ECONOMIC COOPERATION ORAGANIZATION (ECO)

TRAINING COURSE

The National Cartographic Center of Iran with the support of ECO Secretariat holds a training course on:

Application of Geospatial Data in Disaster Risk Reduction

16-17 DEC 2024

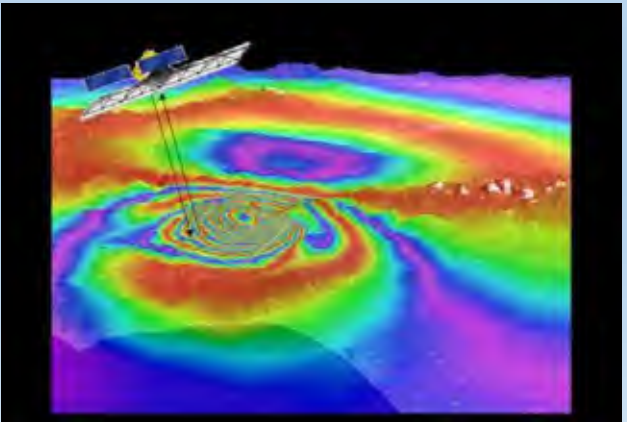
بسم الله الرحمن الرحیم

Application of Geospatial Data in Disaster Risk Reduction

NCC – DEC 2024

SAR Interferometry(**InSAR): principle**

Masoome Amighpey



Outlines:

Part 1
Introduction to Synthetic Aperture Radar (SAR)

Part 2
Introduction to Interferometric SAR (InSAR)

Part 3
An Overview of SAR Data Sources and Tools

Learning Objectives

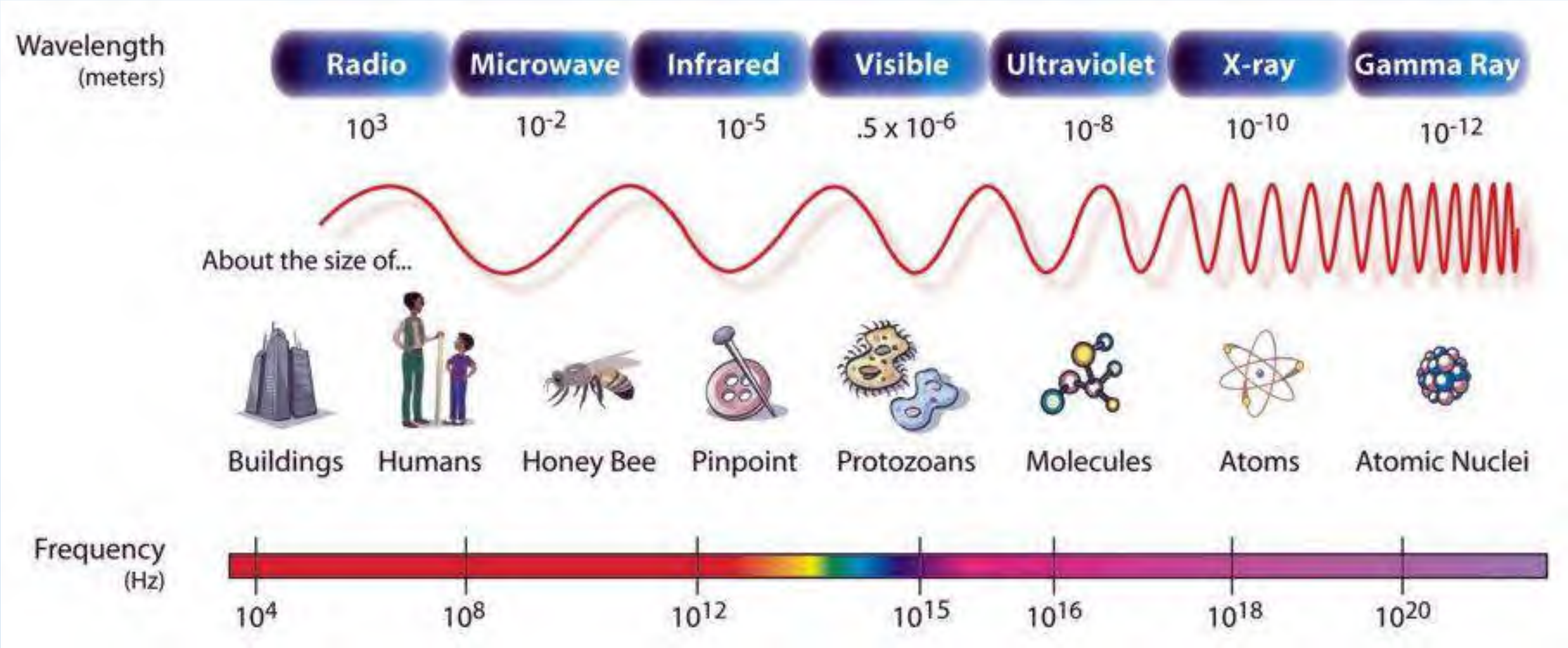
By the end of this presentation, you will be able to:

- Understand the physics of SAR image formation
- Describe the interaction of SAR with the land surface
- Describe the necessary data preprocessing
- Explain what information is available from SAR

The Electromagnetic Spectrum

Optical sensors measure reflected solar light and only function in the daytime
The surface of the Earth cannot be imaged with visible or infrared sensors when there are clouds

Microwaves can penetrate through clouds and vegetation, and can operate in day or night conditions



Advantages and Disadvantages of Radar Remote Sensing Over Optical

Advantages

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

Disadvantages

- Information content is different than optical and sometimes difficult to interpret
- Speckle effects (graininess in the image)
- Effects of topography

Optical vs. Radar

Volcano in Kamchatka, Russia, Oct 5, 1994

Basics of Synthetic Aperture Radar

Active and Passive Remote Sensing

Passive Sensors:

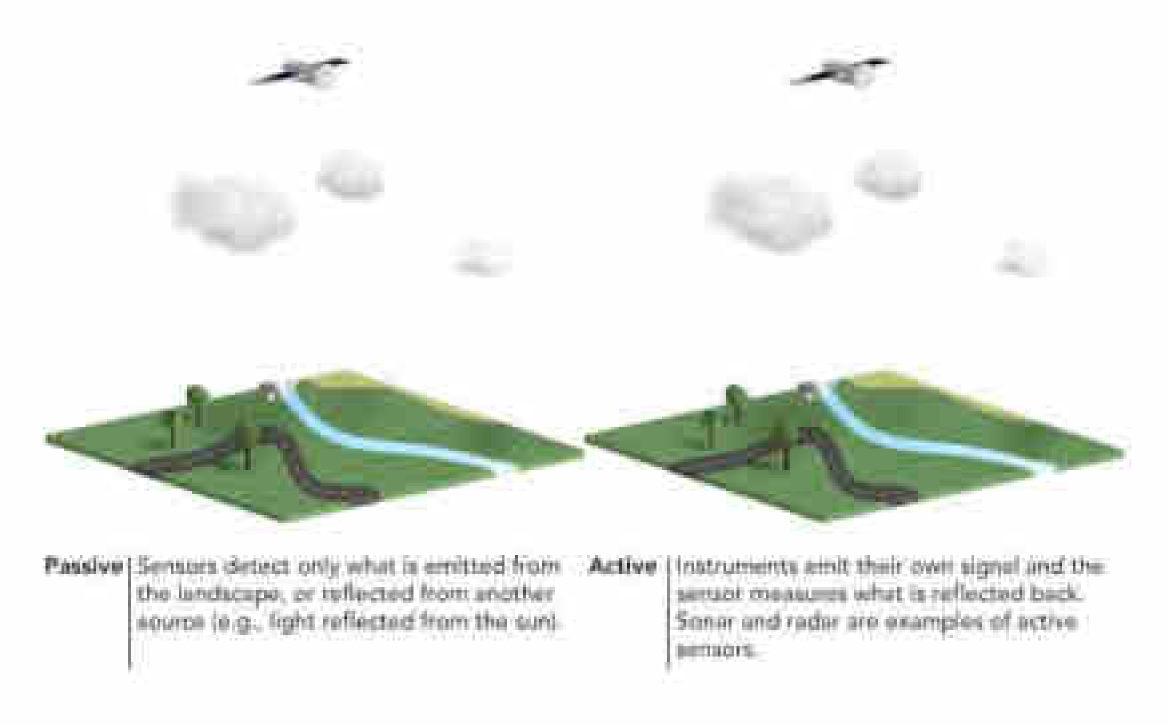
The source of radiant energy arises from natural sources

e.g. the sun, Earth, other “hot” bodies

Active Sensors

Provide their own artificial radiant energy source for illumination

e.g. **radar, synthetic aperture radar (SAR)**, LIDAR

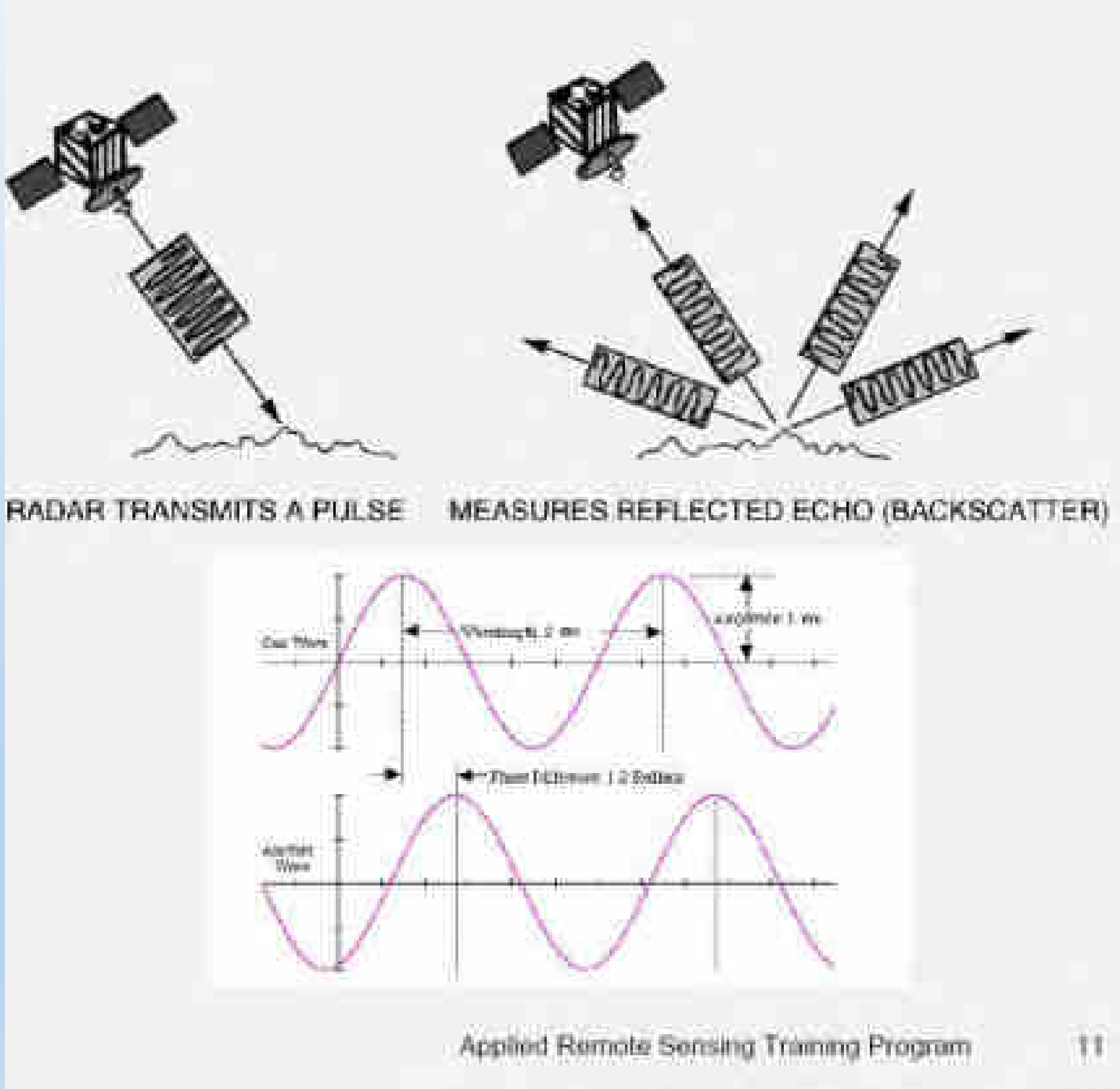


Review of Radar Image Formation

Radar can measure amplitude (the strength of the reflected echo) and phase (the position of a point in time on a waveform cycle)

Radar can only measure the part of the echo reflected back towards the antenna (backscatter)

Radar pulses travel at the speed of light



Radar Parameters to Consider for a Study

Wavelength

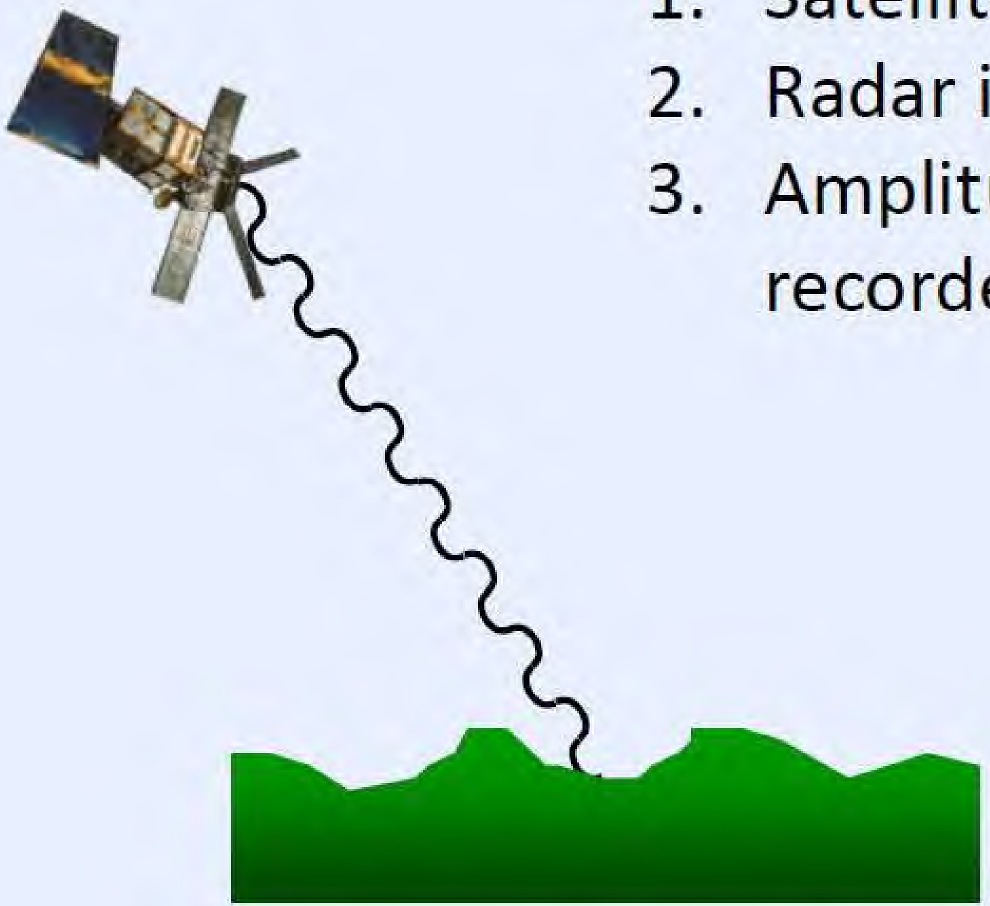
Polarization

Incidence Angle

Synthetic aperture radar (SAR):

There is an inverse relationship between the resolving power of a radar antenna and its length (its “aperture” in radar-speak). A antenna with a 10 m aperture (a typical radar antenna length for several past missions) has resolution of a few kilometers on the ground. Conversely, you would need an antenna with an aperture of several kilometers to image something on the scale of a few tens of meters on the ground—and it would not be feasible to launch or power such a thing in orbit

SAR: How it Works



1. Satellite emits radar pulse
2. Radar is backscattered
3. Amplitude and phase of echo recorded at the satellite

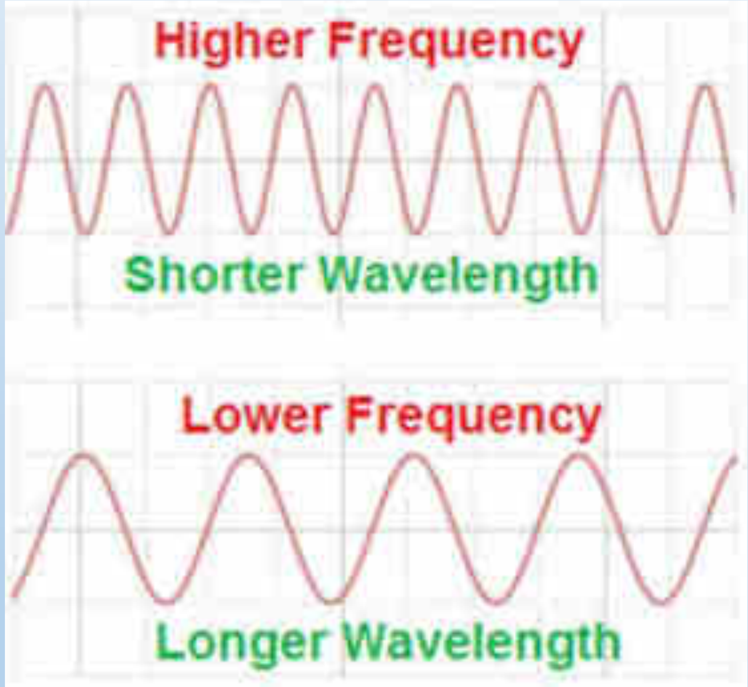
- SAR imaging uses amplitude (intensity) of backscattered echoes
- Radar sees through clouds—all-weather imaging is possible
- Don’t need illumination by the sun—can image day and night
- Surface roughness and slopes control the strength of the backscatter
- Applications: ship tracks, ice tracking, oil slicks, land-use changes, planetary

Picture 1

Radar Parameters: Wavelength

* Wavelengths most frequently used in SAR are in parenthesis

Wavelength =
Speed of light frequency



Radar Parameters: Wavelength

Penetration is the **primary factor** in wavelength selection

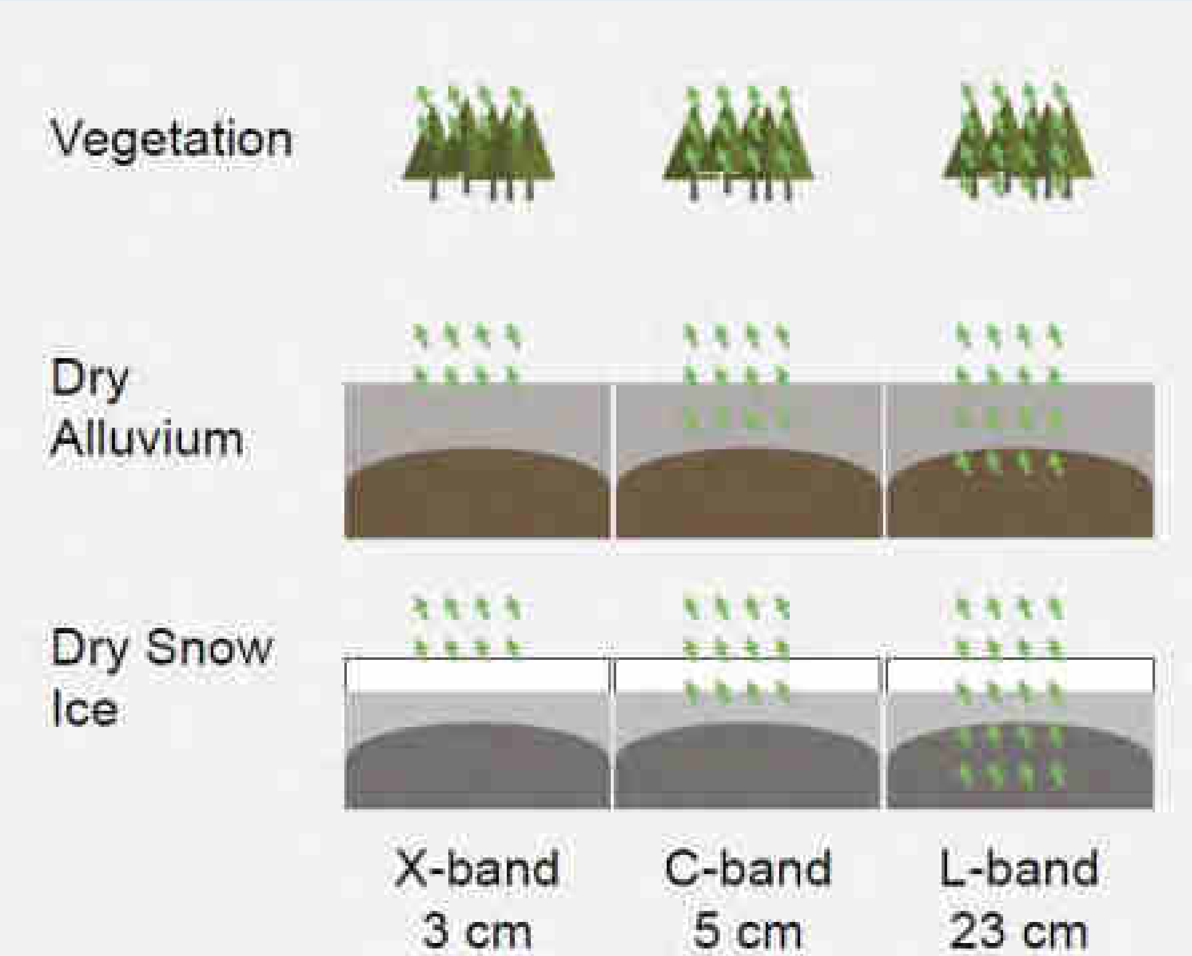
Penetration through the forest canopy or into the soil is greater with longer wavelengths

Commonly Used Frequency Bands

Frequency band	*Frequency range*	*Application Example*
• VHF	300 KHz - 300 MHz	Foliage/Ground penetration, biomass
• P-Band	300 MHz - 1 GHz	biomass, soil moisture, penetration
• L-Band	1 GHz - 2 GHz	agriculture, forestry, soil moisture
• C-Band	4 GHz - 8 GHz	ocean, agriculture
• X-Band	8 GHz - 12 GHz	agriculture, ocean, high resolution radar
• Ku-Band	14 GHz - 18 GHz	glaciology (snow cover mapping)
• Ka-Band	27 GHz - 47 GHz	high resolution radars

Penetration as a Function of Wavelength

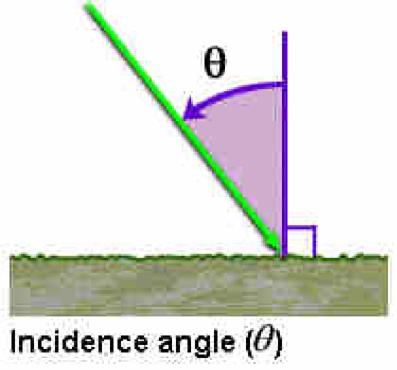
Waves can penetrate into vegetation and (in dry conditions) soil
Generally, the longer the wavelength, the stronger the penetration into the target

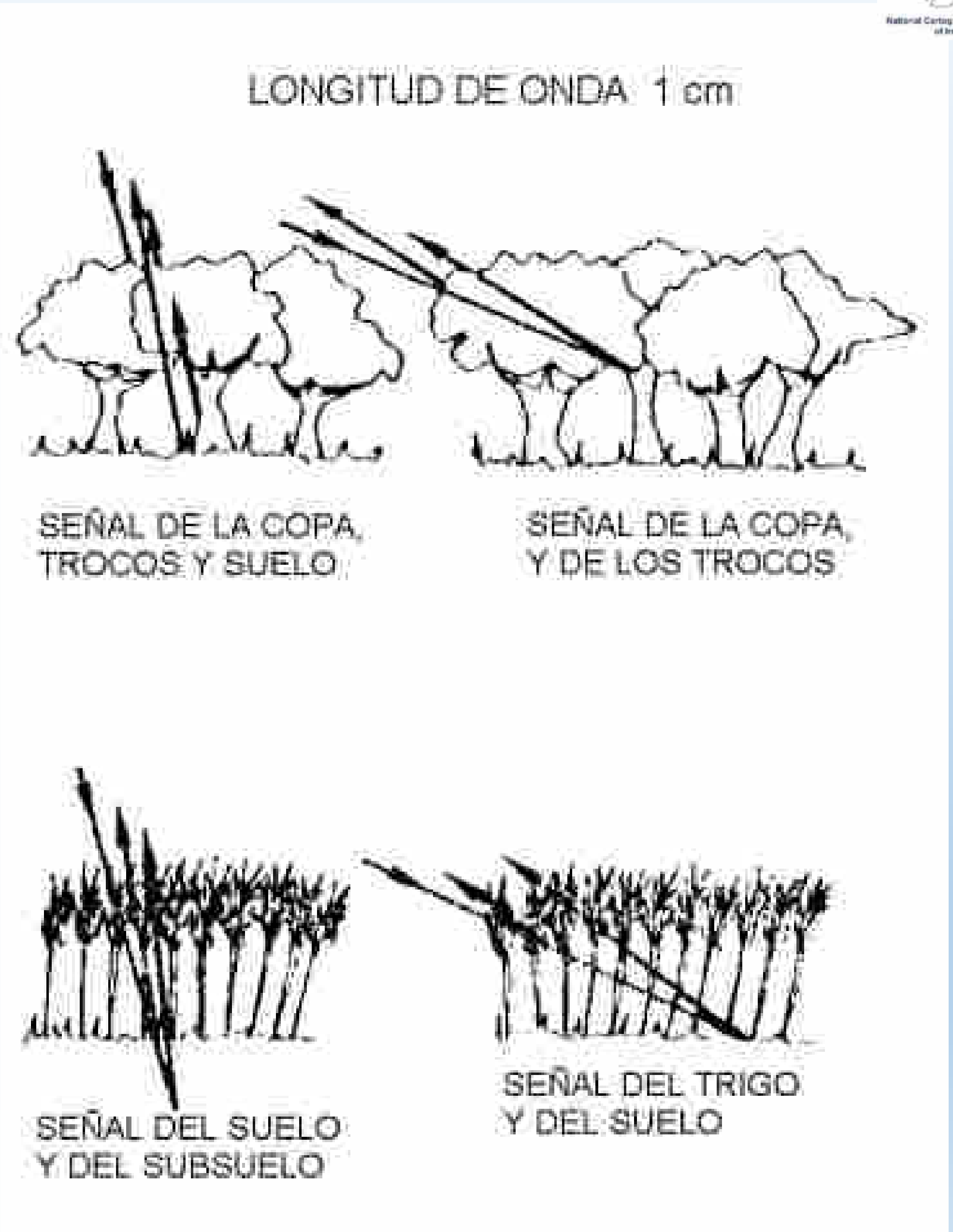


Radar Parameters: Incidence Angle

The angle between the direction of illumination of the radar and the Earth's surface plane

Depending on the height of the sensor, the incidence angle will change





Radar Data from Different Satellite Sensors

Sensor Name	RADARSAT-2	Sentinel-1A	RISAT-1
Agency	Canadian Space Program (CSP)	European Space Agency (ESA)	Indian Space Research Organization (ISRO)
Instrument	C-band SAR (5.4 GHz)	C-band SAR (5.4 GHz)	C-band SAR (5.35 GHz)
Incidence Angle	Side-looking, 15-45° off-nadir	Side-looking, 15-45° off-nadir	36.85°
Polarization	HH, HV, VV, & VH	(VV & VH) or (HH & HV)	HH & HV
Sensor Height at Equator	798 km	693 km	542 km
Orbit	Sun Synchronous (dusk/dawn)	Sun Synchronous (dusk/dawn)	Sun Synchronous (dusk/dawn)
Revisit Time (Orbit Repeat Cycle)	24 days	12 days	25 days

Radar Data from Different Satellites

Sensor Name	RADARSAT-2	Sentinel-1A	RISAT-1
Resolution	100 m	5 m x 20 m	~25 m
Swath Width	500 km (ScanSAR mode)	250 km (IWS mode)	115 km (MRS)
Mean Local Time	6:00 a.m. descending	6:00 a.m. descending	6:00 a.m.
Launch	14 Dec 2007	3 April 2014	26 Apr 2012
Planned Lifetime	7 years minimum	7 years	5 years

Radar Data Available

Legacy:

SeaSAT
1978

JERS-1
1992-1998

ERS 1/2
1991-2011

ENVISAT
2002-2012

ALOS-1
2006-2012

Radarsat-1
1995-2013

Current:

TanDEM-X
2007

Radarsat-2
2007

COSMO-SkyMed
2007

ALOS-2
2014

Sentinel-1
2014

PAZ SAR
2018

SAOCOM
2018

RCM
2018

Future:

NISAR
2025

Biomass
2025

freely acces

Introduction to SAR Interferometry

InSAR

- Interferometric — use wave interference
- Synthetic
- Aperture

  } pretend you have a big radar antenna
- Radar — emit microwaves, measure echoes

InSAR is a method that uses two or more SAR images to measure movements of Earth's surface, by calculating the interference between the phases of the SAR images.

SAR Interferometry (InSAR)

InSAR technique is a powerful tool to retrieve the position and/or the displacement of surface point scatterers through the pixel-to-pixel phase difference processing of couple SAR images acquired over the same scene viewed from comparable well-known acquisition geometries.

We call interferogram the image of the pixel to pixel phase differences. An interferogram is a complex image with (a) magnitude given by the product of the SAR amplitudes and (b) phase (the InSAR phase) given by the path length difference, as well as variations of the scattering properties and the medium conditions.

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SAR Interferometry (InSAR)

Complex coherence

The degree of correlation between two SAR images is measured by the coherence parameter.

$$\gamma = \frac{E\left[S_1 S_2^*\right]}{\sqrt{E\left[|S_1|^2\right] E\left[|S_2|^2\right]}} = |\gamma| e^{-j\varphi}$$

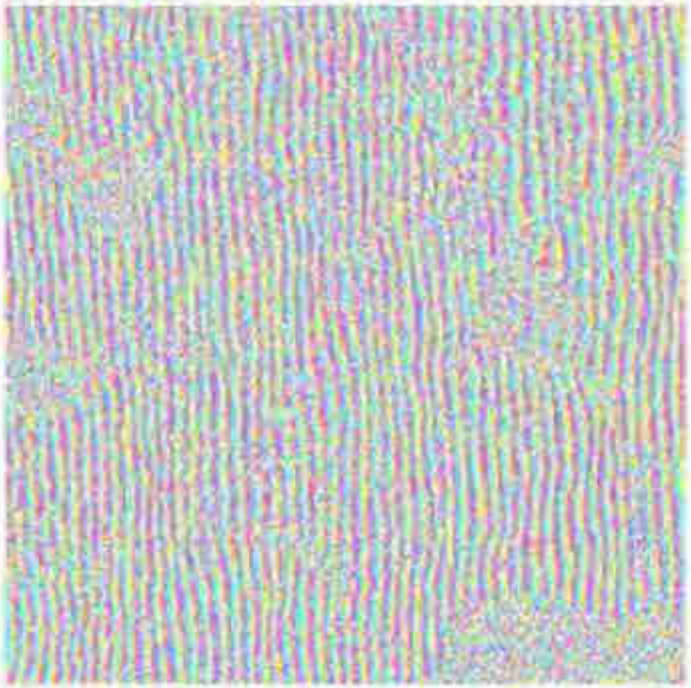
The amplitude is the degree of coherence, the phase is the interferometric phase.

Coherence is a measure of the phase noise or fringe visibility

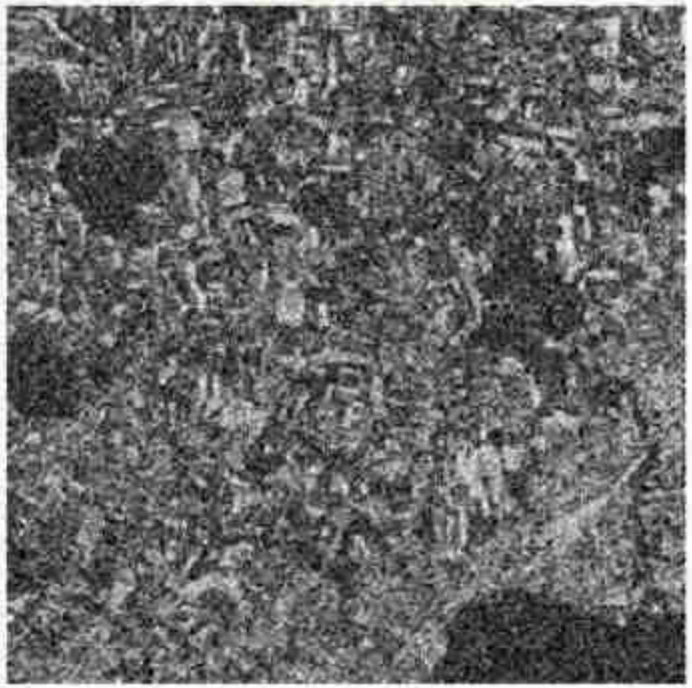
SAR Interferometry (InSAR)

Complex coherence

Interferometric phase



Coherence



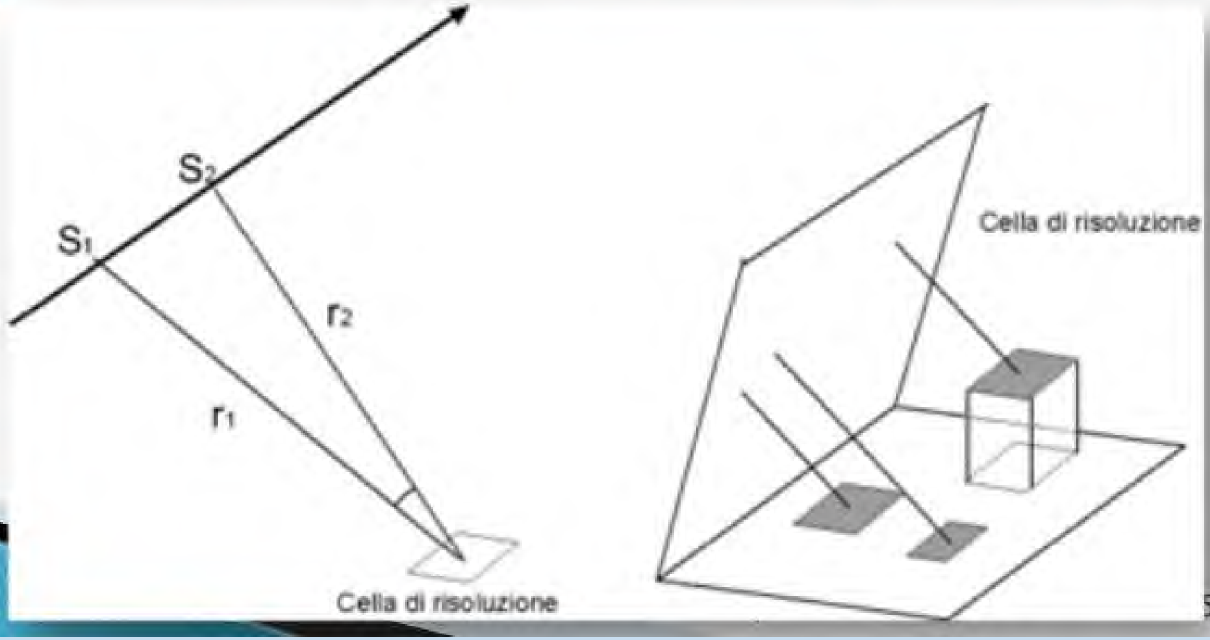
SAR Interferometry (InSAR)

The recorded phase is composed by two terms:

-the propagation phase, relevant to the sensor-to-target distance

-the backscattered phase, due to the surface backscattering

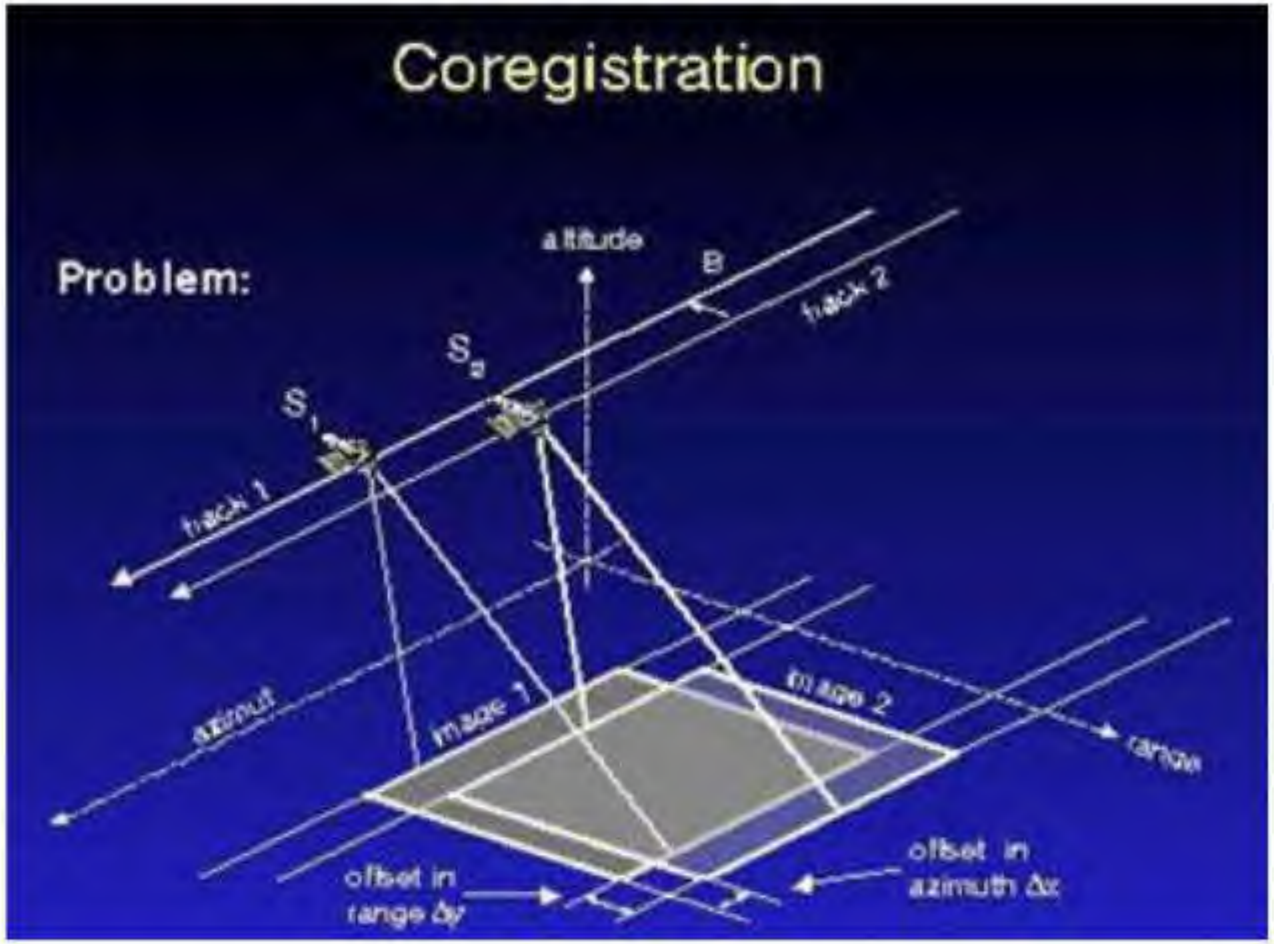
The backscattered phase is obtained as the sum of the phase contribution of each scatterer within the resolution cell on the plane perpendicular to the satellite LOS



SAR Interferometry (InSAR)

The two complex SAR images must be coregistered by interpolating one image (the slave image) to generate imagery at the same pixel locations as the second (the master image).

After registration, the two complex SAR images are multiplied, and the interferometric phase is obtained.



SAR Interferometry (InSAR)

The interferometric phase contains some distinct contributions:

$$\varphi_{\text{int}} = \varphi_f + \varphi_{topo} + \varphi_{displ} + \varphi_{atm} + \varphi_{err}$$

φ_f flat Earth

φ_{topo} topographic phase

φ_{displ} deformation phase

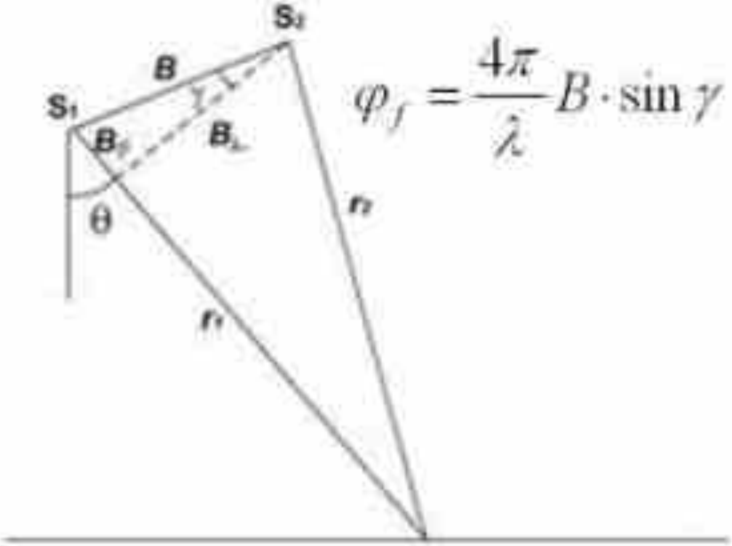
φ_{atm} atmospheric phase

φ_{err} noise (error phase)

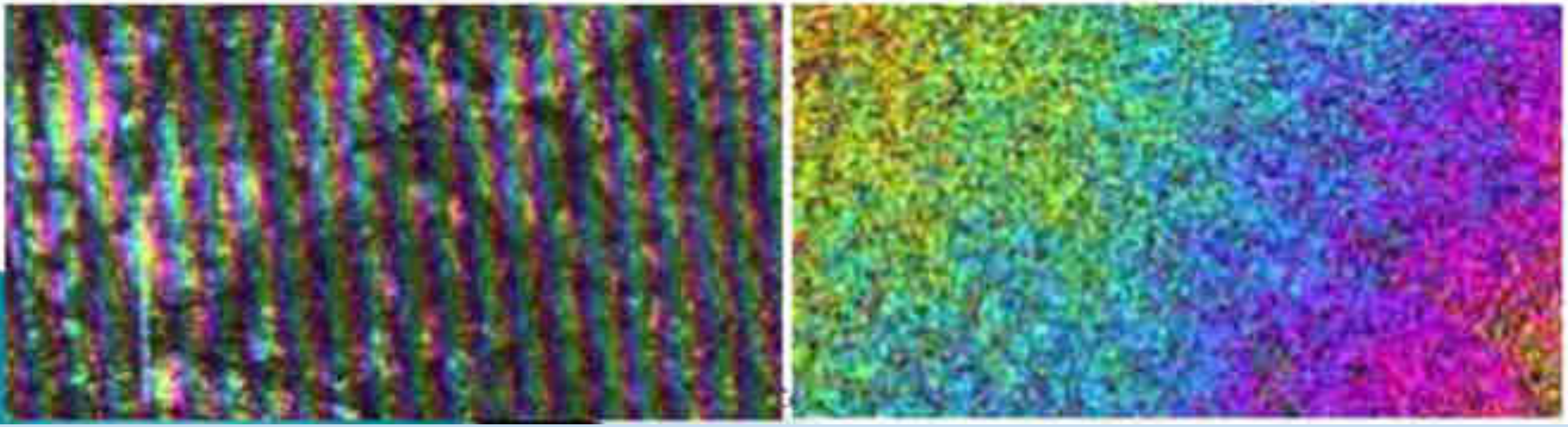
SAR Interferometry (InSAR)

Flat Earth

- Raw interferogram includes a quasi-linear phase trend caused by tilt of terrain surface relative to the baseline
- Flattening removes interferometric phase component using a sphere with radius of curvature derived from the ellipsoid.



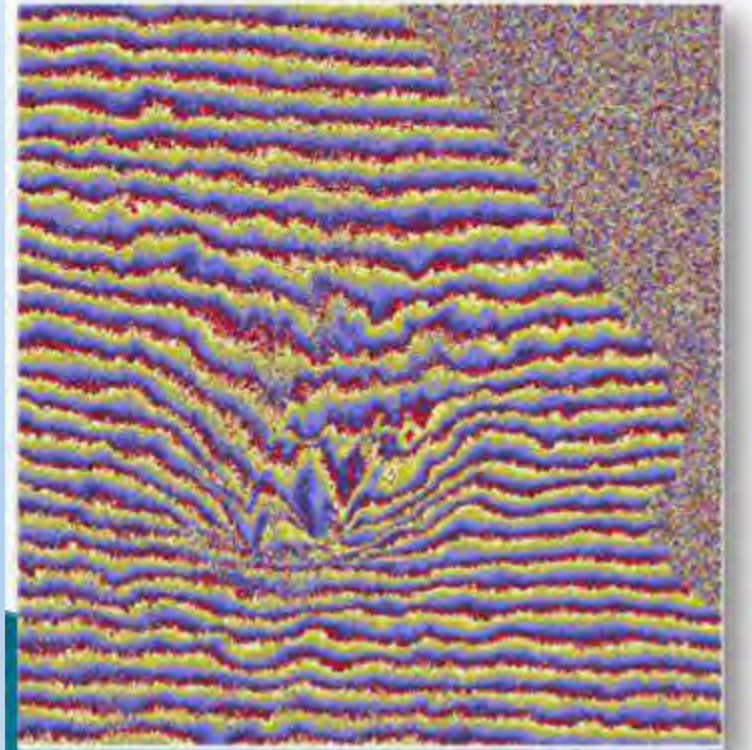
$$\varphi_f = \frac{4\pi}{\lambda} B \cdot \sin\gamma$$



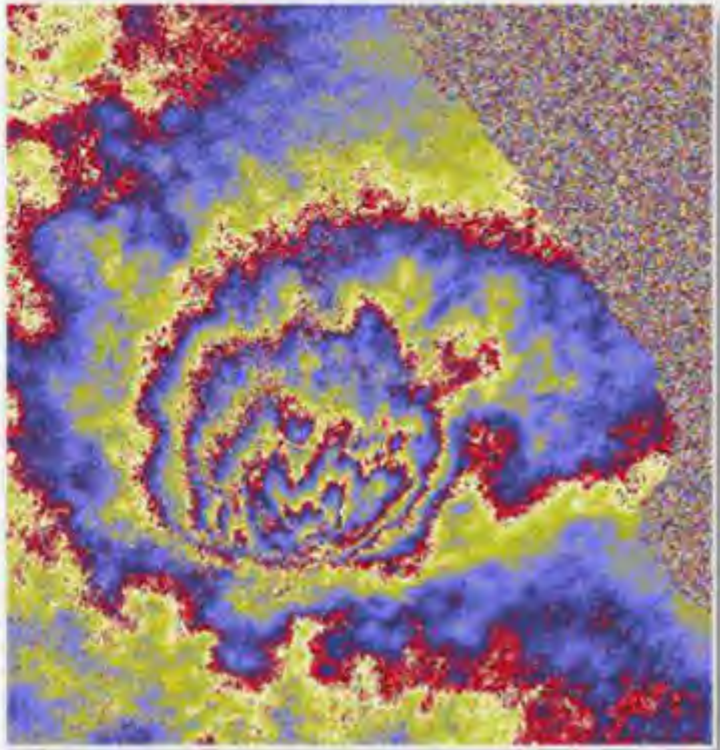
SAR Interferometry (InSAR)

Flat Earth

Unflattened interferogram



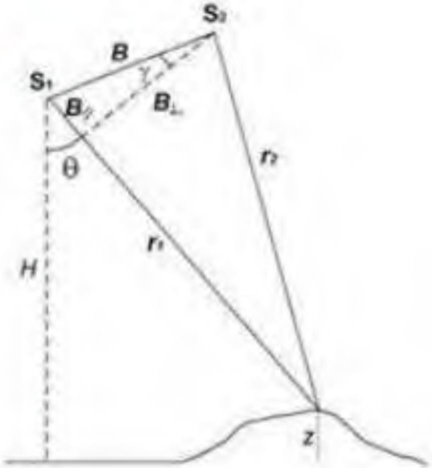
Flattened interferogram



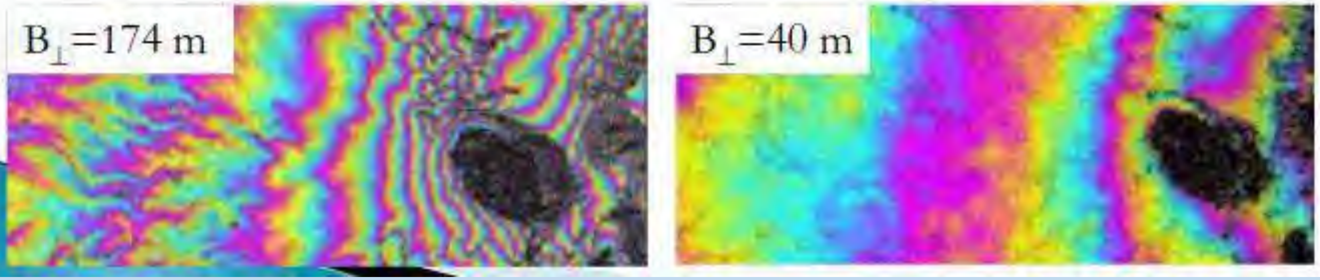
SAR Interferometry (InSAR)

Topographic phase

The topographic phase contains the information relative to the relief. The spacing between the fringes depends on the perpendicular baseline: the longer the perpendicular baseline, the narrower the fringes

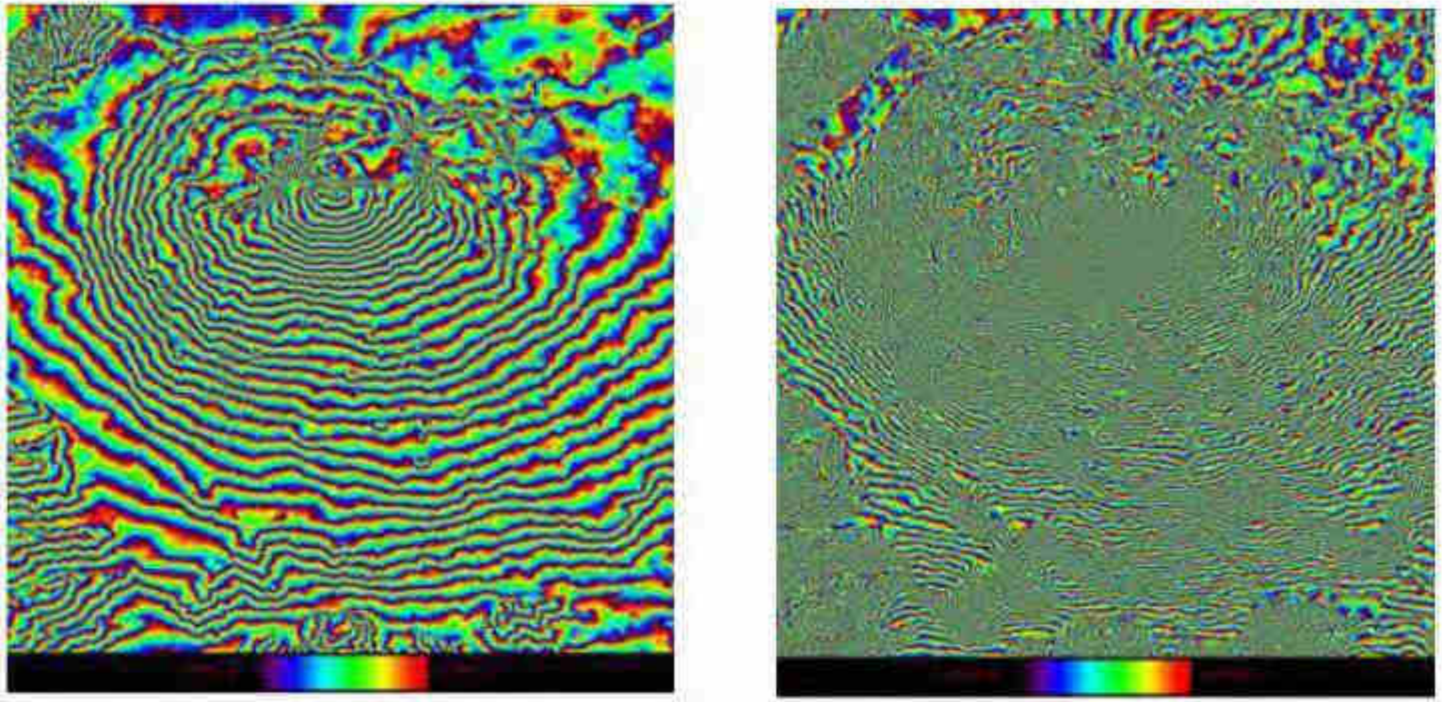


$$\frac{4\pi}{\lambda}(r_2 - r_1) \cong -\frac{4\pi}{\lambda} B \cdot \sin\gamma - \frac{4\pi}{\lambda} B_{\perp} \cdot \frac{z}{r_1 \sin\vartheta} = \varphi_f + \varphi_{topo} \qquad H \cong z - r_1 \sin\vartheta$$



SAR Interferometry (InSAR)

Topographic phase



Baseline doubling

SAR Interferometry (InSAR)

Topographic phase

The ambiguity height is the elevation difference corresponding to a full phase cycle (2π):

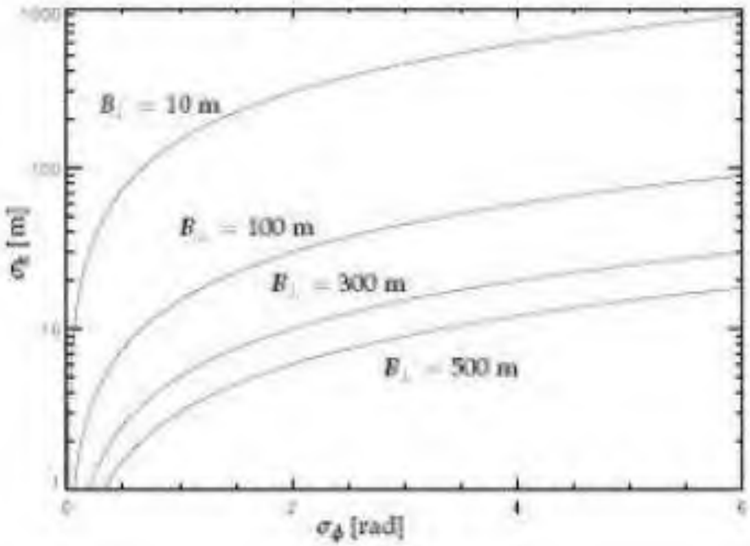
$$\Delta z_{amb} = \frac{\partial z}{\partial \phi_t} = \frac{\lambda r \sin \vartheta}{4\pi B_\perp} \qquad z = \frac{\lambda}{4\pi B_\perp} \phi_t r \sin \vartheta \qquad \sigma_z = \frac{\lambda}{4\pi} \sigma_{\phi_t} \frac{r \sin \vartheta}{B_\perp}$$

ERS satellites: $\lambda = 5.6\ cm \quad R = 833\ Km \quad \vartheta = 23°$

$$\Delta\phi_t = 2\pi \Longrightarrow \sigma_z = \frac{\pi}{6}$$

$$B_\perp = 80\ m \Longrightarrow \Delta z = 120\ m \quad \sigma_z = 10\ m$$

$$B_\perp = 800\ m \Longrightarrow \Delta z = 12\ m \quad \sigma_z = 1\ m$$

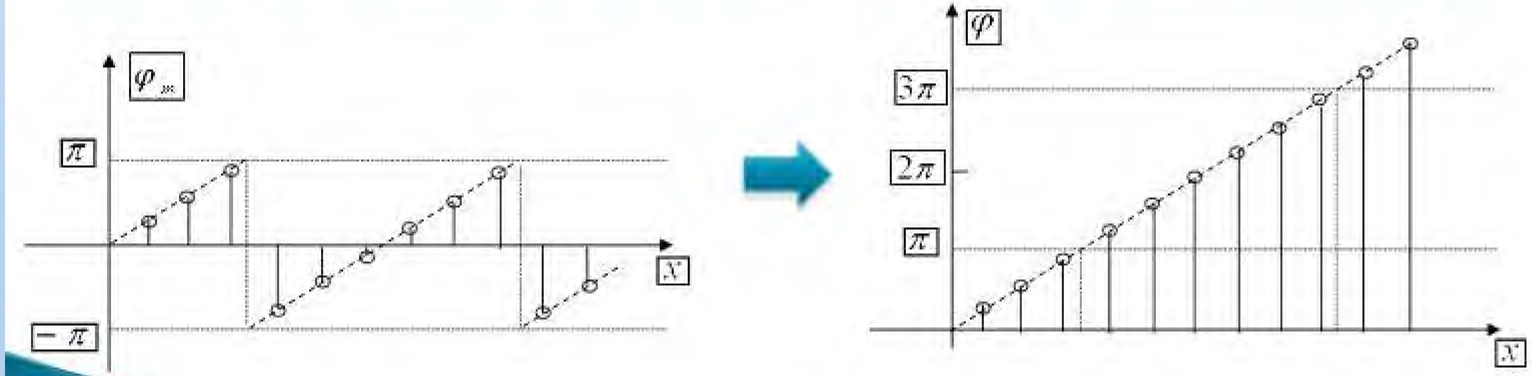


SAR Interferometry (InSAR)

Phase ambiguity

The interferometric phase is generally modulus 2π.

A phase unwrapping method can be then applied to calculate the exact phase value in order to extract correct information about the scene (the elevation).



SAR Interferometry (InSAR)

Phase ambiguity

The interferometric phase component is known save for 2Nπ:

$$\varphi_{\text{int}} = \varphi_f + \varphi_{topo} + \varphi_{displ} + \varphi_{atm} + \varphi_{err} + 2N\pi$$

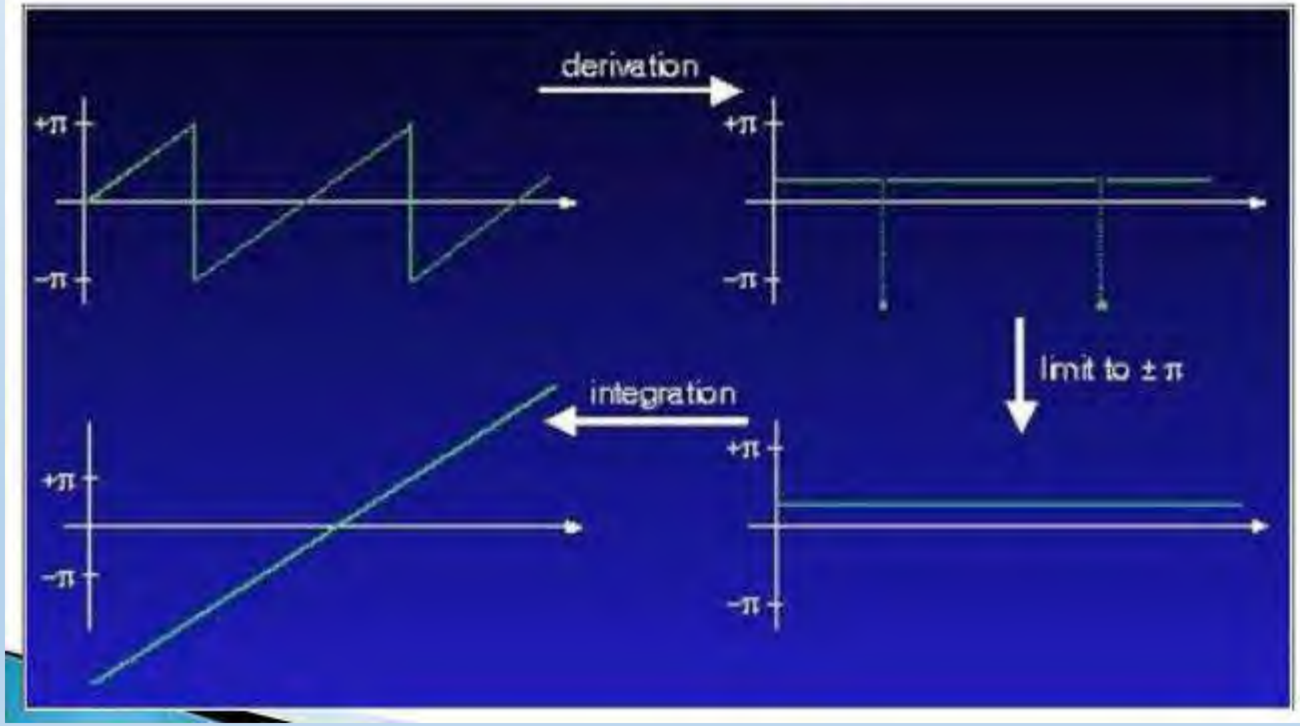
Phase unwrapping algorithms can be applied to retrieve φ from the "wrapped phase" φ_m :

$$\varphi_m = \langle \varphi \rangle$$

$$]-\pi, \pi]$$

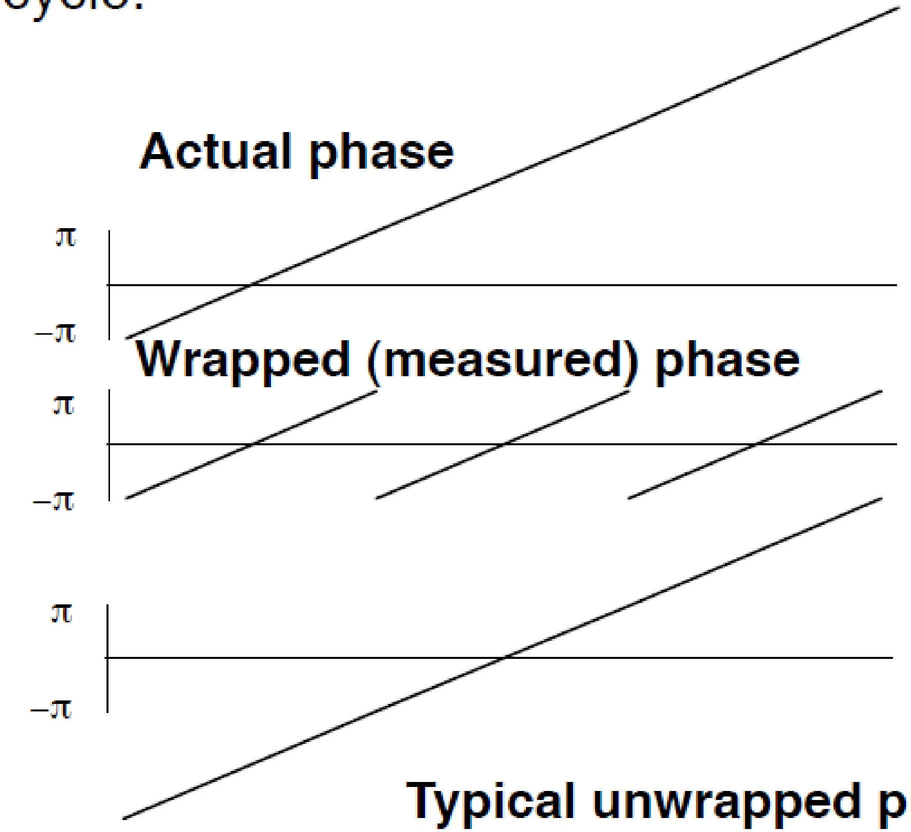
SAR Interferometry (InSAR)

Phase ambiguity



Phase Unwrapping

Elements of the phase unwrapping problem: From the measured, wrapped phase, unwrap the phase from some arbitrary starting location, then determine the proper ambiguity cycle.



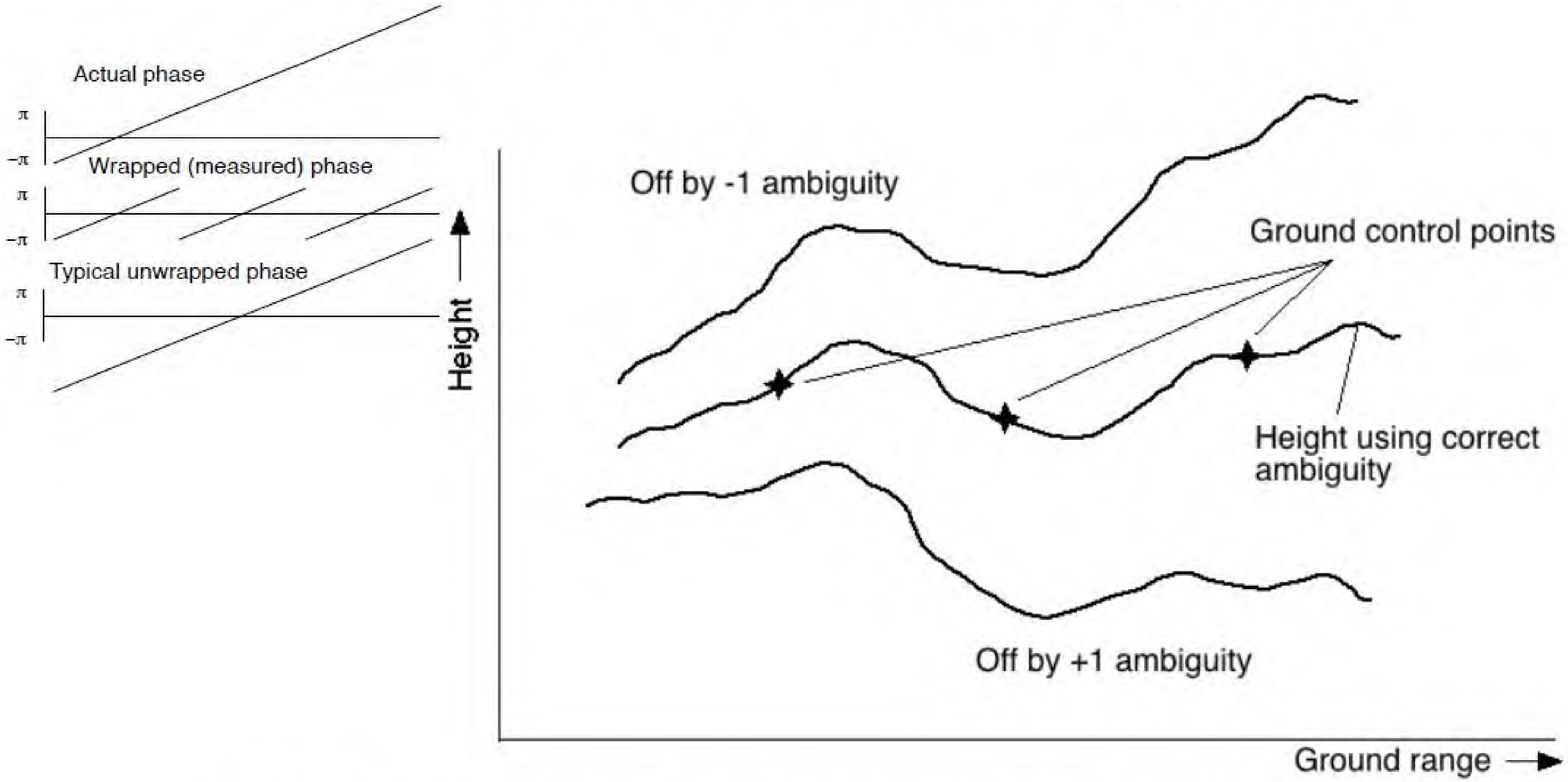
$$\phi = -\frac{4\pi}{\lambda}\left(\rho_1 - \rho_2\right) \cong -\frac{4\pi}{\lambda}\vec{B}\cdot\hat{n}_{los}$$

$$\phi_{meas} = \mathrm{mod}\left(\phi, 2\pi\right)$$

$$\phi_{unw} = \bigcup\left(\phi_{meas}\right) = \phi + 2\pi k$$

where k is an integer to return the absolute phase

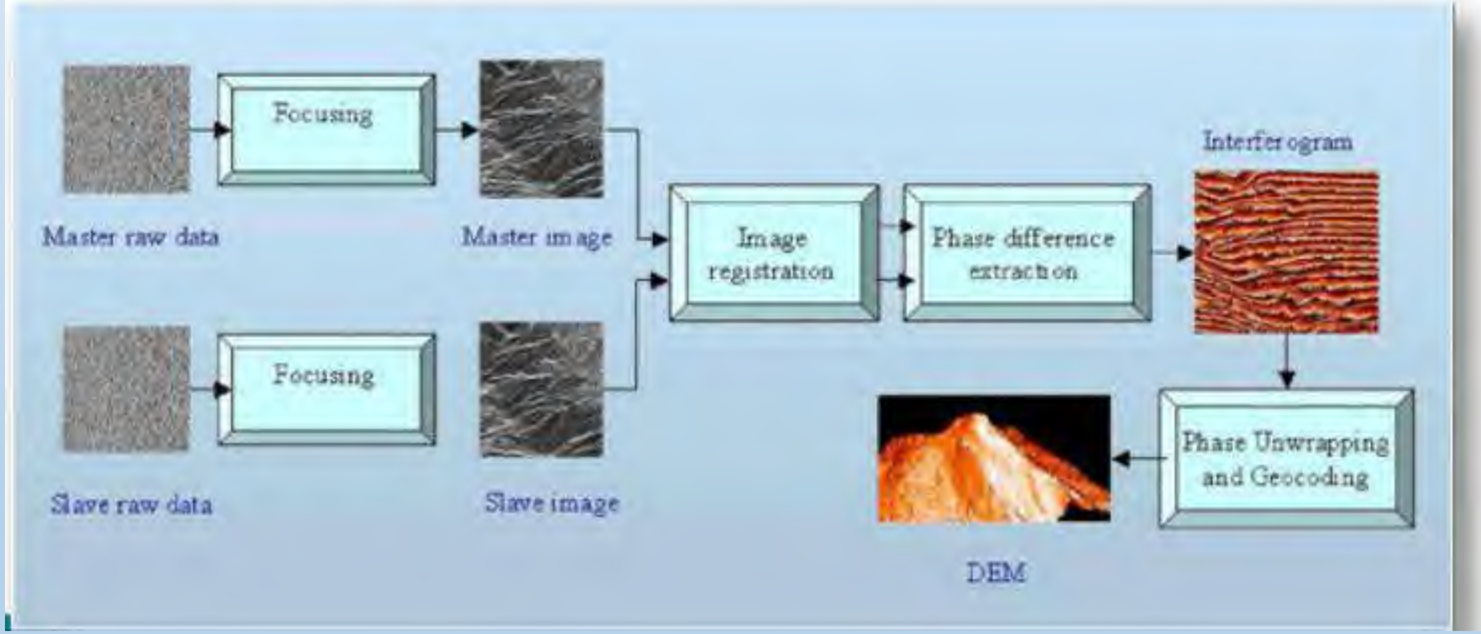
Absolute Phase Determination



Ground control reference points can be used to determine the absolute phase ambiguity

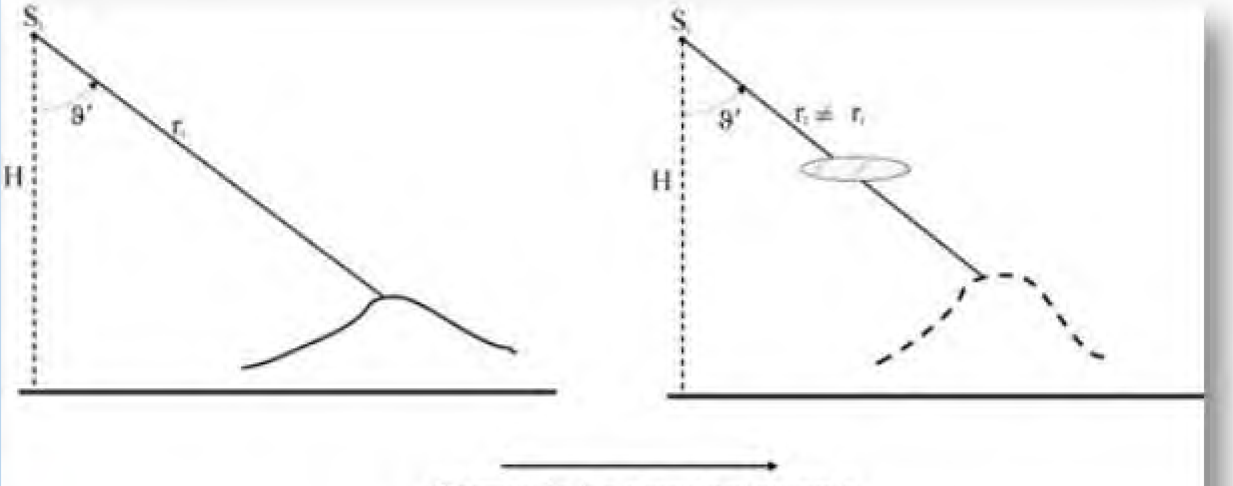
SAR Interferometry (InSAR)

From SAR raw data to Interferogram



SAR Interferometry (InSAR)

Atmospheric phase



Change in the propagation path
due to atmospheric turbolence, no deformation

SAR Interferometry (InSAR)

Atmospheric phase

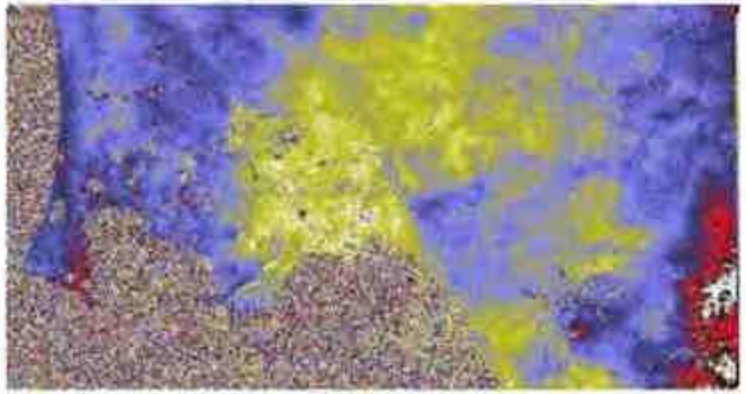
- The phase due to atmospheric artifacts does not depend on the baseline and its sensitivity to the atmosphere is related to the wavelength (Longer wavelengths are less sensitive to atmospheric distortions).

- A propagation delay (Dl) of 2cm would result in an additional phase of an almost full fringe at C-band but only of 1/6th of a fringe at L-band.

- In case of stronger delays, the spatial phase variations might be so large that at higher frequencies phase unwrapping could fail because of more cycles being wrapped.

SAR Interferometry (InSAR)

Temporal decorrelation effects



07/05/1996-08/05/1996
Baseline temp. = 1 day

02/06/1999-06/02/2002

Baseline temp. = 980 days

Baseline ort. = 3 m

Differential SAR Interferometry (DInSAR)

- Differential SAR Interferometry (DInSAR) is an InSAR technique addressed to measure the Earth surface displacements with centimetric accuracy.
- DInSAR is used in seismology, for instance, when an earthquake takes place. Two SAR images, one pre-seismic and one post-seismic, are acquired. The interferometric phase is computed.
- Using a DEM, the topographic phase is canceled. The residual phase contains also the eventual surface deformation effect (differential interferogram). Each differential fringe corresponds to a full phase cycle (2π) and represents a sensor-to-target distance change (LOS change) of $\lambda/2$. For C-Band sensors it is about 2.8 cm.

Differential SAR Interferometry (DInSAR)

Be S1 and S2 two SAR satellites. The interferometric phase is:

$$\varphi_{\text{int}} = \varphi_f + \varphi_{topo} + \varphi_{displ} + \varphi_{atm} + \varphi_{err} + 2N\pi$$

The residual phase contains, besides atmosphere and

Noise phase component, the displacement

projected onto the LOS.

Observed phase is sum of many components

Correlated with baseline

Uncorrelated in time

PS pixels have low noise

$$\phi_{insar} = \phi_{def} + \phi_{topo} + \phi_{atm} + \phi_{orbit} + \phi_{noise}$$

Correlated locally-spatially

Correlated globally-spatially

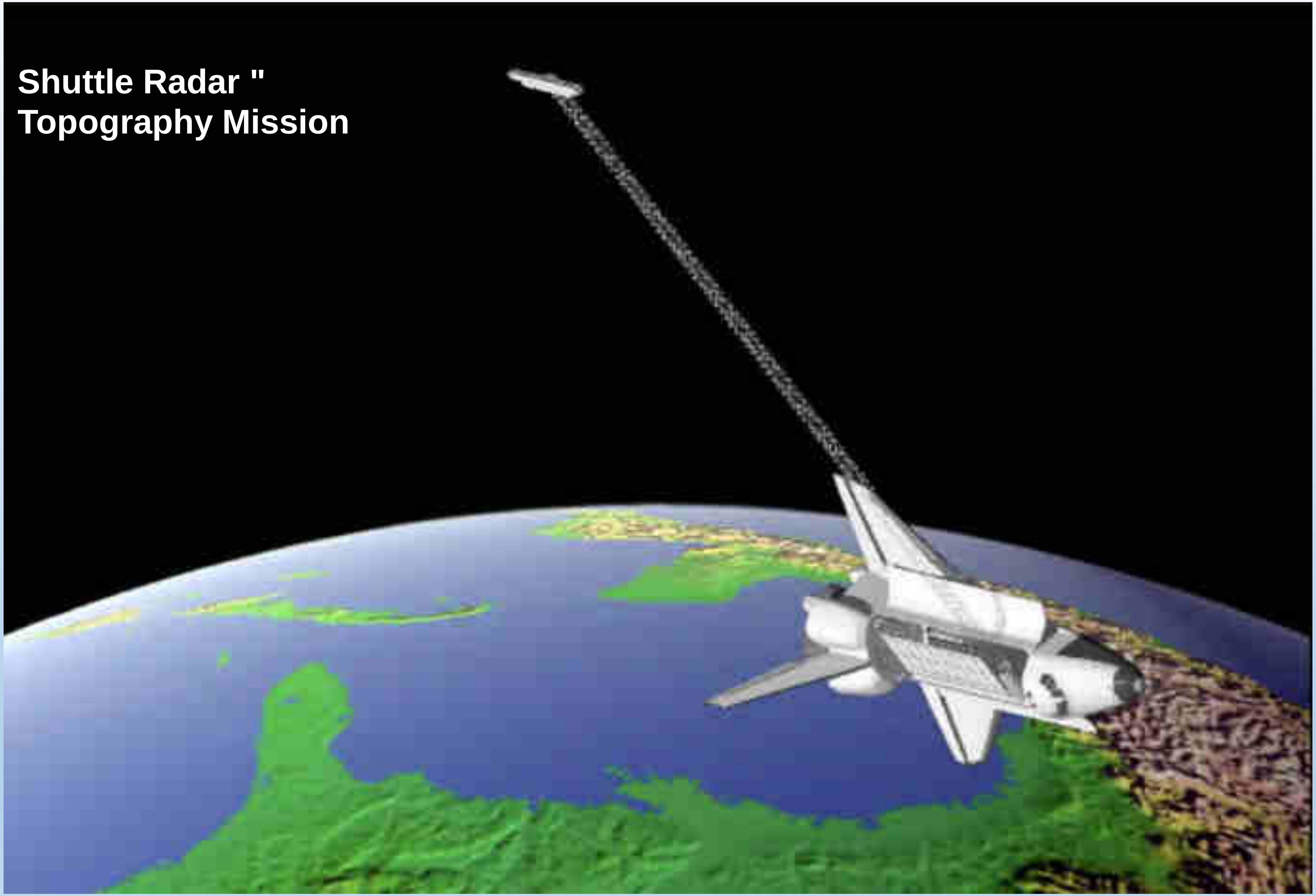
Interferometry Applications"

•" Mapping/Cartography

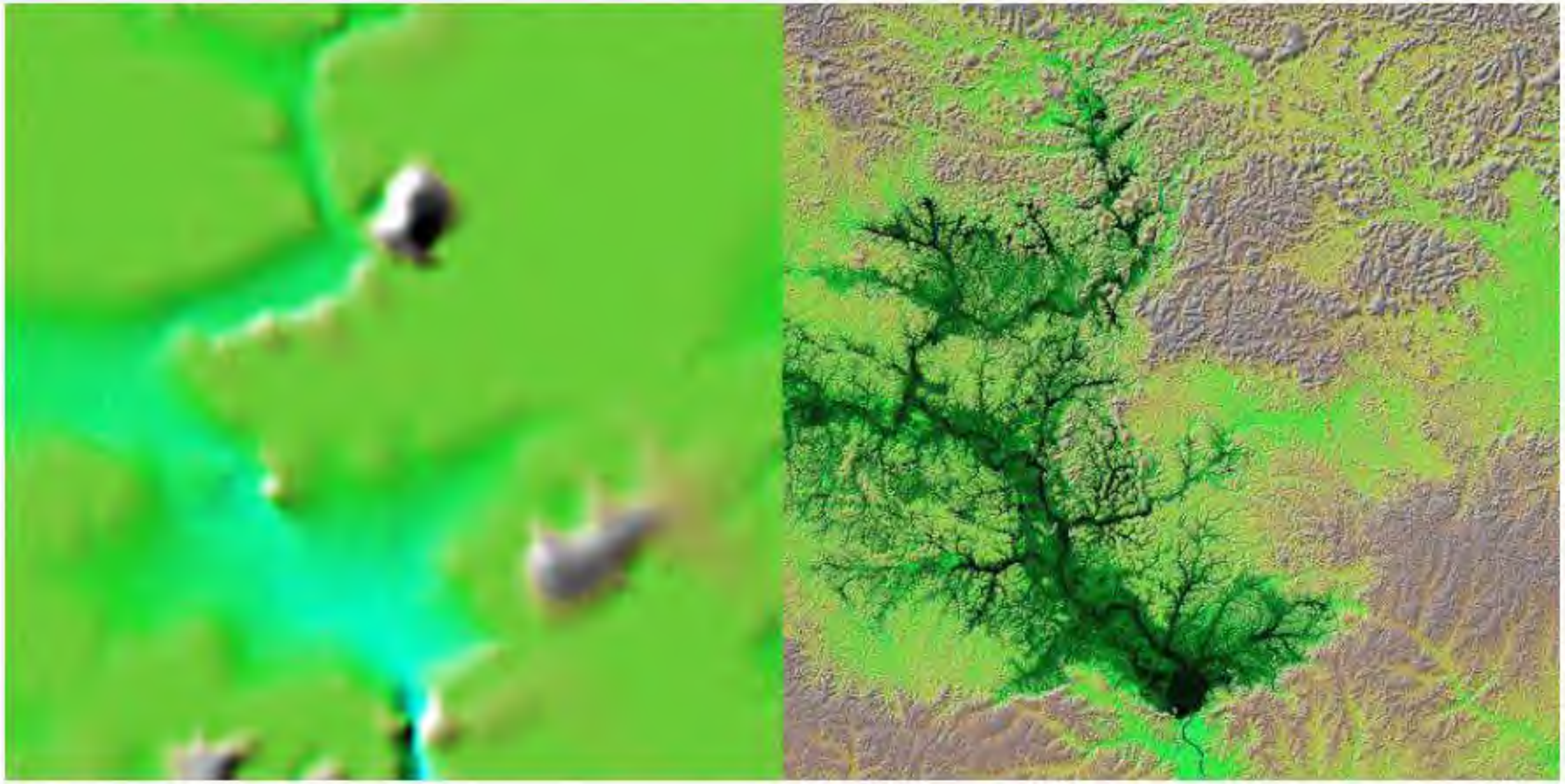
–" Radar Interferometry from airborne platforms is routinely used to produce topographic maps as digital elevation models (DEMs).
•" 2-5 meter circular position accuracy!
•" 5-10 m post spacing and resolution!
•" 10 km by 80 km DEMs produced in 1 hr on mini-supercomputer!
–" Radar imagery is automatically geocoded, becoming easily combined with other (multispectral) data sets.!
–" Applications of topography enabled by interferometric rapid mapping!
•" Land use management, classification, hazard assessment, intelligence, urban planning, short and long time scale geology, hydrology!

•" Deformation Mapping and Change Detection!

–" Repeat Pass Radar Interferometry from spaceborne platforms is routinely used to produce topographic change maps as digital displacement models (DDMs).!
•" 0.3-1 centimeter relative displacement accuracy!
•" 10-100 m post spacing and resolution!
•" 100 km by 100 km DDMs produced rapidly once data is available!
–" Applications include!
•" Earthquake and volcano monitoring and modeling, landslides and subsidence!
•" Glacier and ice sheet dynamics!
•" Deforestation, change detection, disaster monitoring


Shuttle Radar "
Topography Mission

SRTM Resolution Improvement



GTOPO30 DEM

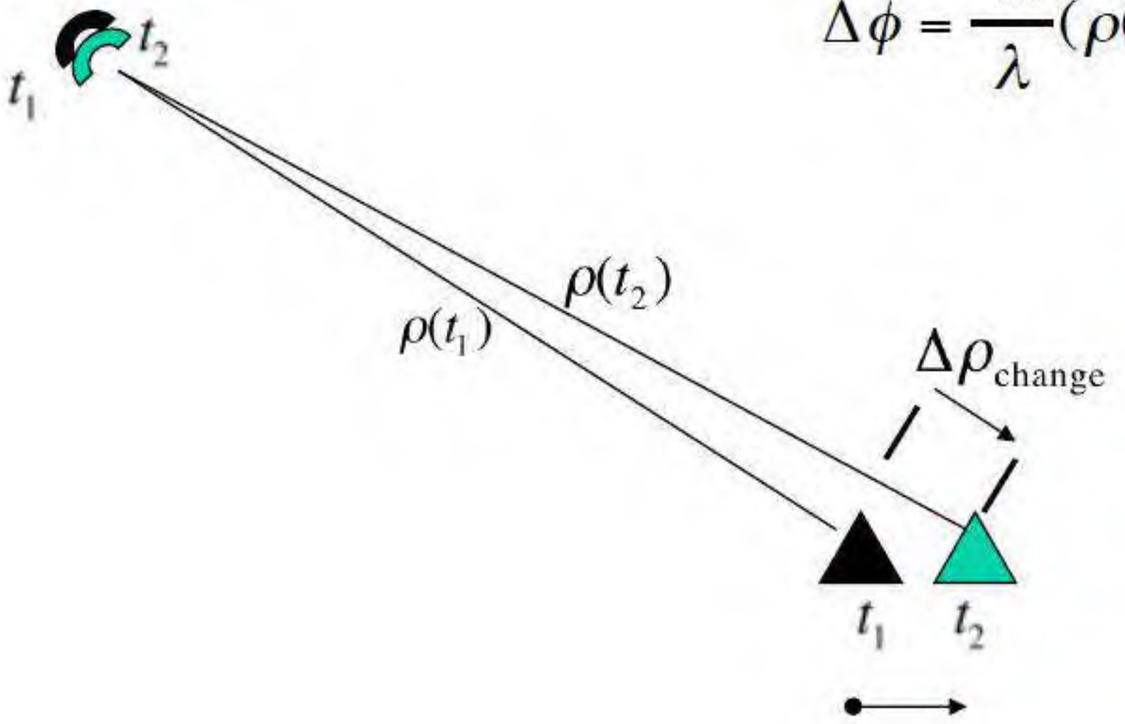
SRTM DEM with radar image overlay

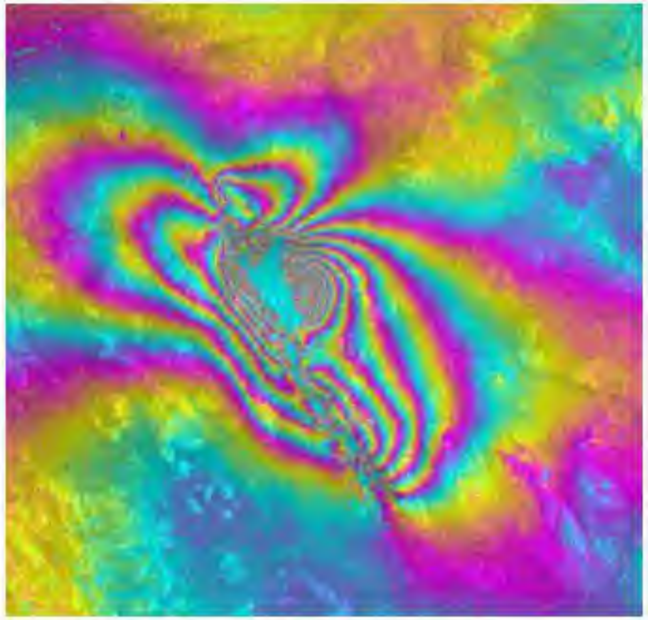
Lake Balbina,
Brazil

Differential Interferometry

When two observations are made from the same location in space but at different times, the interferometric phase is proportional to any change in the range of a surface feature directly.

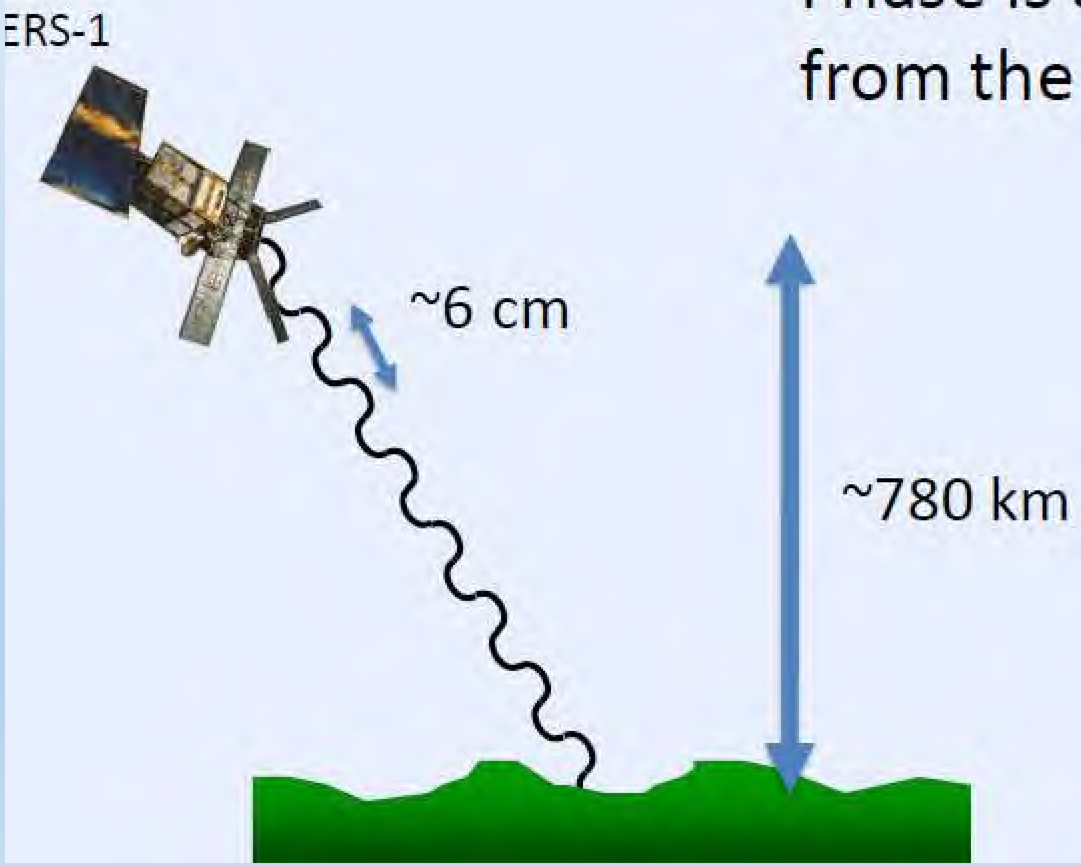
$$\Delta\phi = \frac{4\pi}{\lambda}(\rho(t_1) - \rho(t_2)) = \frac{4\pi}{\lambda}\Delta\rho_{change}$$



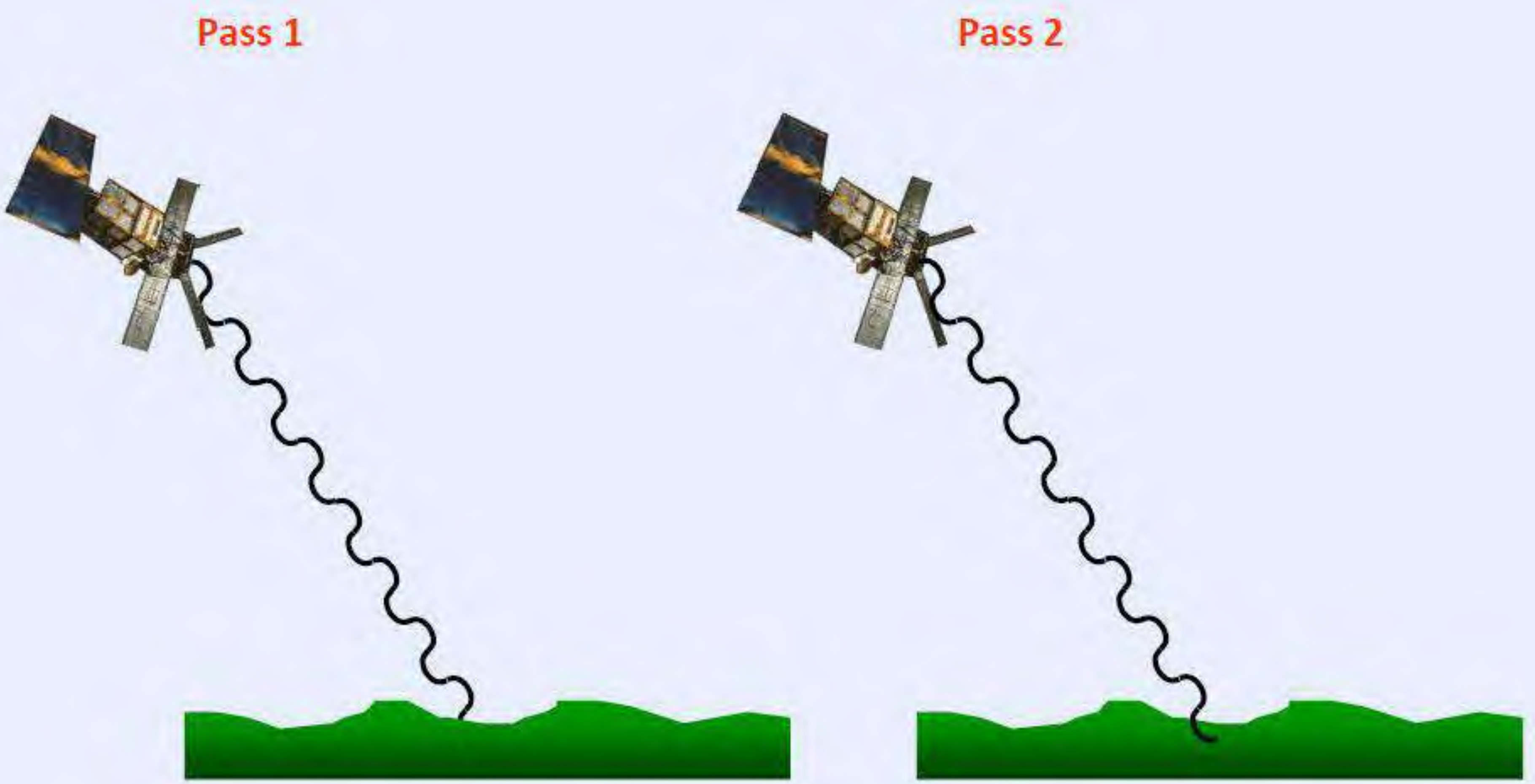


WHAT ABOUT THE PHASE?

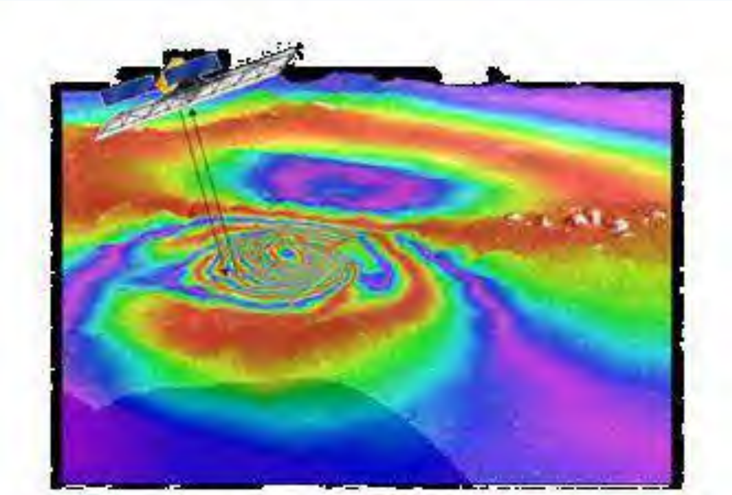
Phase is a function of the distance from the satellite to the ground.

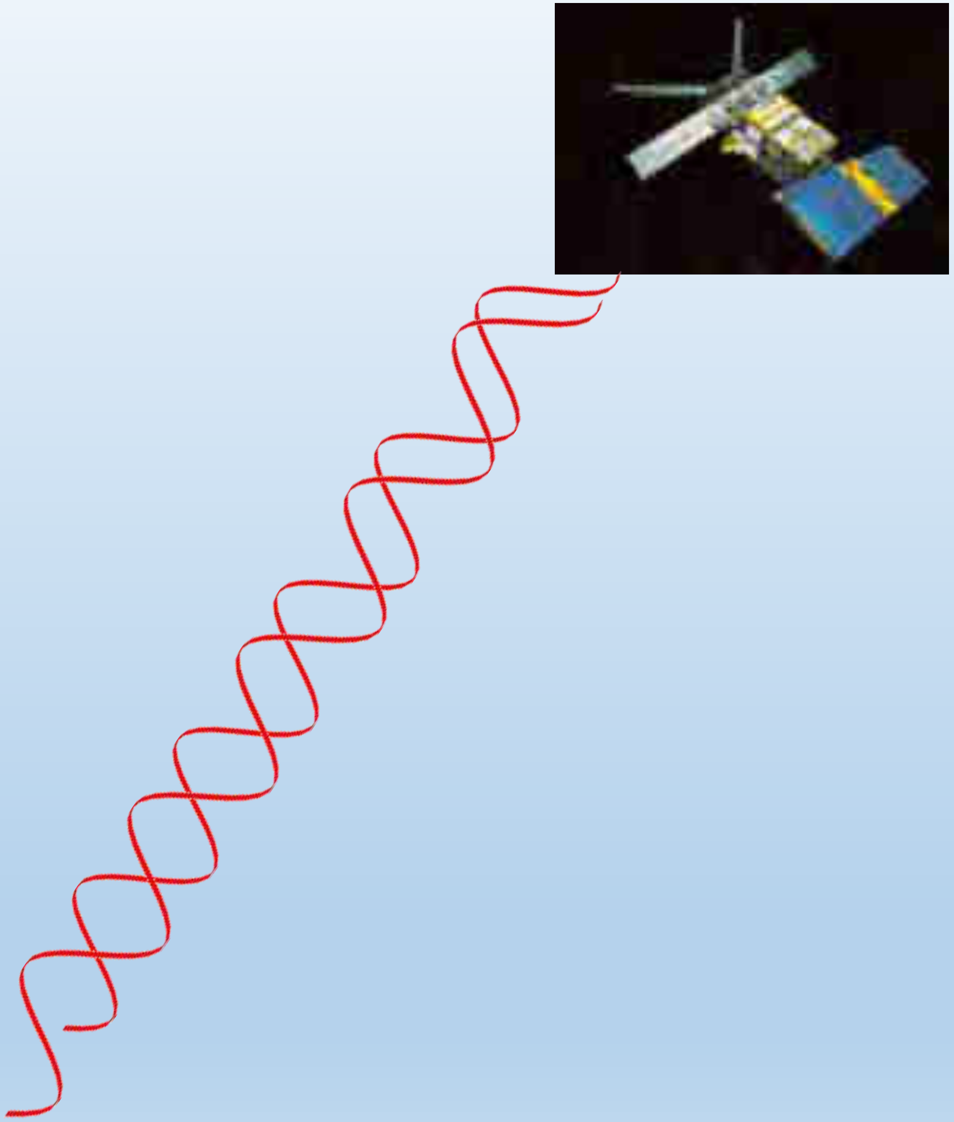


Recall that one wavelength of path length is equivalent to 2π of phase. Given that radar satellites orbit at several hundred km of elevation, it is not feasible to count the number of phase cycles for a single image . . .



. . . So what we do is compare (difference) the phase from two different passes of the same satellite over the same point on the ground. Assuming that we can correct for the position of the satellite (and we can), then any difference in phase between the two passes must be related to a change in distance between the satellite and the ground (i.e. a movement of the ground).





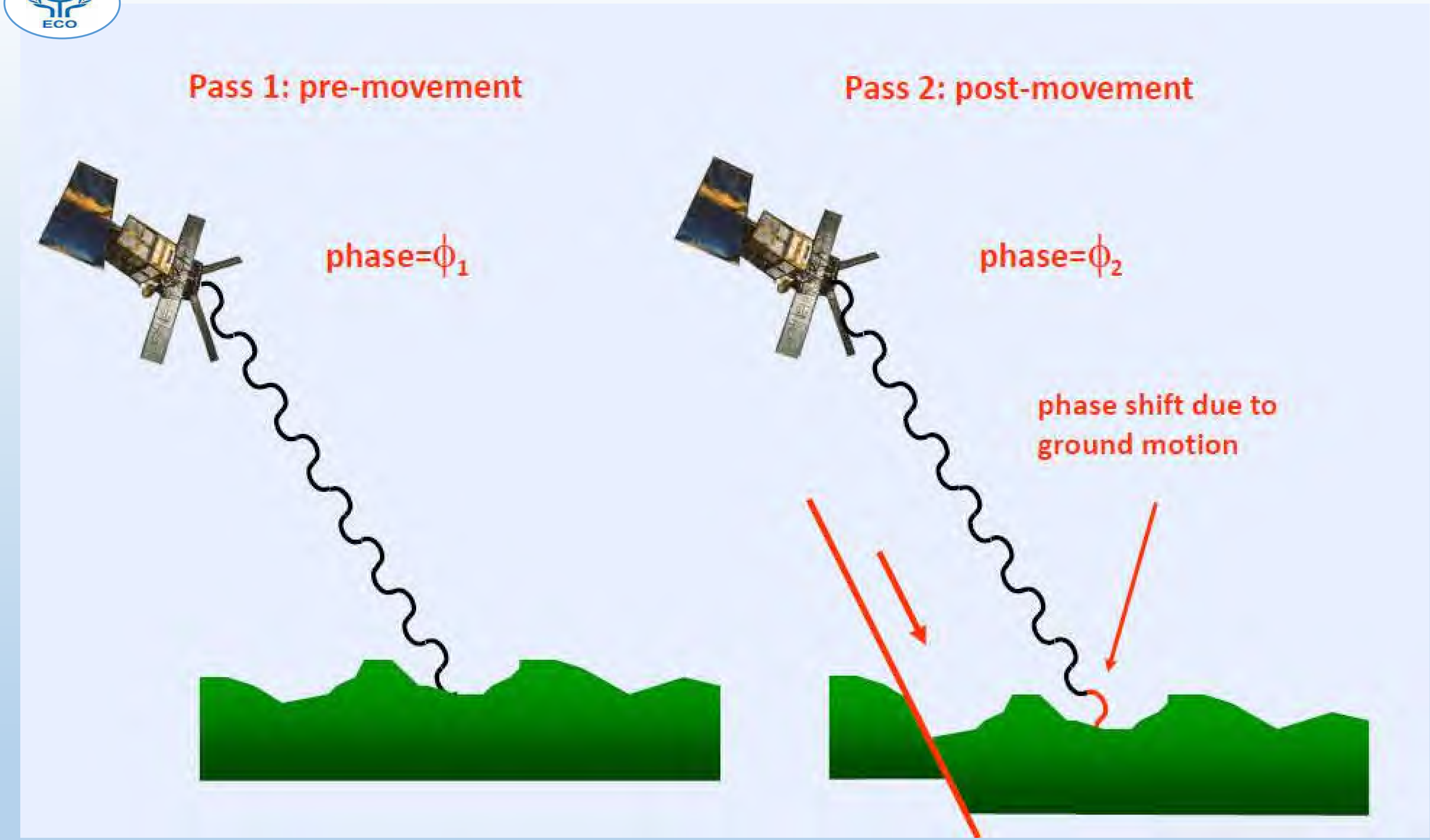
1- first image

2- earth displacement

3- second image

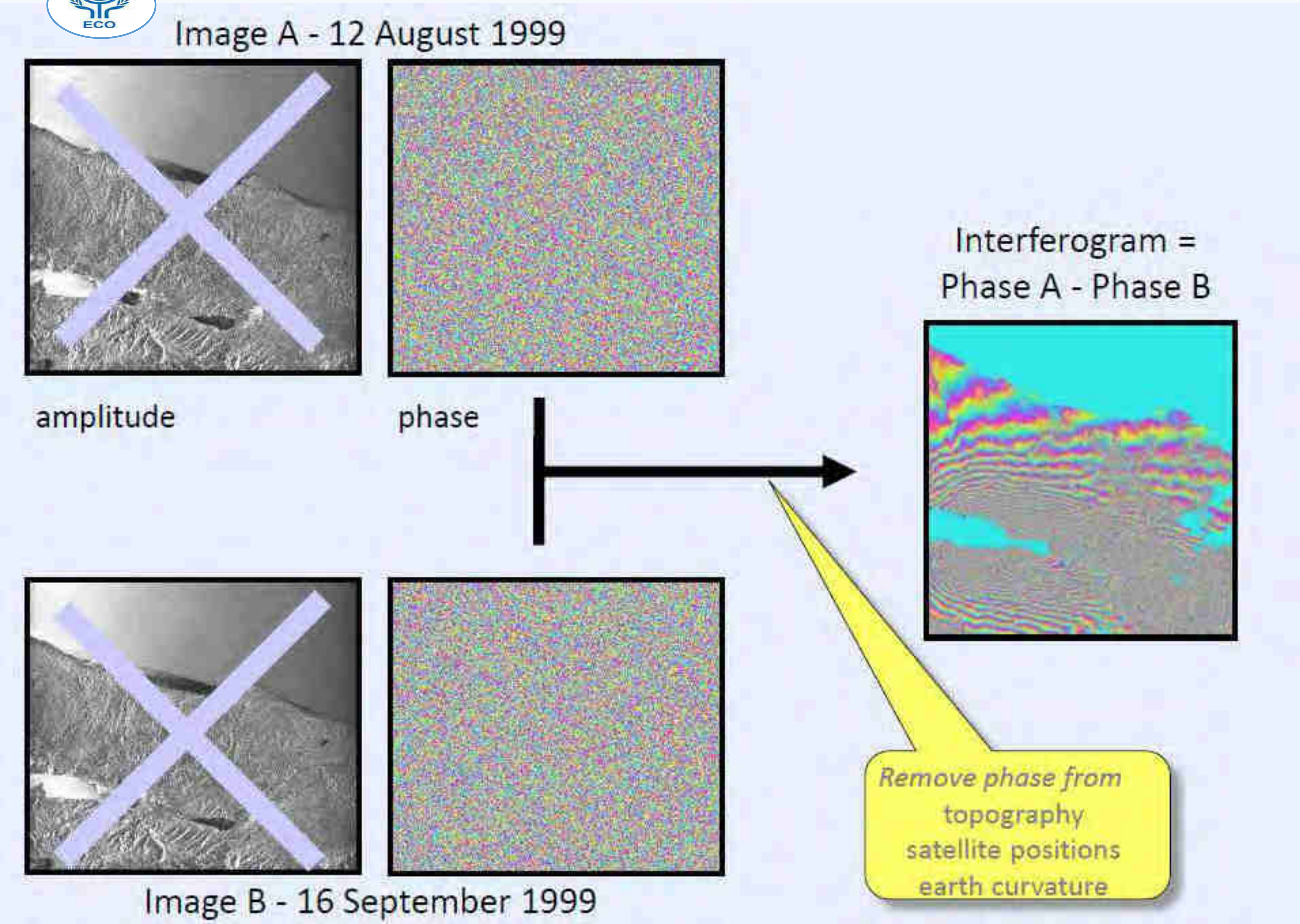
4- measuring the phase difference between 2 images

5- calculating displacement

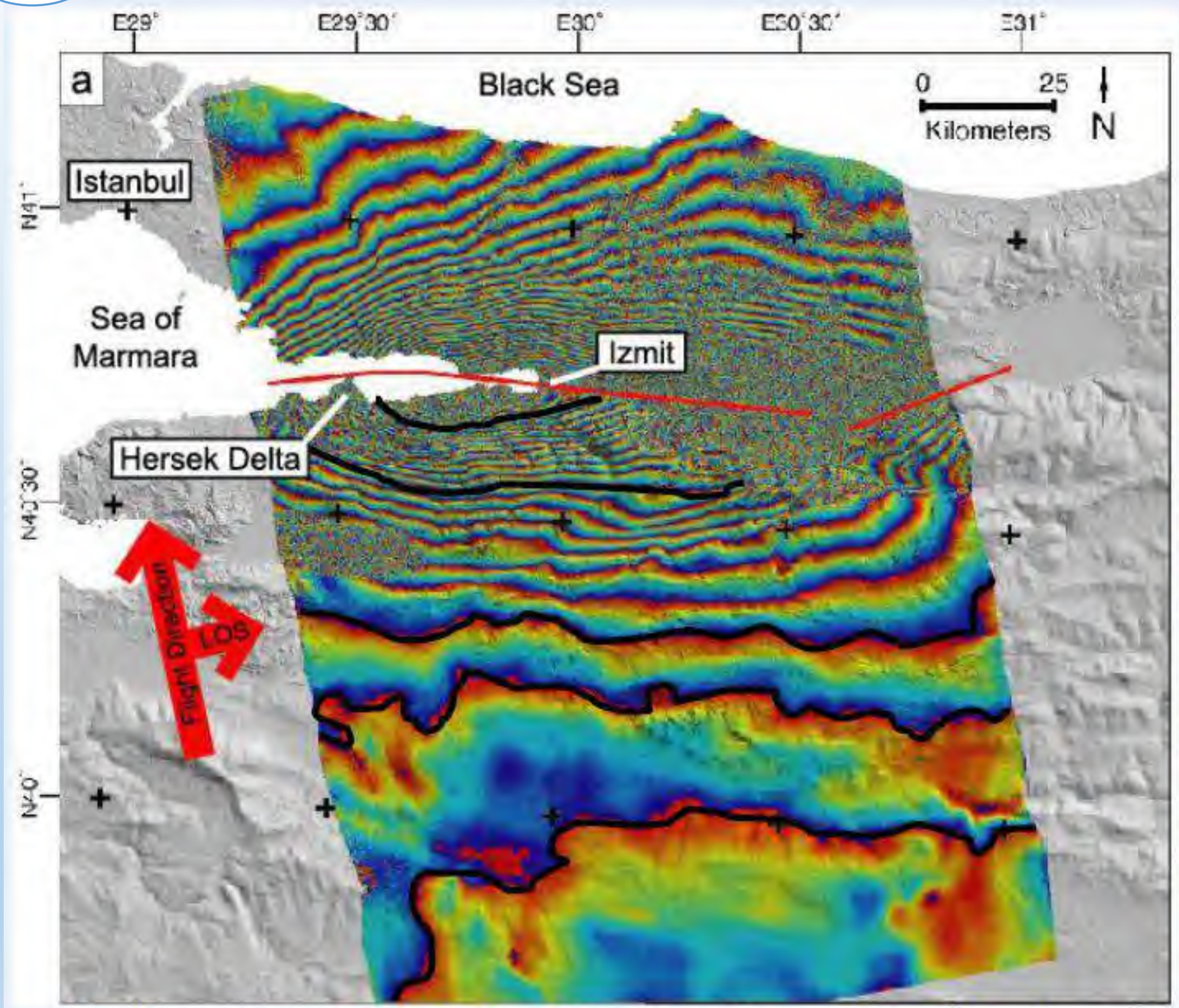


So if the ground moves, we can detect a phase shift when we subtract the phase of the second image from the phase of the first!

It is important to note that we can only measure displacement of the ground toward or away from the satellite, in the line-of-sight direction between the two. Everything we measure is a “line-of-sight” displacement.



Here is how w e an InSAR ima (we call them "interferograms"). Two SAR images are shown, amplitudes on the left, phases on the right. They are both from the same area of Turkey, acquired five weeks apart in the summer of 1999. The amplitude images are used to match and align the two SAR images to each other, to make sure that when you difference the phase, you are differencing the phase for the "same" pixels. The various corrections that are made to the phase rely



(-20) 567 mm range decrease

(-10) 283 mm range decrease

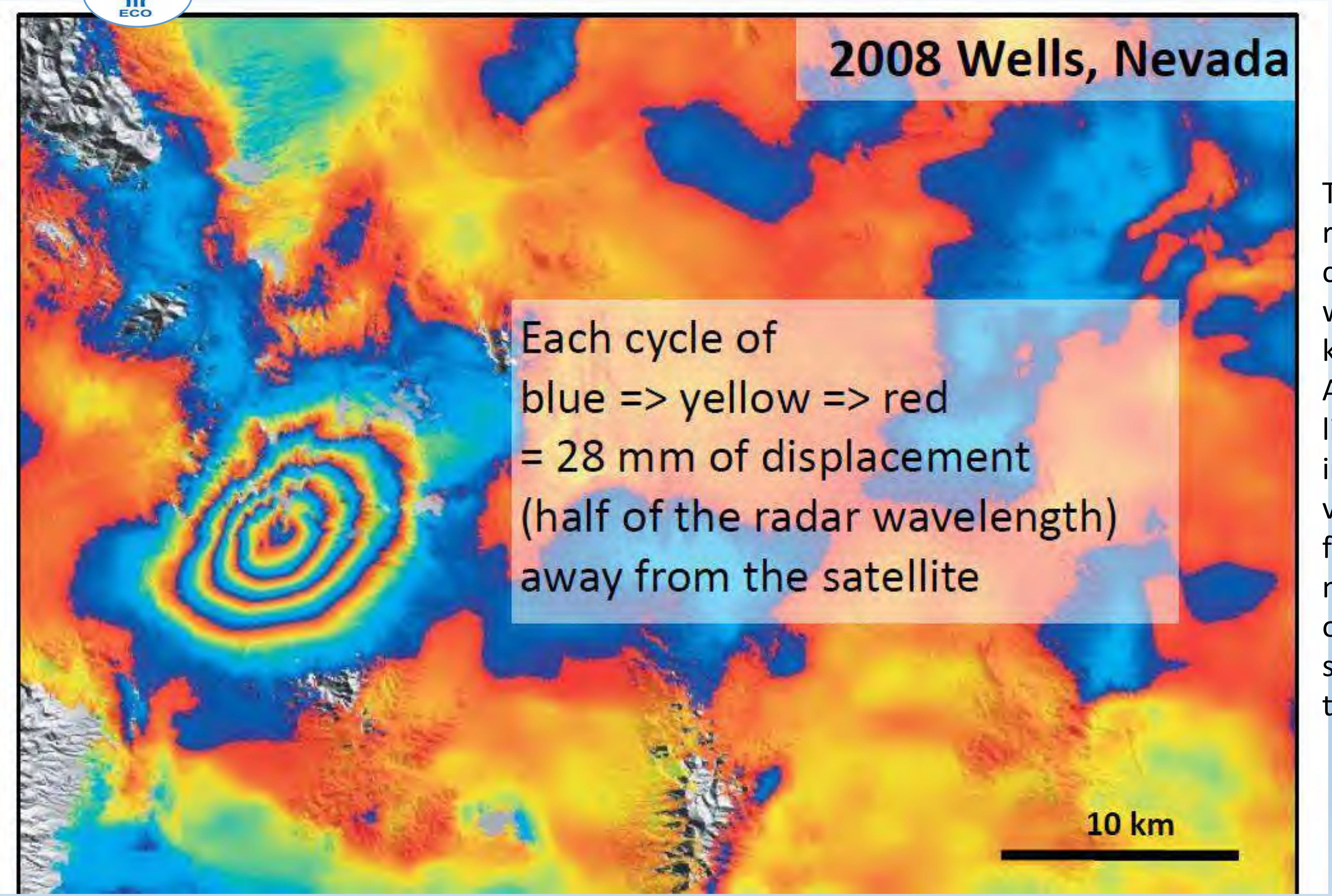
(-2) 57 mm range decrease

(-1) 28 mm range decrease

(0) 0 mm range change

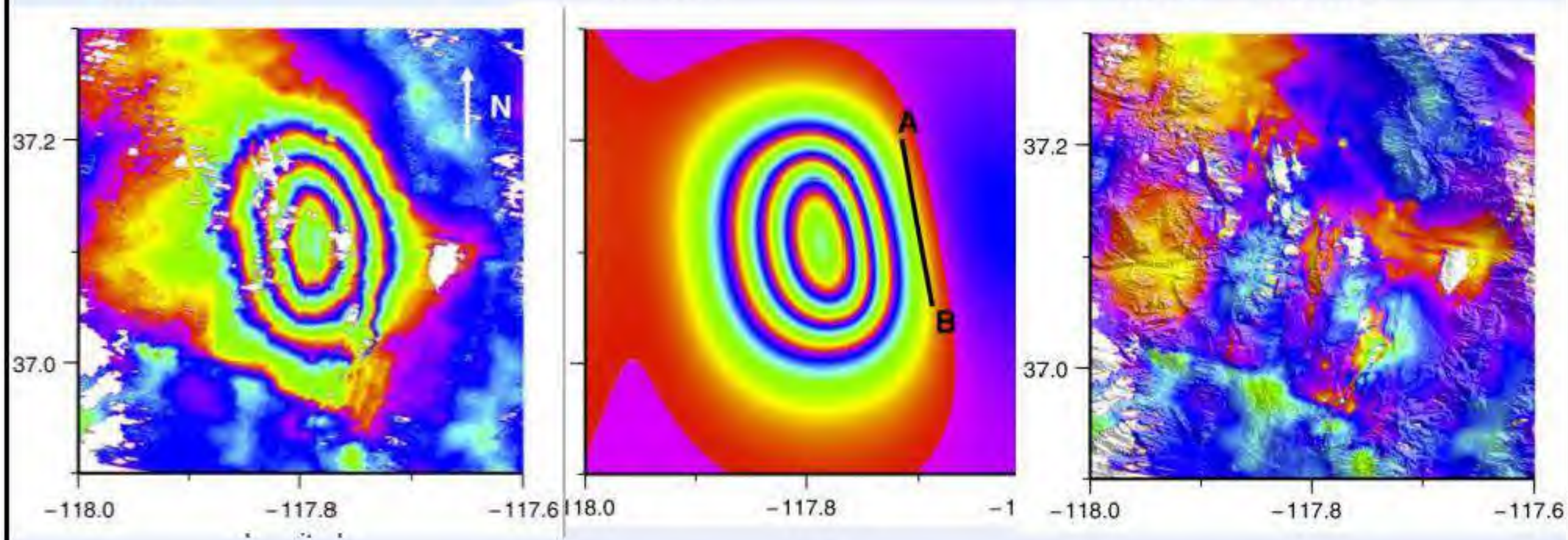
17 August 1999, Izmit earthquake (Turkey)

Tim Wright



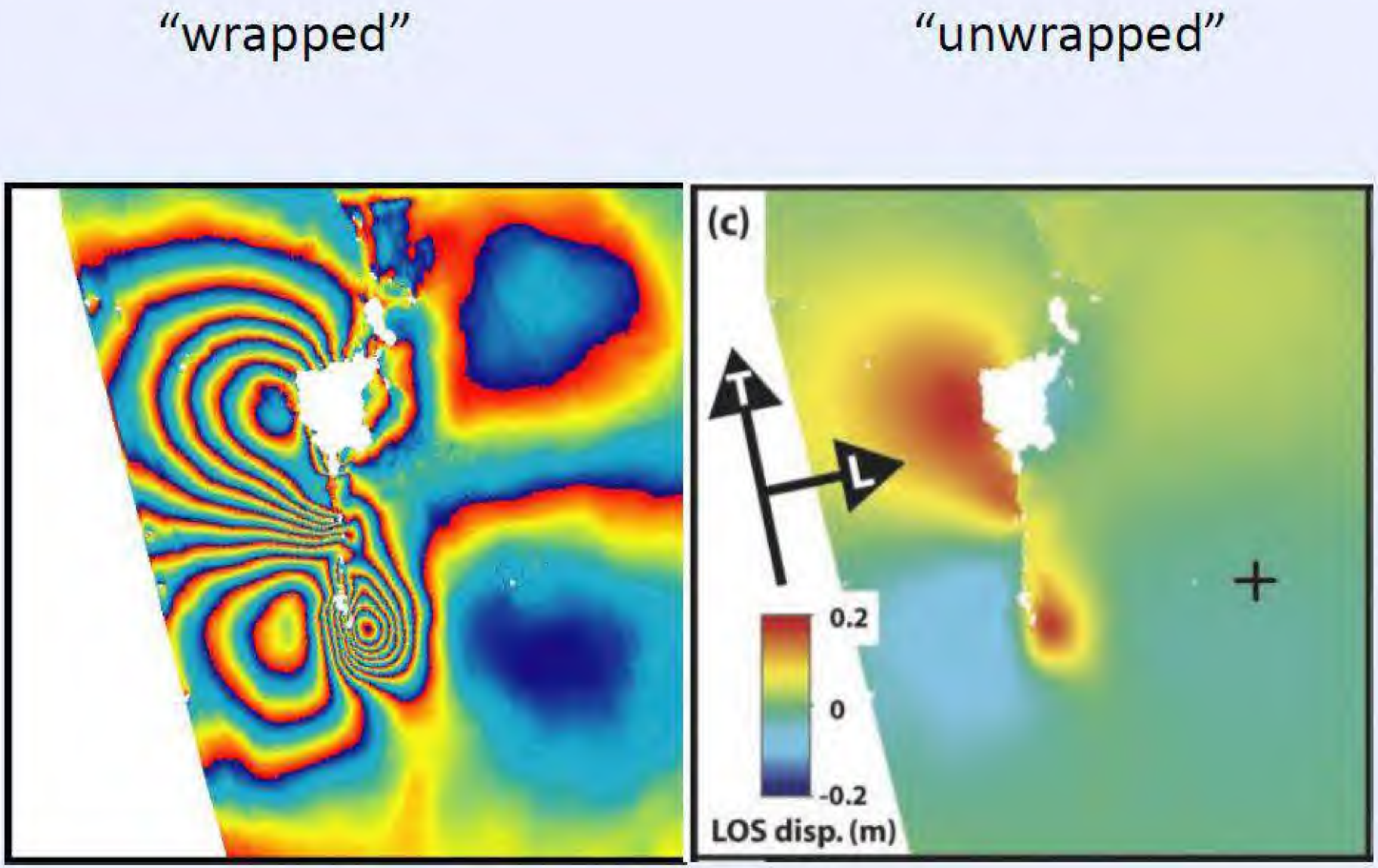
The earthquake is represented by four concentric fringes. The whole pattern is about 10 km long and 8 km wide. Assuming that all of the line-of-sight deformation in this case represents vertical deformation, the four fringes represent a maximum of about 12 cm of subsidence of the surface, at the center of the pattern.

data | model | data – model

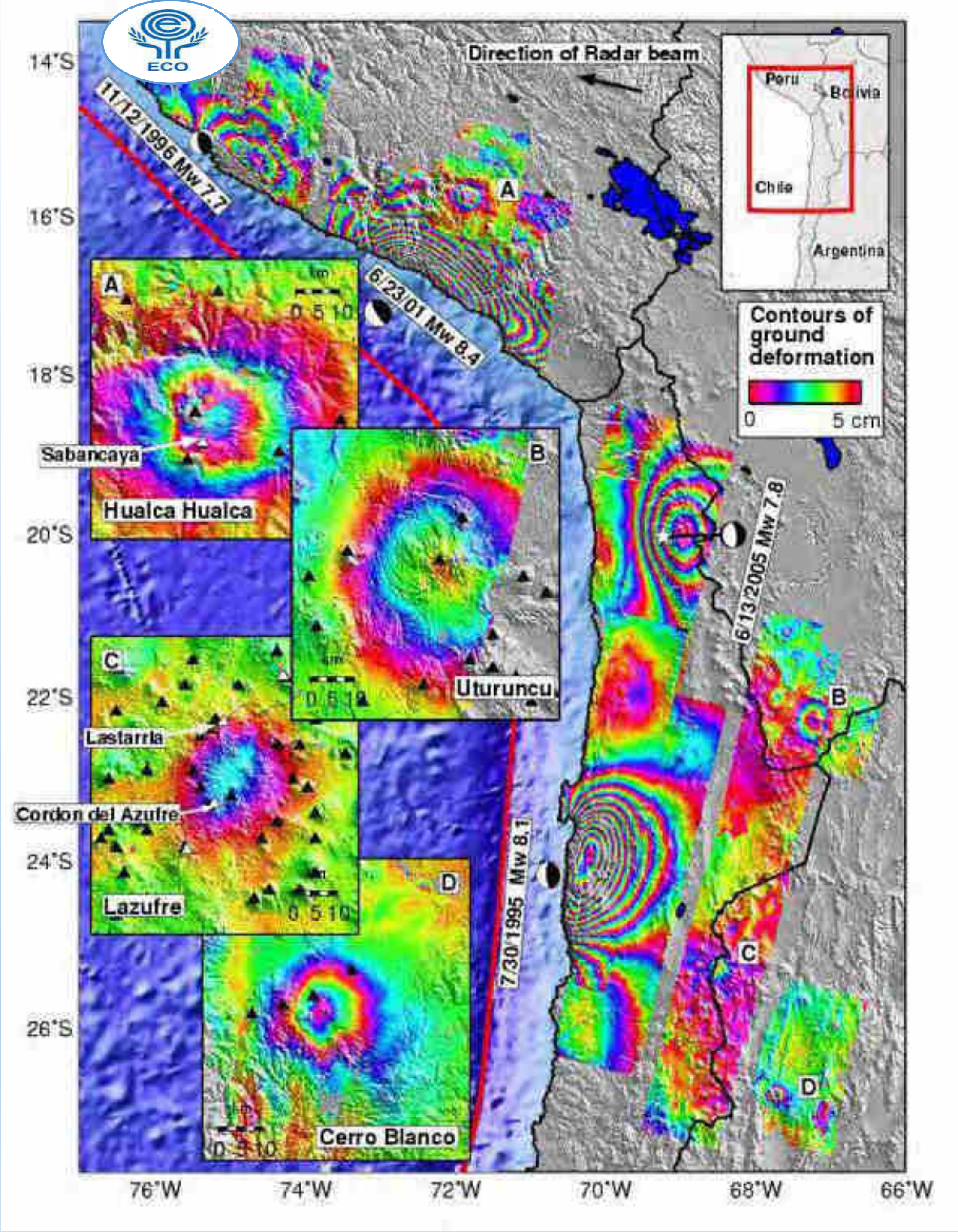


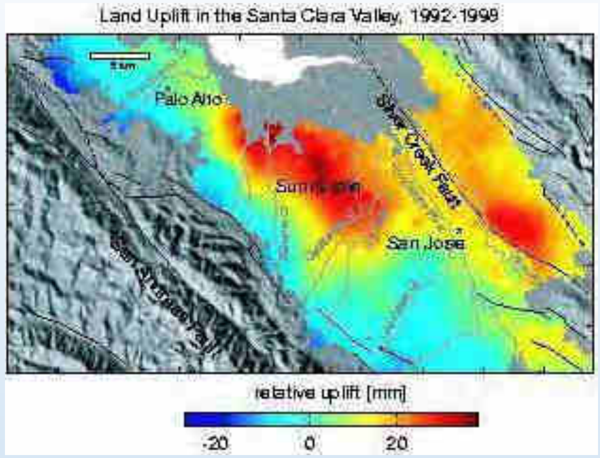
Strike:	172°
Dip:	38°
Rake:	–95°
M_w:	6.06

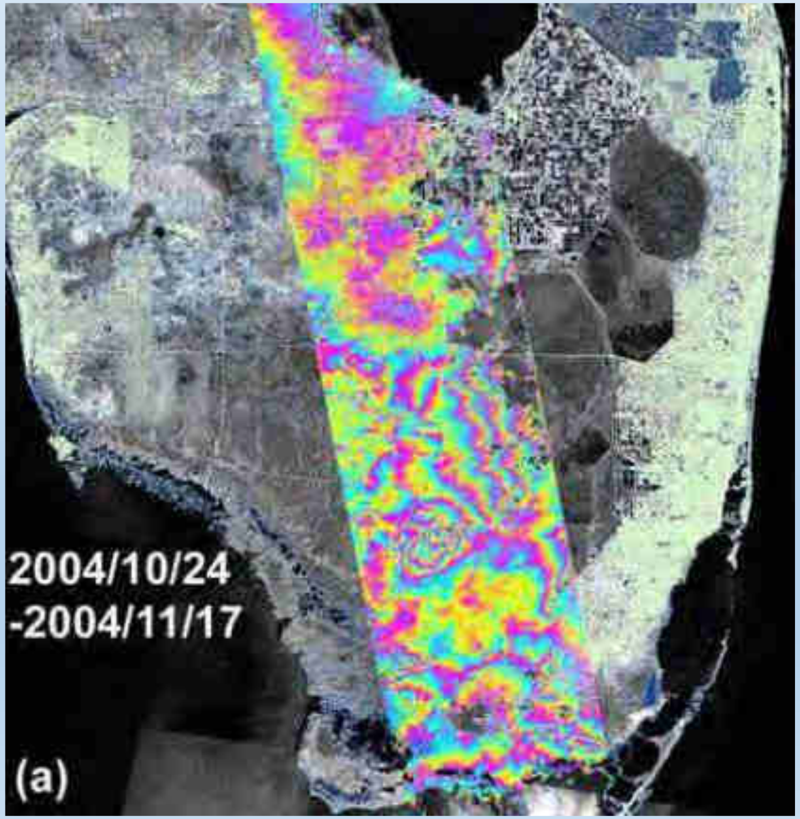
Weston et al., 2012

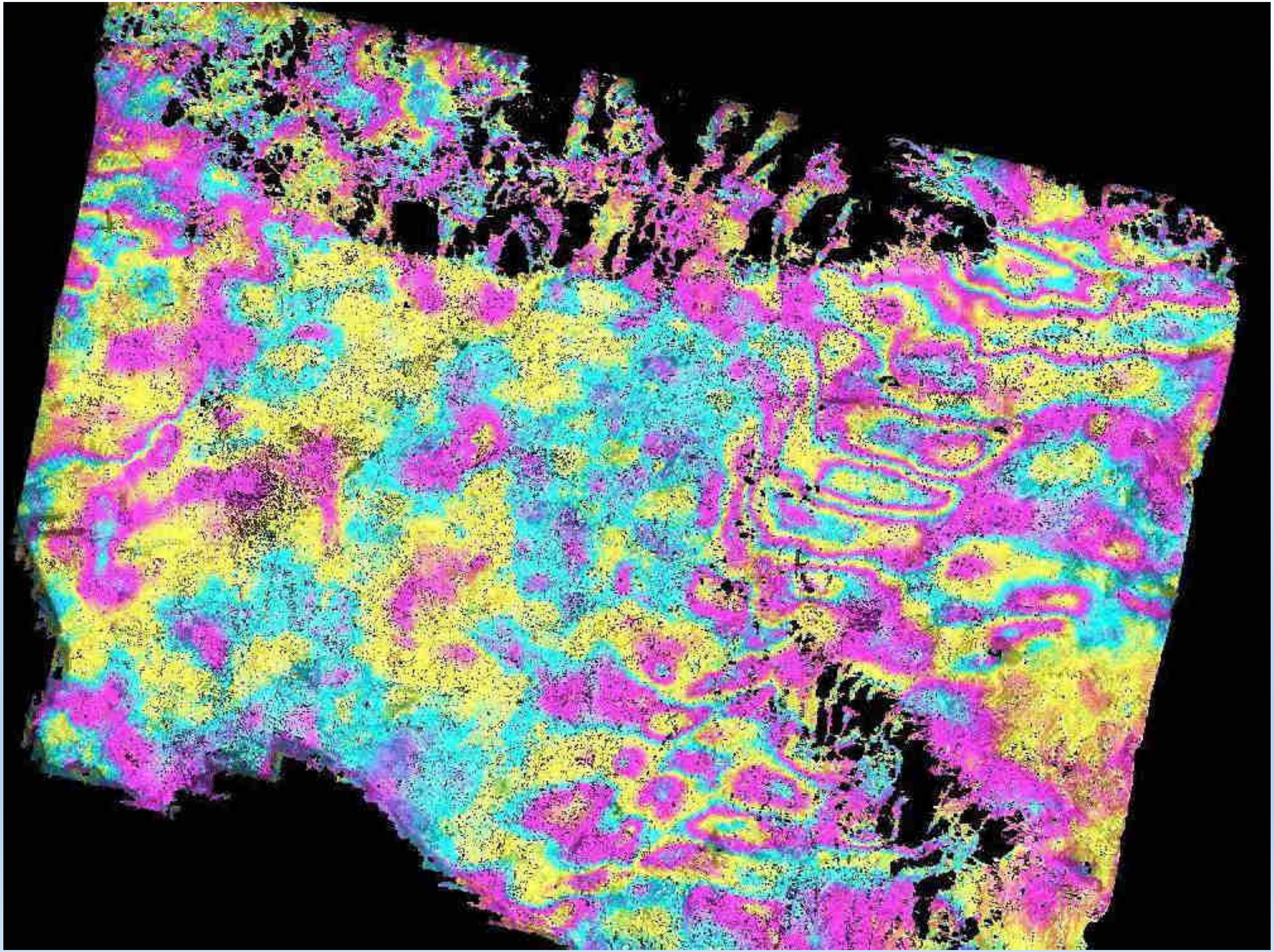


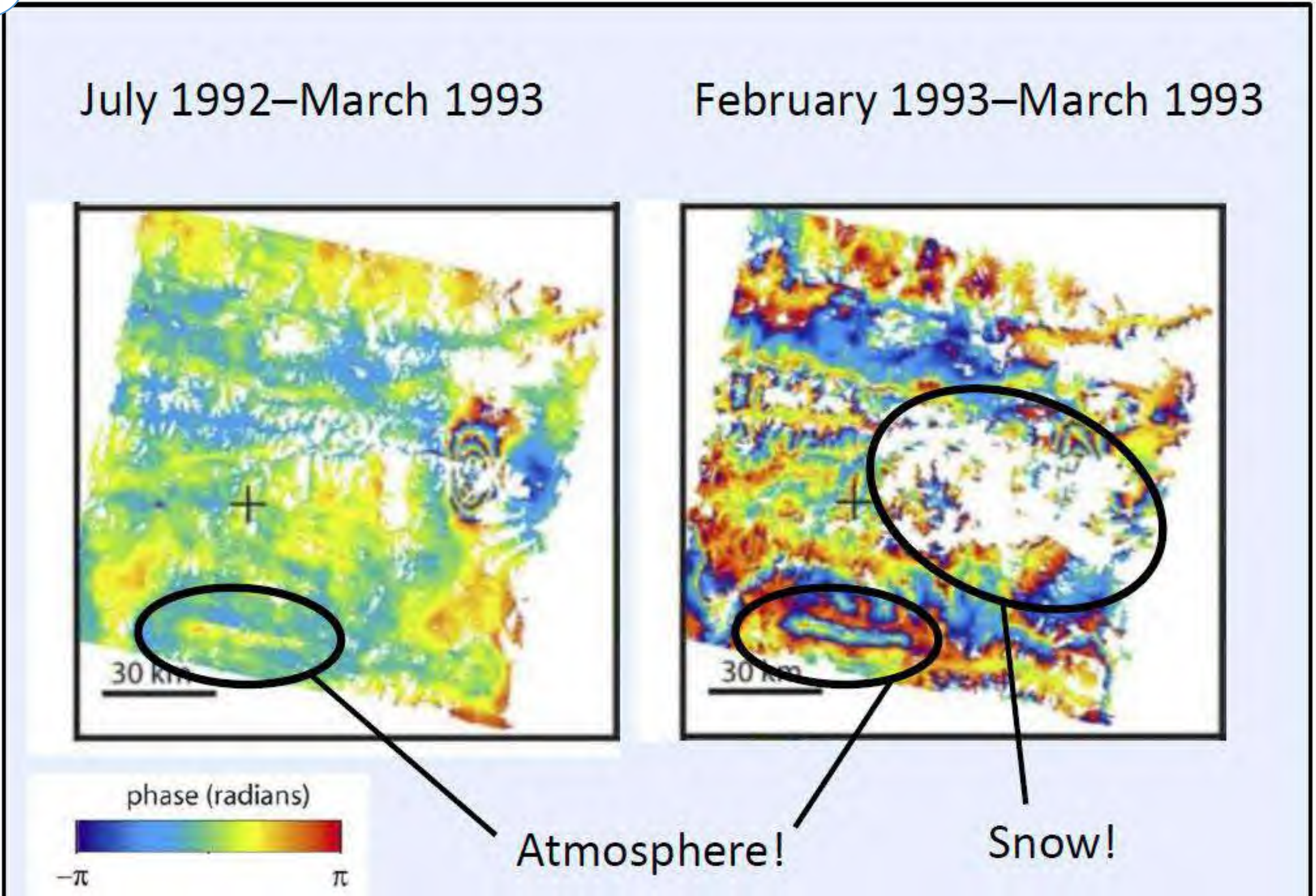
an interferogr strike-slip eart (Bam, Iran, 20 presented two different ways. On the left is the "wrapped" interferogram, which is the form we have seen several times already, with multiple fringes defining the deformation pattern . On the right is an "unwrapped" interferogram where the displacements associated with each fringe have been added together to give the total displacement—these are typically easier to interpret than the wrapped interferograms


Direction of Radar beam
Peru
Bolivia
Chile
Argentina
Contours of ground deformation
0
5 cm
11/12/1996 Mw 7.7
6/23/01 Mw 8.4
6/13/2005 Mw 7.8
7/30/1995 Mw 8.1
14°S
16°S
18°S
20°S
22°S
24°S
26°S
76°W
74°W
72°W
70°W
68°W
66°W
A
B
C
D
Sabancaya
Hualca Hualca
Uturuncu
Lastarria
Cordon del Azufre
Lazufre
Cerro Blanco
km
0 5 10


Land Uplift in the Santa Clara Valley, 1992-1999
Palo Alto
Sunnyvale
San Jose
Silver Creek Fault
San Andreas Fault
relative uplift [mm]
-20
0
20


2004/10/24
-2004/11/17
(a)





July 1992–March 1993
February 1993–March 1993
30 km
30 km
phase (radians)
−π
π
Atmosphere!
Snow!

Atmospheric "Noise"

Refraction of microwaves by water vapor
"Static" part can resemble topography
"Turbulent" part can resemble deformation

DECORRELATION

Changes in radar scattering properties of pixels
Vegetation, snow, flooding, the passage of time…
Longer radar wavelengths less susceptible

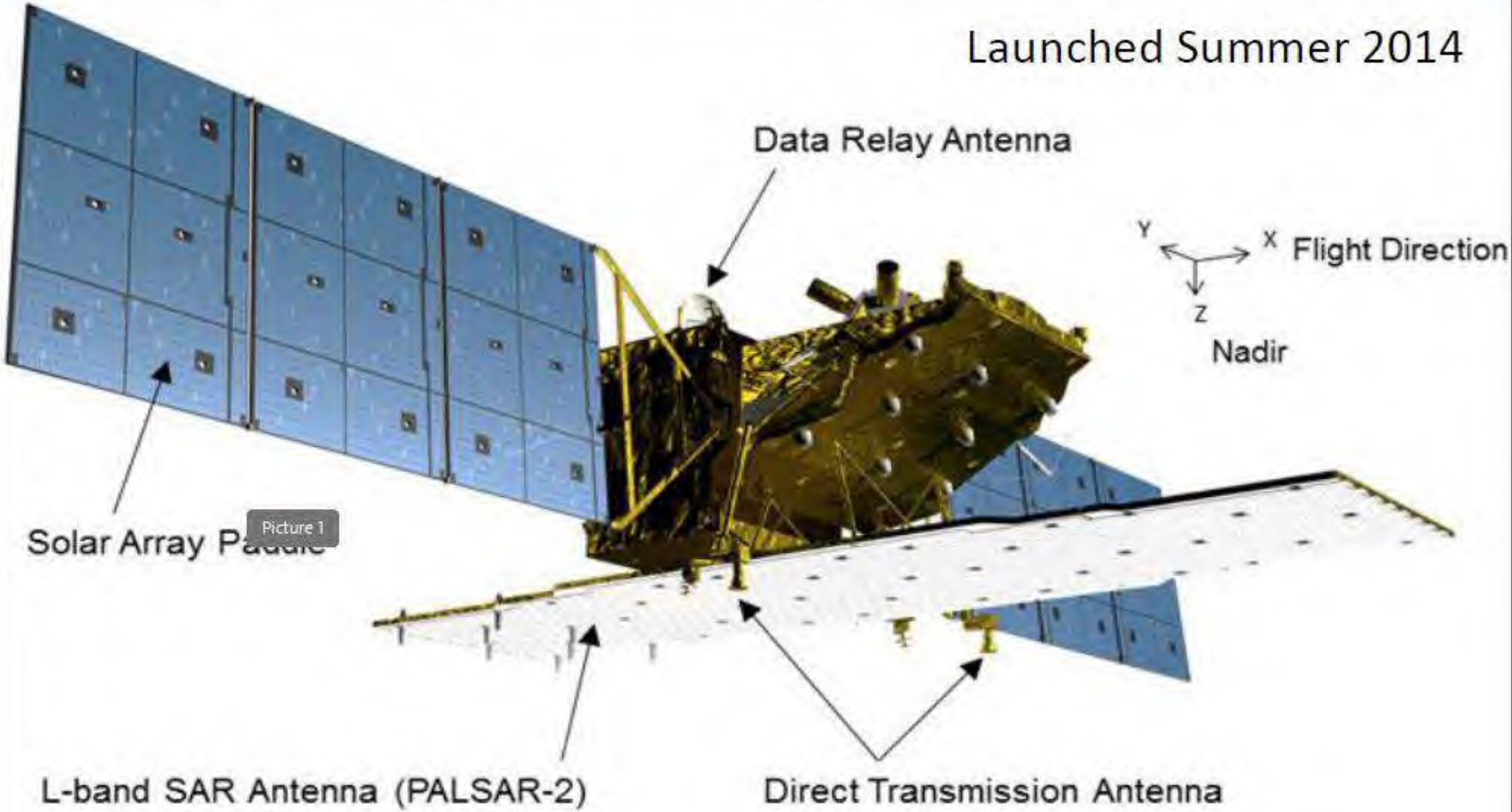

SENTINEL-1A and -1B
European Space Agency
Launch Q2 2014, 2016
12 (and then 6) day repeat in same orbit
mean post event wait => 3 days
ascending + descending => mean wait < 3 days

ALOS-2 by Japanese Aerospace Exploration Agency

14-day repeat in same orbit

23 cm wavelength – less decorrelation

Launched Summer 2014



Strengths and Limitations"

•" The major strengths for using radar differential interferometry are!

–" Wide area coverage!
–" Millimeter scale accuracy locally!
–" Geophysically useful even without other data sets!
–" Complementary to established geodetic and seismic tools
(e.g. GPS and leveling)!

•" Although there has been great success using radar differential interferometry for deformation measurement its application can be limited by!

–" Temporal decorrelation of the surface!
–" Other surface changes!
–" Atmospheric and ionospheric effects!
–" Poor DEM availability and Quality or lack of DEM pair