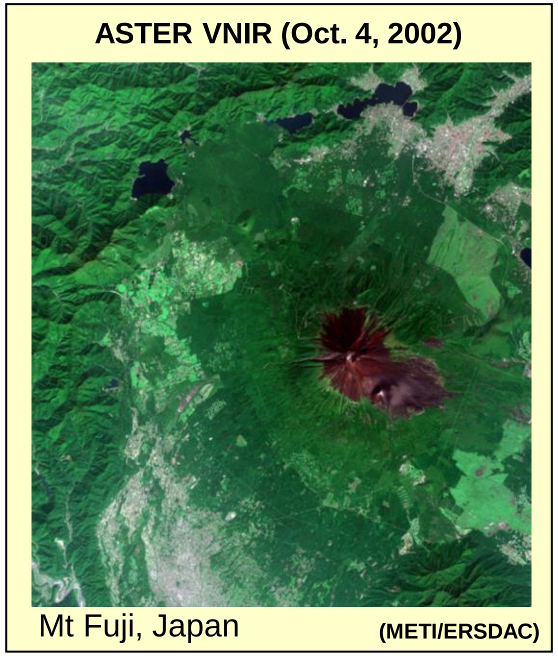
Shadow effects are sensitive to look angle, elevation (slope) and to ground range position (between NR and FR)

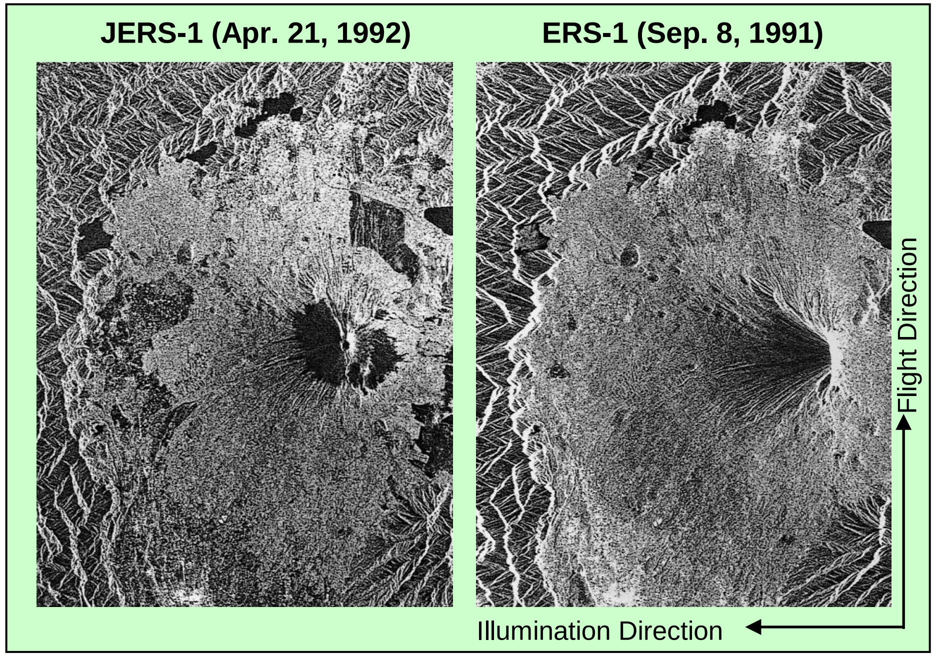
Summary of geometric distortions



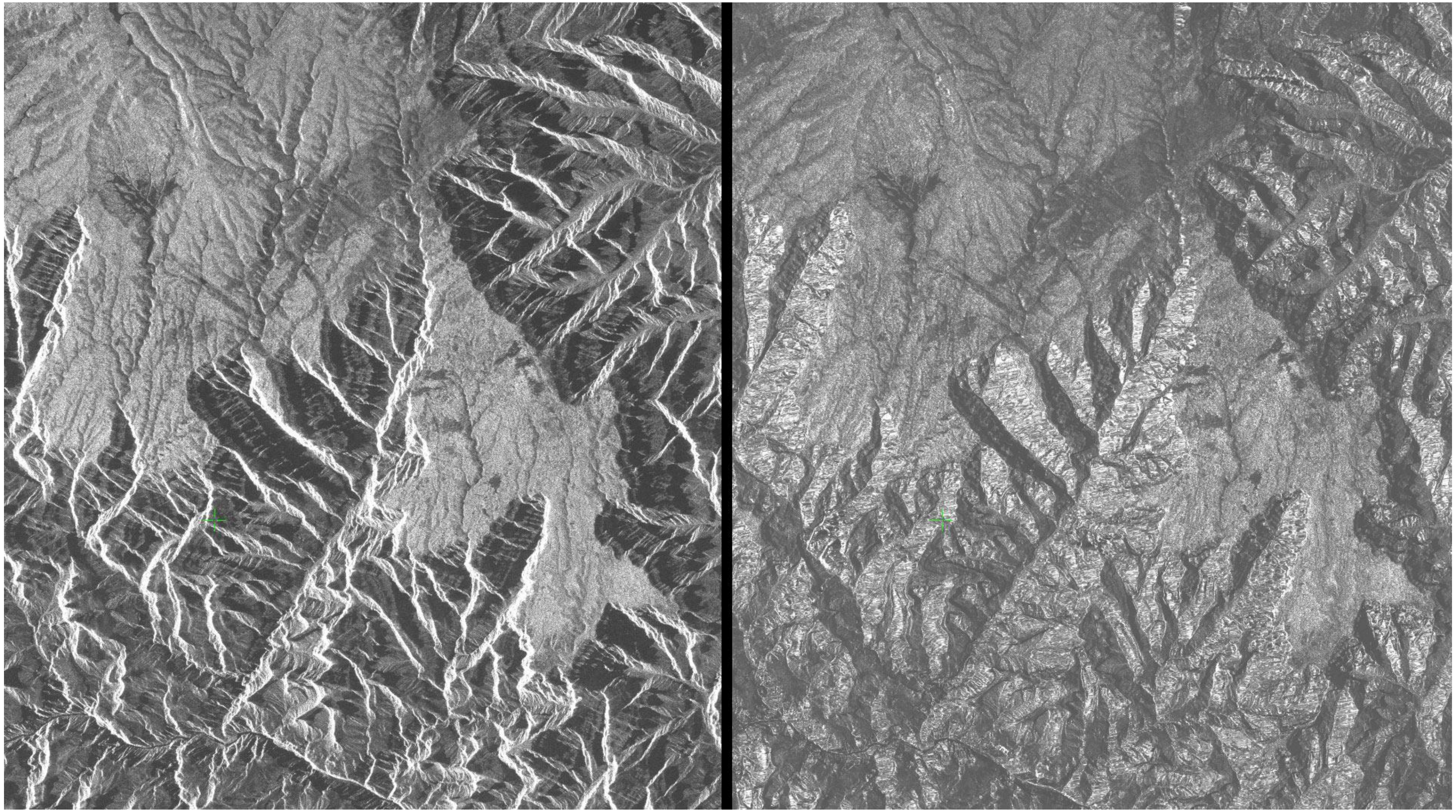
ERS-1 image shows more distortion from foreshortening than JERS-1 image because ERS-1 has a smaller view angle than JERS-1.





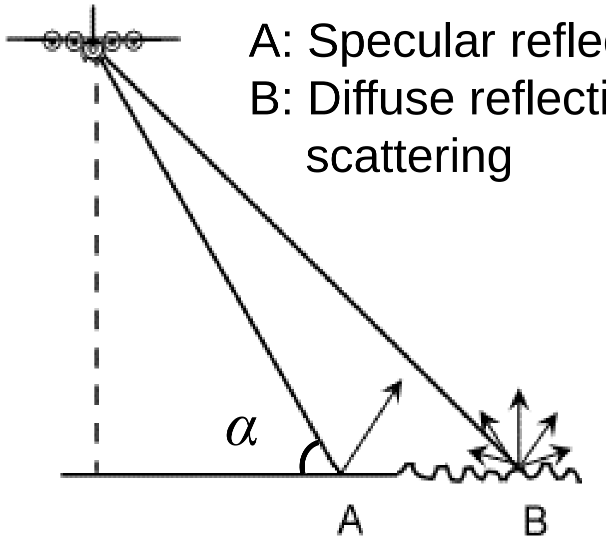


Slope-related terrain distortions can be corrected using a DEM

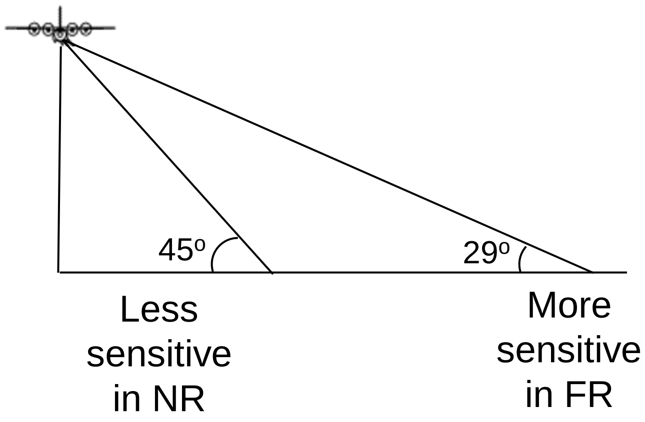


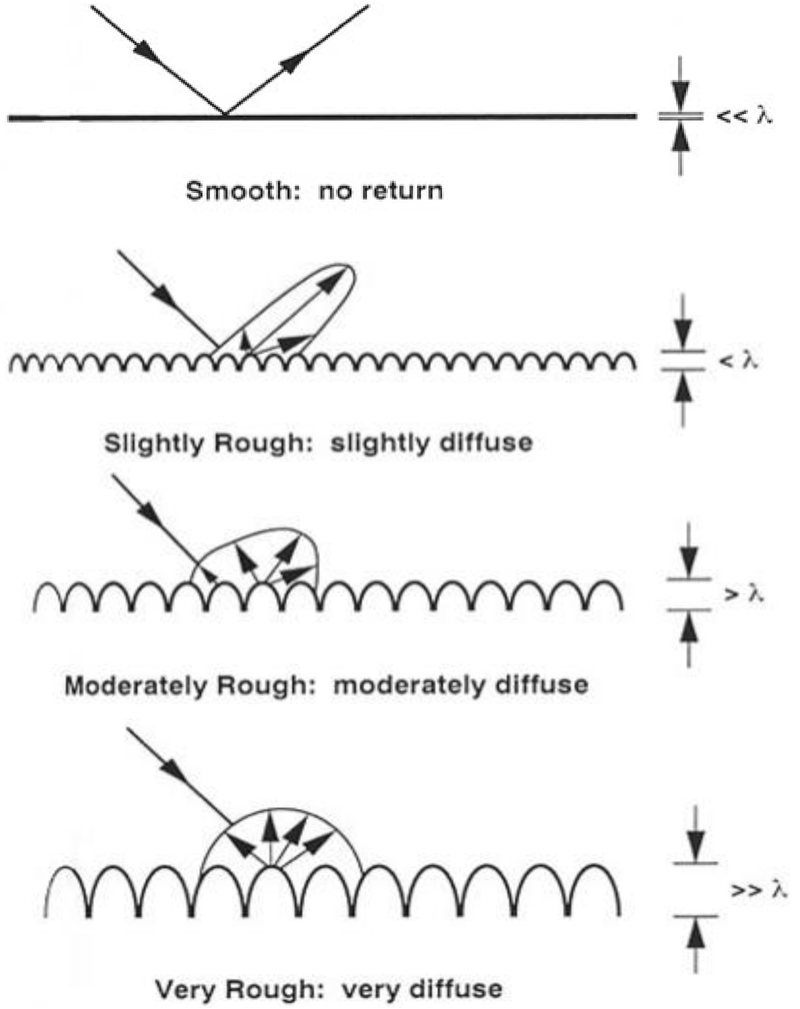
These two images of part of the Grand Canyon are processed from the same PALSAR data. The image on the left is uncorrected. The image on the right is terrain-corrected. In the uncorrected image, the sides of the canyon appear to be stretched on one side and compressed on the other side. Click to enlarge. ASF DAAC 2014; Includes Material © JAXA/METI 2008.

b. How SAR 'sees' surface roughness



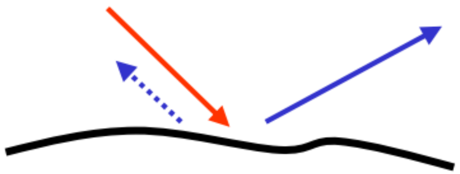
A: Specular reflection
B: Diffuse reflection or scattering



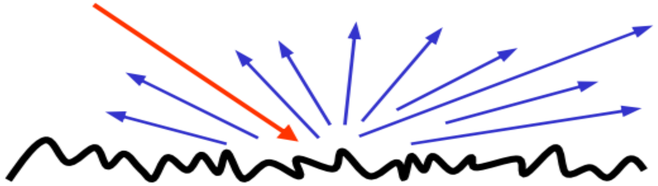


Rayleigh criterion (roughness threshold): $$h < \frac{\lambda}{8 \sin \alpha}$$

where h is the height of surface irregularity, or surface roughness, λ the wavelength and α the angle between incident EMR and the land surface.

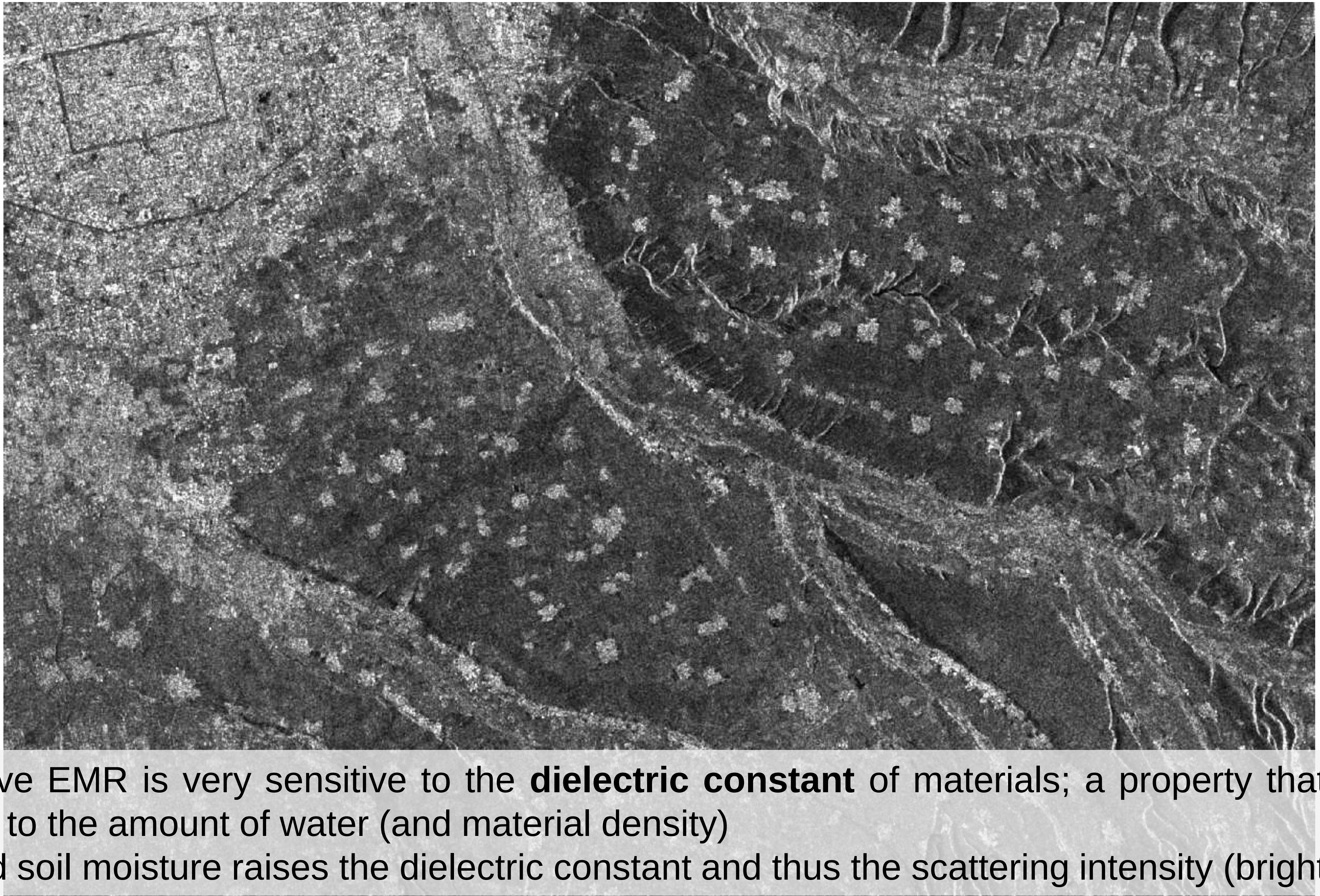


Mud fragments (smooth surface) **low** radar backscatter



Lime stone **Higher backscatter** because of rougher surface

c. Sensitivity to dielectric



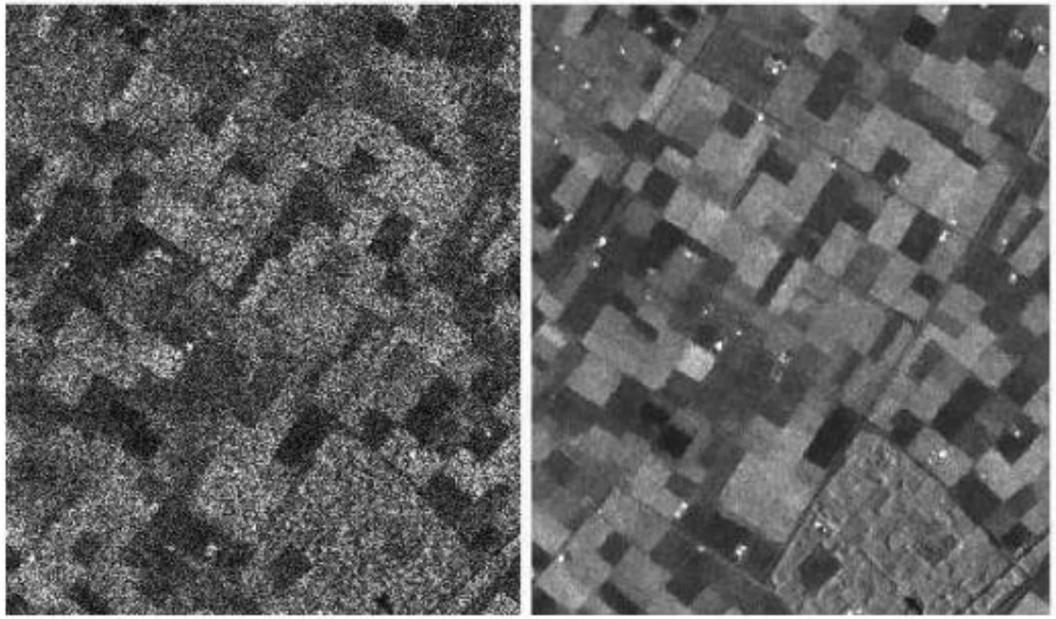
- Micro-wave EMR is very sensitive to the **dielectric constant** of materials; a property that changes in response to the amount of water (and material density)
- Increased soil moisture raises the dielectric constant and thus the scattering intensity (brighter)

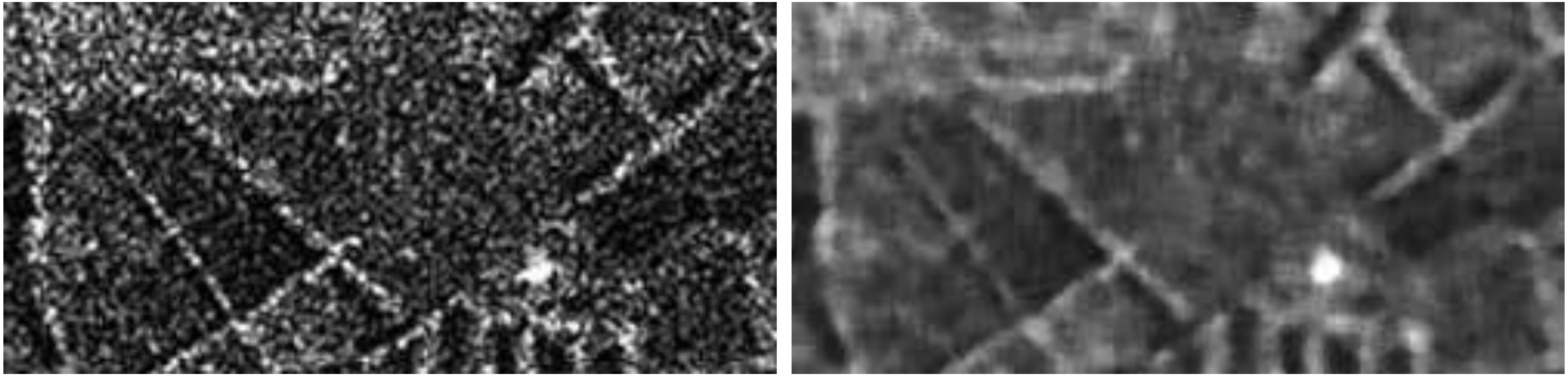
Other scattering effects

i. Radar speckle

Since radar waves are coherent (i.e. in phase), the backscattered waves, from every element in the scene constructively and destructively interfere with each other, creating a 'salt and pepper' effect across images, called ***speckle*** noise.

These can be reduced by filtering - to remove these high-frequency speckles

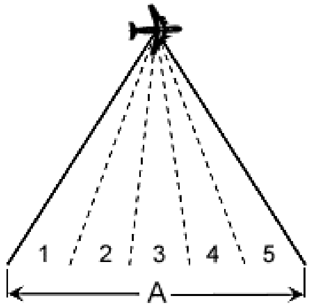




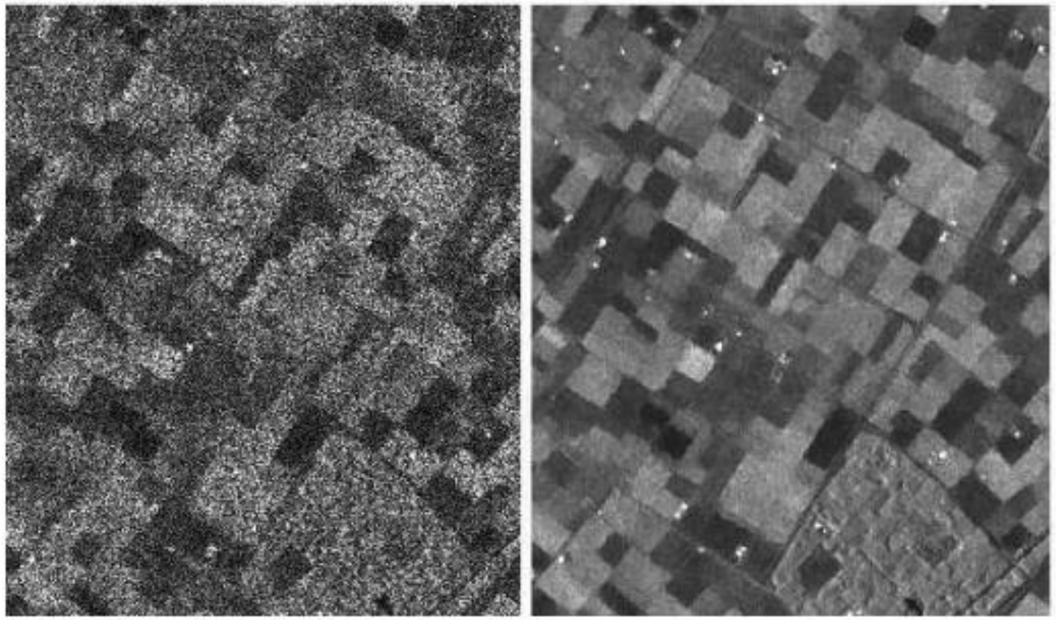
Smooth filtering to remove speckles

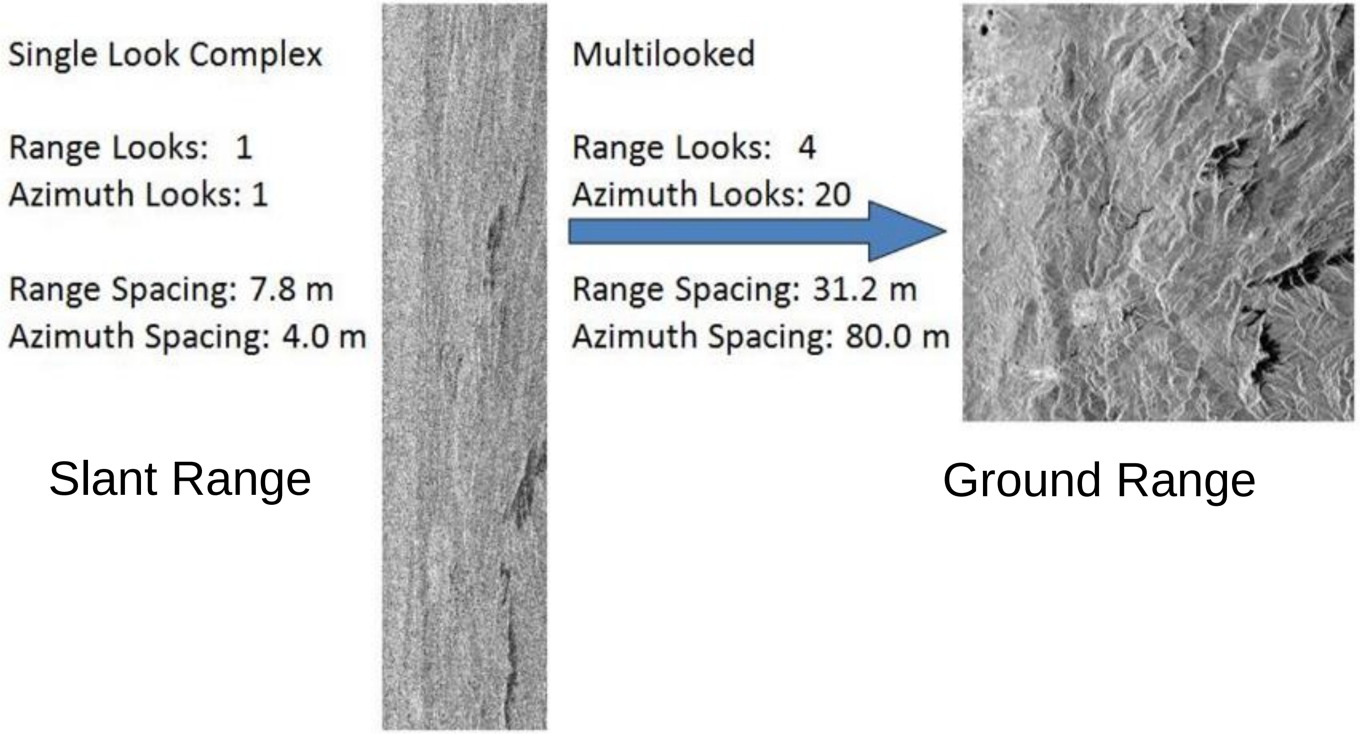
i. Radar speckle reduction

Speckle reduction by multi-looking



Speckles are randomly distributed so they can be reduced by averaging, or 'multi-looking'





Slant Range

Ground Range

- Multi-looking produces a smoother image with nominal pixel size
- Generated by **averaging over several range looks and azimuth looks**, improving radiometric resolution but **degrading spatial resolution.**
- The multi-looked image has less noise (speckle) and approximate square pixels after being converted from slant range to ground range

Multi-looking to reduce speckle

Speckle reduces & image quality improves

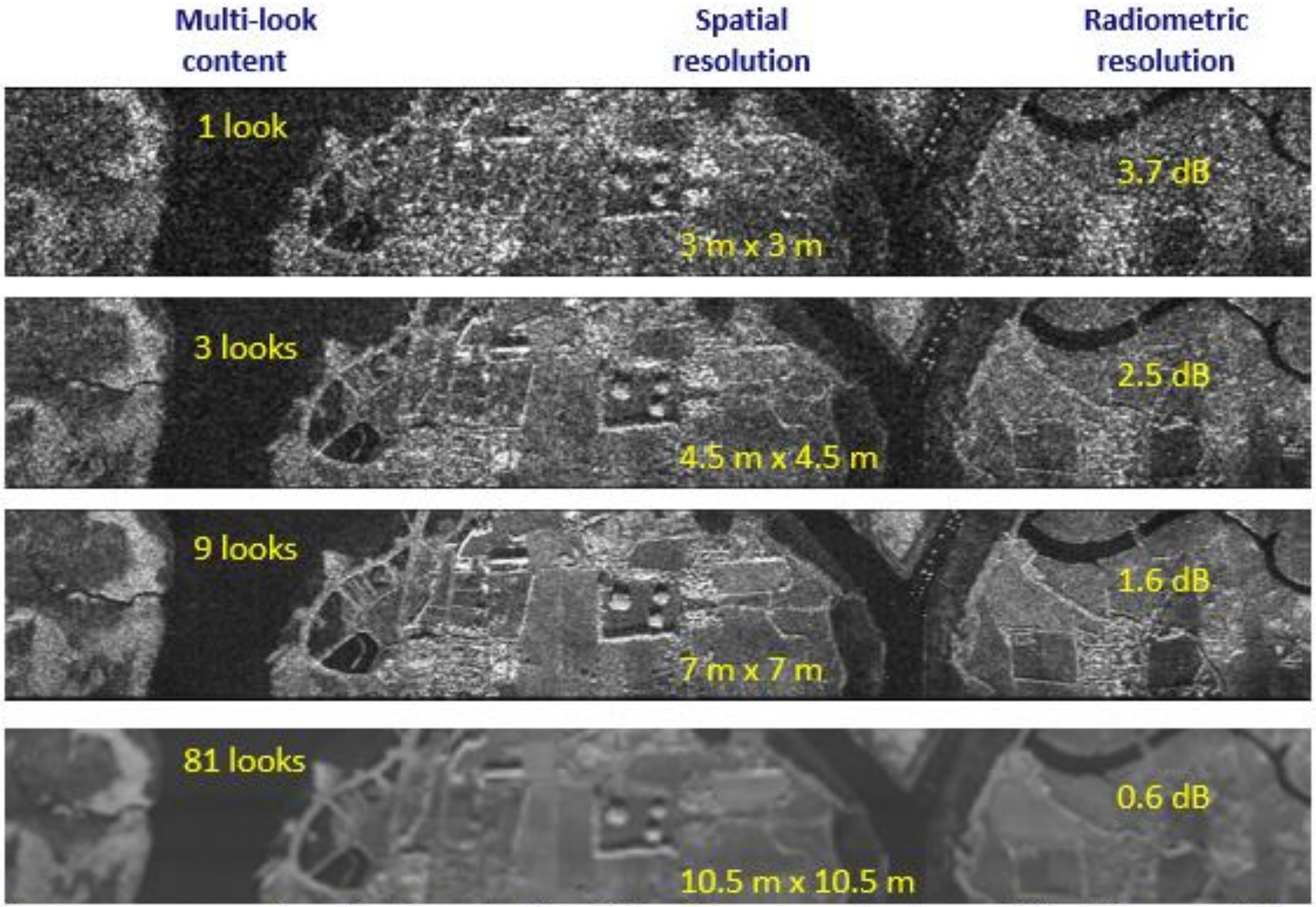
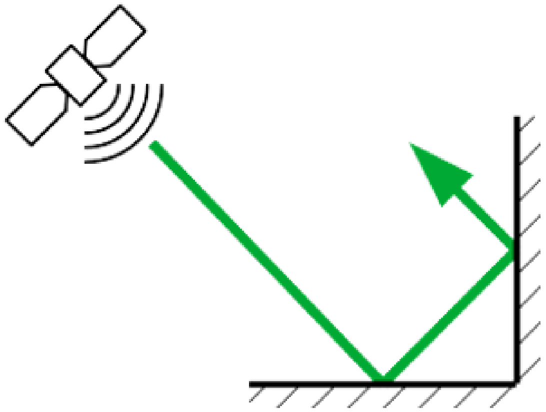
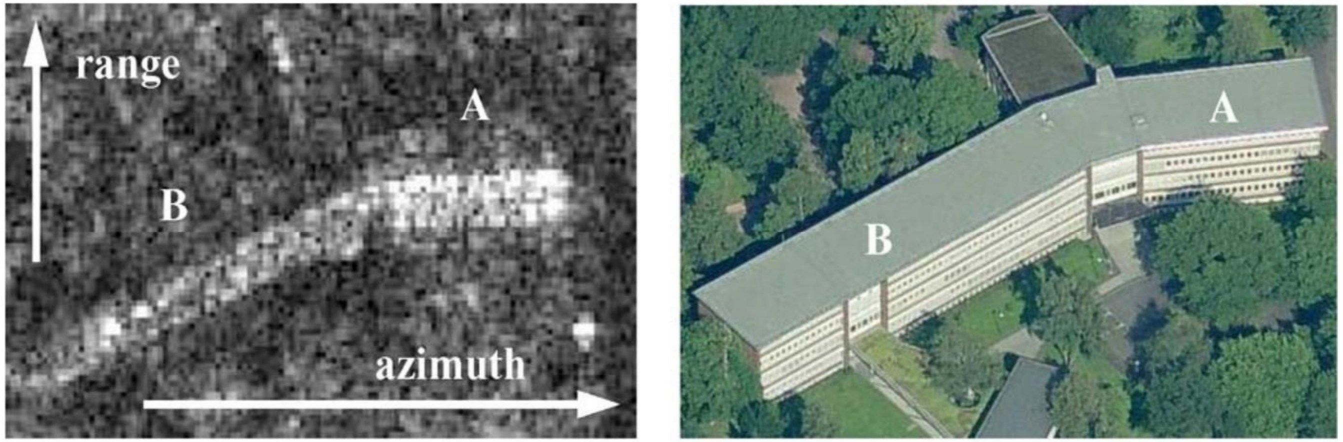


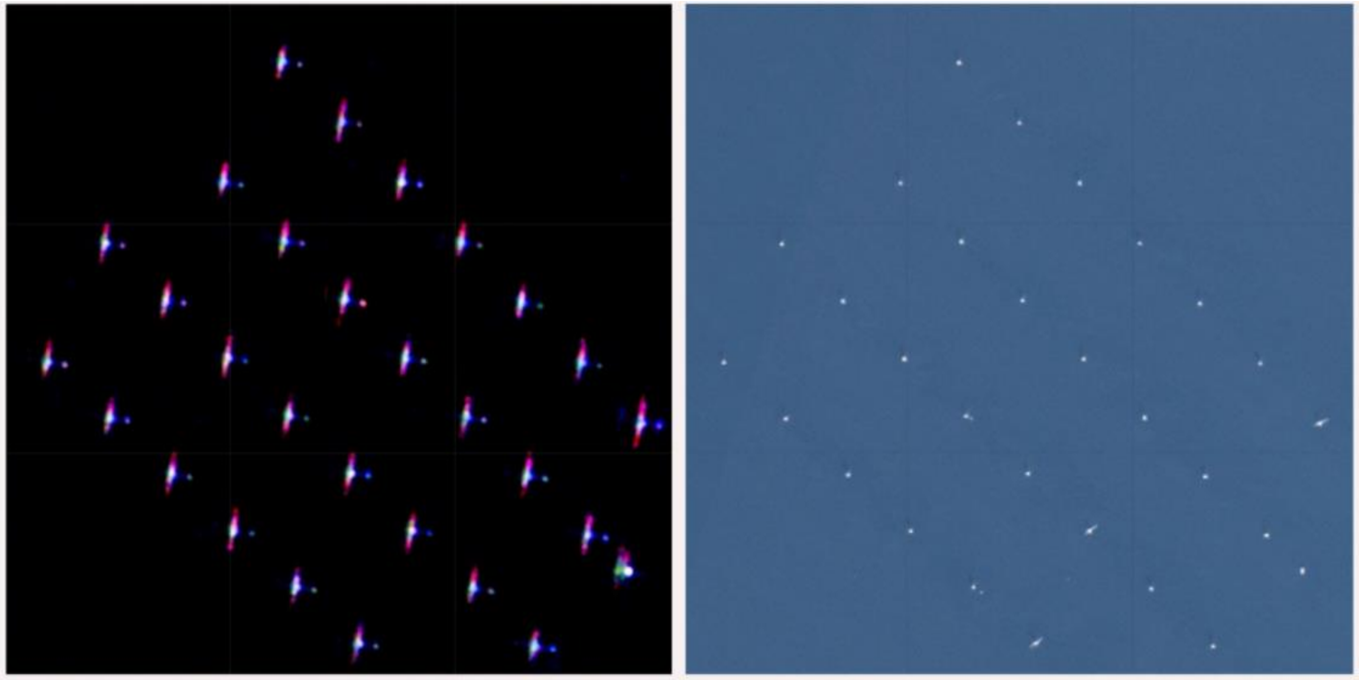
Image sequence showing impact of multi-looking; normally demand for higher spatial resolution reduces number of looks possible.
Simulation based on airborne NovaSAR-S test data. [© Airbus Defence and Space]

Spatial resolution reduces

ii. Corner reflections

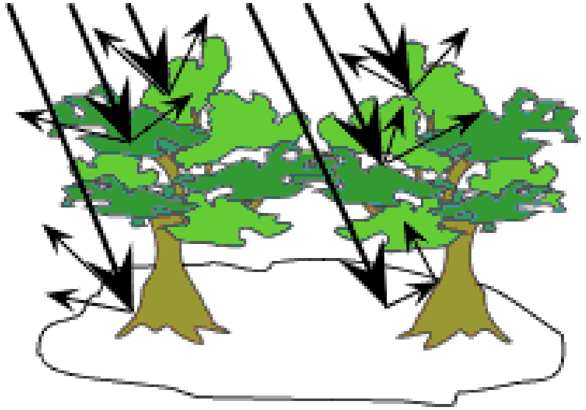






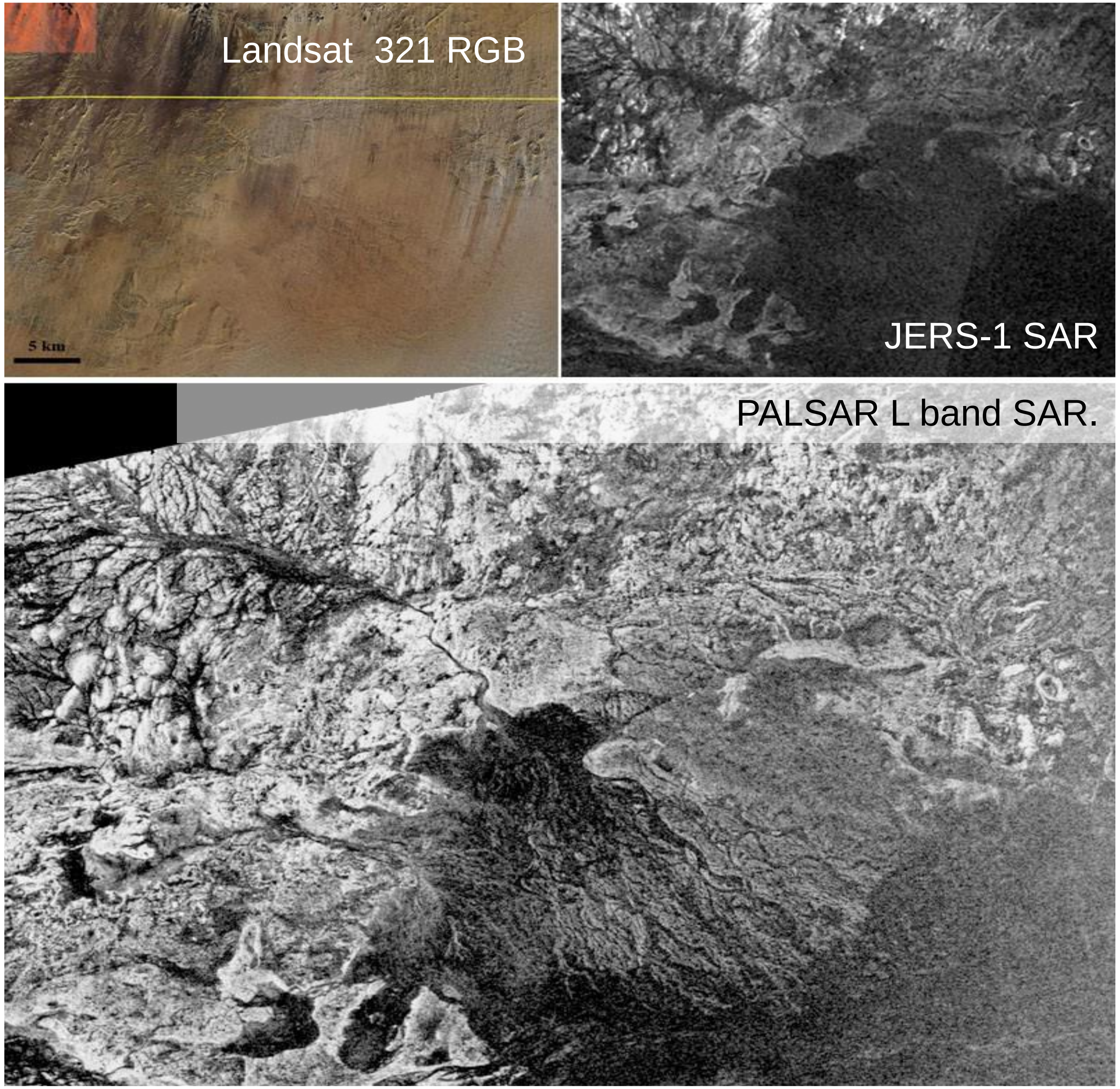
Features that have two surfaces (usually smooth) at the right angle may cause corner reflection if the ‘corner’ faces the general direction of the radar antenna. **Double bounce** effect of a corner reflector will result in the incident radar energy reflect back to radar antenna directly.

iii. SAR penetration and volume scattering



Volume Scattering

Scattering of radar energy within a volume or medium, and usually consists of multiple bounces and reflections from different components within the volume.



Substrate Penetration

If the target is very dry and the surface appears smooth to the radar, the radar energy may penetrate below the surface, either through:

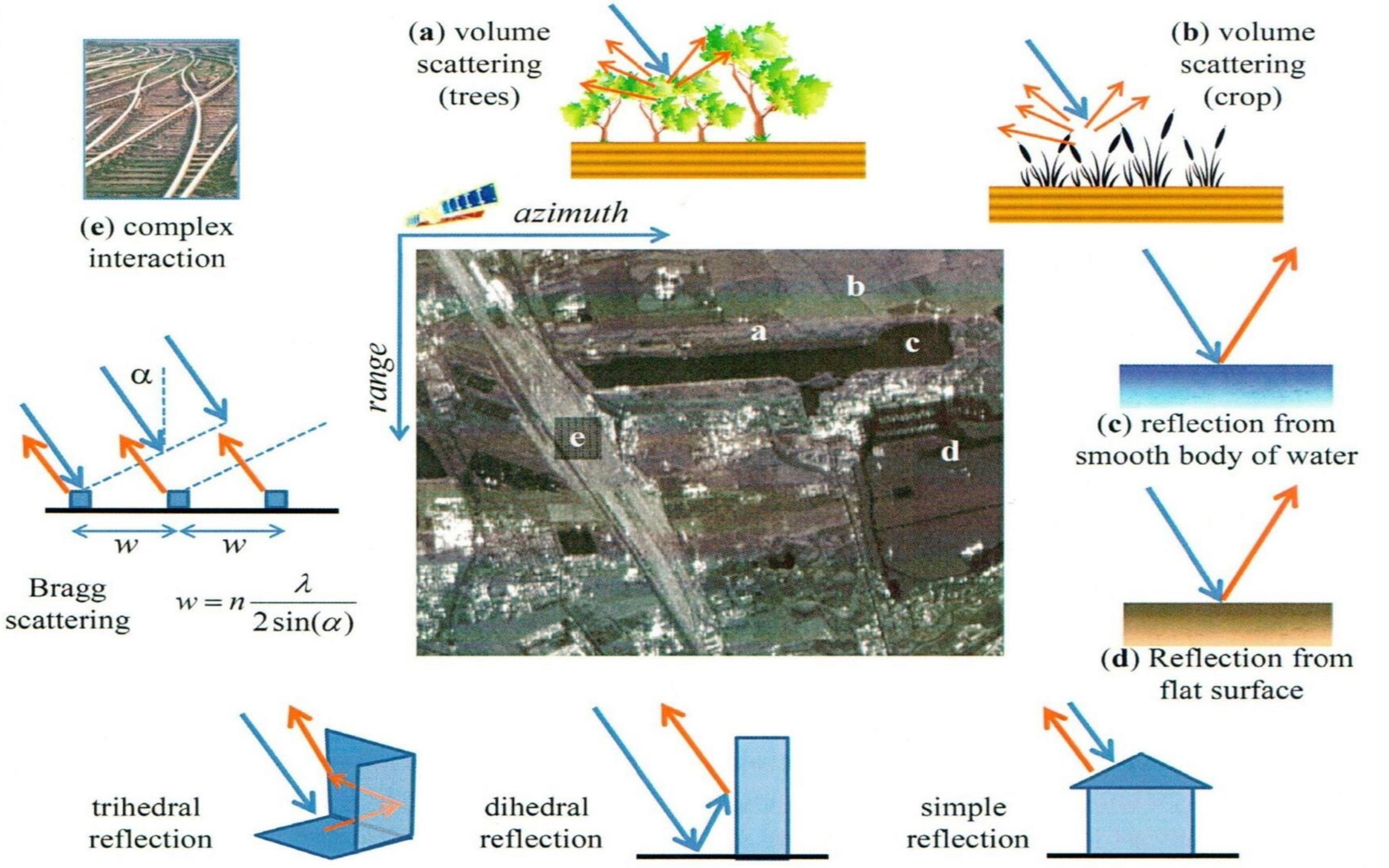
i. Discontinuous (e.g. forest canopy), or

ii. Homogeneous surface (e.g. soil, sand, or ice)

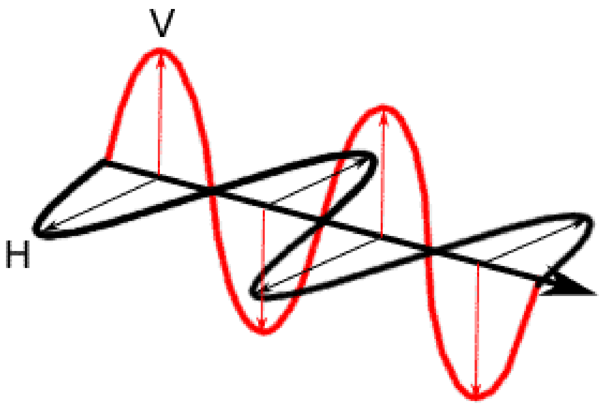
For a given surface, longer wavelengths can penetrate farther/deeper than shorter wavelengths.

Damp river channel buried by dry desert sands
PALSAR L band penetrates sand to reveal
paleodrainage channels in the lower part of the scene

Summary of complex scattering mechanisms



Effect of Radar Polarization



Polarization refers to the orientation of the electric field.

Radar systems can be designed to transmit/receive microwave radiation either horizontally polarized (H) or vertically polarized (V) or both.

Like-polarized:

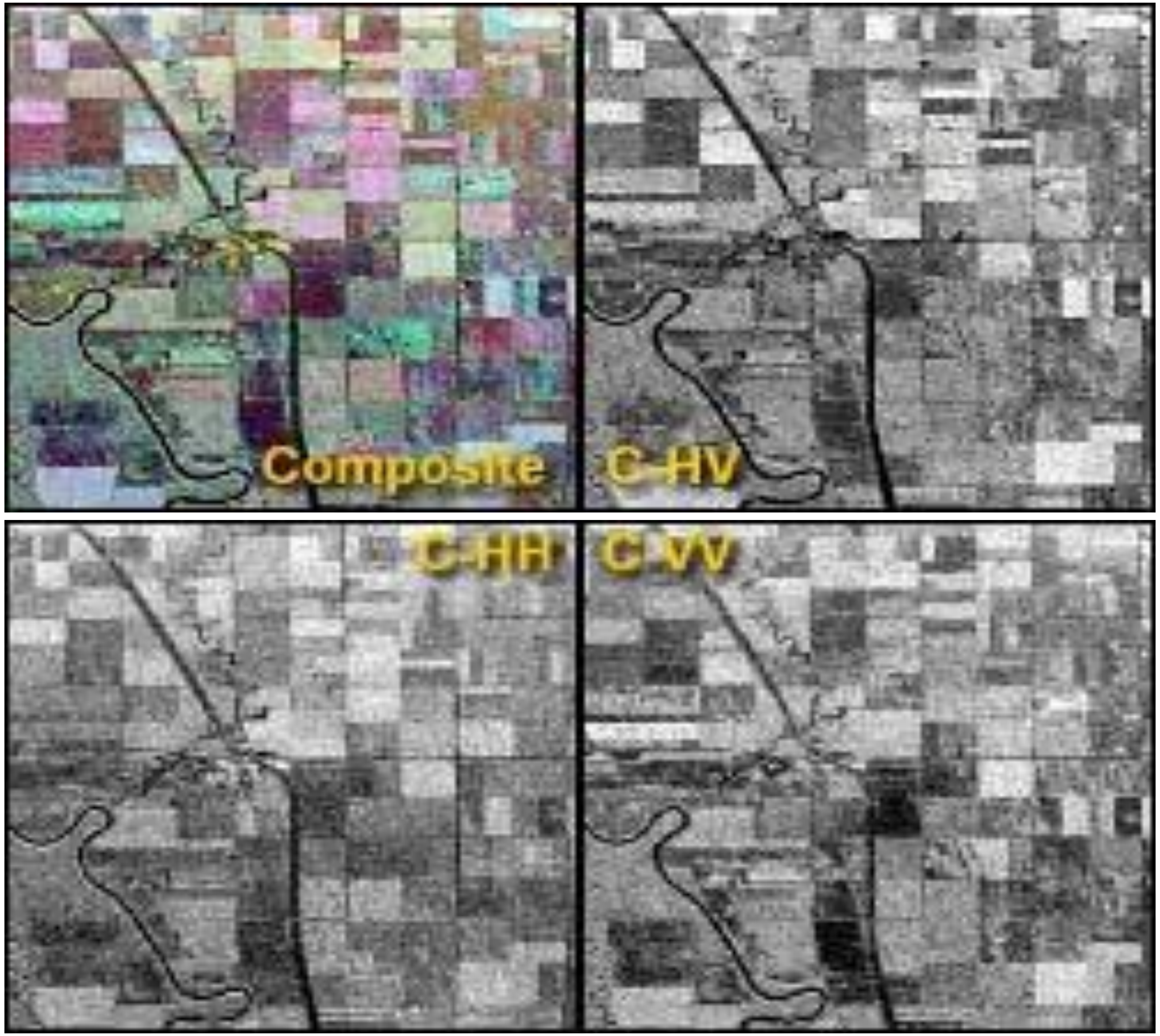
HH - for horizontal transmit and horizontal receive.

VV - for vertical transmit and vertical receive.

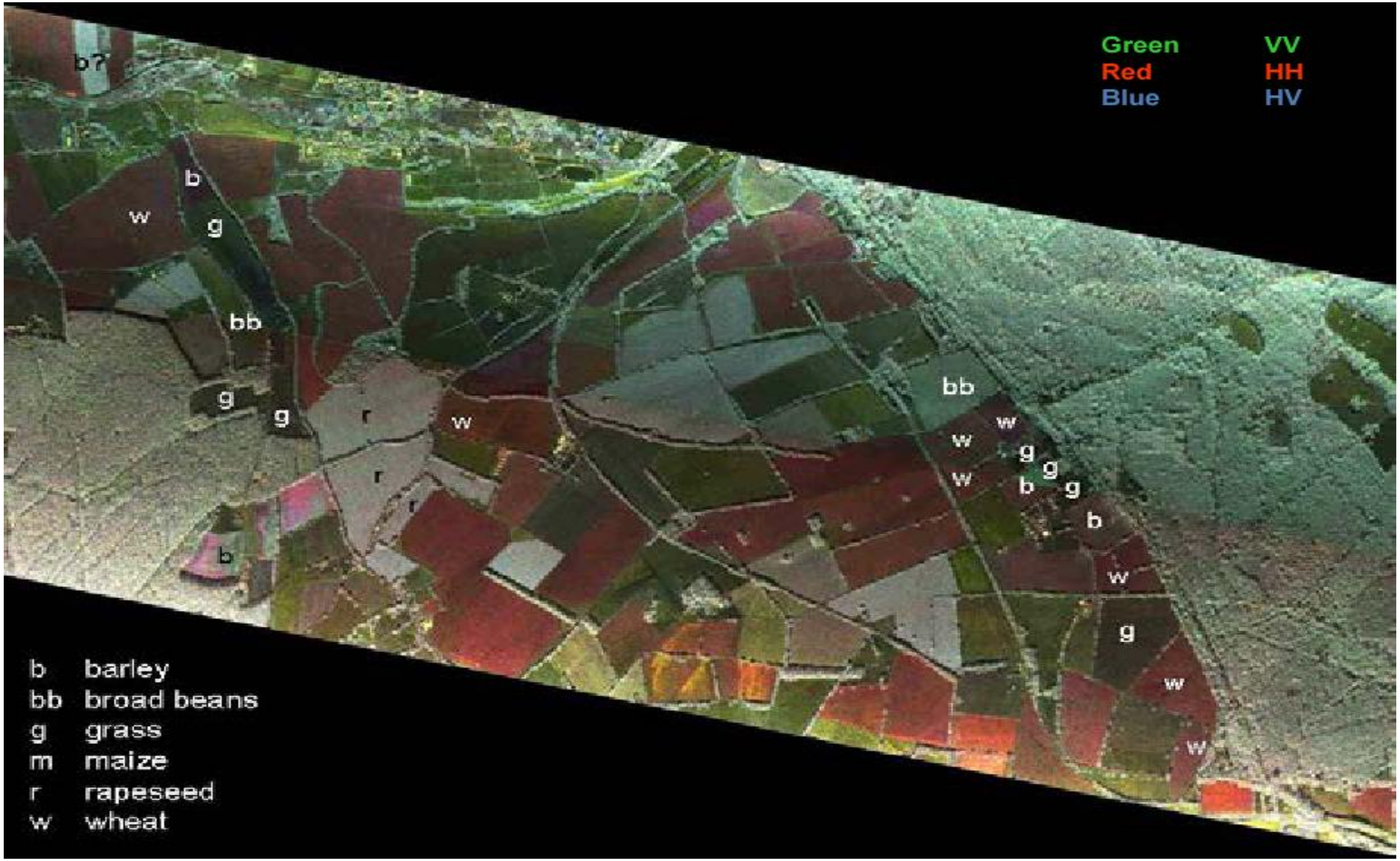
Cross-polarized:

HV - for horizontal transmit and vertical receive.

VH - for vertical transmit and horizontal receive.



Radar Polarization X-band multi-polarimetric SAR colour composite



courtesy of Airbus Space and Defense

NovaSAR

2018+

Swath 55 – 750 km
Orbit Alt 580 km (sun-sync)
Near equatorial orbit

S-band SAR: 10 cm (3.2 GHz)
Full quad polarisation,
Look angles 16 - 73°
Spatial res 20 – 30 m

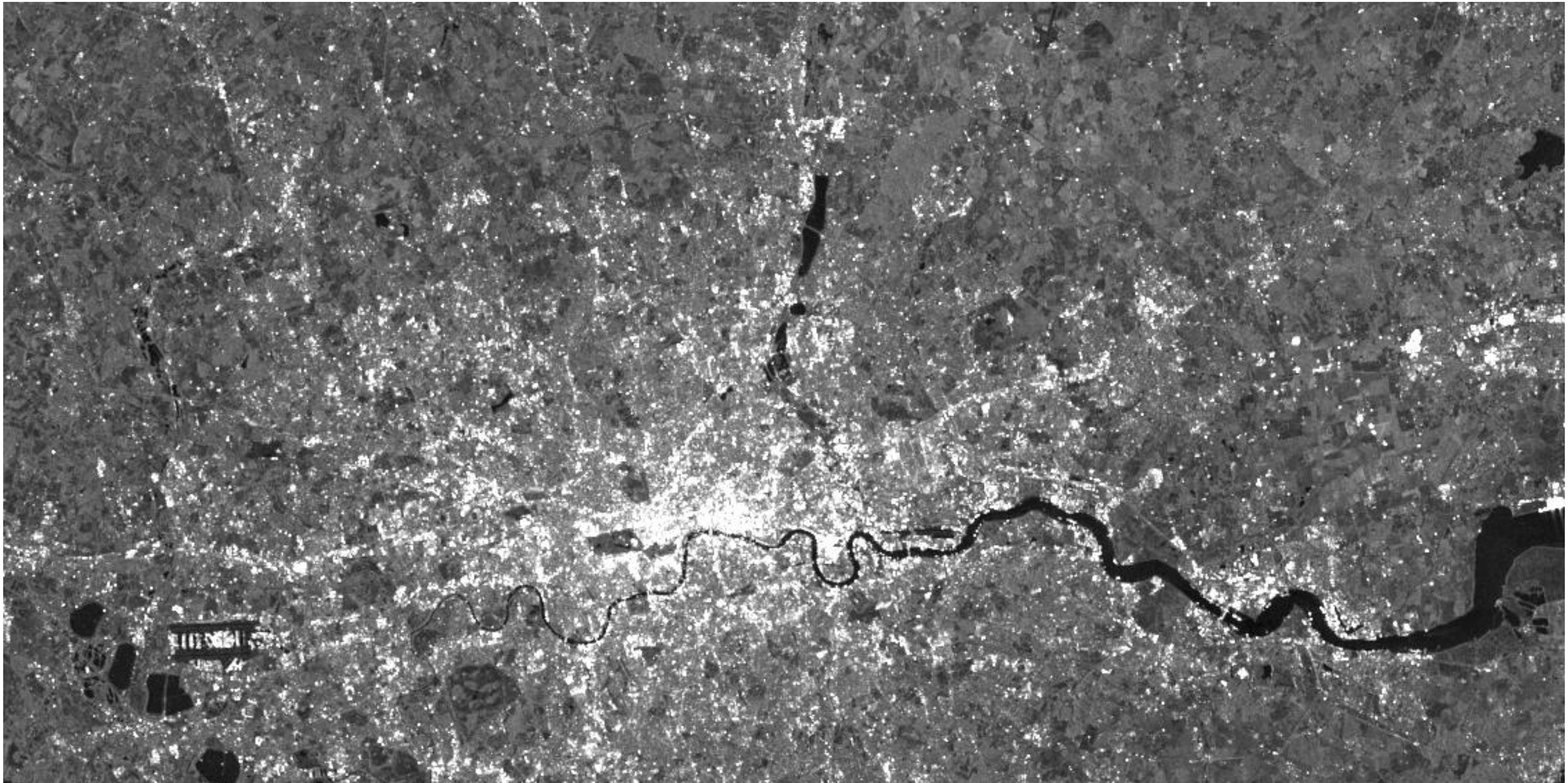
Ship monitoring (commercial)
Modes: ScanSAR. Maritime, Stripmap & ScanSAR Wide

SAR satellite bands and the general characteristics of their associated datasets

Band	Wavelength (cm)	Relative penetration	Typical Spatial Resolution (m)	Geolocation precisions (m)	Measurement precisions (mm)	Footprint (km)
X	3.8 – 2.4	Low	High (1-3)	1	High (2 - 3)	From 4 x 4 to 30 x 50
C	7.5 – 3.8	Medium	Medium (5-30)	5 - 10	Medium (4 - 5)	From 20 x 20 to 250 x 170
S	7.5 - 15	Medium	Medium (5-30	5 - 10	Medium (4 - 5)	20 - 400
L	30 – 15	High	Low (30-40)	5 - 40	Low (10 - 20)	From 25 x 25 to 350 x 350
P	30 - 100	High	Low (50 - 200)	2 - 4	Medium to high (1 - 5)	10 -20

5.3 Applications in geoscience and environmental fields

First Sentinel 1A image of London



Flood monitoring, mapping and analysis

Spaceborne SAR can provide excellent views of the flood, because of:

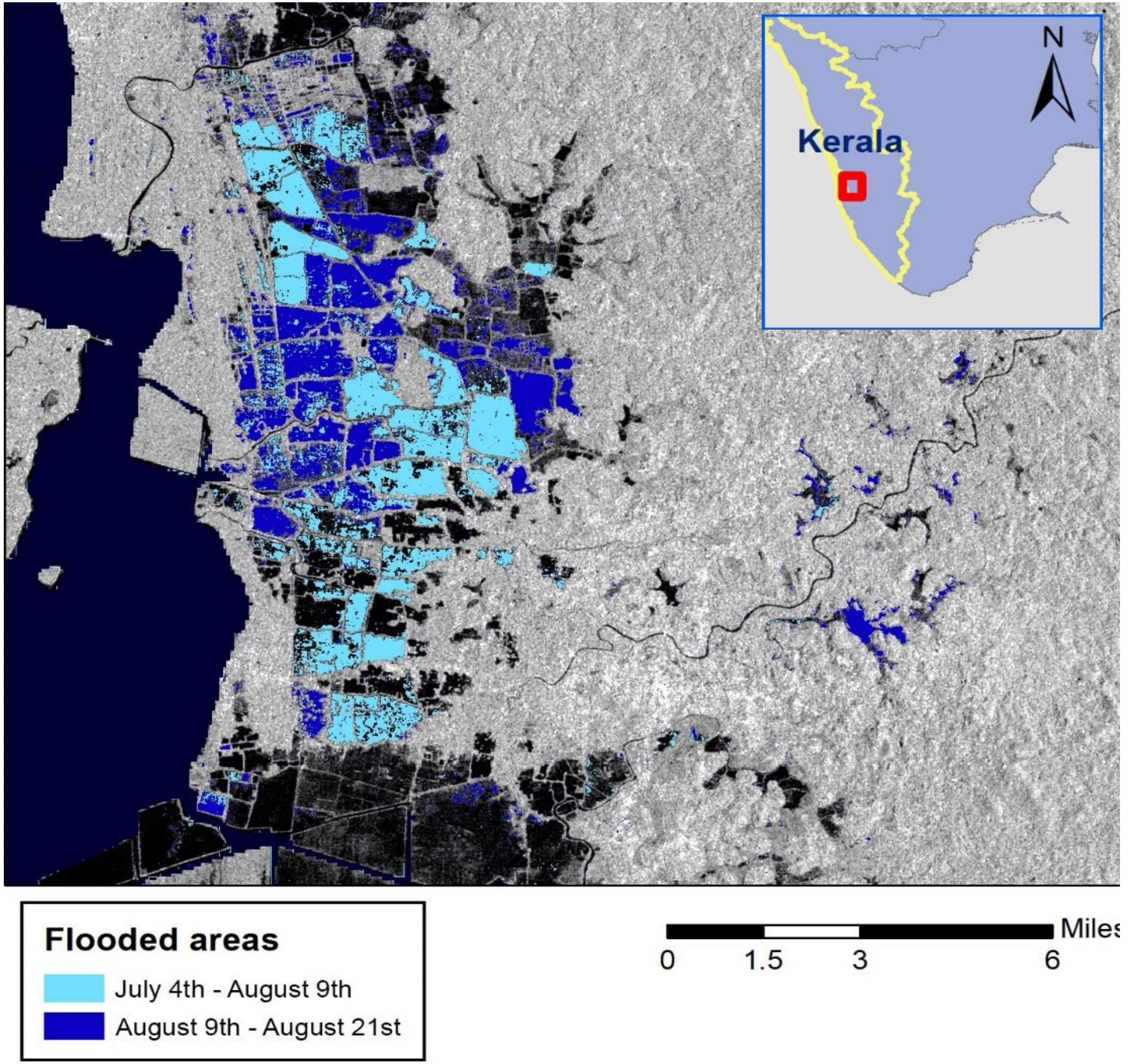
- **day/night-all-weather imaging**
- **sensitivity to the land/water differences**
- **regular, high temporal frequency imaging**

Here, Kerala, India with flood analysis performed between July 4th and August 9th, and between August 9th and August 21st.

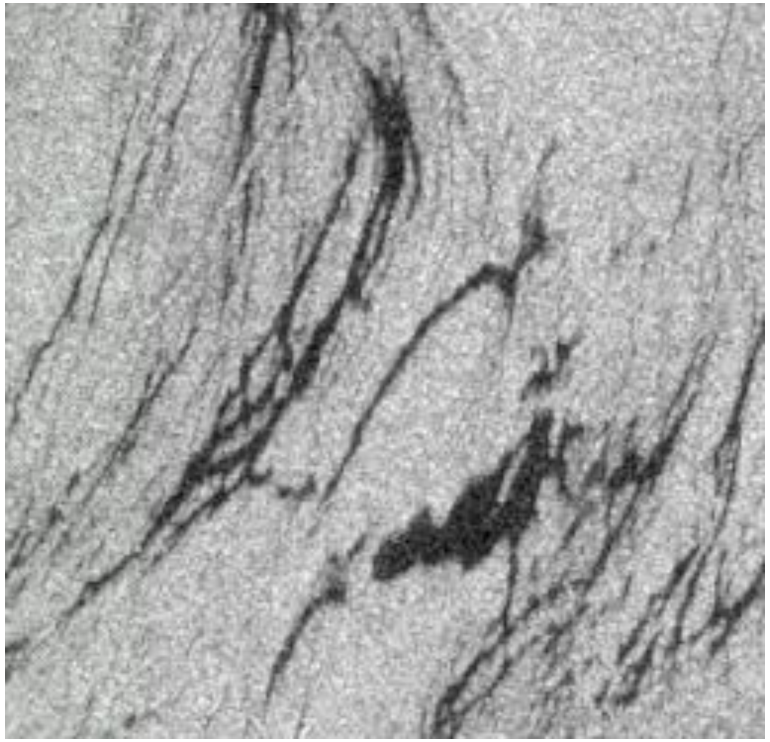
This portion of Kerala alone, 29,426 hectares (72,713 acres or over 113 square miles) of land, became flooded between August 9th and August 21st.

The black areas were already covered in water before the floods

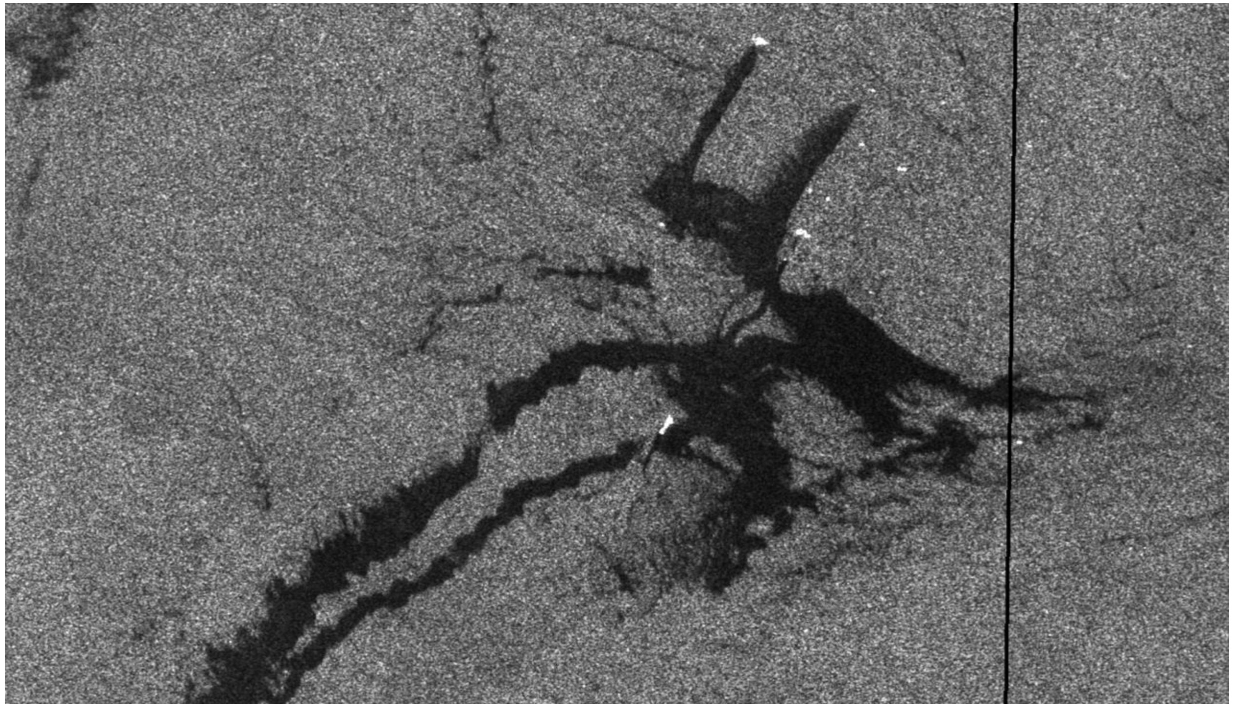
The image also shows river channels and agricultural fields that are flooded.



Oil slicks and seeps detection



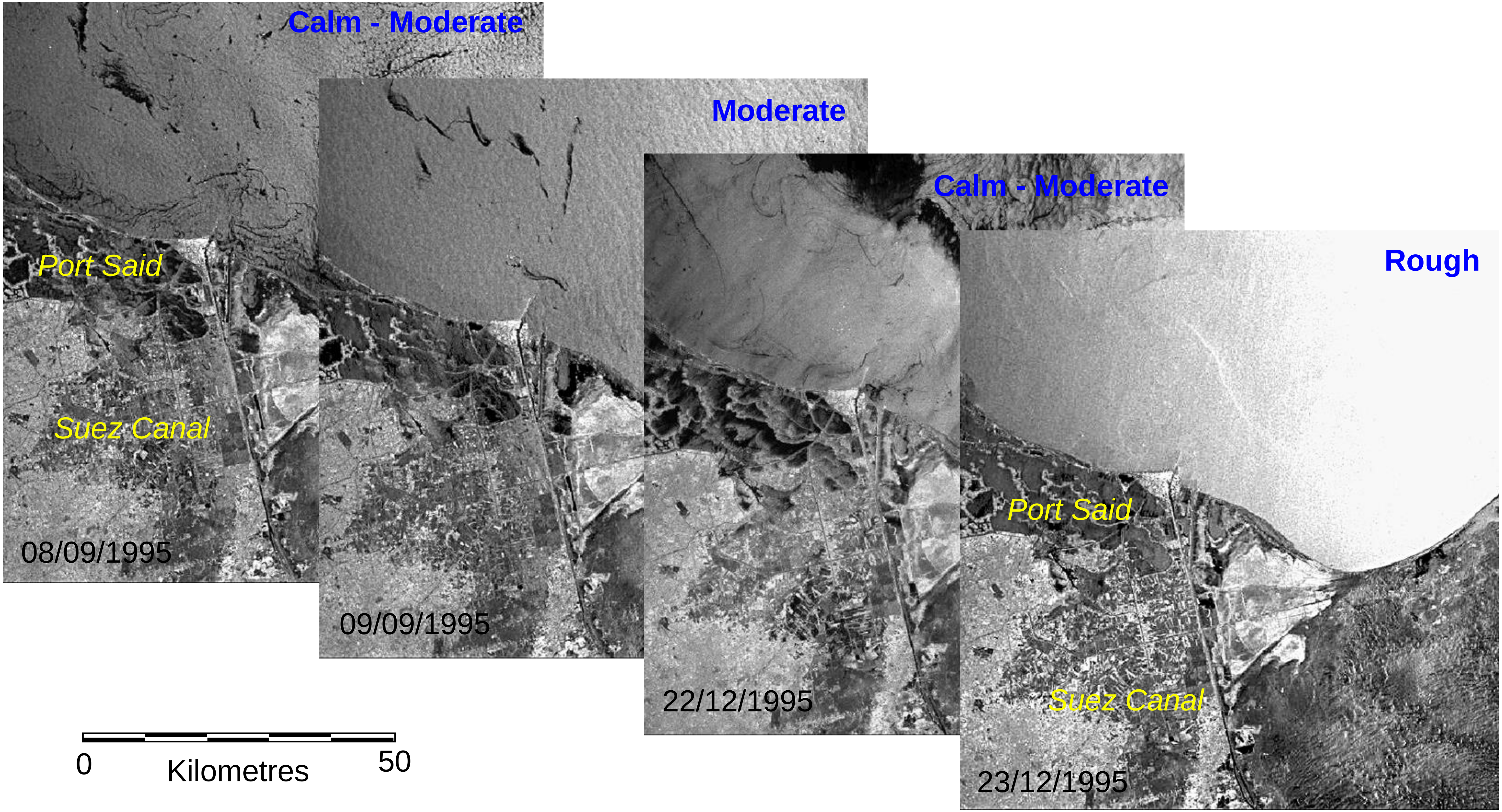
- Oil slicks appear as dark features because the oil smooths out the small waves by increased viscosity.
- On a smooth sea surface, most of the SAR signal is specularly reflected away from the antenna, causing dark appearance – so oil is invisible – e.g. if wind speed is very low, the sea surface is smooth everywhere and again
- In strong wind, the sea surface will be rough (whether oil slicks or not) and wind speeds of <8-9 m/s are required for reliable detection, and detection is also prevented



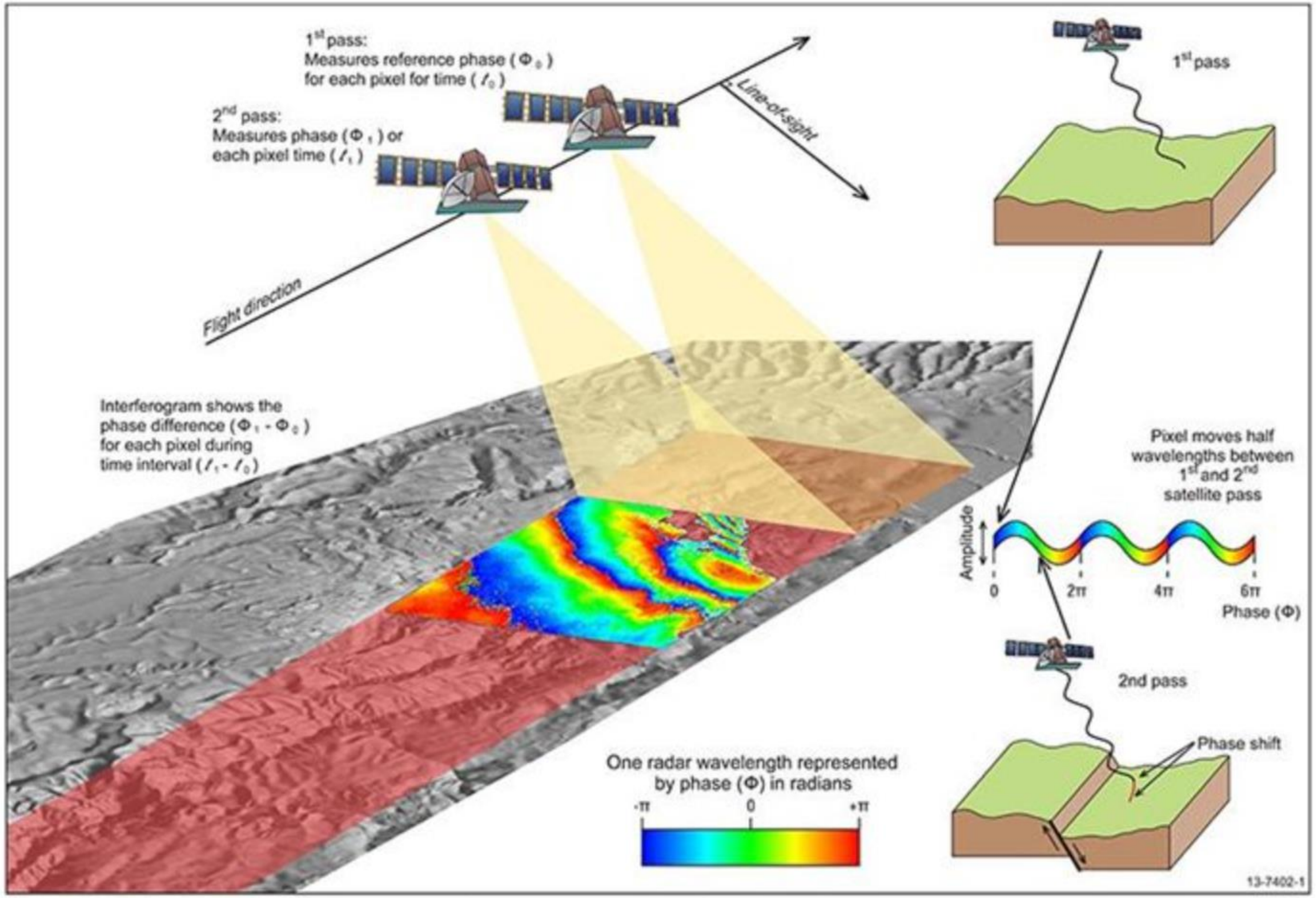
- Oil slicks move with wind, current and can remain attached to the point source of the vessel causing them
- Oil seeps have a point source which does not move, and is not associated with a man-made object

Effects of wind on sea surface roughness

(Nile Delta, ERS-1 SAR)



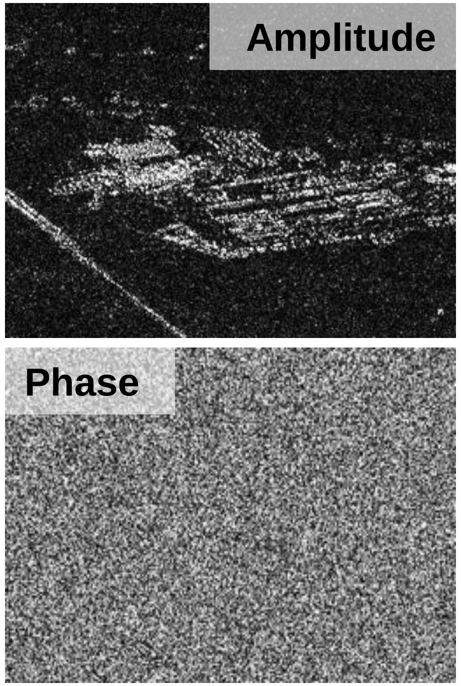
Measuring cm- and mm-scale ground movements from space: SAR Interferometry (InSAR) & Time-series InSAR



Very active area of research & development and, increasingly, operational use in industry

How InSAR works – basic InSAR for elevation extraction

(InSAR = Interferometric Synthetic Aperture Radar)



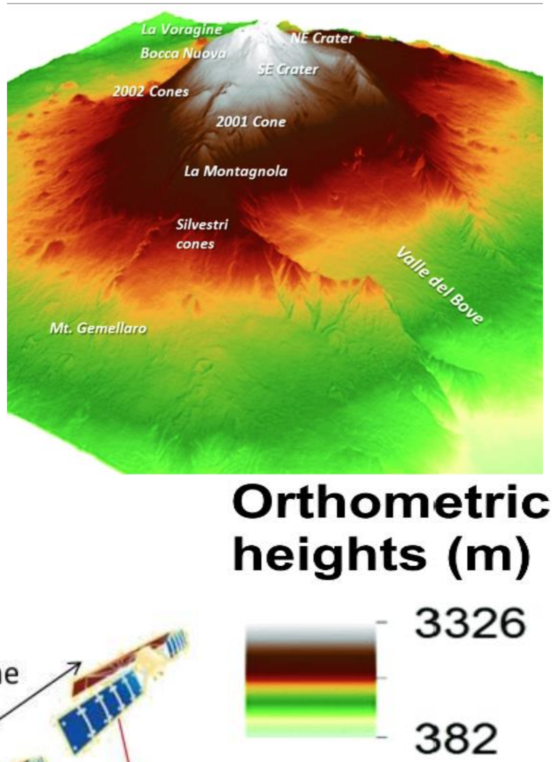
SAR ***interferogram*** *or* 'map' of the ***phase difference*** (ϕ) between the two coherent Single Look Complex images: $\phi = \varphi_1 - \varphi_2$

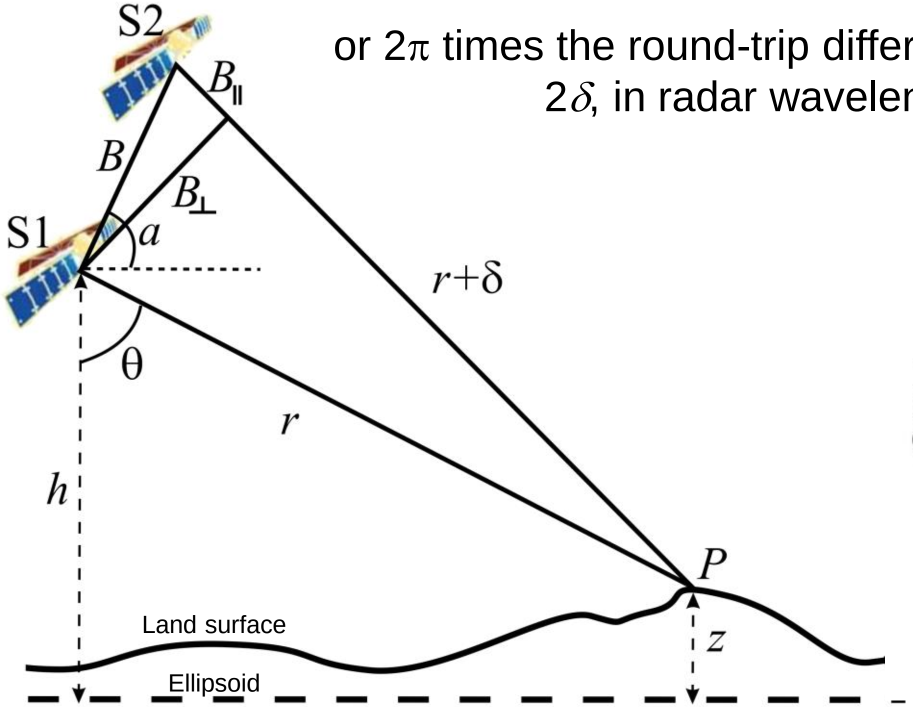
Position P observed twice from S1 & S2, from distance r (slant range) and from $r + \delta$.

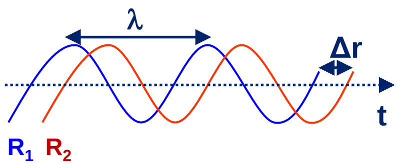
Distance difference between returned radar signals for a round-trip is 2δ, and the measured phase difference ϕ (interferogram) is:

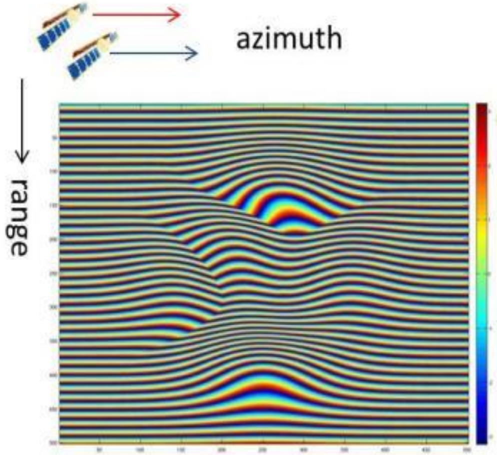
$$\phi = \frac{4\pi}{\lambda}\delta$$

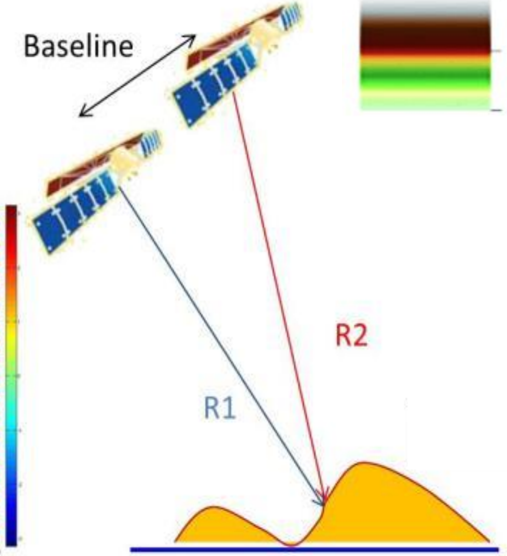
or 2π times the round-trip difference, 2δ, in radar wavelength λ



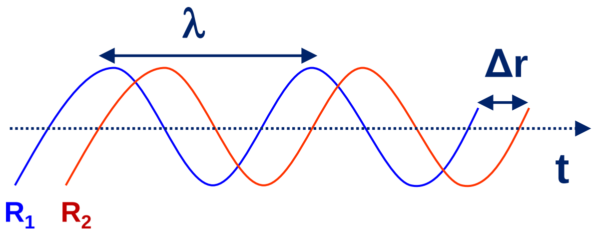




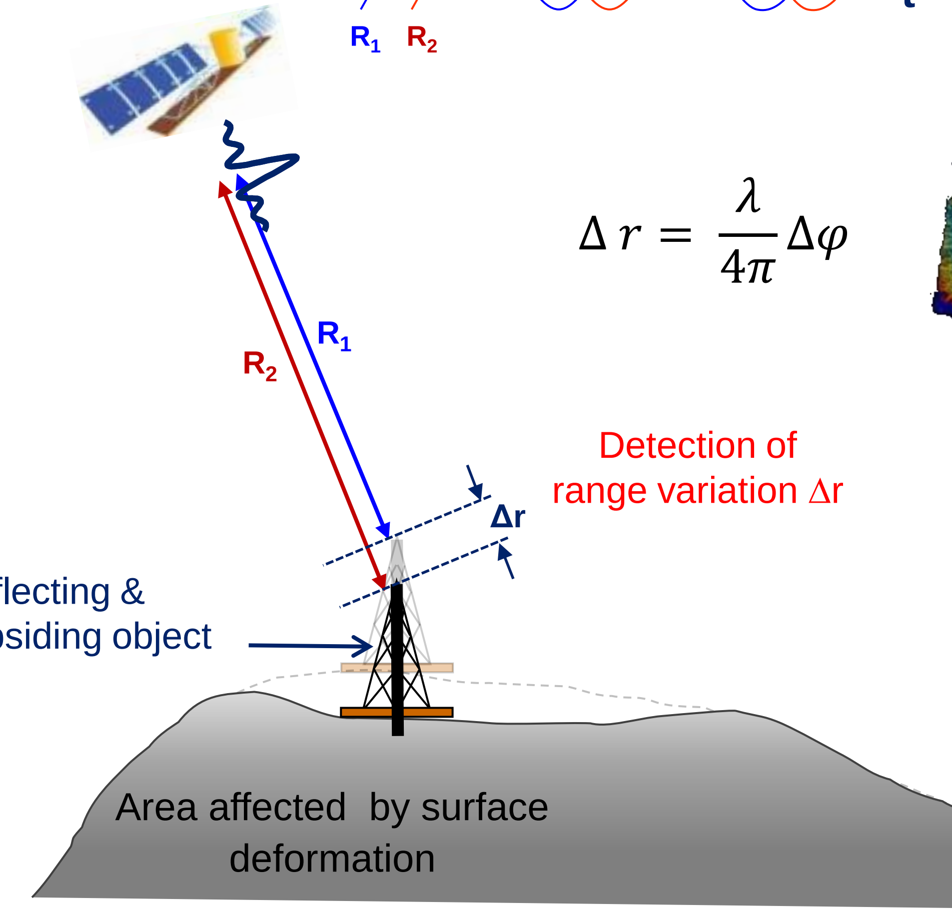




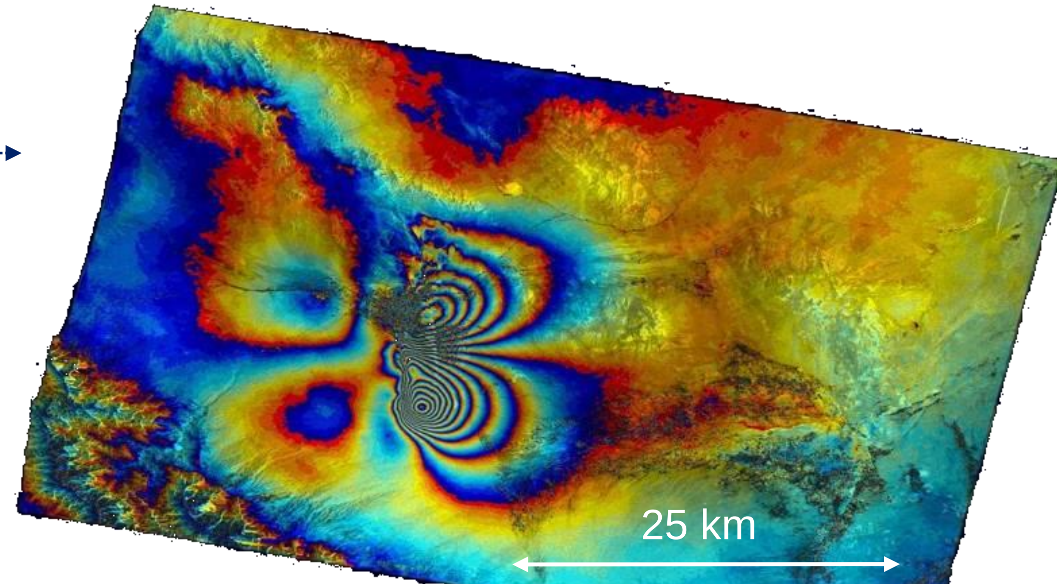
And for centimetre-scale change detection using Differential InSAR (DInSAR)



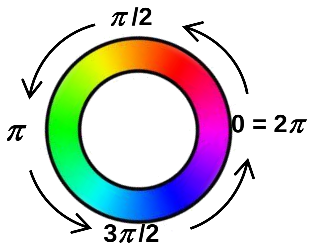
$$\Delta r = \frac{\lambda}{4\pi}\Delta\varphi$$

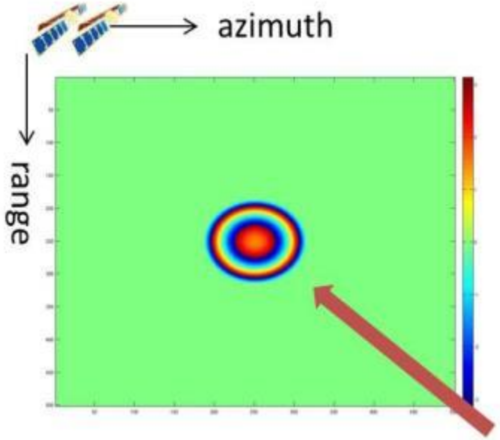


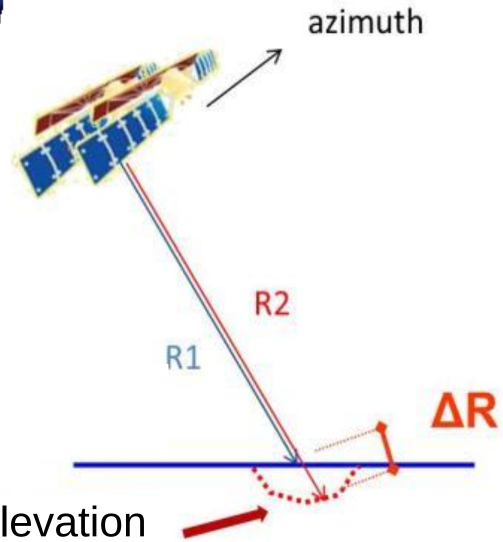
M. Basillico, TRE Altamira



BAM Earthquake, Iran (Dec 26, 2003), Mw 6.6
Co-seismic interferogram (LoS direction)





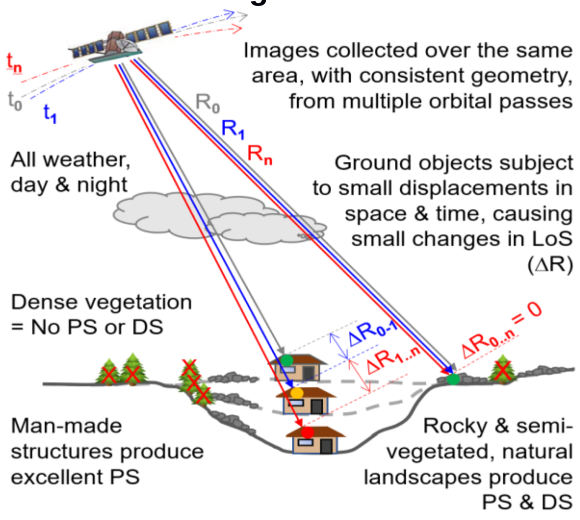


Elevation change

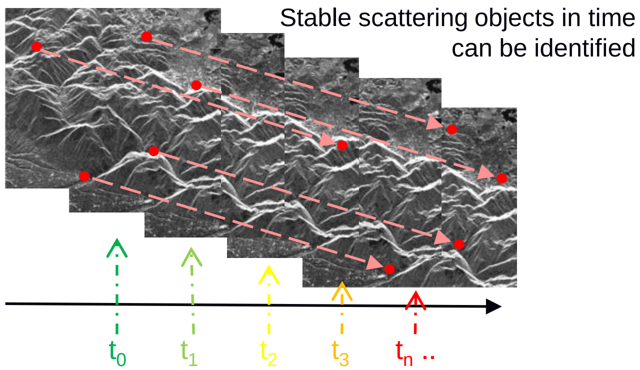
Time-series InSAR

A graphical illustration of one method

1. Persistently scattering objects can be tracked by detecting consistent increments of ΔR (Range of Line of SIght) through a time-series of images

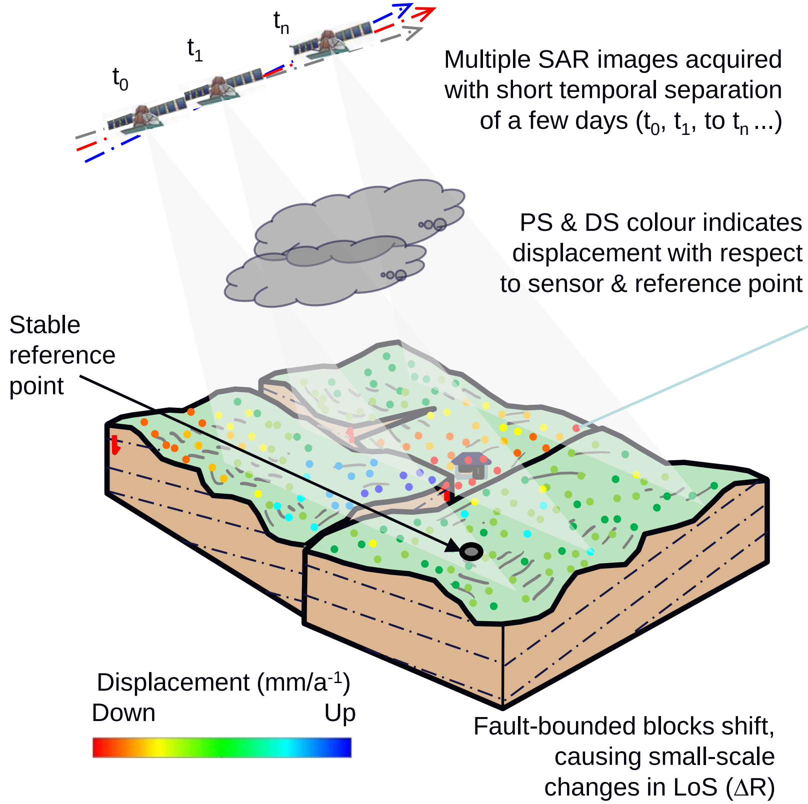


2. Stack of 20+ SAR images with short temporal separation (of a few days)



Stable points in the time-series displacement model become candidate persistent scatterers, in 3. Others that depart from this model are displacing and can be tracked, as shown in 4.

3. Dataset of measurement points is generated and colour-coded to indicated their state of stability or of motion

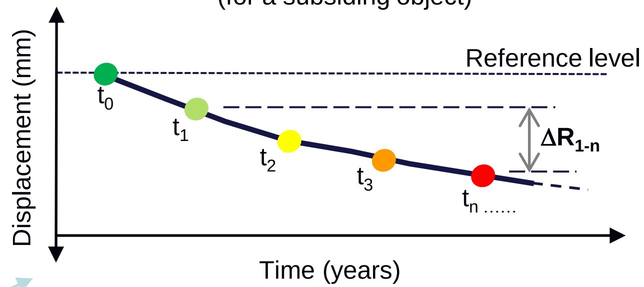


Time-series InSAR

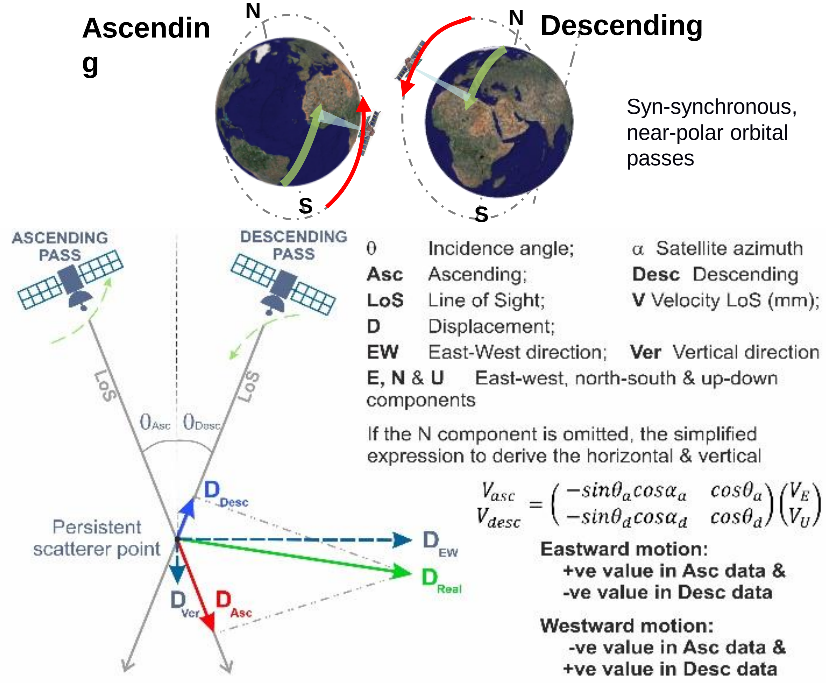
Conceptual cartoon illustration of how time-series InSAR can be used to provide millimetre scale Line of Sight (LoS) measurements of ground motion, in urban and rural environments, from multiple satellite images, over large areas, without the need for in-situ instrumentation, and that they can be decomposed into 2D (vertical & horizontal components of motion from ascending & descending orbital passes. Measurements can be correlated between SAR images and precision improved by integration with GNSS data.

4. Each persistently scattering point (PS & DS) provides a time-series of displacement

(for a subsiding object)



5. SAR image stacks from descending & ascending orbital passes allow decomposition of 2D motion



Time-series PS InSAR: to monitor small scale motions

London PS ground velocities between 2011 and 2017 is shown.

Red = downward movement >2 mm/yr

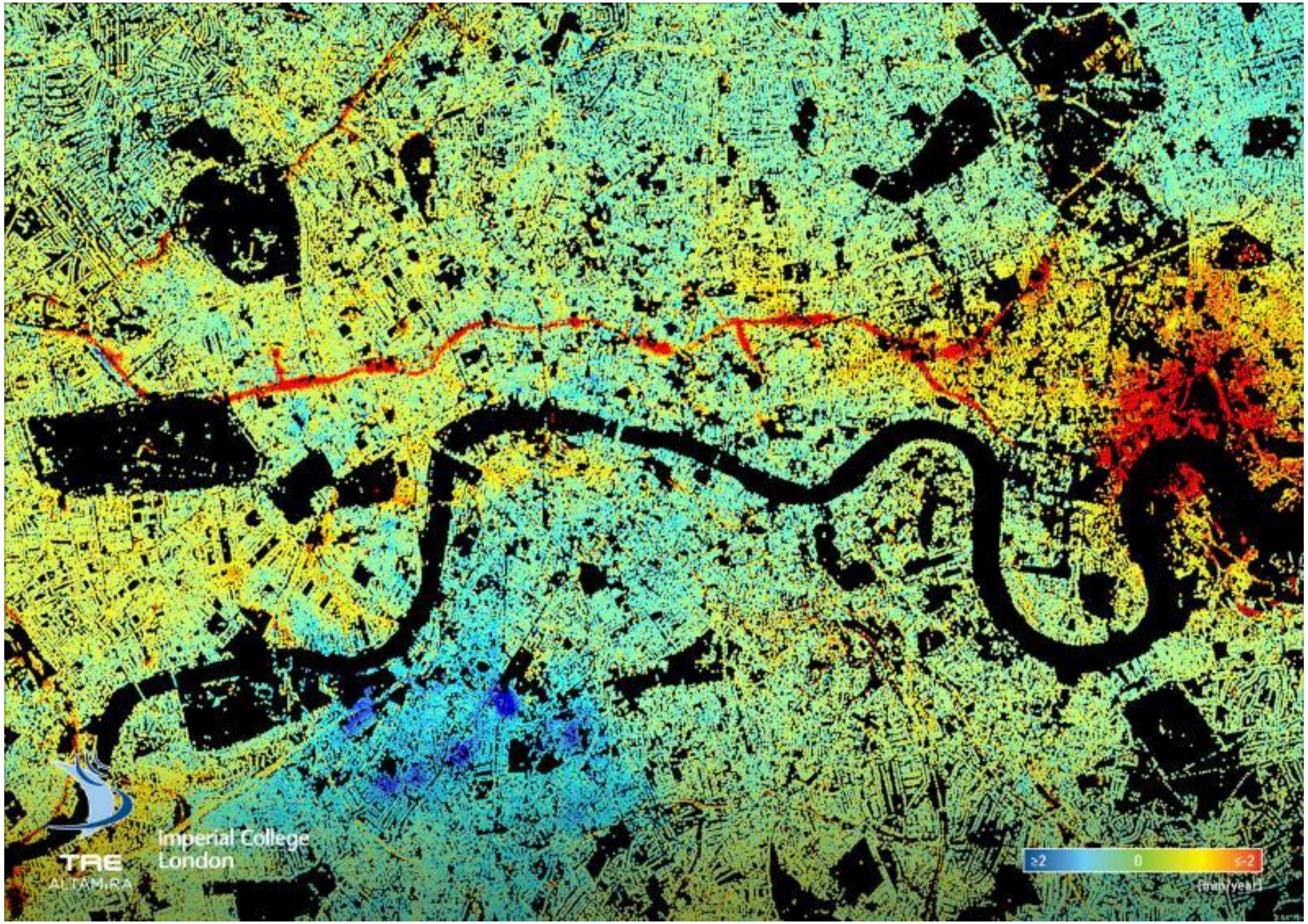
Blue = upward movement >2 mm/yr

Tunnelling and station construction for *Crossrail.*

Groundwater extraction at stations near Canary Wharf.

Ground rebounding (heave) after de-watering has stopped at the *Northern Line Extension* project

These results demonstrate the value of InSAR in urban areas, and for monitoring engineering projects.



Ground motion across London, from Bischoff et al., 2019

Elizabeth Line (Crossrail) Construction

2011-2017 TerraSAR-X SqueeSAR™ data

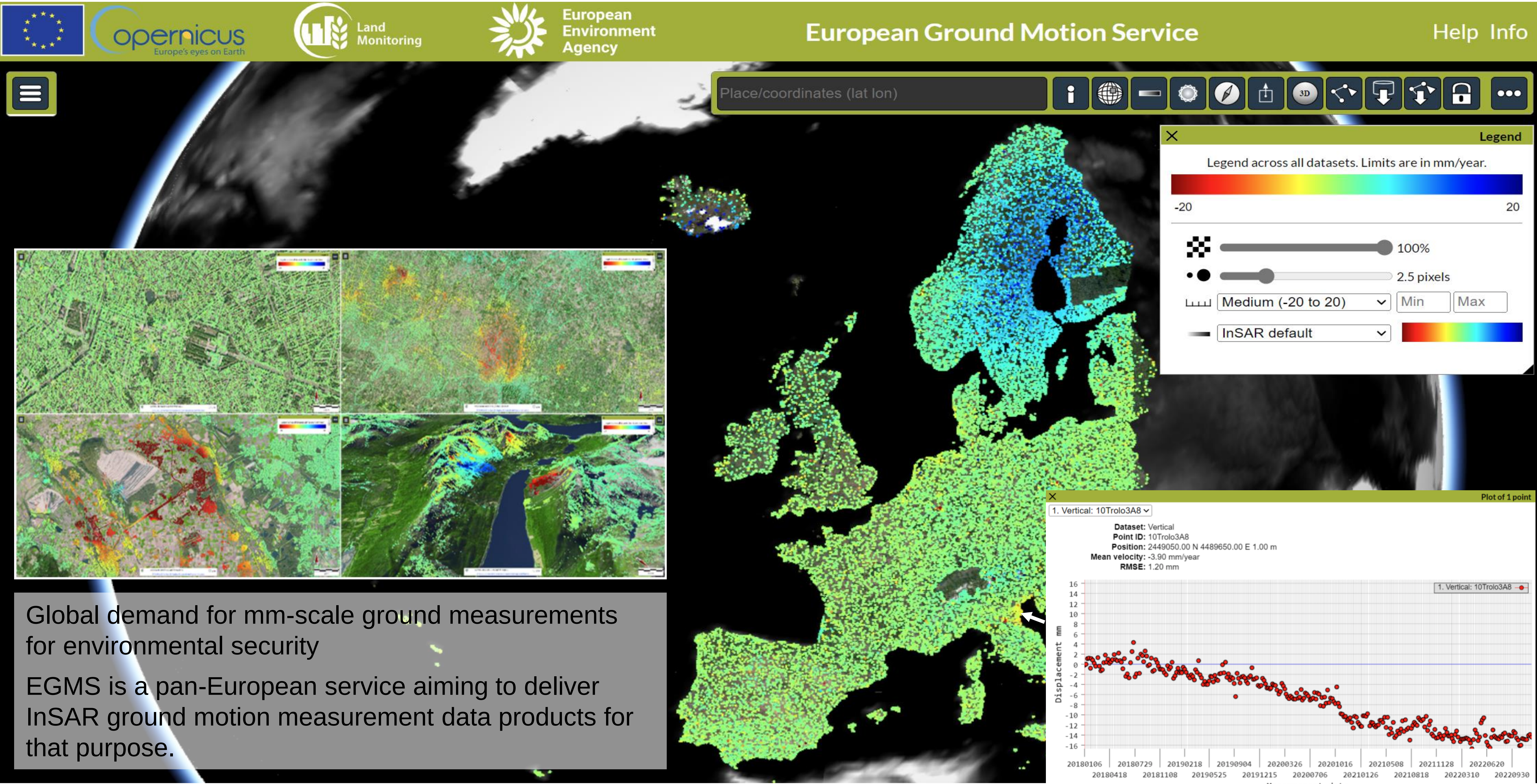
Total displacement with respect to 1st May 2011 (mm)

-20 0 20

Christine Bischoff PhD

Global demand for InSAR data and services

https://egms.land.copernicus.eu/



Global demand for mm-scale ground measurements for environmental security

EGMS is a pan-European service aiming to deliver InSAR ground motion measurement data products for that purpose.