EART97051 Environmental Data (EDSML) - Earth Observation & Remote Sensing

5 Introduction to Radar Remote Sensing

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Lesson plan

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

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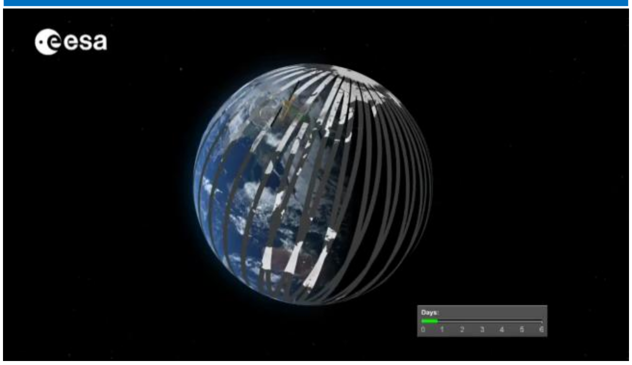
5. Radar Remote Sensing

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



From Sentinel-1 and many others

Animation credit: European Space Agency

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- **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**
- **All weather and any-time operation**, means imaging radar is widely used in EO remote sensing

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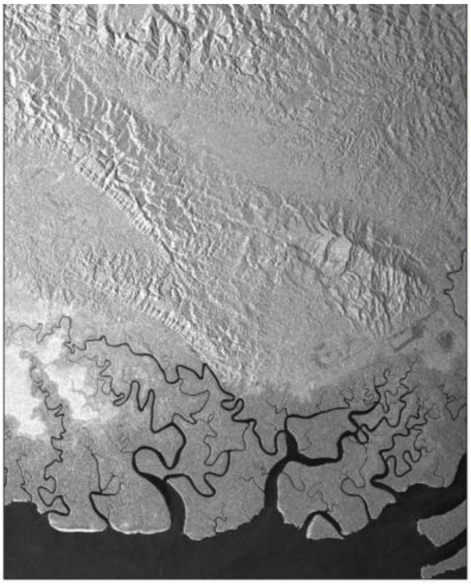
Advantages & disadvantages of radar


Radar


Optical

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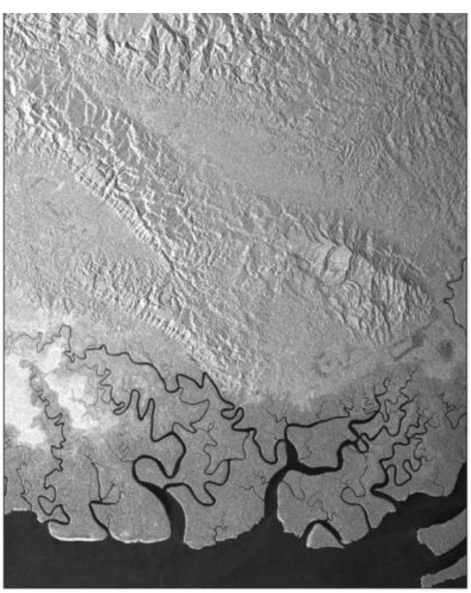
Advantages & disadvantages of radar


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 effects (difficulty in visual interpretation)
3. Geometric distortions
4. Complex effect of surface roughness

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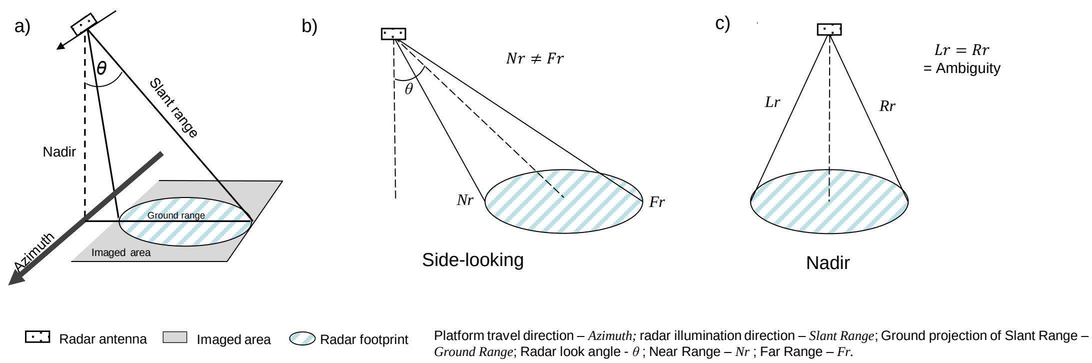
5.1 Imaging Radar System

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.



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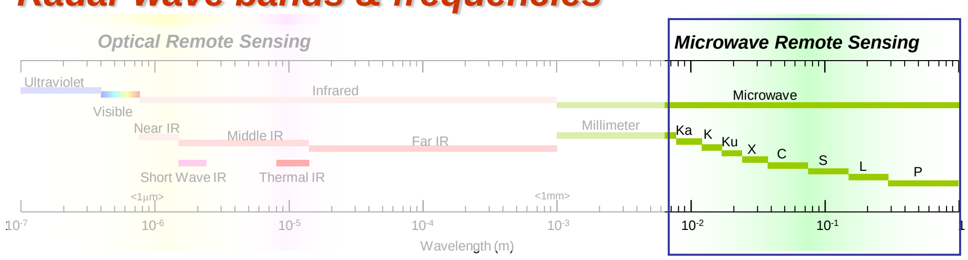
Radar wave bands & frequencies



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.

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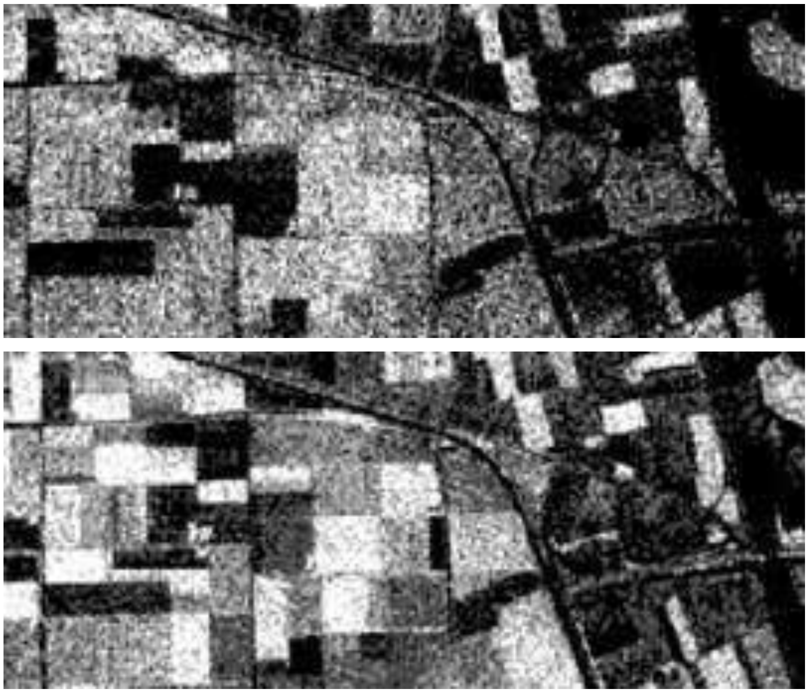

C Band

L Band

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SAR signals: amplitude

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).

The amplitude may imply a <u>complex signal</u>, including both magnitude and the <u>phase</u>.

It is used to quantify Intensity of the radar backscatter (*$I = A^2$*)

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Comparing optical and SAR images

Multi-look SAR amplitude image

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

Optical (panchromatic) image

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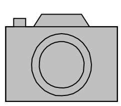
Comparing optical and SAR images



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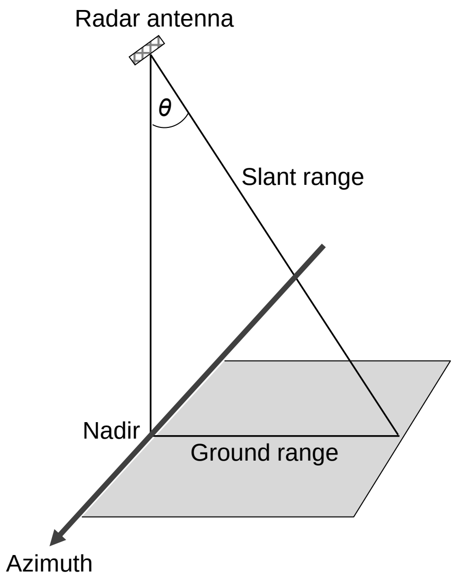
Radar imaging geometry



- 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

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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, the 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).**

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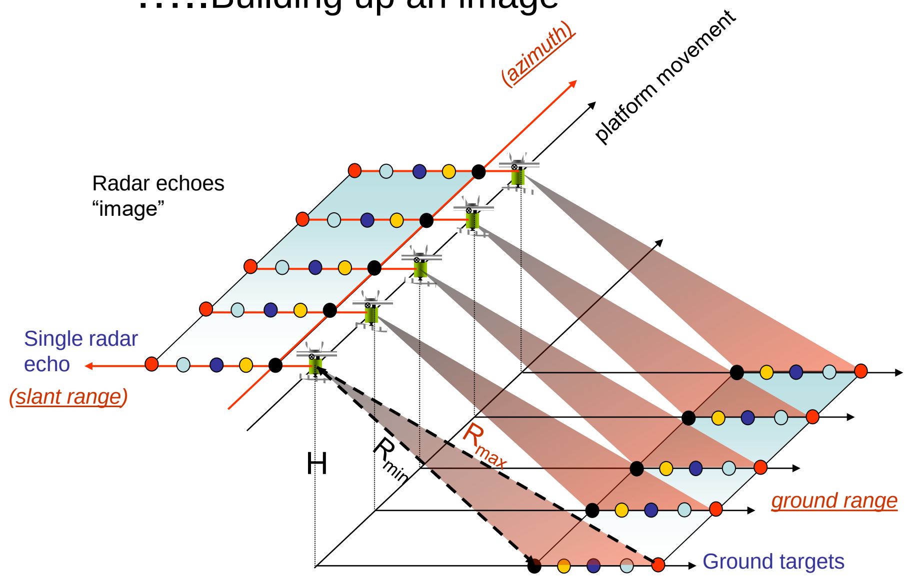
Radar acquisition schema

…..Building up an image



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b) Synthetic Aperture Radar (SAR)

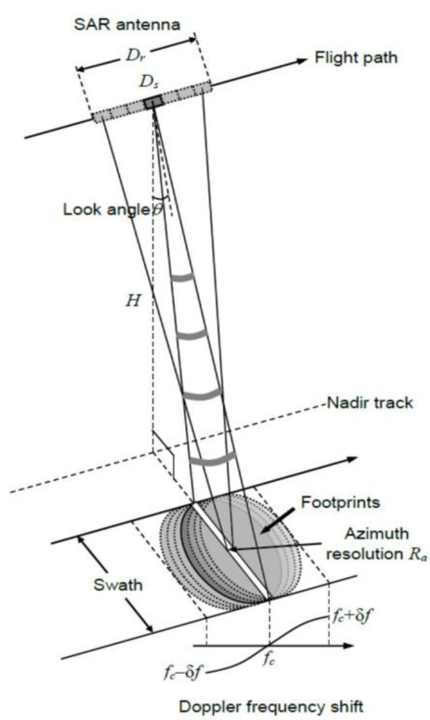
Principle of SAR:

- 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)

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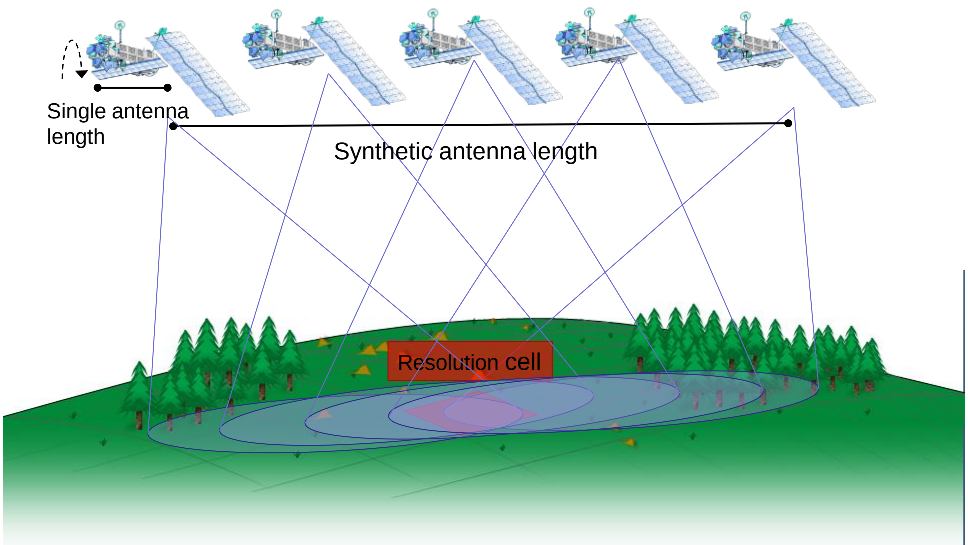
SAR image acquisition



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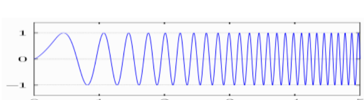
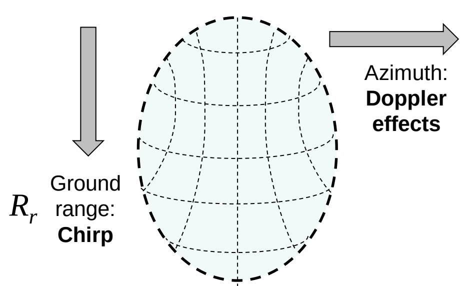
Ground range resolution of SAR (R_r)

- GR resolution is extracted from the return time of radar echo signal: far range signal returns later than near range signal. R_r is generally lower than R_a
- 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.





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

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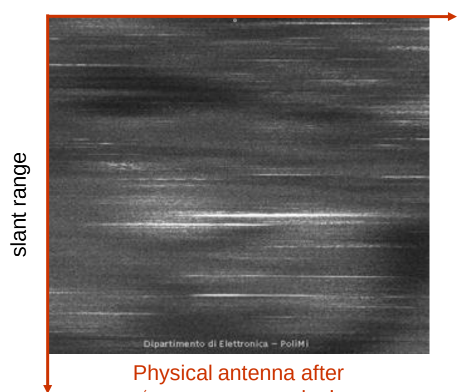
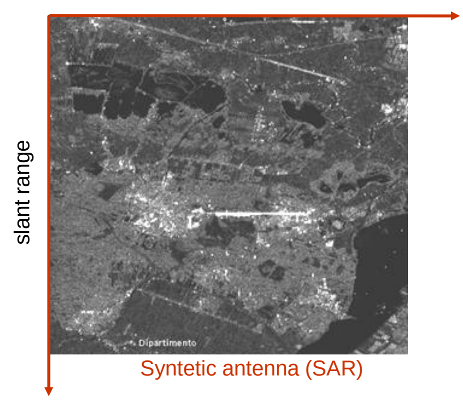
SAR images

1. In general the bigger the antenna, the better is azimuth resolution
2. For **metre-scale resolution** in the image, you would need an 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)

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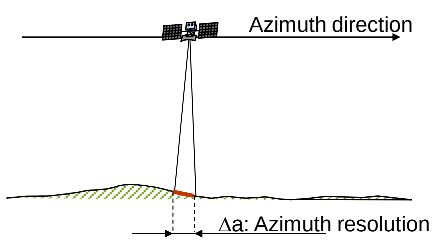
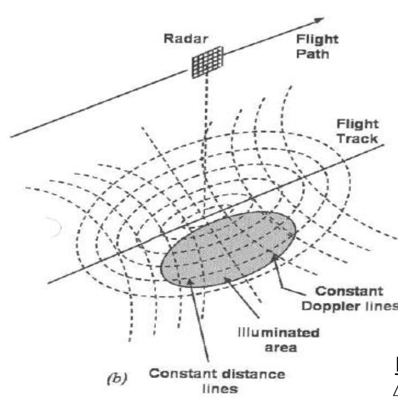
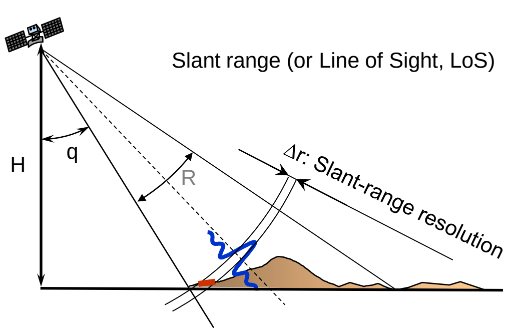
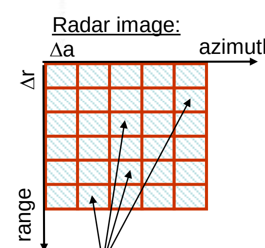
Radar resolution summary









A radar image is a pixel array, where each pixel is a singular resolution cell.

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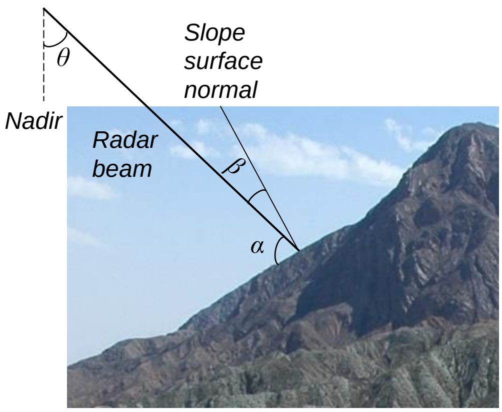
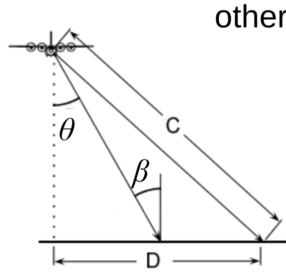
5.2 Characteristics of SAR Images

a. Distortions caused by imaging geometry

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





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

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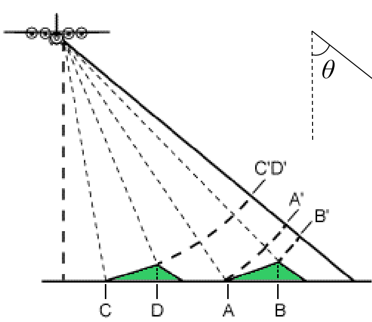
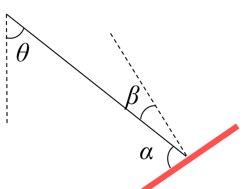
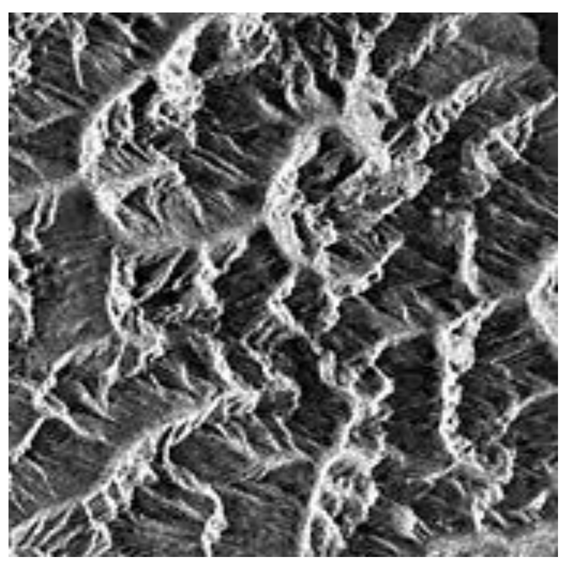
Geometric distortion: foreshortening





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)



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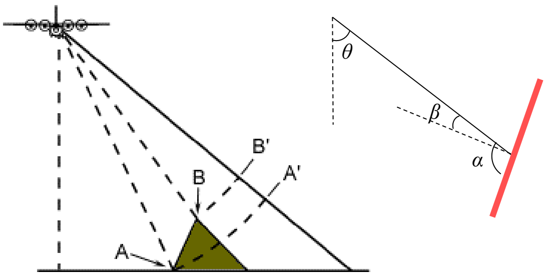
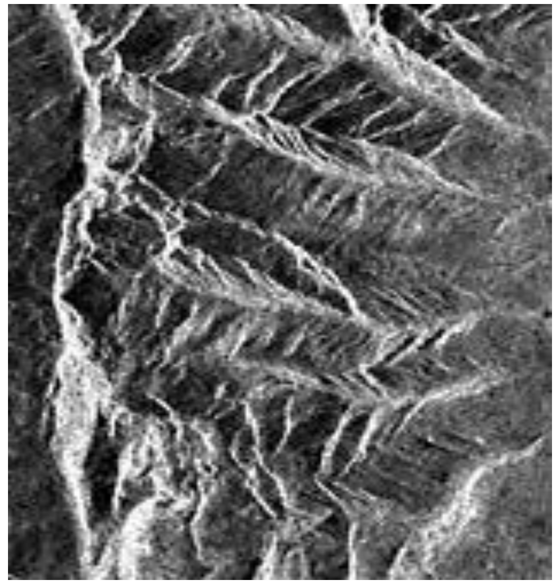
Geometric distortion: layover





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)

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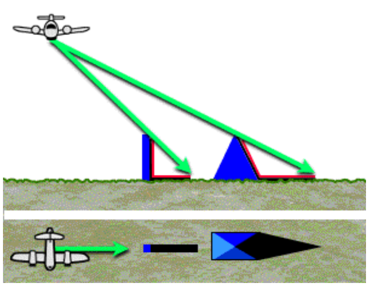
Geometric distortion: radar shadow



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)

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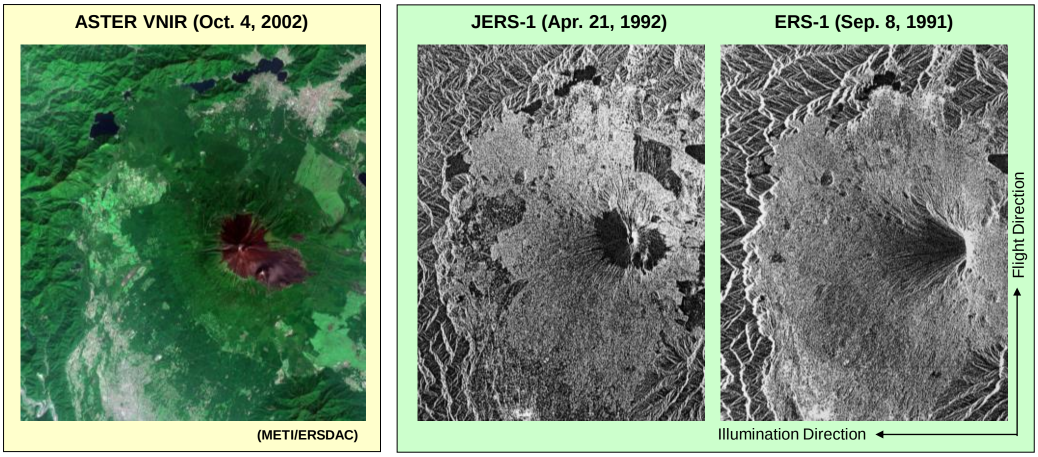
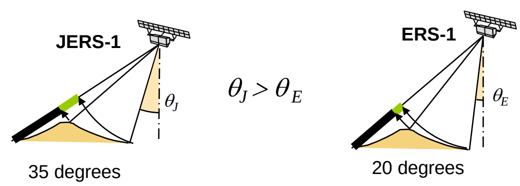
Comparison between optical sensor and SAR



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



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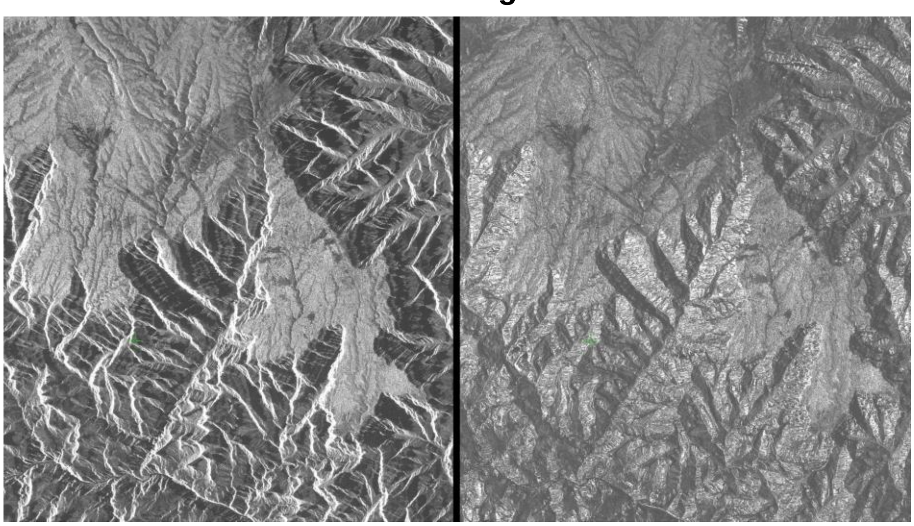
Terrain distortions can be corrected using a DEM



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.

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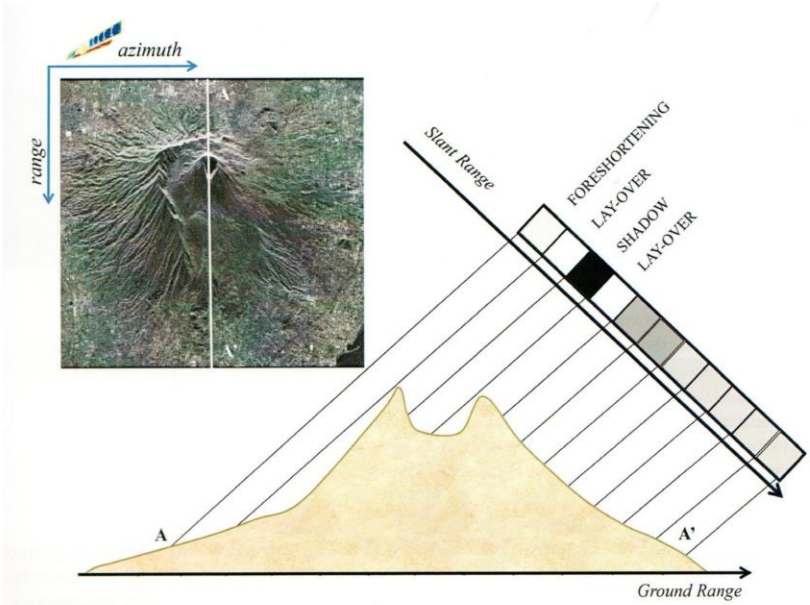
Summary of geometric distortions



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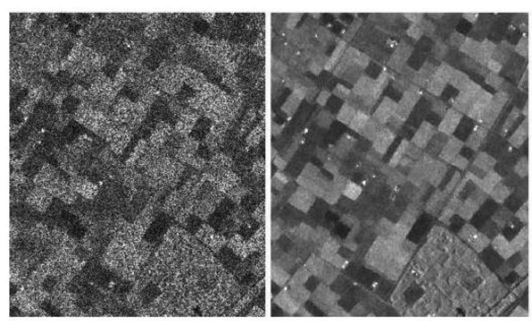
b. Interaction between radar signal and ground

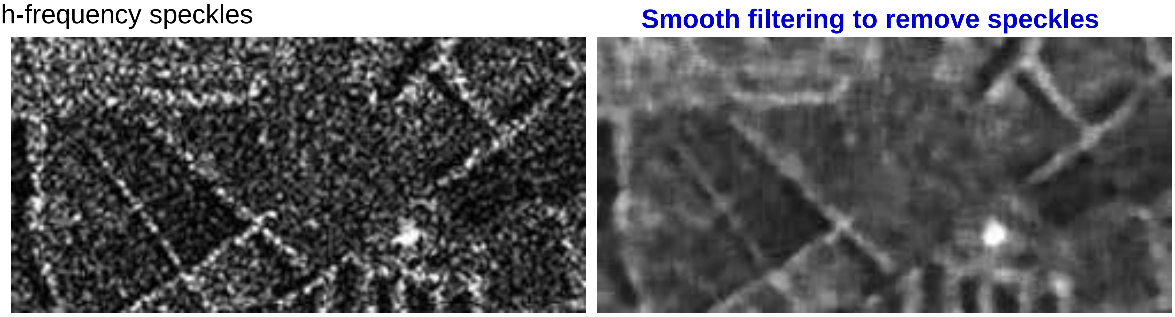
Radar Speckle

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



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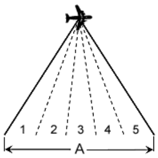
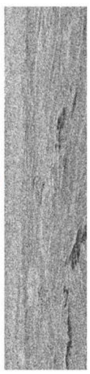
Interactions between radar signal and ground

Speckle reduction by multi-looking



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



Single Look Complex

Range Looks: 1
Azimuth Looks: 1

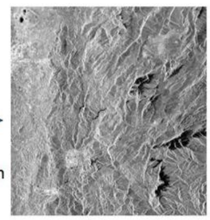
Range Spacing: 7.8 m
Azimuth Spacing: 4.0 m

Slant Range

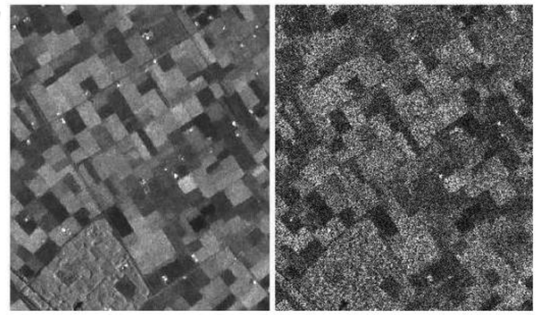
Multilooked

Range Looks: 4
Azimuth Looks: 20

Range Spacing: 31.2 m
Azimuth Spacing: 80.0 m



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 multilooked image has less noise (speckle) and approximate square pixels after being converted from slant range to ground range

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Multi-looking to reduce speckle

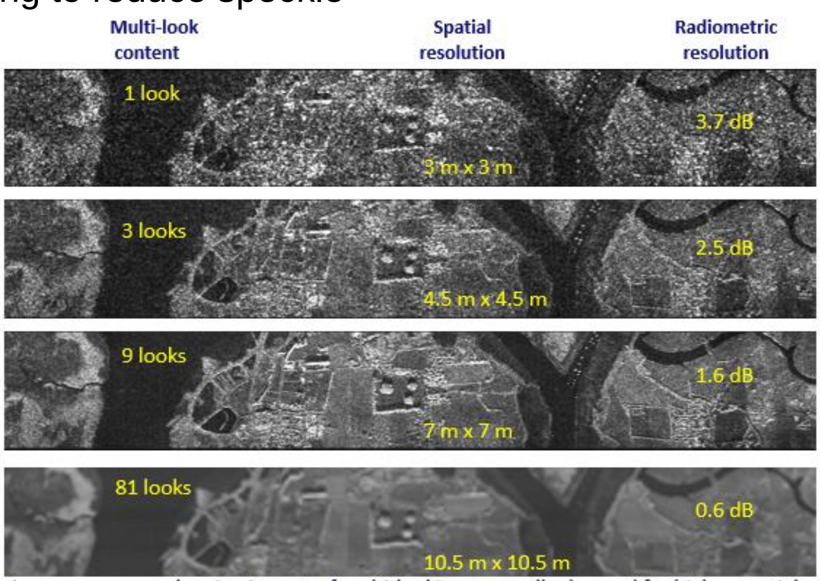

Image sequence showing impact of multi-looking; normally demand for higher spatial resolution reduces number of looks possible.
Simulation based on airborne NovaSAR-S test data. [© Airbus Defence and Space]

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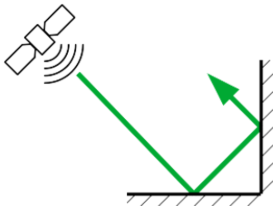
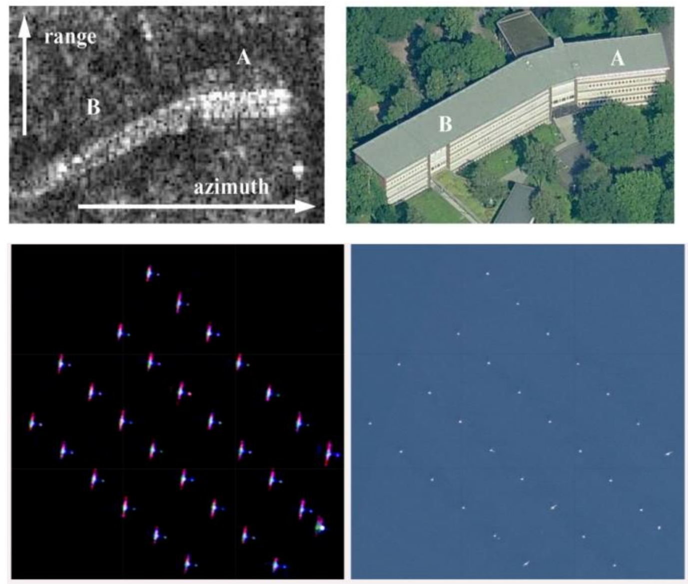
Corner reflections





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.

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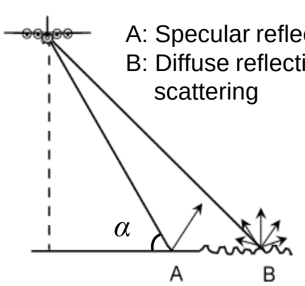
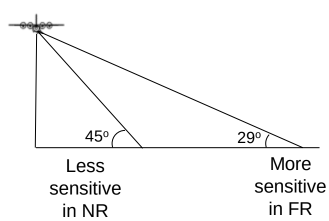
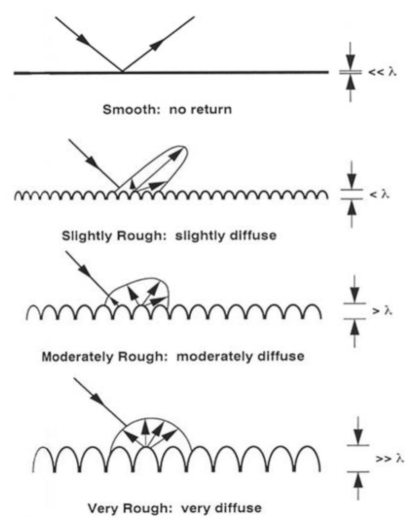
SAR Image Roughness



A: Specular reflection
B: Diffuse reflection or scattering

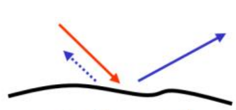




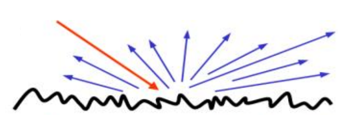
Rayleigh criterion (roughness threshold):

$$h < \frac{\lambda}{8\sin\alpha}$$

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

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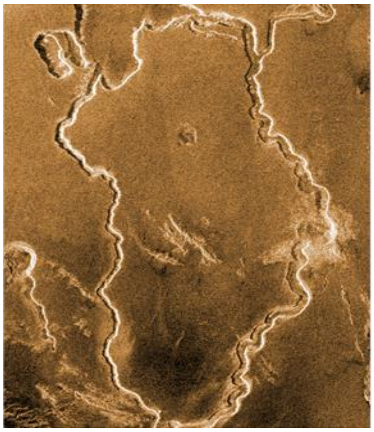
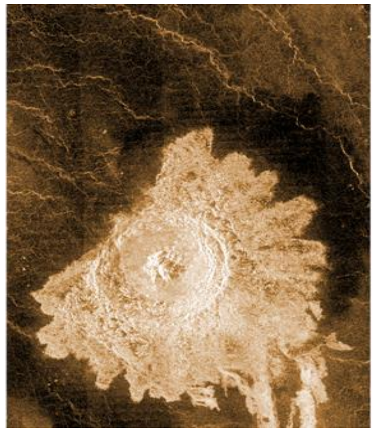
SAR sensitivity





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

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

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

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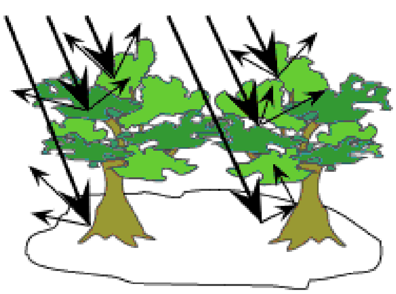
SAR penetration and volume scattering



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 with leaves and branches), or

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

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

Volume Scattering

If the radar energy manages to penetrate through the topmost surface, then volume scattering may occur

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

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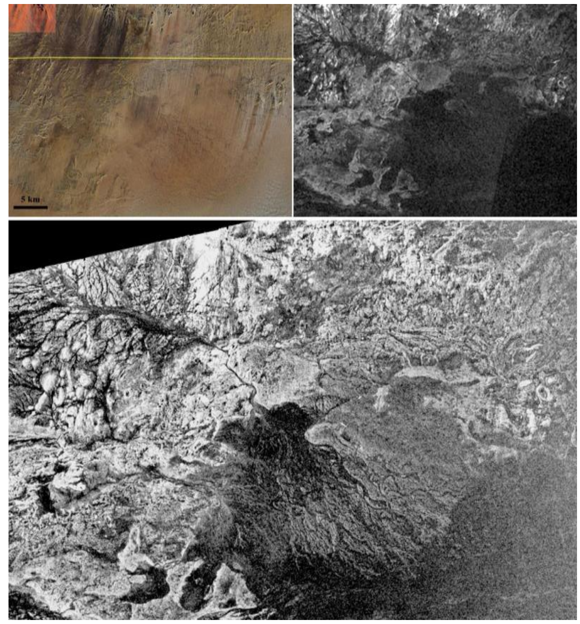
Ground penetration and sub-surface mapping

- SAR imaging can penetrate considerable depth of dry sand (and ice)
- A key parameter affecting SAR penetration depth is the **dielectric constant** - this increases dramatically with the increasing moisture in surface scattering materials and quickly reduces the SAR penetration depth to nearly zero.
- Radar wavelength is another important factor:
  - Longer wavelength enables greater penetration depth.



Landsat (top left), JERS-1 (top right) and PALSAR image (bottom) of a region located around 21˚55'N, 26˚36'E. PALSAR much better reveals paleodrainage channels in the lower part of the scene.

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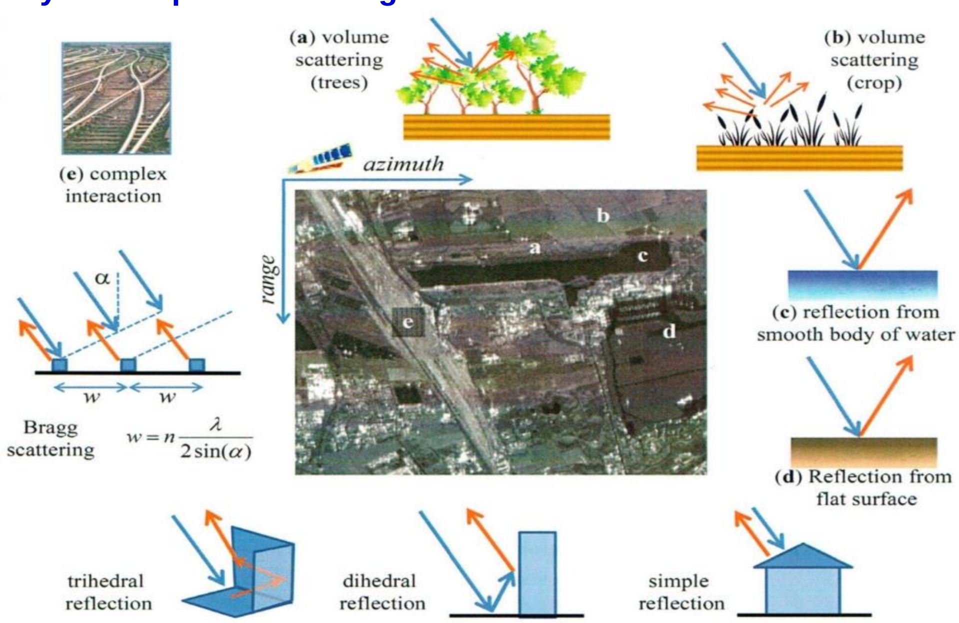
Summary of complex scattering mechanisms



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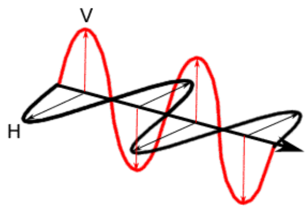
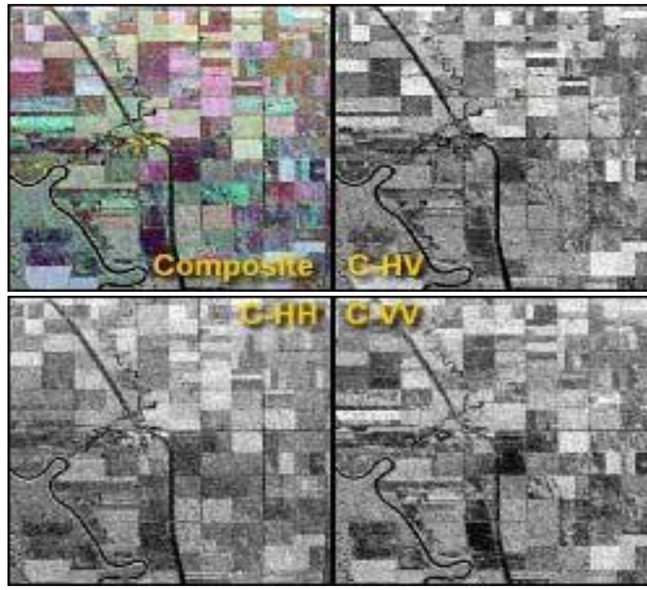
c. Radar Polarization



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.

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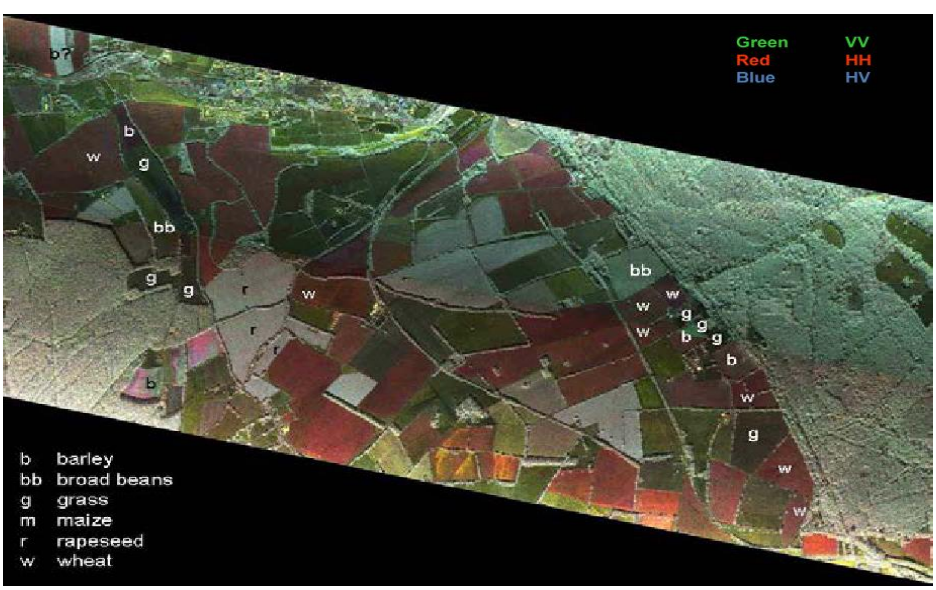
Radar Polarization

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

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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

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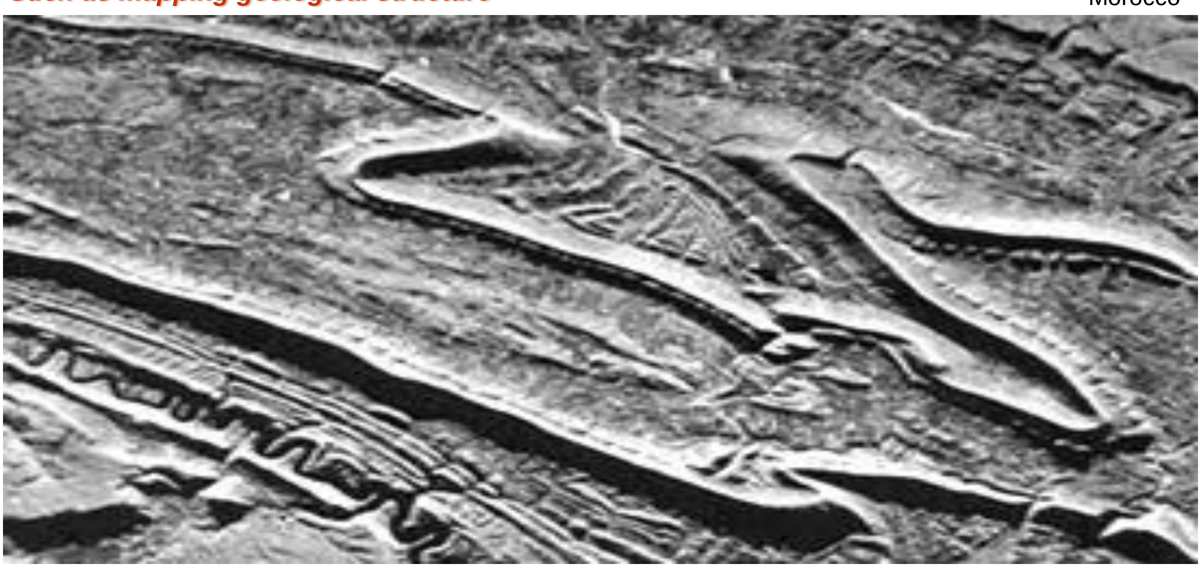
Applications in geoscience and environmental fields

Such as mapping geological structure

Morocco



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Flood monitoring, mapping and analysis

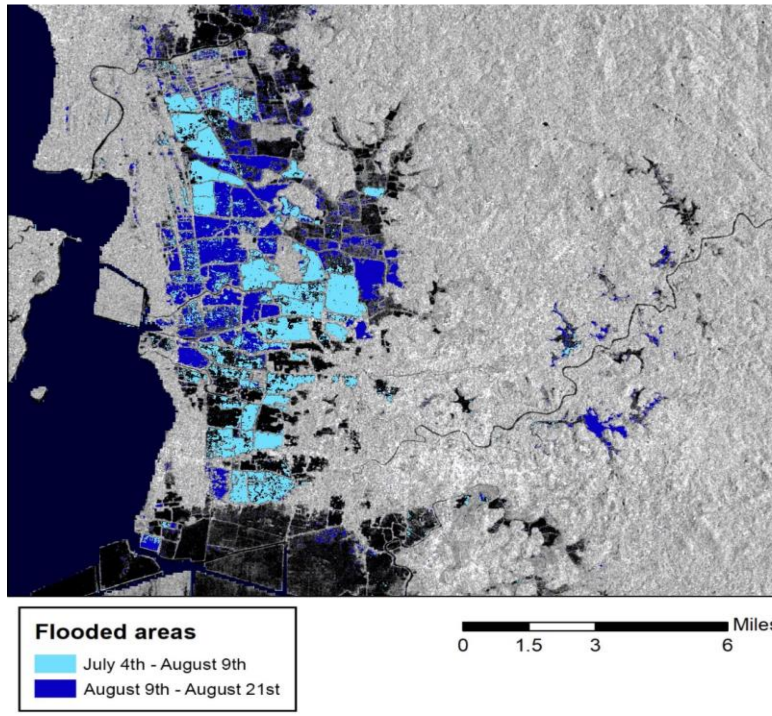
Spaceborne SAR can provide excellent views of the flood, because of its **day/night-all-weather imaging**, and its **sensitivity to the land/water** differences.

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.



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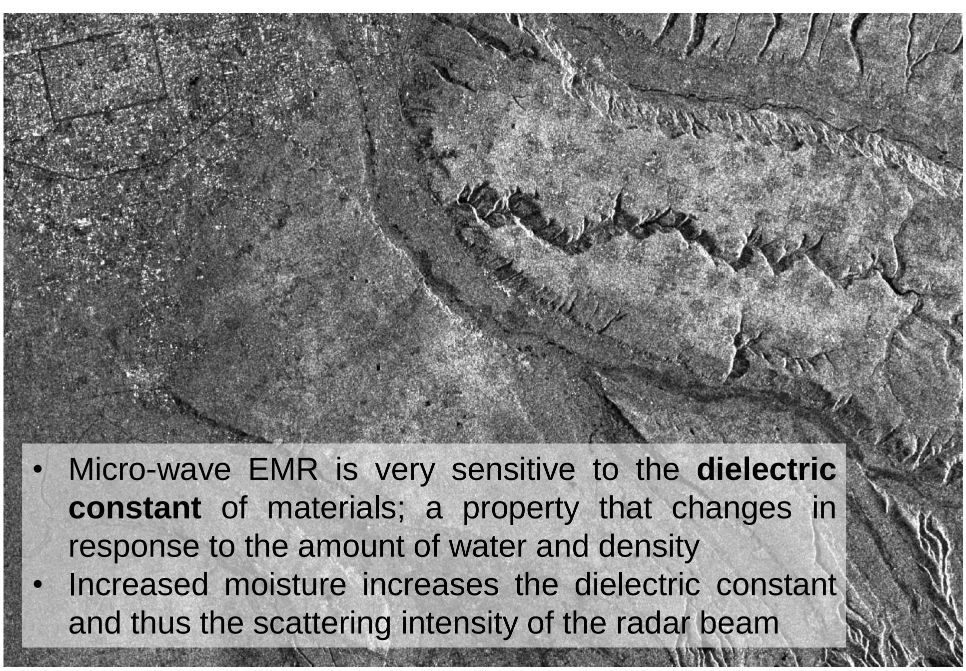
Soil moisture mapping



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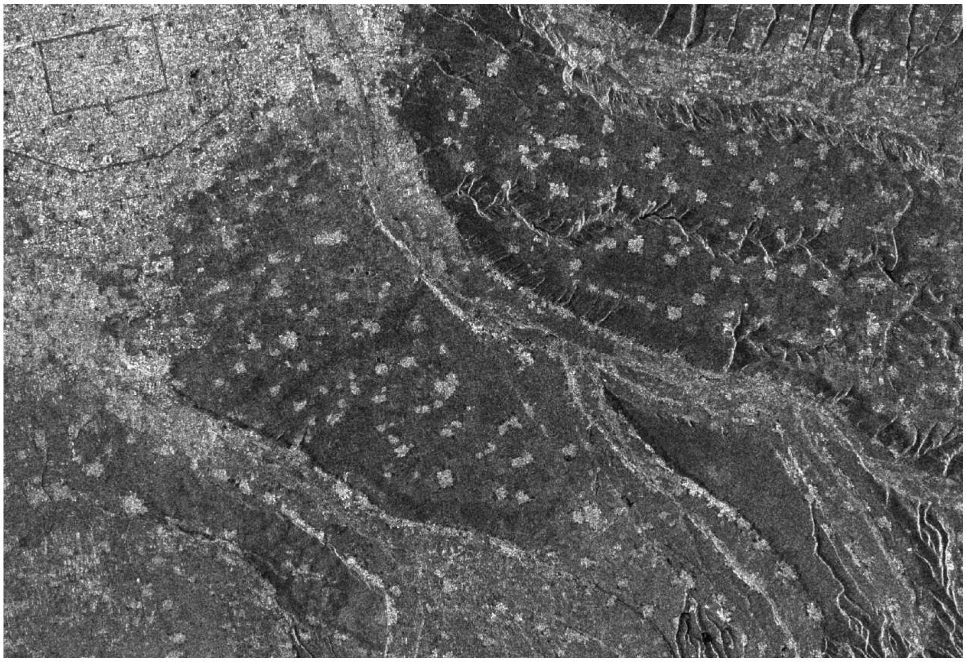
Soil moisture mapping



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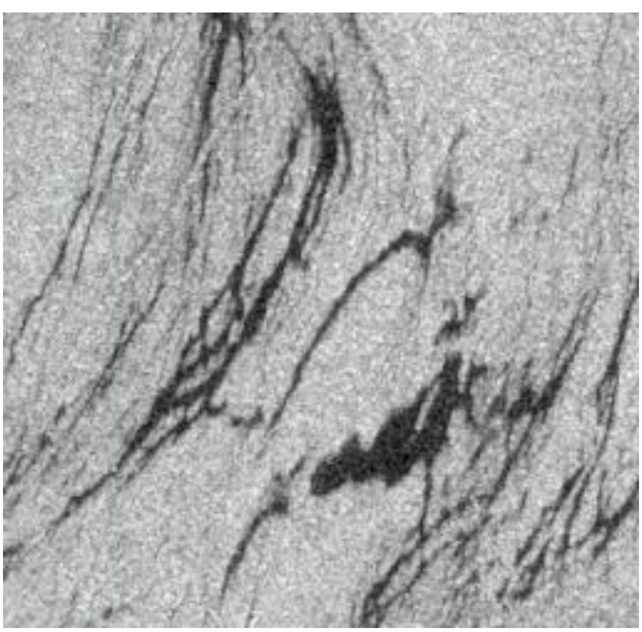
Oil slick detection



- Oil slicks appear as dark features because the oil smoothes 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 features.
- Environmental factors, e.g. wind, can alter the behaviour of the sea in the vicinity of slicks. 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.
- Conversely, if wind speed is very low, the sea surface is smooth everywhere and again, the detection is no longer effective.

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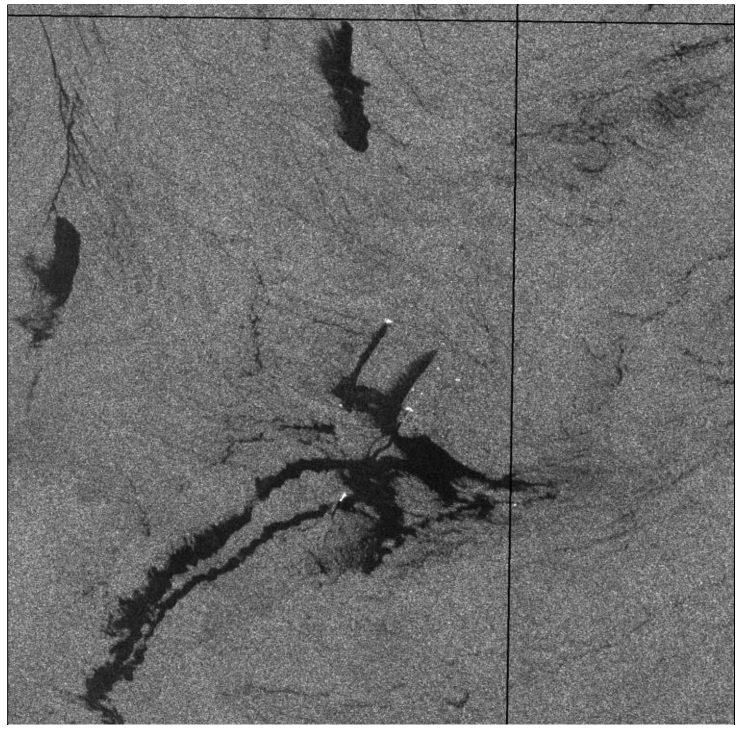
Oil slick detection

A typical case of leakage from oil production.



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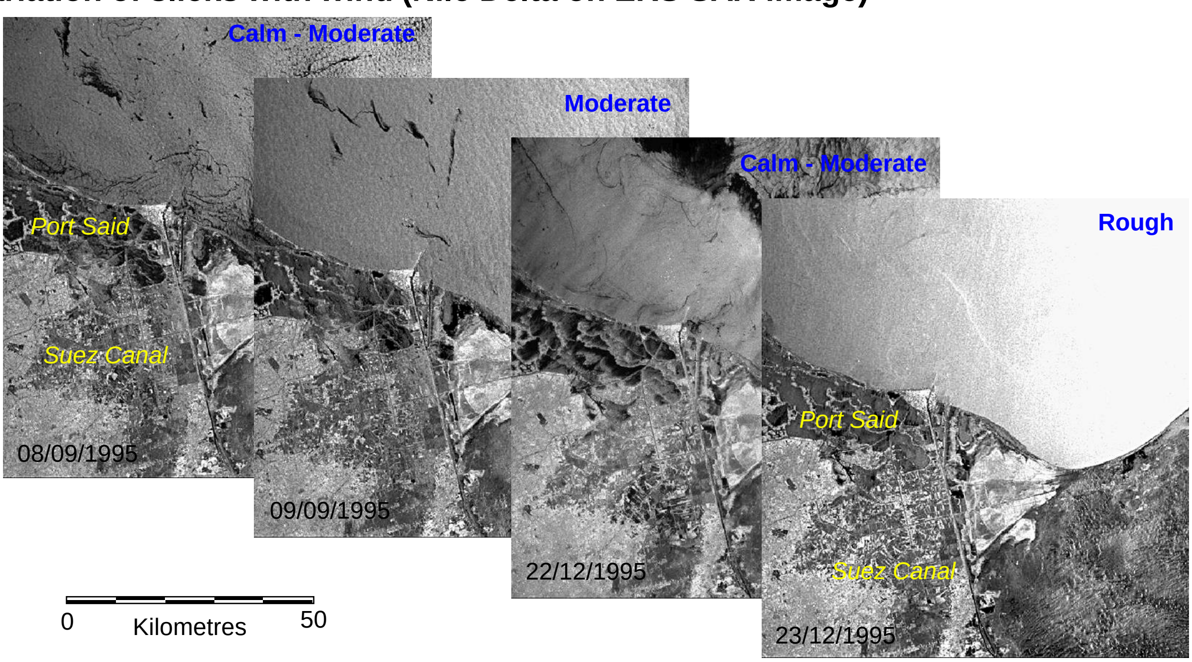
Variation of slicks with wind (Nile Delta on ERS SAR image)



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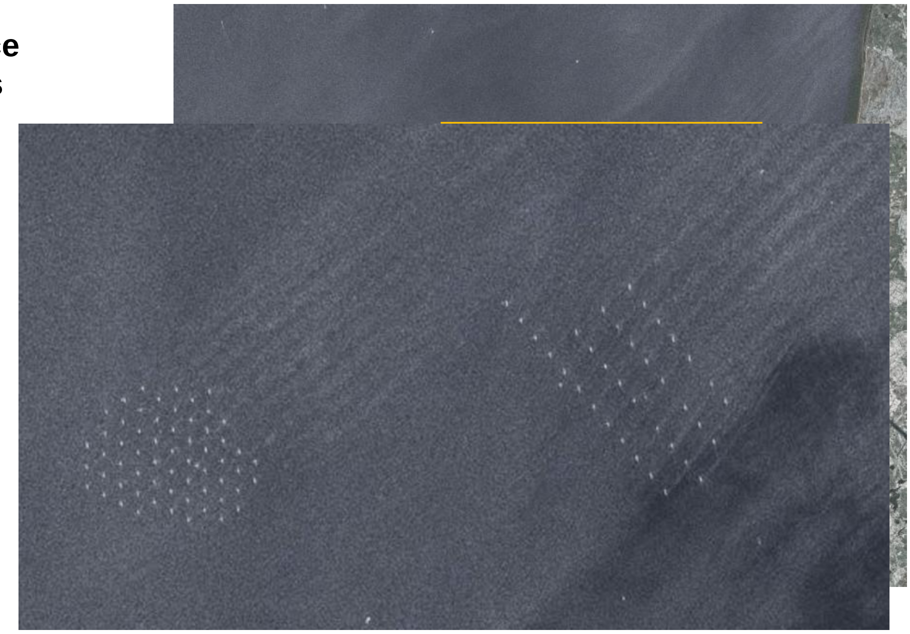
Sea surface roughness

Windfarms & ships offshore southern UK



What are these streaks?

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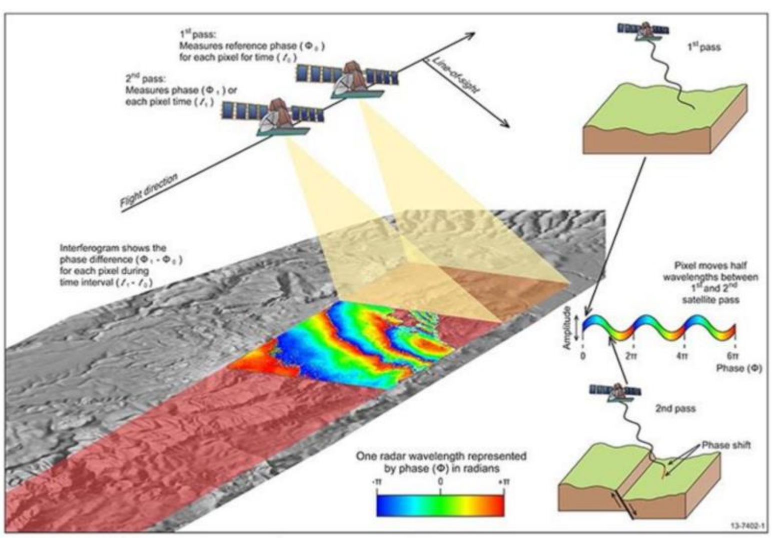
Measuring cm- and mm-scale ground movements from space: SAR Interferometry (InSAR) & Time-series InSAR



More on this in a minute!

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

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5.4 Summary (& revision!)

- In this chapter, we introduced the **basic principles and characteristics** of radar remote sensing and its applications.
- As a ranging system, a radar has to be configured **side looking** to avoid ambiguity and thus geometric distortion is not avoidable. The major geometric distortion of a radar imaging system include: **foreshortening**, **layover** and **radar shadow**.
- For a real aperture radar, a large diameter of antenna enables high azimuth resolution however, this is not realistic for airborne and spaceborne imaging radar systems. A clever solution is the synthetic aperture radar (**SAR**) system that exploits Doppler frequency shift effect to compose a virtual large antenna by a small antenna on a steady moving platform and thus to achieve a high azimuth resolution. The high resolution in ground range direction is achieved by modulating the high frequency radar beam with a low frequency "**chirp**".
- Image information is a function of **slope, roughness** and **dielectric**
- All radar images are subject to **speckles**; this effect can be alleviated by **multi-look** processing and filtering.
- **Corner reflection** are caused by vertical (angular) surfaces producing very strong return signal by double bouncing.
- **Roughness** of terrain surface largely determines an image's brightness while **volume scattering** properties closely relates to the **penetration** ability of radar imaging.

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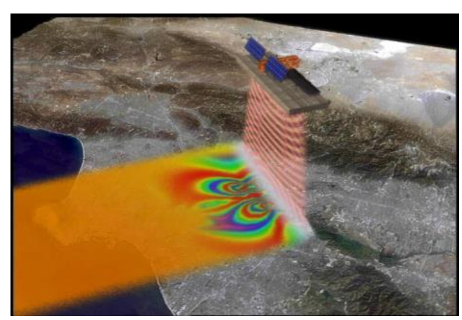
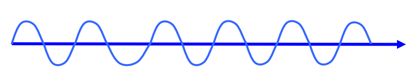
VERY brief principles of interferometric SAR (InSAR)



- Interferometry uses the differential phase of the reflected radiation, either from multiple passes along the same trajectory and/or from multiple displaced phase centres (antennas) on a single pass
- A Single Look Complex (**SLC**) SAR data product is composed of:
  - Complex pixel numbers recording the **amplitude (A)** and **intensity,** i.e. energy of backscattered microwave field returned from targets and
  - **Phase (ϕ)** of the signal which is determined by the distance between the target and the radar antenna, and the wavelength of the radar beam
  - Where Intensity = Amplitude^2
- Both *Amplitude* and *Phase* information are needed for interferometric processing.
- Given any complex number (c) of any SLC pixel, where $c = a + ib$ (and where $i = \sqrt{-1}$) the Magnitude of c is given as: $M_c = \sqrt{a^2 + b^2}$ and Mc = Amplitude
- And the phase angle of c *(for a single image)* is: $\varphi = \arctan\left(\frac{b}{a}\right)$



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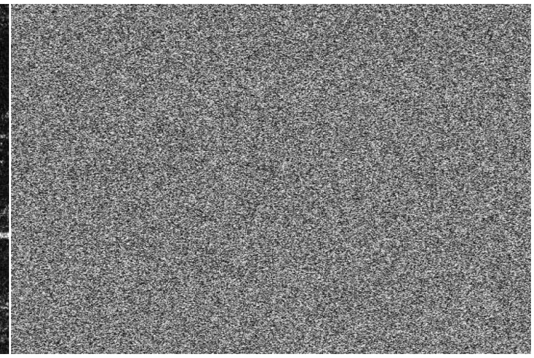
SAR SLC data

A SAR image is a set of pixel values representing both **amplitude** and **phase** values

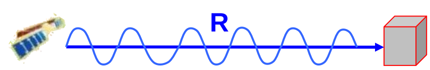
Amplitude

Amplitude $(A) = \sqrt{I^2 + Q^2}$



Phase (recorded in modulo 2π)

Phase (ϕ) = $atan(Q/I)$



Phase is related to the sensor-target distance (R)

where $I = A\cos(\phi)$ *and* $Q = A\sin(\phi)$
and I is the real and Q is the imaginary component (Quadrature) of the backscattered echoes

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Summary of SAR data components

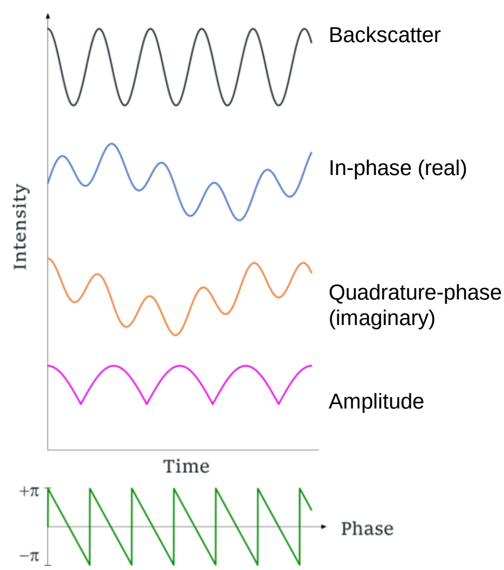
SAR SLC records both real or **in-phase (I)** and imaginary or **quadrature-phase (Q)** components of the backscatter echoes, to reconstruct the intensity and location of each echo.

In-phase (I), Quadrature-phase (Q):

Amplitude $(A) = \sqrt{I^2 + Q^2}$

Phase $(\phi) = atan(Q/I)$

$I = A\cos(\phi)$ *and* $Q = A\sin(\phi)$



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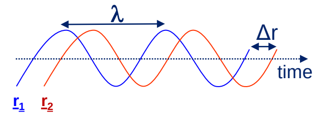
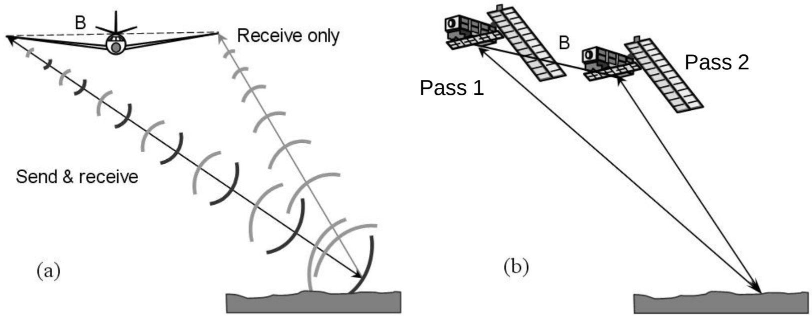
The purpose of InSAR is to derive an SAR ***interferogram***, which is a 'map' of the **<u>phase difference</u>** (ϕ) between the two coherent SLC images (often called *fringe pair*): $\phi = \varphi_1 - \varphi_2$



We can derive the two SLC images by:



(a) Airborne single-pass SAR interferometer with an active antenna (sending and receiving signals) and a passive antenna (receiving only), separated by a distance (B); or

(b) Repeat-pass SAR interferometer – imaging the same area from two visits with a minor orbital drift B *(and time separation* B_{temp}*)*

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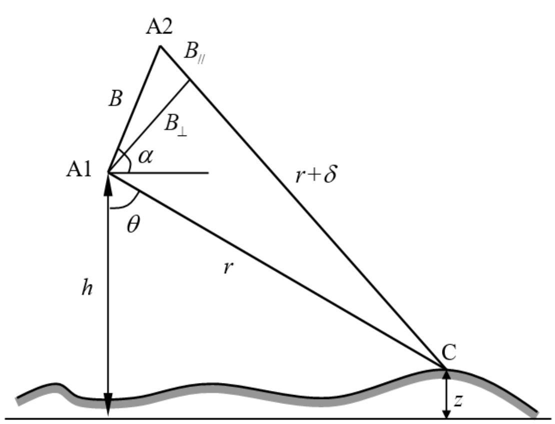
Basic InSAR geometry

To understand the relationship between phase difference and the InSAR imaging geometry, let us consider a SAR system observing the same ground swath from two positions, A1 and A2.

Ground point C is then observed twice from distance r (slant range) and r + δ. The distance difference between the 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.

So the δ contains geometric information about the elevation z of the ground at every point in the SAR image

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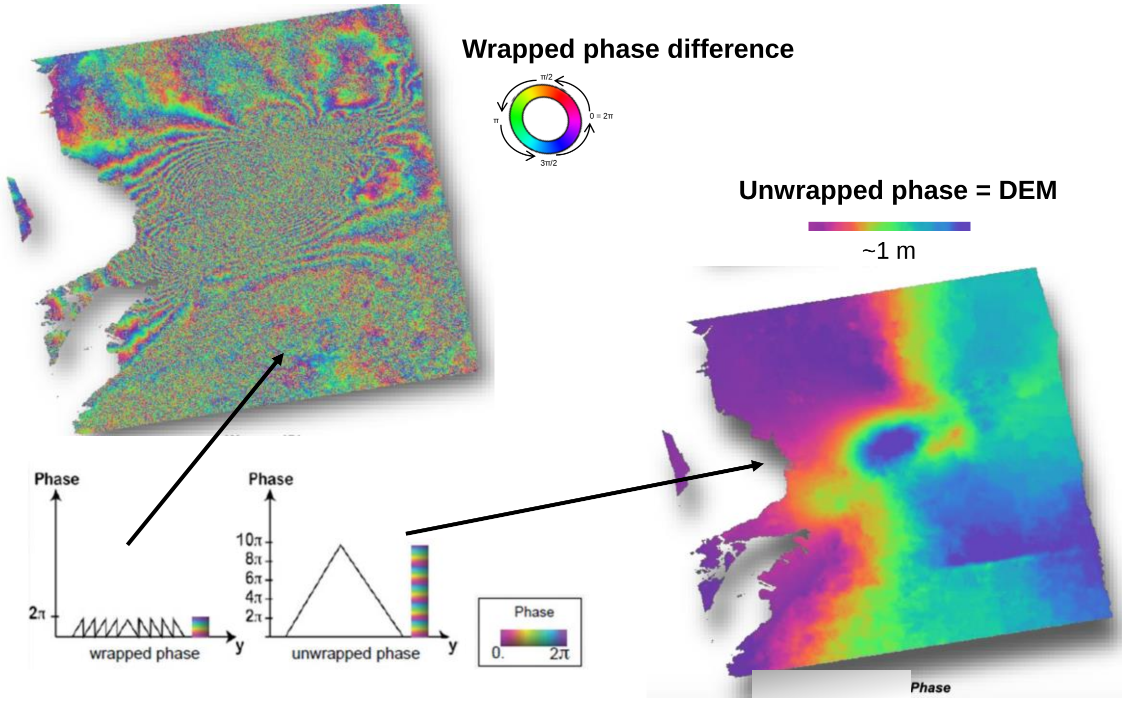

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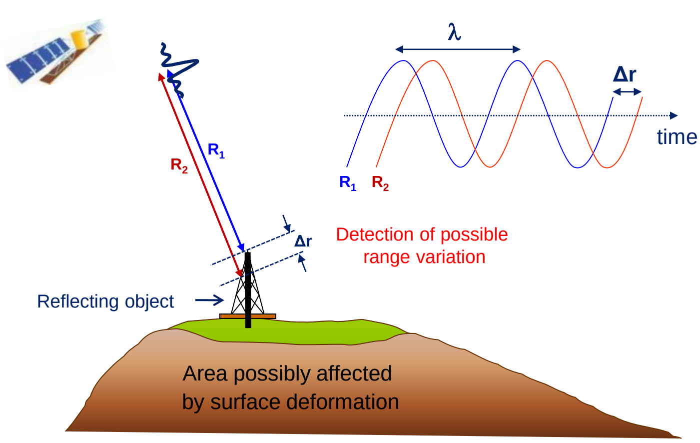
Differential InSAR principle for ground level change detection



Using two coherent beams of radar energy, from a satellite, separated in time and space, we can extract the distance as a function of the phase of the wave – **Differential InSAR**

Changes in phase represent changes in **wave travel-time & distance** from the satellite to the ground (and back again).

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

Diagram/Animation credit: M. Basillico of TRE Altamira

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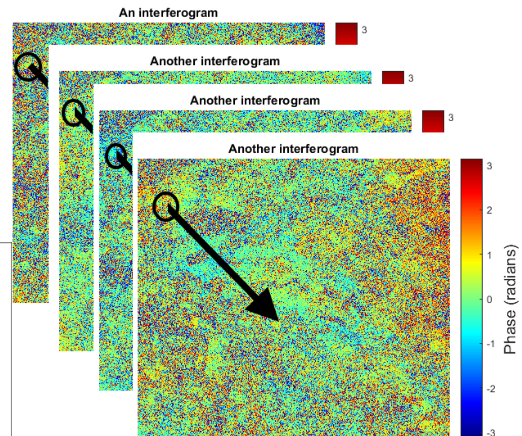
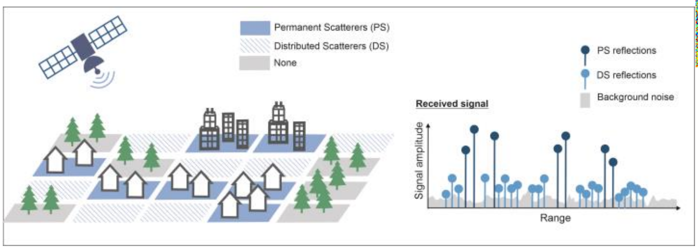
Looking for stable reflectors/scatterers in time

$$\Delta\varphi = \varphi_{defo} + \underbrace{\varphi_{topo} + \varphi_{flat} + \varphi_{orbit}}_{\text{Geometry}} + \underbrace{\varphi_{tropo} + \varphi_{iono}}_{\text{Atmosphere}} + \varphi_{scat} + \varphi_{noise}$$

Over several years & 100s of SAR images, we can track objects scattering





For phase factors [2] Ferretti et al., (2001) Permanent Scatterers in SAR interferometry. IEEE TGRS

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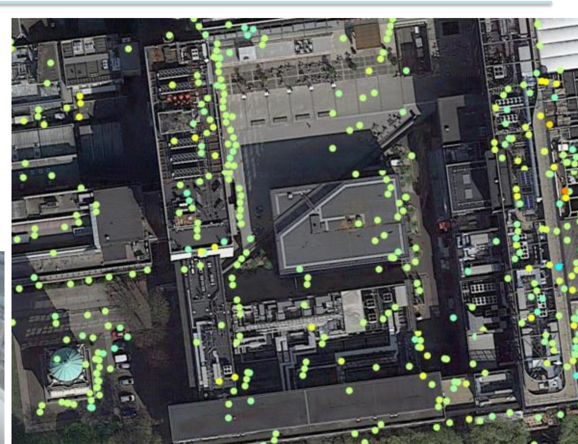
Permanent or Persistent Scatterers

- A scatterer is any object responsible for a measurable radar echo
- PS are scatterers which exhibit stable reflectivity values that are coherent over long periods of time
- Exposed man-made structures such as buildings, streetlights and transmission towers make excellent **point PS**, as do exposed rock outcrops
- Generally, we cannot predict point PS locations a priori, but corner reflectors may be used
- Using **long SAR image time-series, we can track very small motions of the PS** (motions too small for DInSAR to resolve)



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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

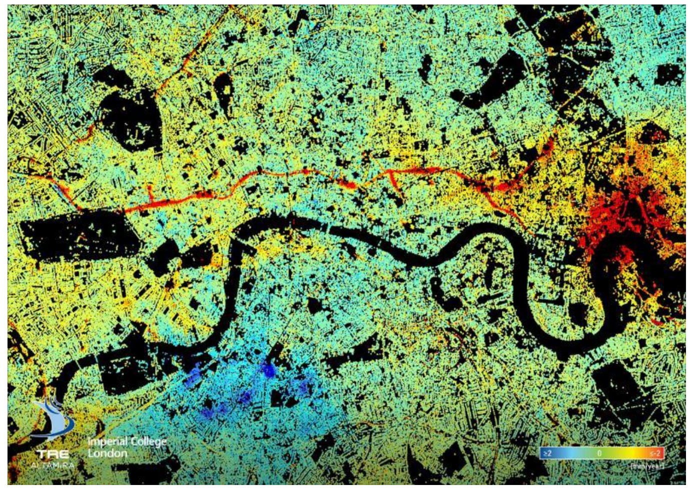
Blue = upward movement >2 mm/yr

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

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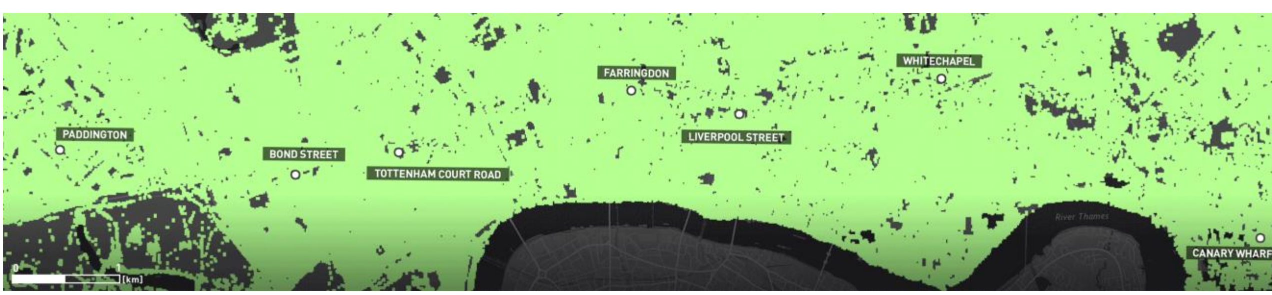
Elizabeth Line (Crossrail) Construction



2011-2017 TerraSAR-X SqueeSAR™ data

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

-20 0 20

Christine Bischoff PhD

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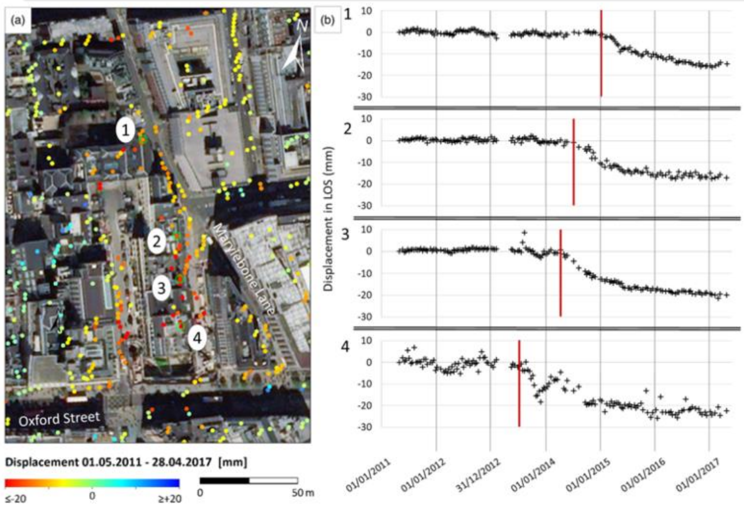
Detect the subsidence caused by tunnelling



- Response of buildings to the tunnelling works for London Underground's recent Bond St Station upgrade
- Time series of four PS, with their location indicated in circles in
- Red line indicates start of settlement – charts northward **progress of Tunnel Boring Machine** (TBM) under Bond Street

Urban tunnelling

Bischoff et al., 2019

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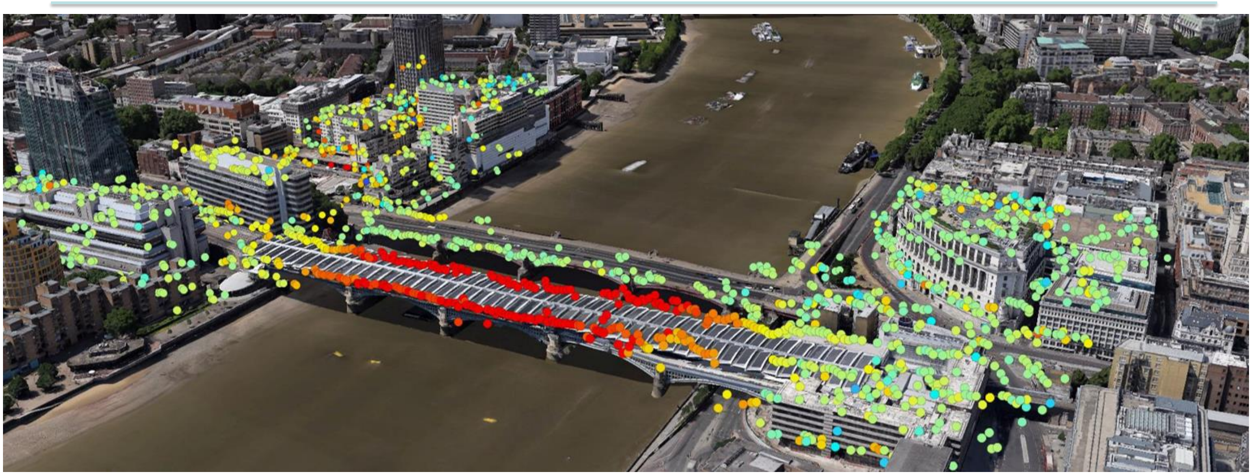
Detect subsidence of new constructions



New Blackfriars bridge subsiding unevenly

Urban development

Bischoff et al., 2019

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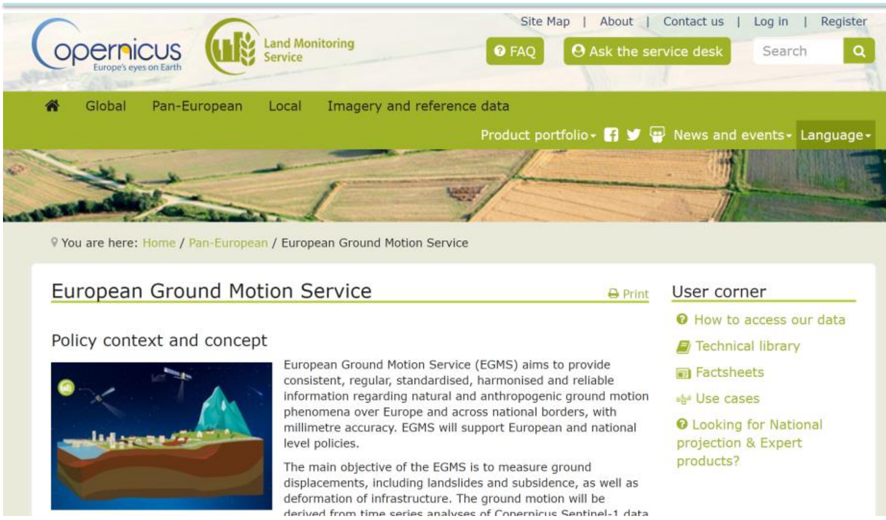
Global demand for InSAR data and services



Global demand for InSAR data for environmental security

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

There is still a slow uptake of InSAR products in certain industrial sectors

CIRIA guidelines on EO for infrastructure currently in writing

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It’s nearly the end of course!

- But you can ask any questions, any time
- There are tons of online resources
- Remote Sensing & Photogrammetry Society (and other related Learned Societies) have student & young professional activities and opportunities, careers stuff, online courses bursaries & travel awards

- Earth Observation Network (EON) Twitter: @ImperialEON www.imperial.ac.uk/earth-observation-network

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New Imperial College Earth Observation research Network

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