InSAR: theory and interferogram processing

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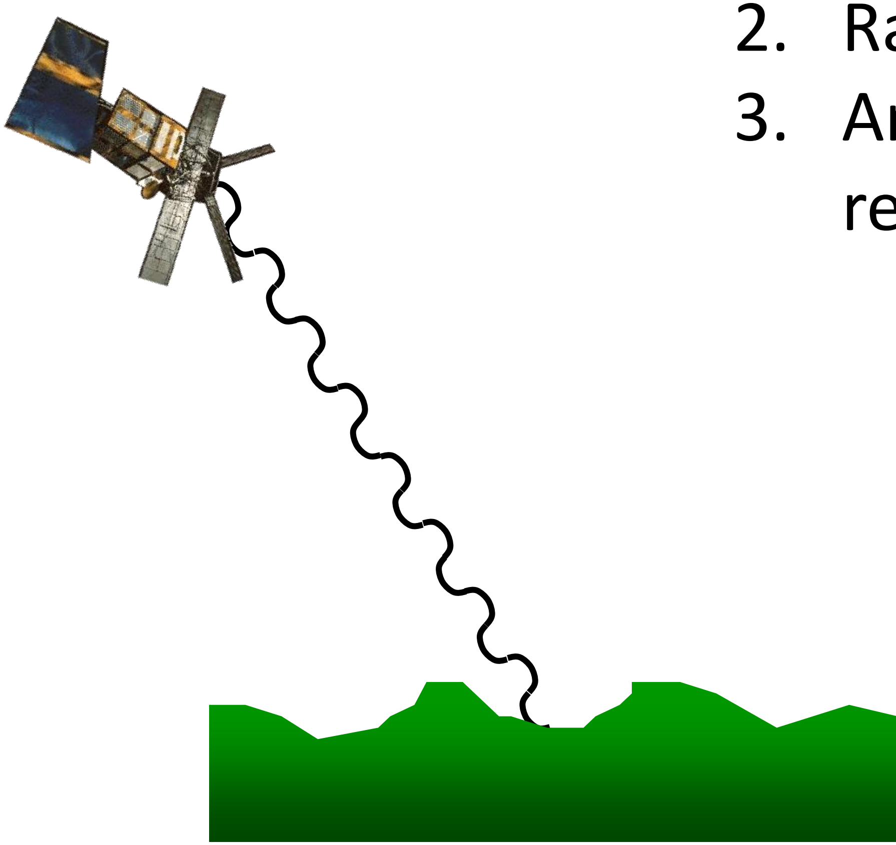
Outline

- (SAR and) InSAR, the basic concepts
- How to interpret interference fringes
- Contributions to interferometric phase
- Interferogram processing steps

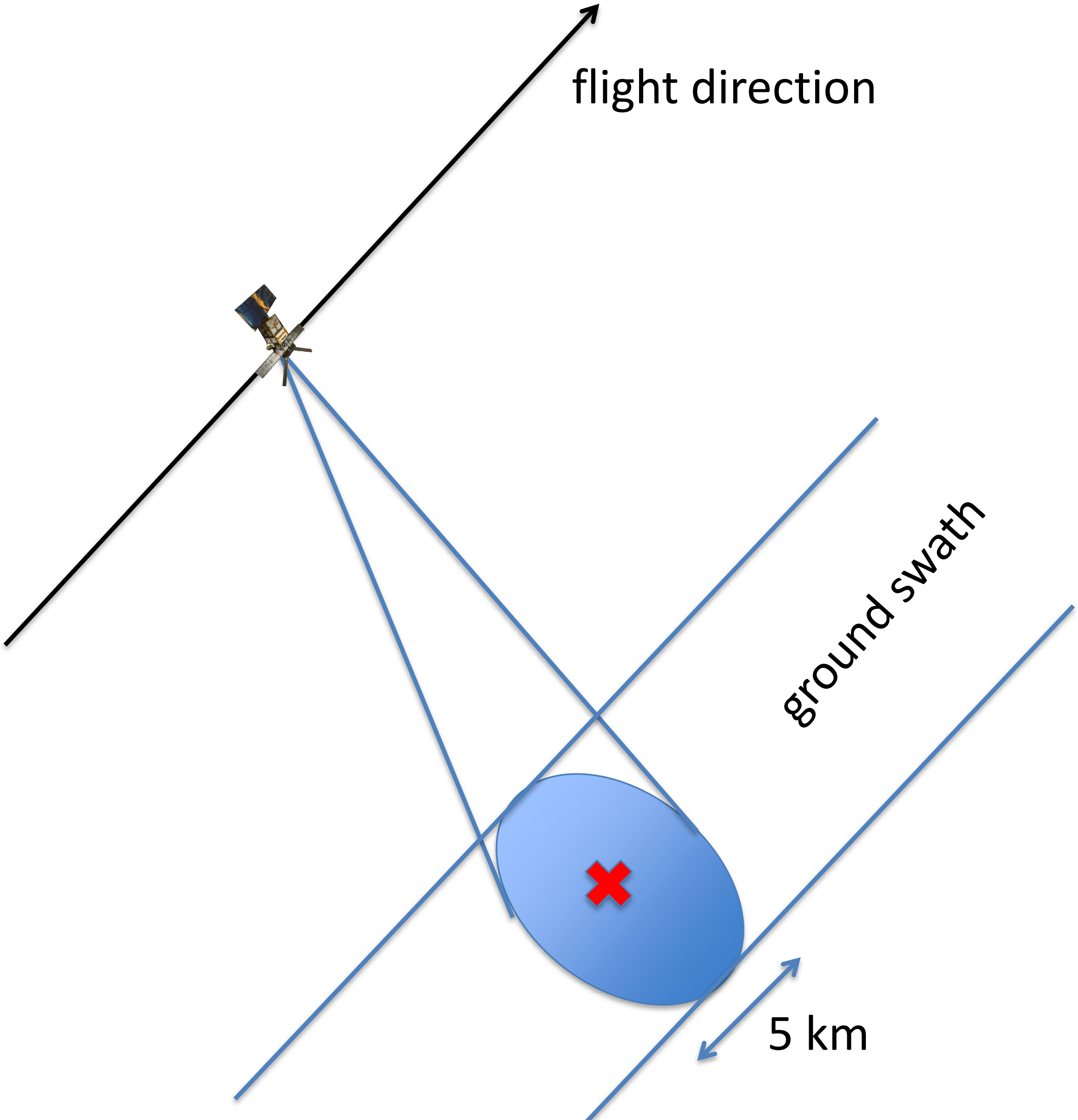
InSAR

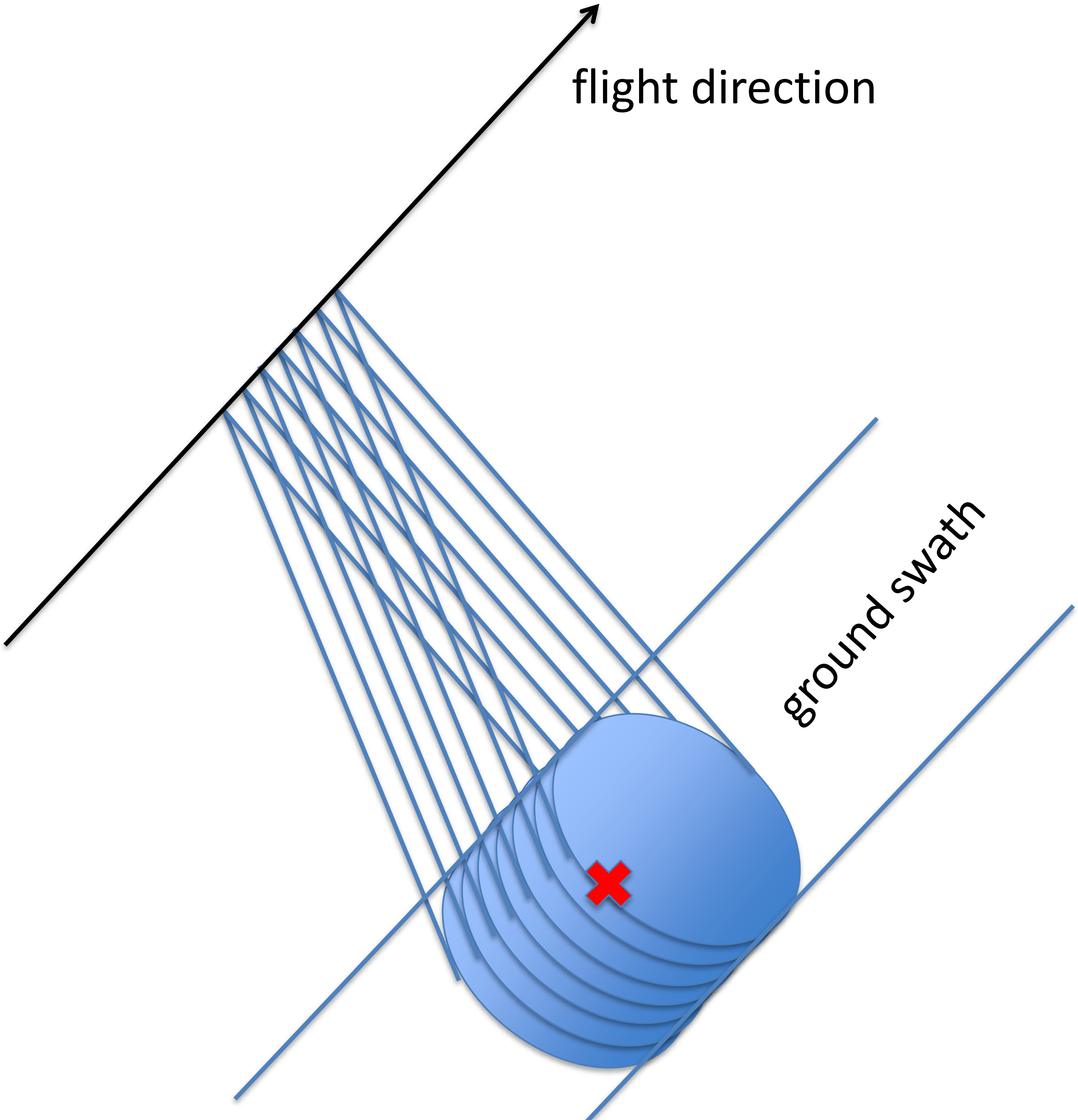
Interferometric	–	use wave interference
Synthetic	}	pretend you have a big radar antenna
Aperture		
Radar	–	emit microwaves, measure echoes

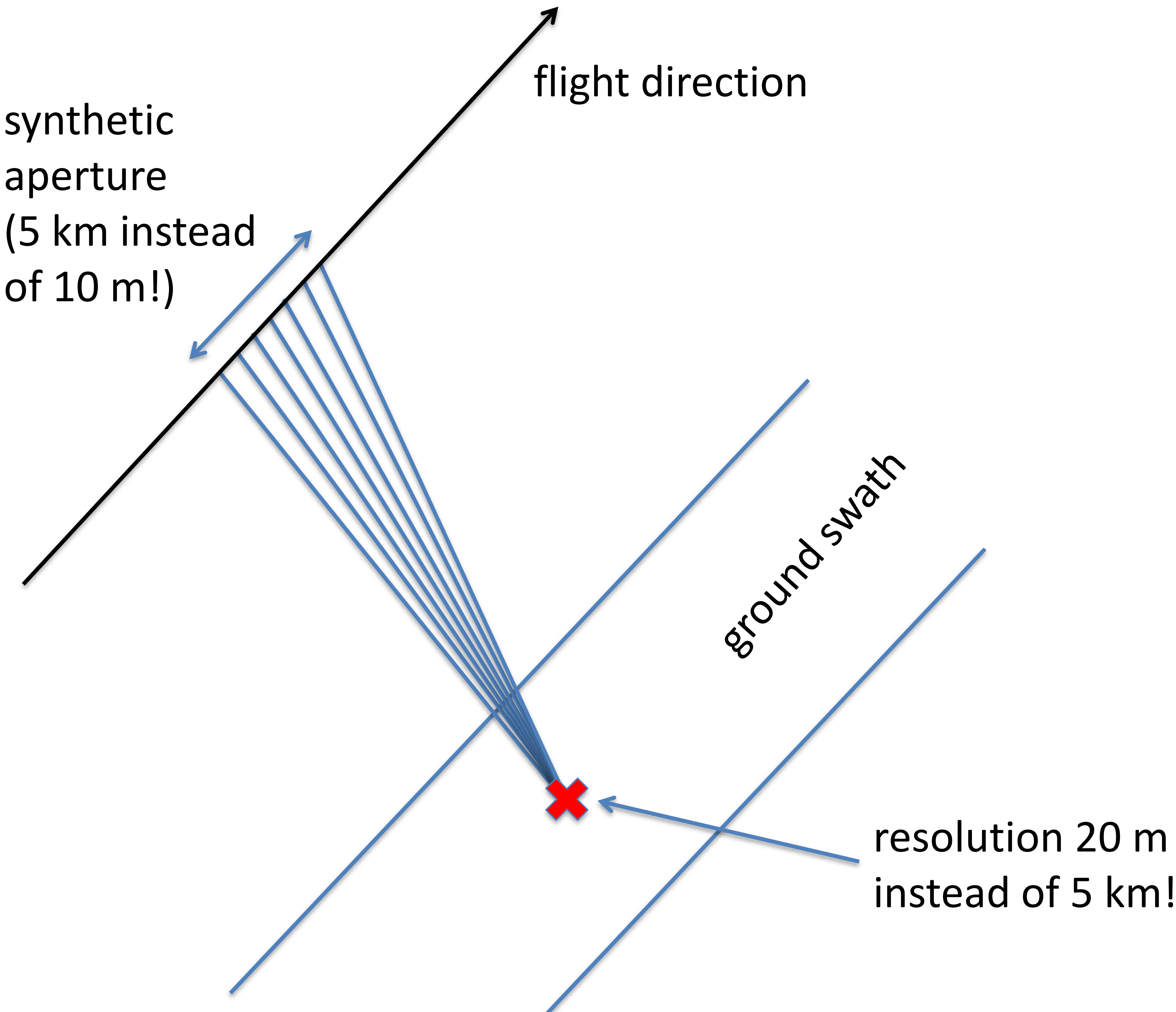
SAR: how it works

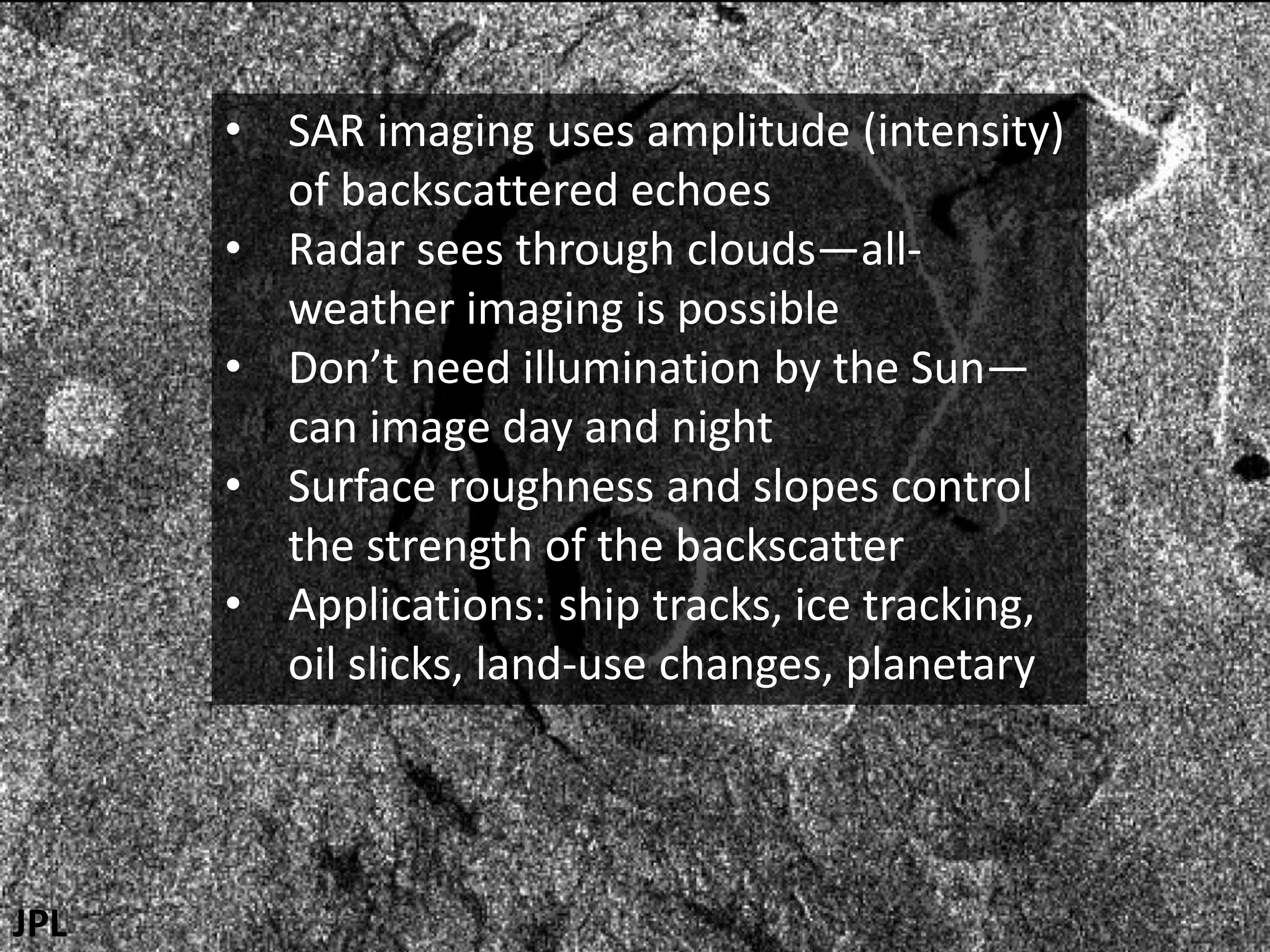


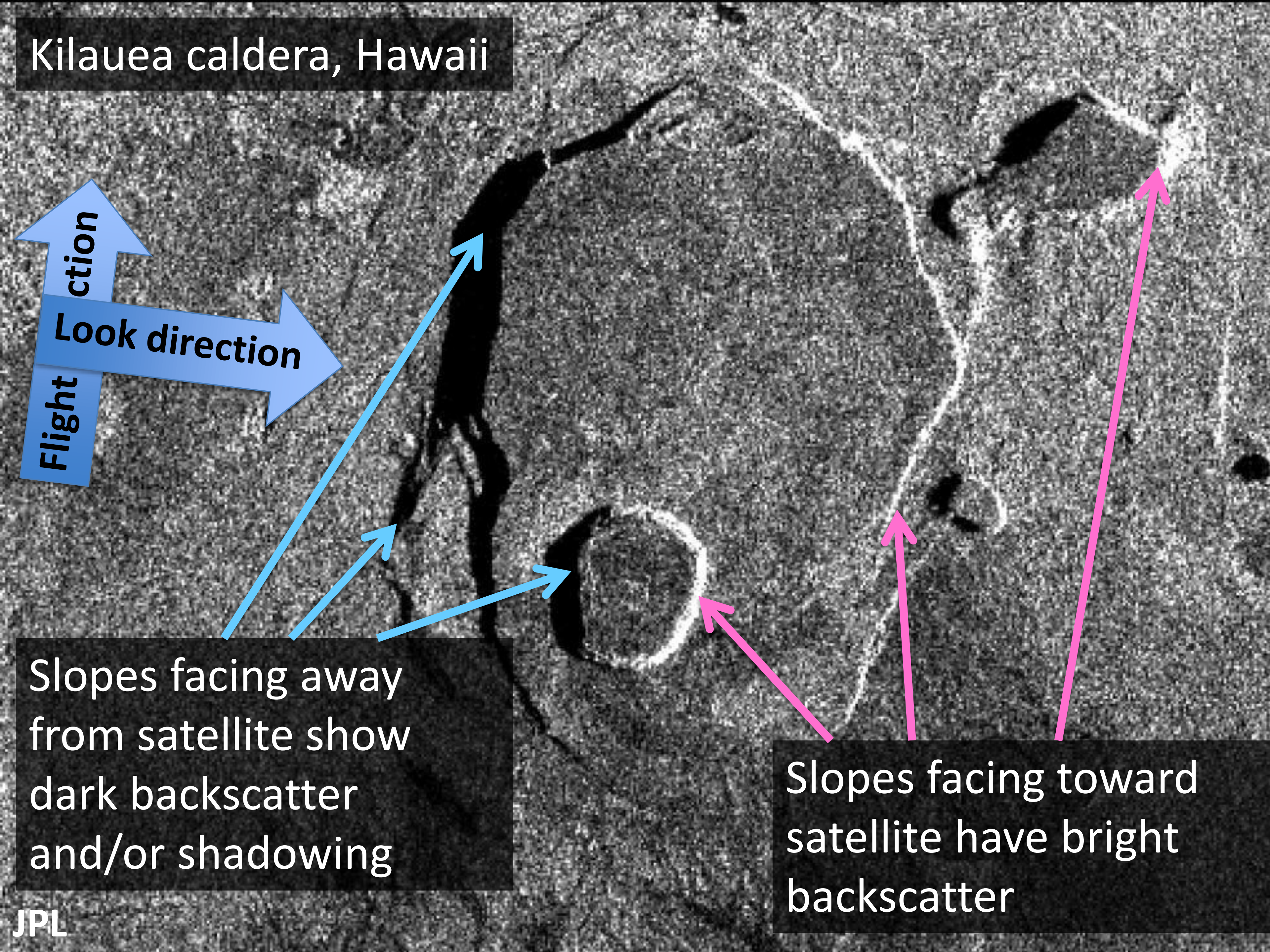
1. Satellite emits radar pulse
2. Radar is backscattered
3. Amplitude and phase of echo recorded at the satellite

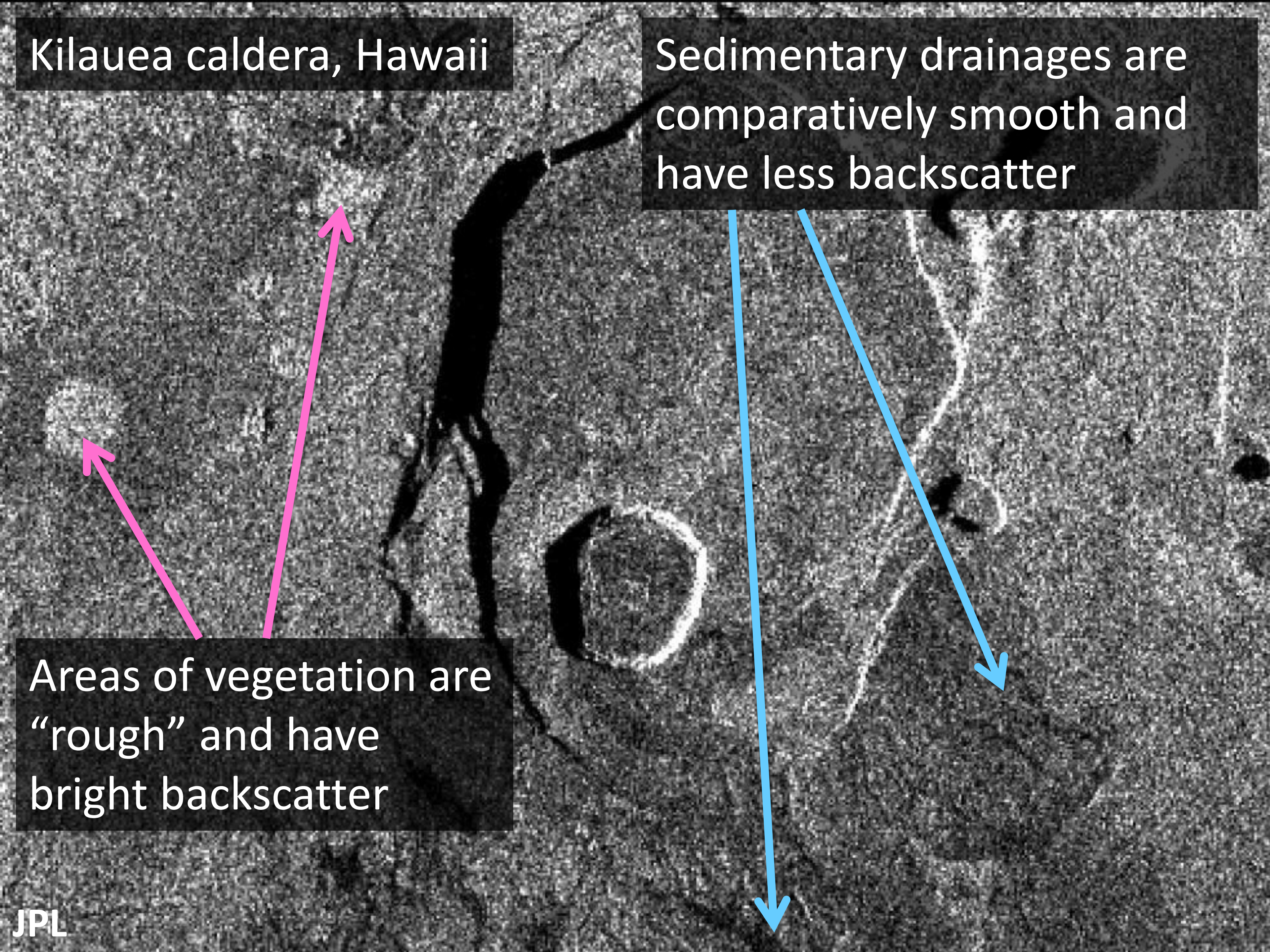

flight direction
ground swath
5 km


flight direction
ground swath


flight direction
synthetic
aperture
(5 km instead
of 10 m!)
ground swath
resolution 20 m
instead of 5 km!

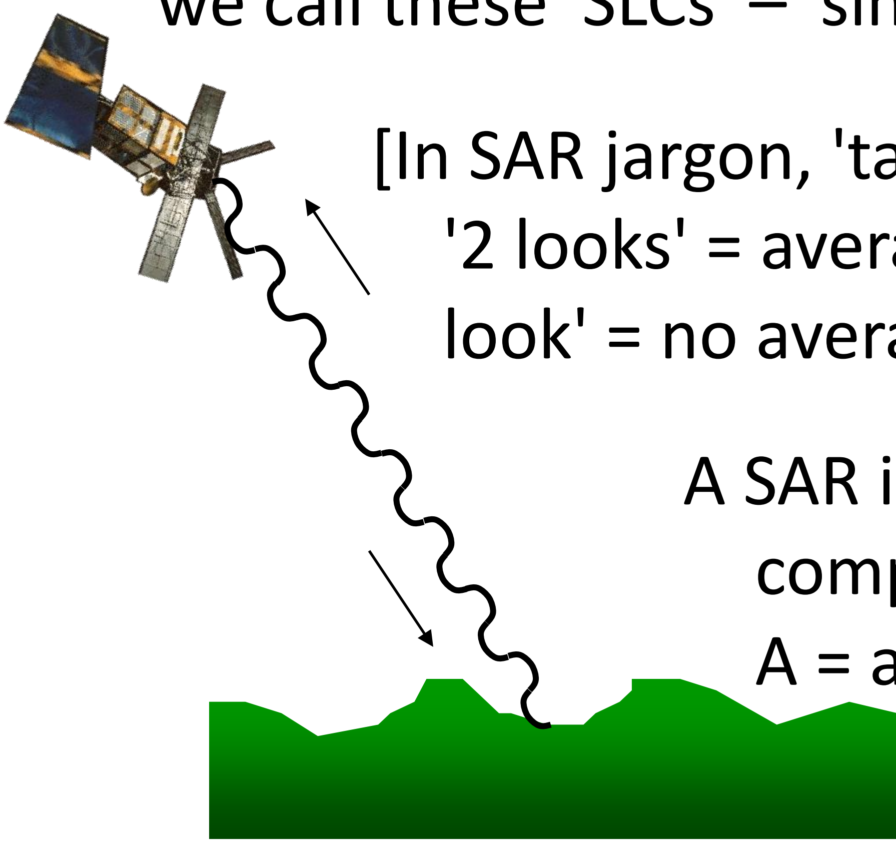

• SAR imaging uses amplitude (intensity) of backscattered echoes
• Radar sees through clouds—all-weather imaging is possible
• Don't need illumination by the Sun—can image day and night
• Surface roughness and slopes control the strength of the backscatter
• Applications: ship tracks, ice tracking, oil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


Kilauea caldera, Hawaii
Flight direction
Look direction
Slopes facing away from satellite show dark backscatter and/or shadowing
Slopes facing toward satellite have bright backscatter
JPL


Kilauea caldera, Hawaii
Sedimentary drainages are comparatively smooth and have less backscatter
Areas of vegetation are "rough" and have bright backscatter
JPL

Single Look Complex images

All full resolution SAR images have both an amplitude component and a phase component; we call these 'SLCs' – 'single look complex'

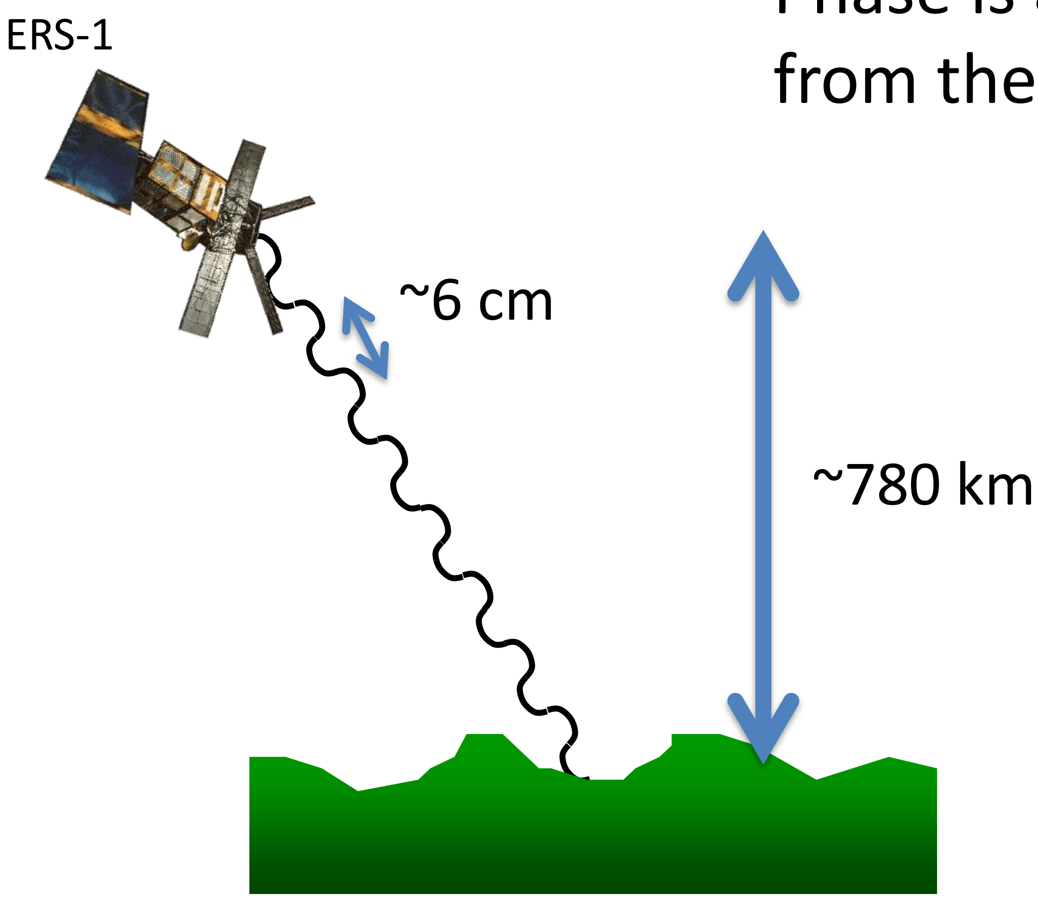


[In SAR jargon, 'taking looks' = spatial averaging, '2 looks' = averaged over 2 x 2 pixels, 'single look' = no averaging]

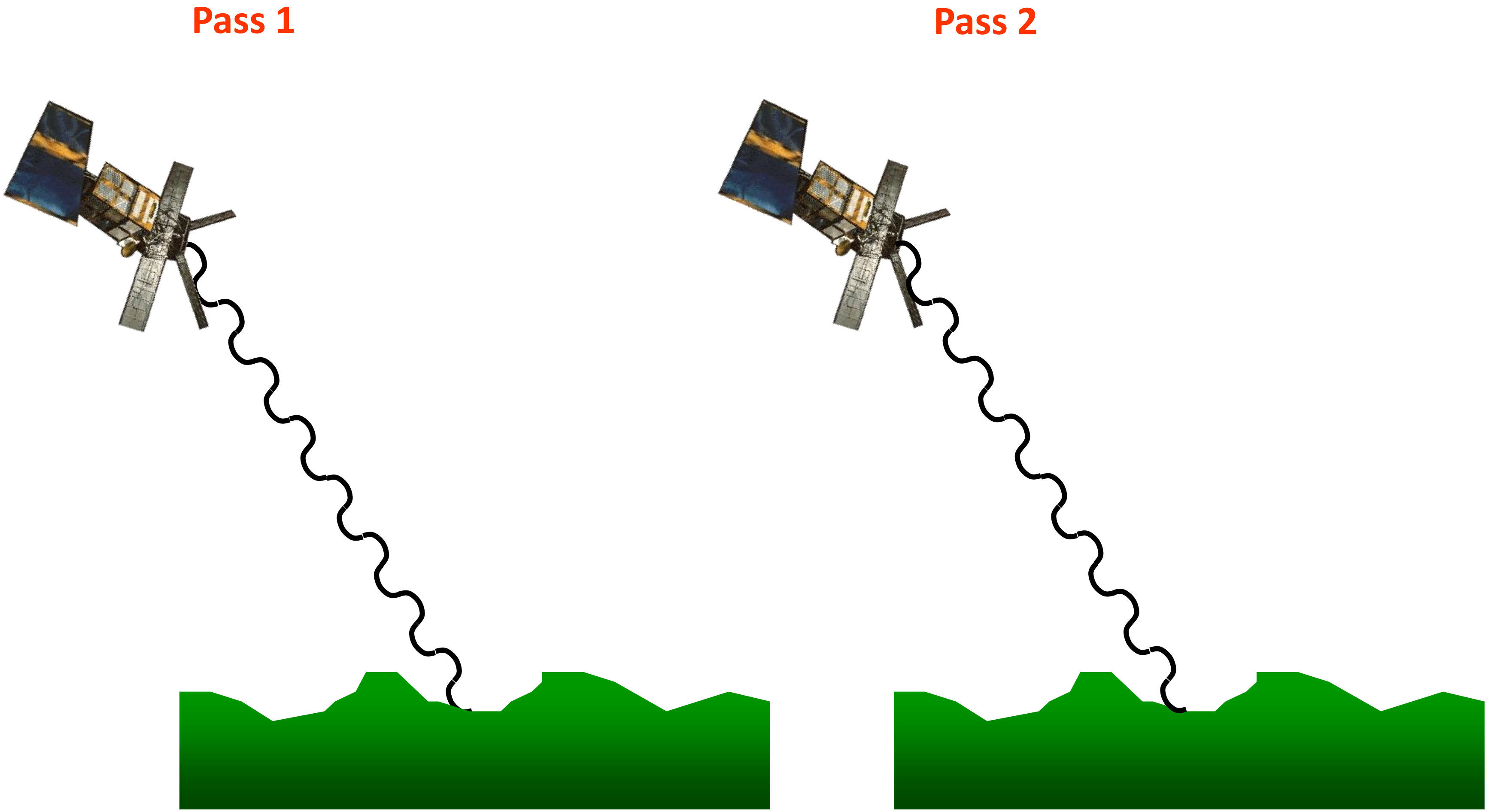
A SAR image can be represented as a complex number: $S = A\,e^{i\phi}$, where A = amplitude, ϕ = phase

What about the phase?

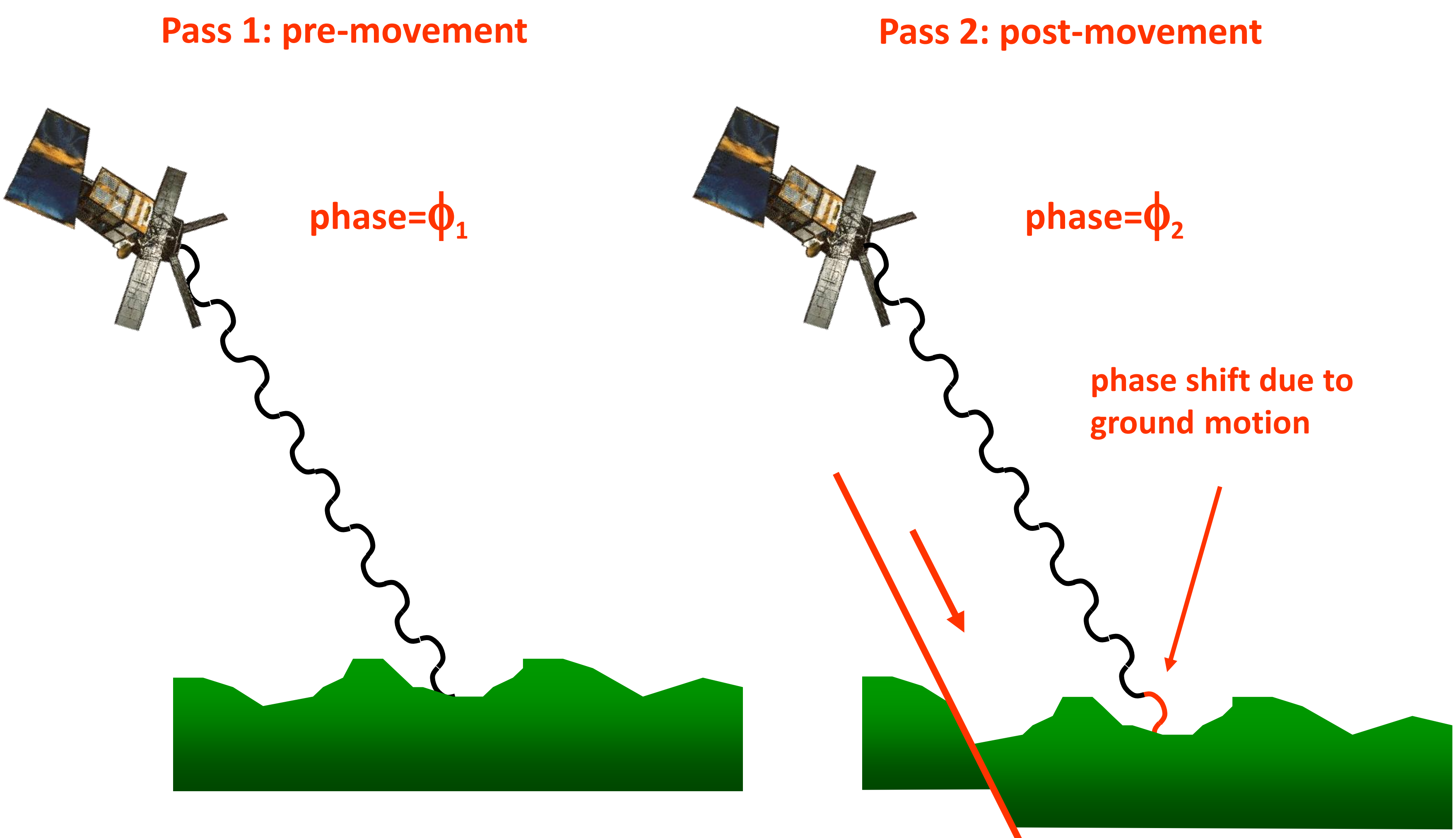
Phase is a function of the distance from the satellite to the ground.



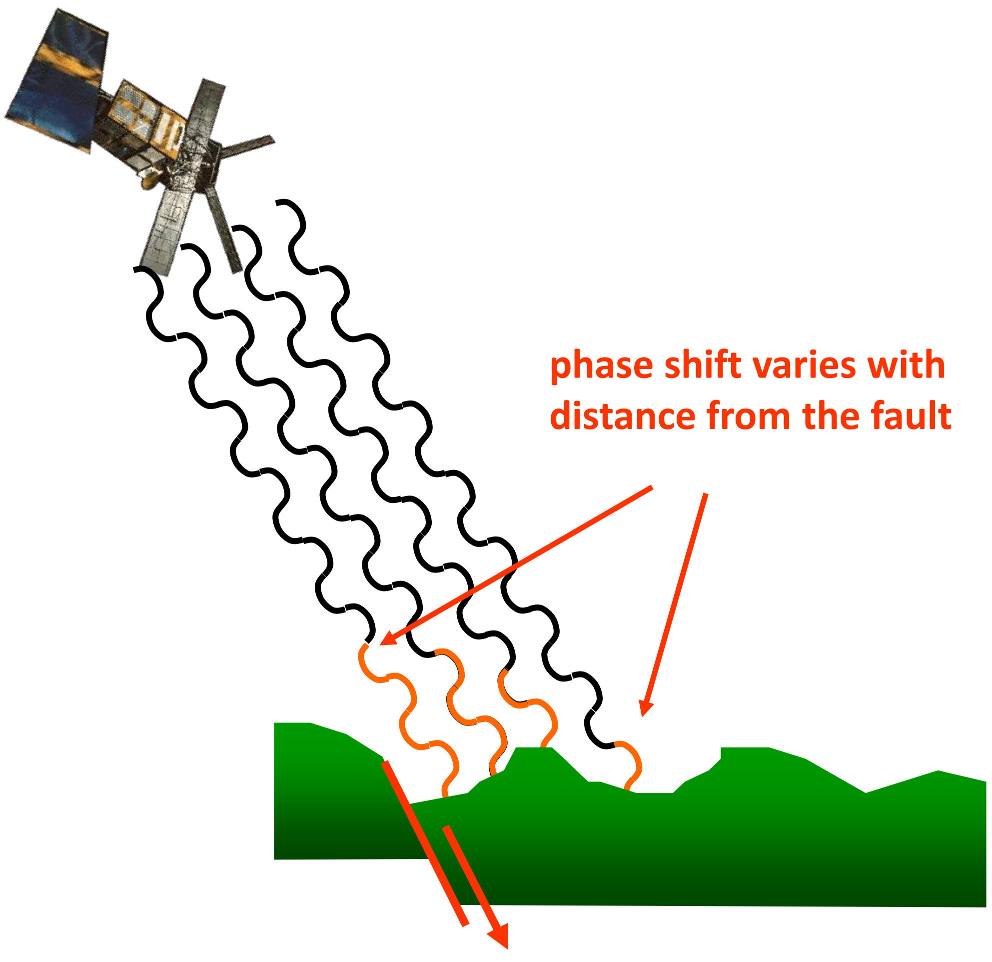
InSAR: How it works

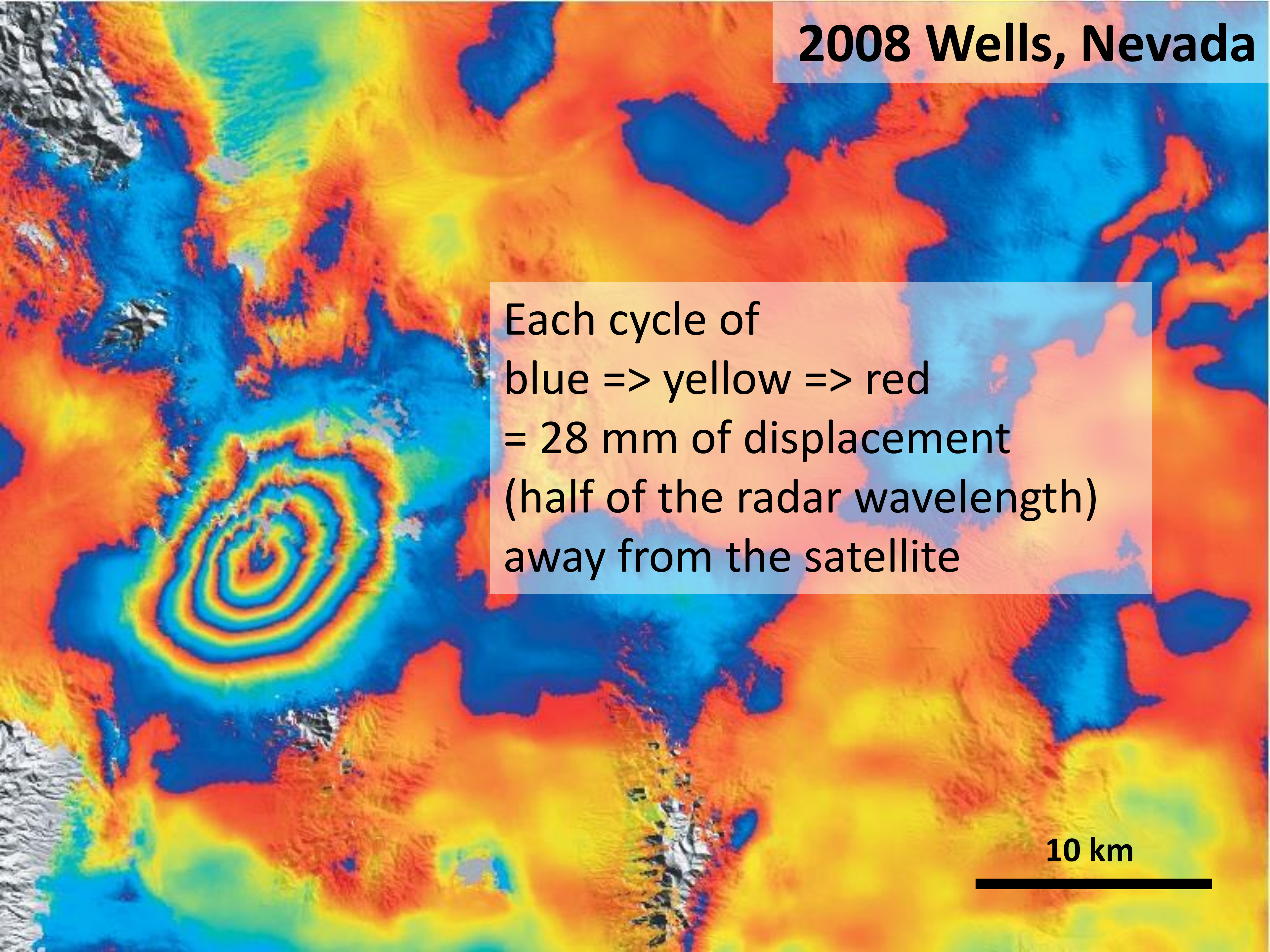


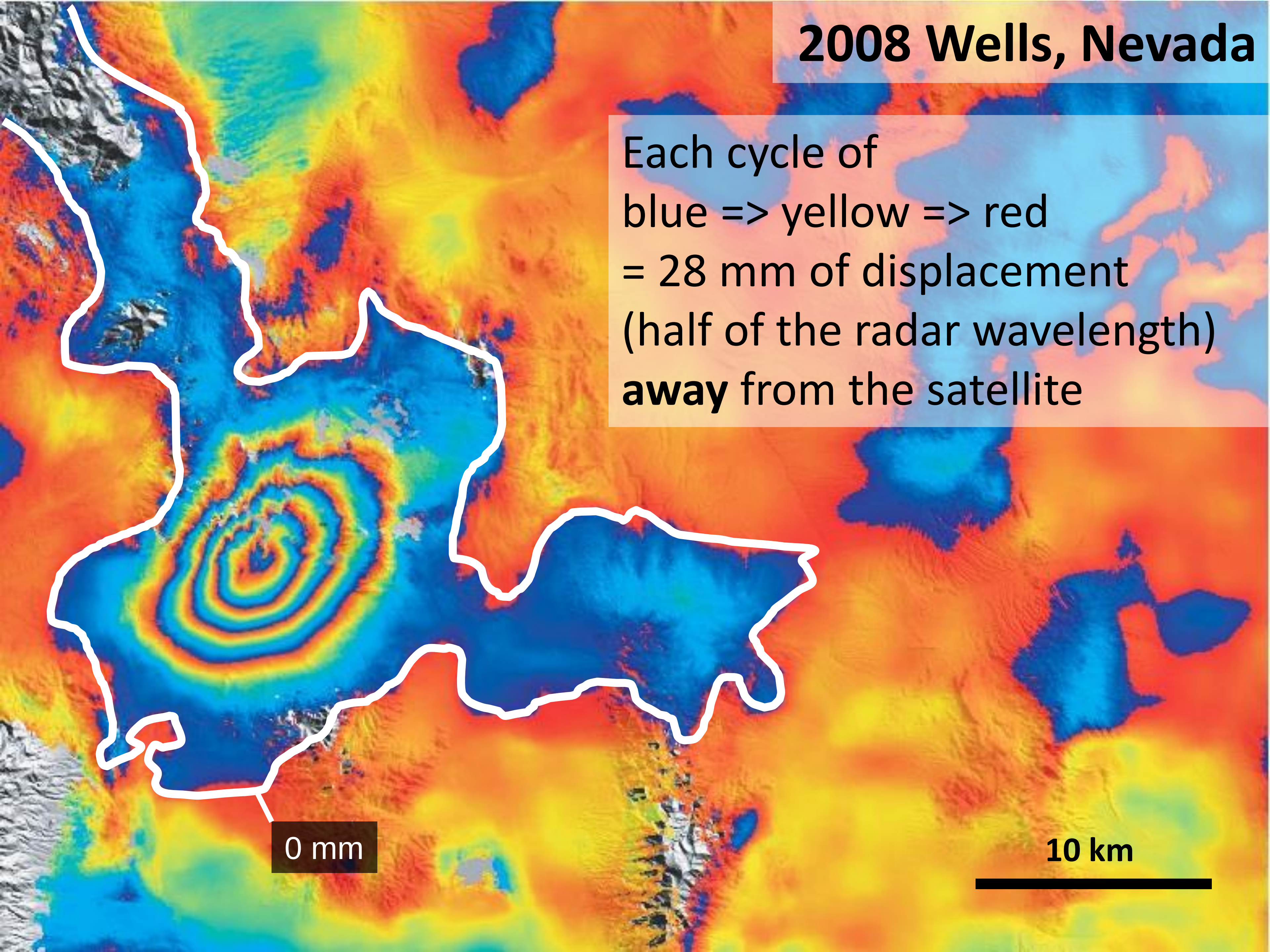
InSAR: How it works

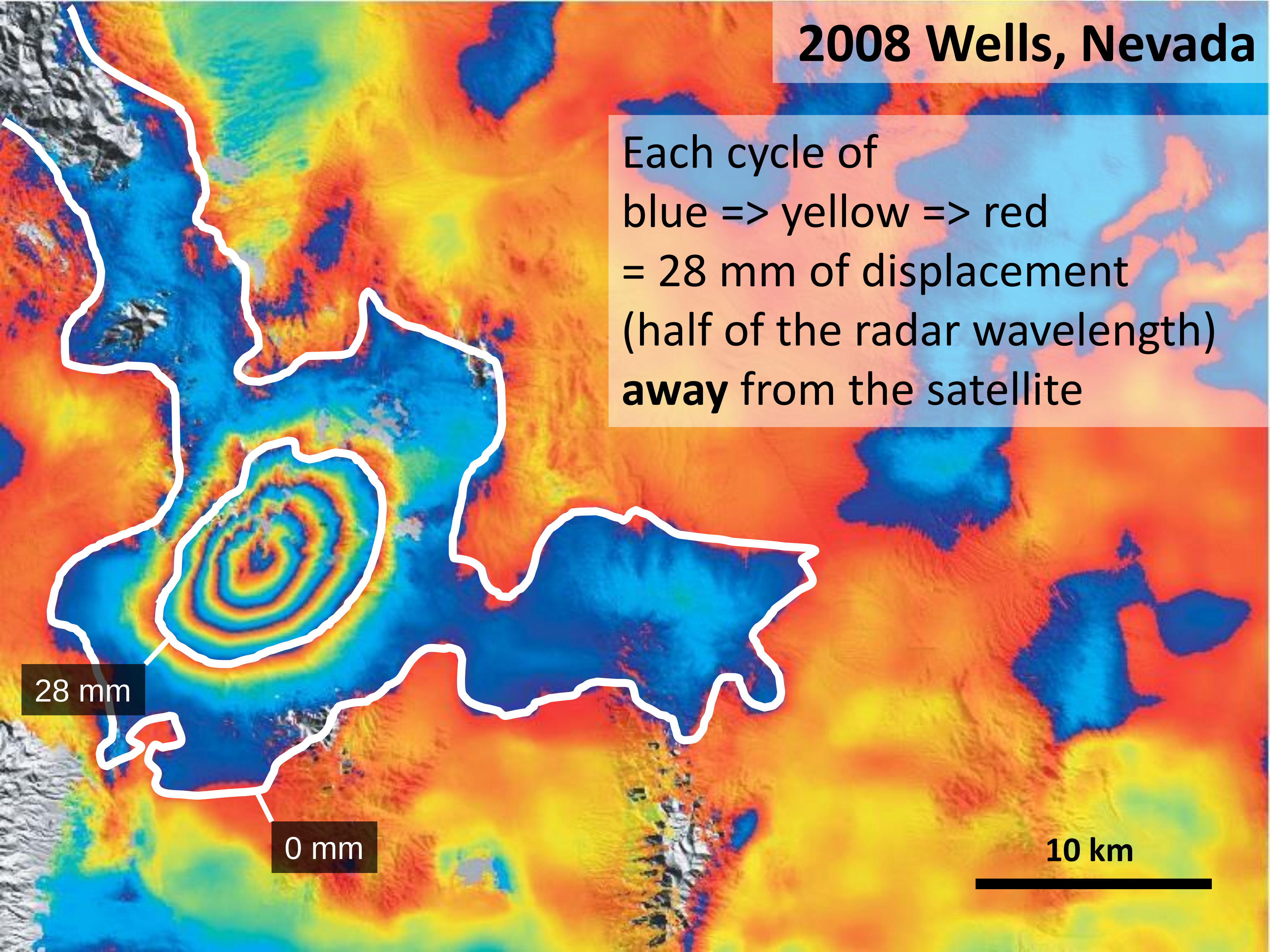


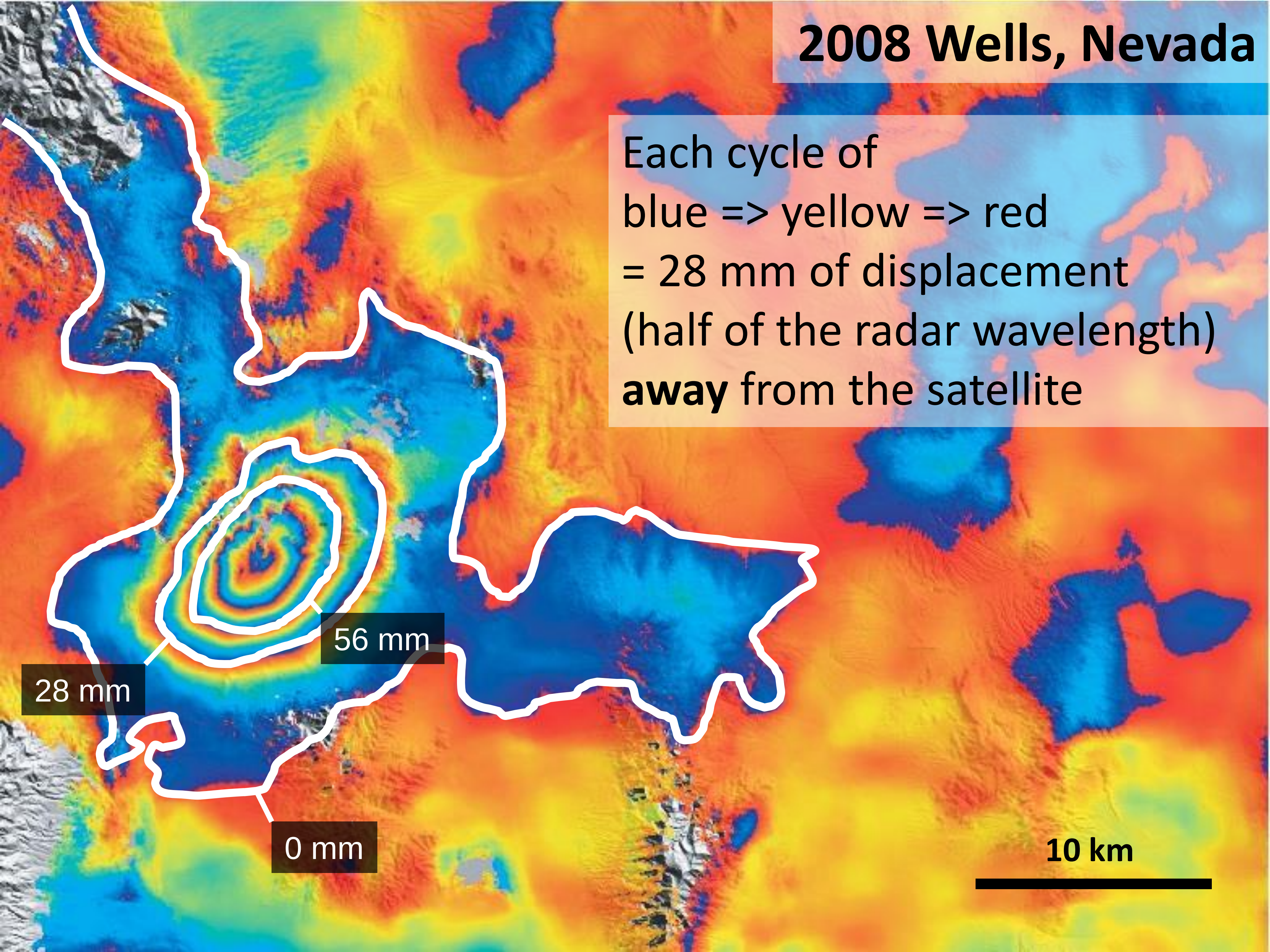
InSAR: How it works



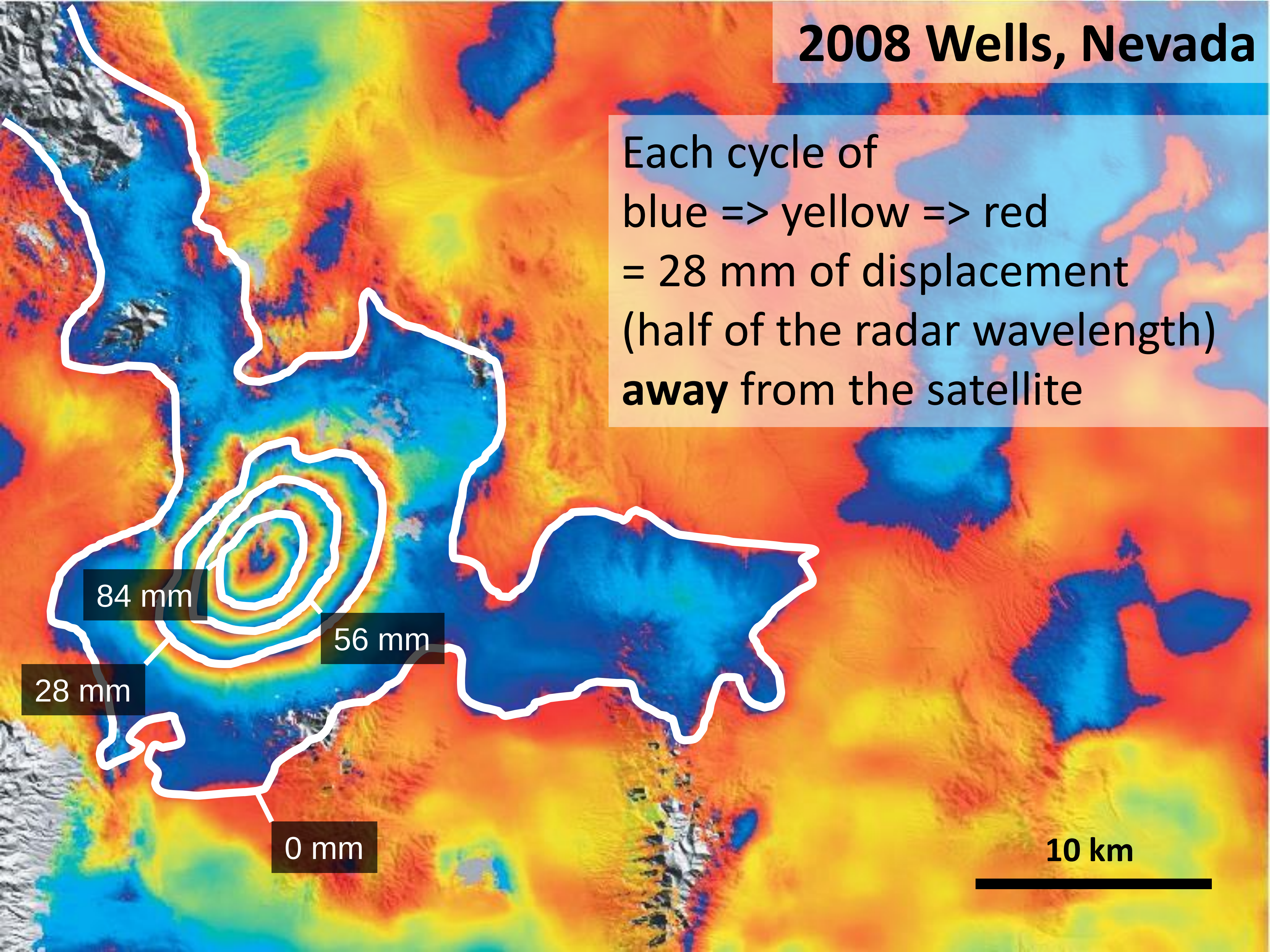

2008 Wells, Nevada
Each cycle of
blue => yellow => red
= 28 mm of displacement
(half of the radar wavelength)
away from the satellite
10 km

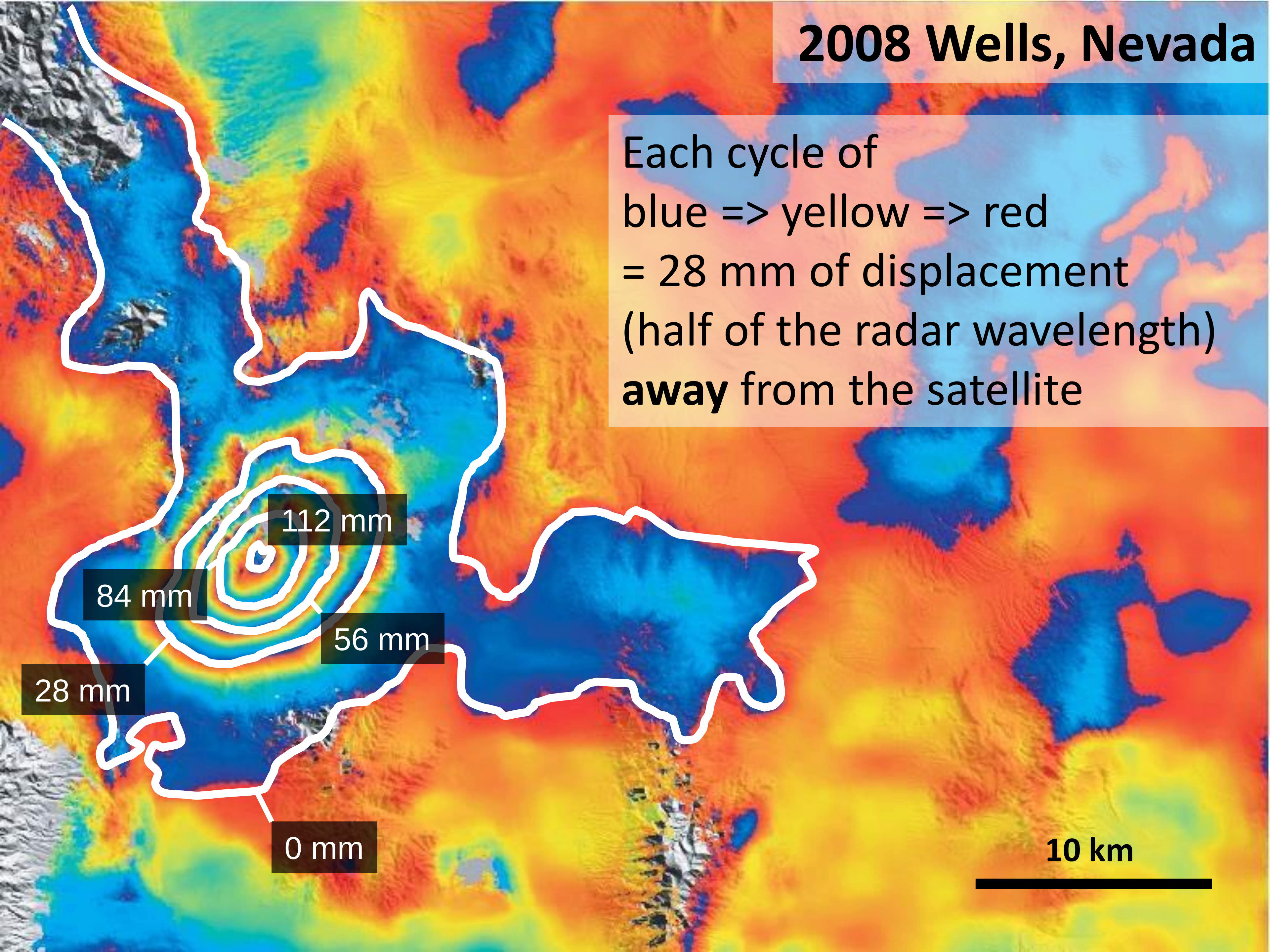

2008 Wells, Nevada
Each cycle of
blue => yellow => red
= 28 mm of displacement
(half of the radar wavelength)
away from the satellite
0 mm
10 km


2008 Wells, Nevada
Each cycle of
blue => yellow => red
= 28 mm of displacement
(half of the radar wavelength)
away from the satellite
28 mm
0 mm
10 km



2008 Wells, Nevada
Each cycle of
blue => yellow => red
= 28 mm of displacement
(half of the radar wavelength)
away from the satellite
56 mm
28 mm
0 mm
10 km


2008 Wells, Nevada
Each cycle of
blue => yellow => red
= 28 mm of displacement
(half of the radar wavelength)
away from the satellite
84 mm
56 mm
28 mm
0 mm
10 km


2008 Wells, Nevada
Each cycle of
blue => yellow => red
= 28 mm of displacement
(half of the radar wavelength)
away from the satellite
112 mm
84 mm
56 mm
28 mm
0 mm
10 km

Components of interferometric phase

$$\boxed{\Delta\phi_{\text{int}} = \underline{\Delta\phi_{\text{orb}}} + \underline{\Delta\phi_{\text{topo}}} + \underline{\Delta\phi_{\text{atm}}} + \underline{\Delta\phi_{\text{pixel}}} + \underline{\Delta\phi_{\text{def}}}}$$

The phase of an individual interferogram can be divided into five parts:

Three are related to the difference in distance between the satellite and the ground

One is related to the difference in the properties of the medium that the radar pulse moves through

One is related to the change in properties of the pixel on the ground

Differential InSAR (DInSAR)

$$\boxed{\Delta\phi_{\text{int}} = \cancel{\Delta\phi_{\text{orb}}} + \cancel{\Delta\phi_{\text{topo}}} + \Delta\phi_{\text{atm}} + \Delta\phi_{\text{pixel}} + \Delta\phi_{\text{def}}}$$

A differential interferogram is one in which the effects of orbital baselines and topography have been removed

To most scientists (if not most engineers) this removal is implicit when we talk about InSAR, but technically it is DInSAR!

(D)InSAR processing in practice

A typical processing chain will have multiple steps, usually (but not always) in this order:

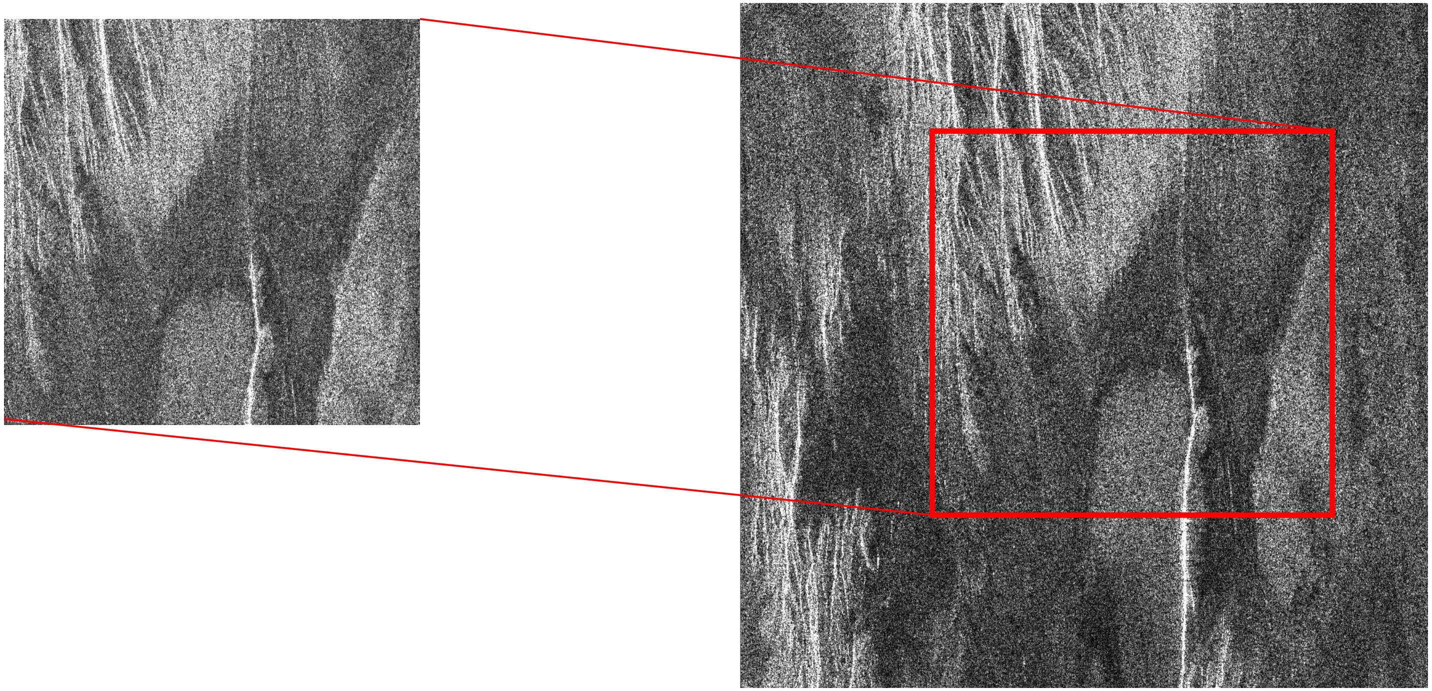
1) Matching (coregistering) the SLCs
2) Forming the interfeogram by differencing phases
3) Removing the effects of orbit position and Earth curvature
4) Registering the interferogram to a DEM; removing the effects of topography
5) Filtering and unwrapping

Measuring image offsets

A critical stage of the processing is the matching of the two SLCs – unless the images are correctly coregistered, the differencing of the phase will not work

This is achieved by cross-correlating subsets of the two images so that the shift between the two images can be estimated at multiple points between the images

Measuring image offsets



The subset of the second image is cross-correlated with the approximately corresponding area in the master, within a certain tolerance

Measuring image offsets

This is typically achieved in the Fourier domain – it is quicker, and it also allows matching to be achieved to sub-pixel accuracy(!)

This is possible because, in effect, each image is a discrete sampling of a continuous function (the Earth's surface)…

…with a sufficient number of samples, we can match the shape of that continuous function, and we can do that with sub-pixel resolution

Forming the interferogram

Formally, an interferogram is formed by multiplying one SLC image by the complex conjugate of the other

[Recall, an SLC image can be written as $S = A\,e^{i\phi}$]

If there are two SLCs, S_1 and S_2, the interferogram formed from them, I, is given by

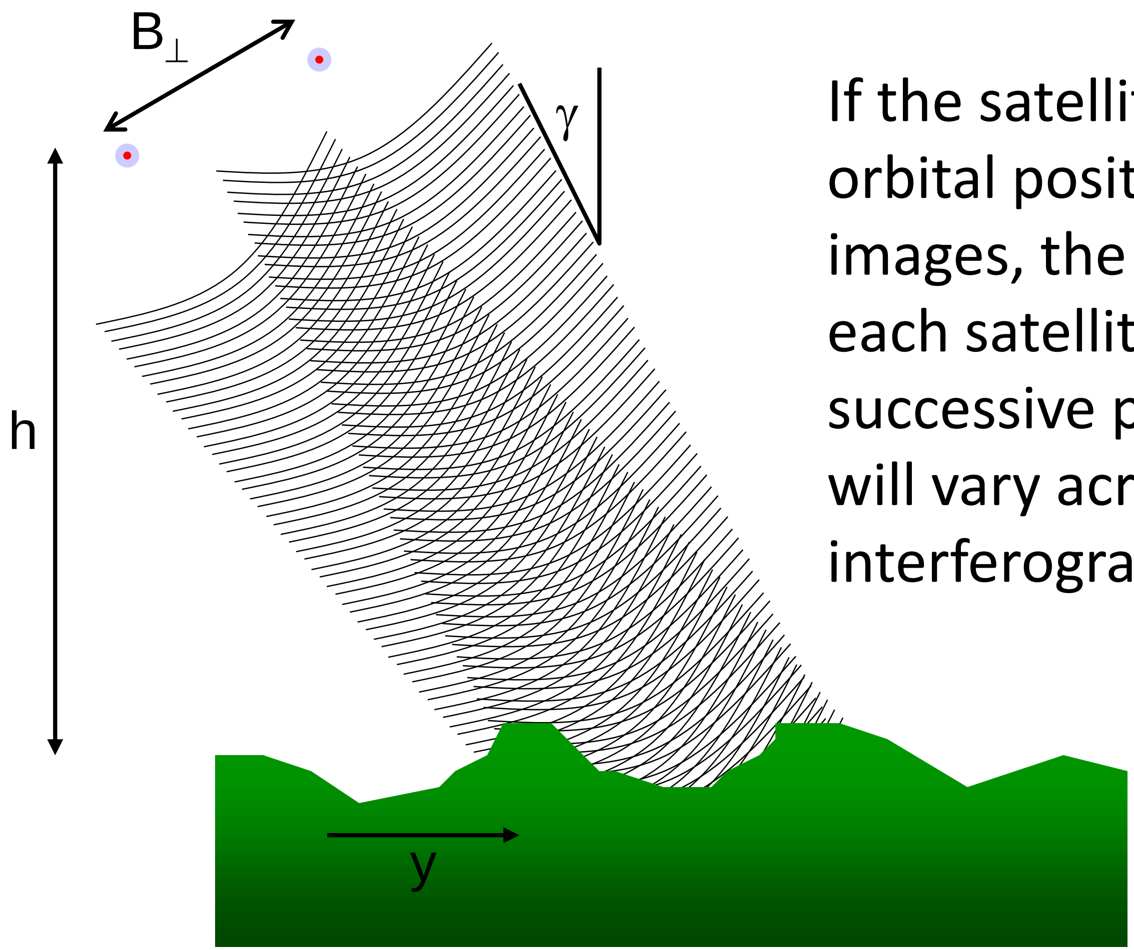
$$I = S_1 S_2^* = A_1 A_2 \exp(\phi_1 - \phi_2) i$$

(S_1 and S_2 are often referred to as the 'master' and 'slave' images)

Usually, we ignore the amplitude part, and concentrate on the phase difference, $\phi_1 - \phi_2 = \Delta\phi$

Orbital phase (1)

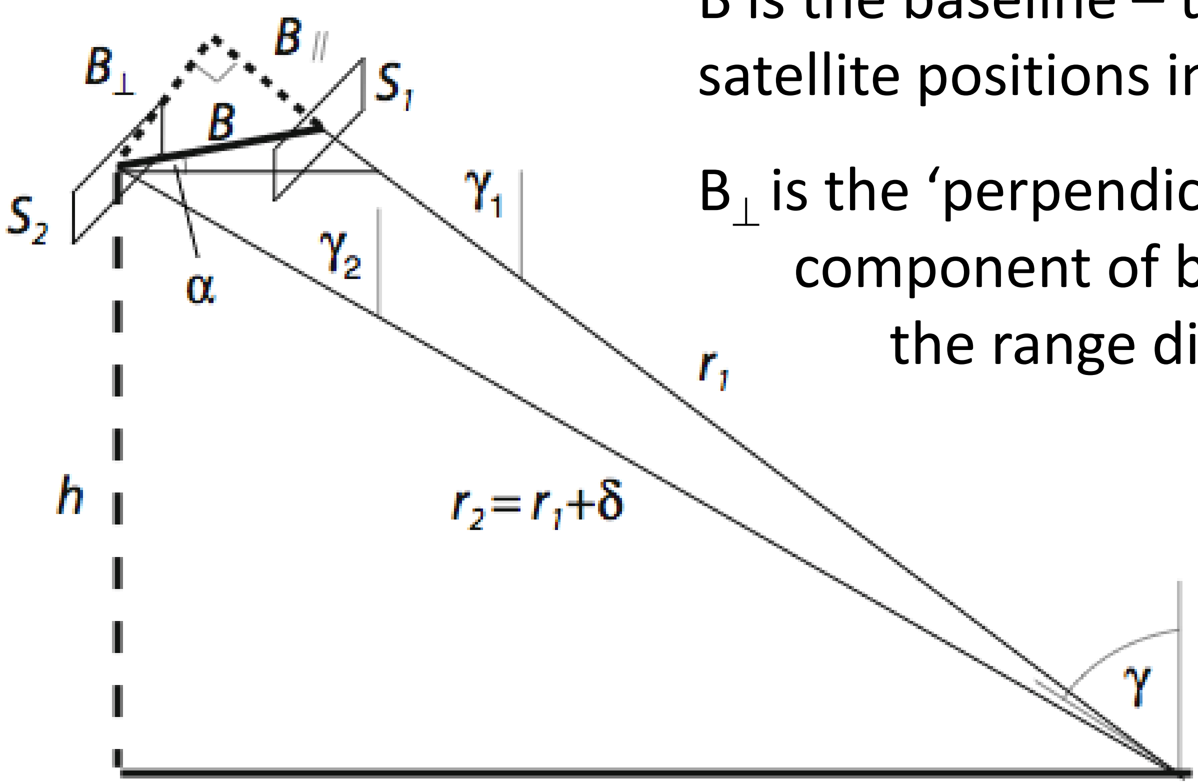
$$\Delta\phi_{\mathrm{int}} = \Delta\phi_{\mathrm{orb}} + \Delta\phi_{\mathrm{topo}} + \Delta\phi_{\mathrm{atm}} + \Delta\phi_{\mathrm{pixel}} + \Delta\phi_{\mathrm{def}}$$



If the satellite is in different orbital positions for the two images, the distance between each satellite position and successive points on the ground will vary across the whole interferogram

Orbital phase (2)

$$\boxed{\Delta\phi_{\text{int}} = \Delta\phi_{\text{orb}} + \Delta\phi_{\text{topo}} + \Delta\phi_{\text{atm}} + \Delta\phi_{\text{pixel}} + \Delta\phi_{\text{def}}}$$



B is the baseline – the distance between satellite positions in the cross-track plane

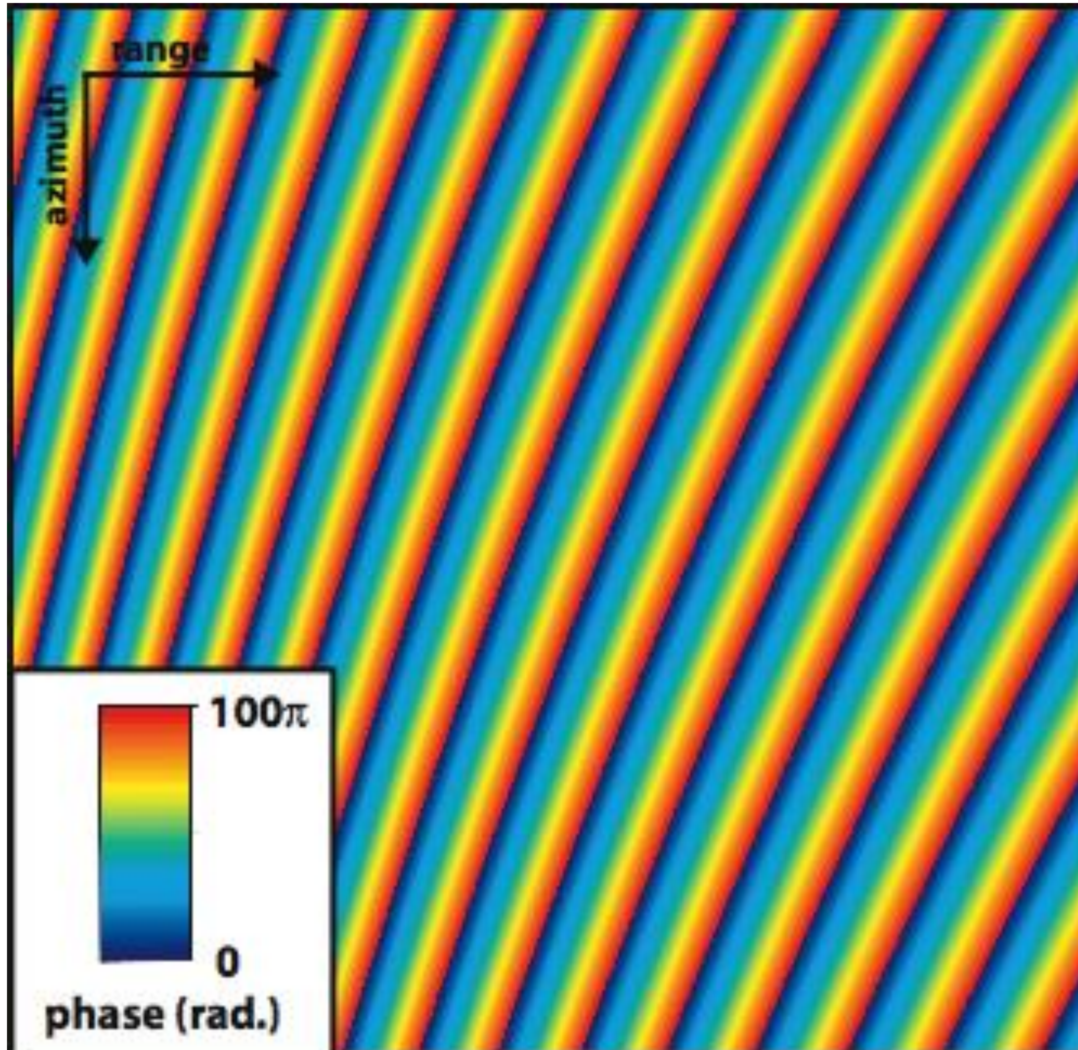
$B_{\perp}$ is the 'perpendicular baseline', the component of baseline perpendicular to the range direction

$$\frac{\partial \phi}{\partial y} = \frac{4\pi B_{\perp} \cos^2 \gamma}{h\lambda}$$

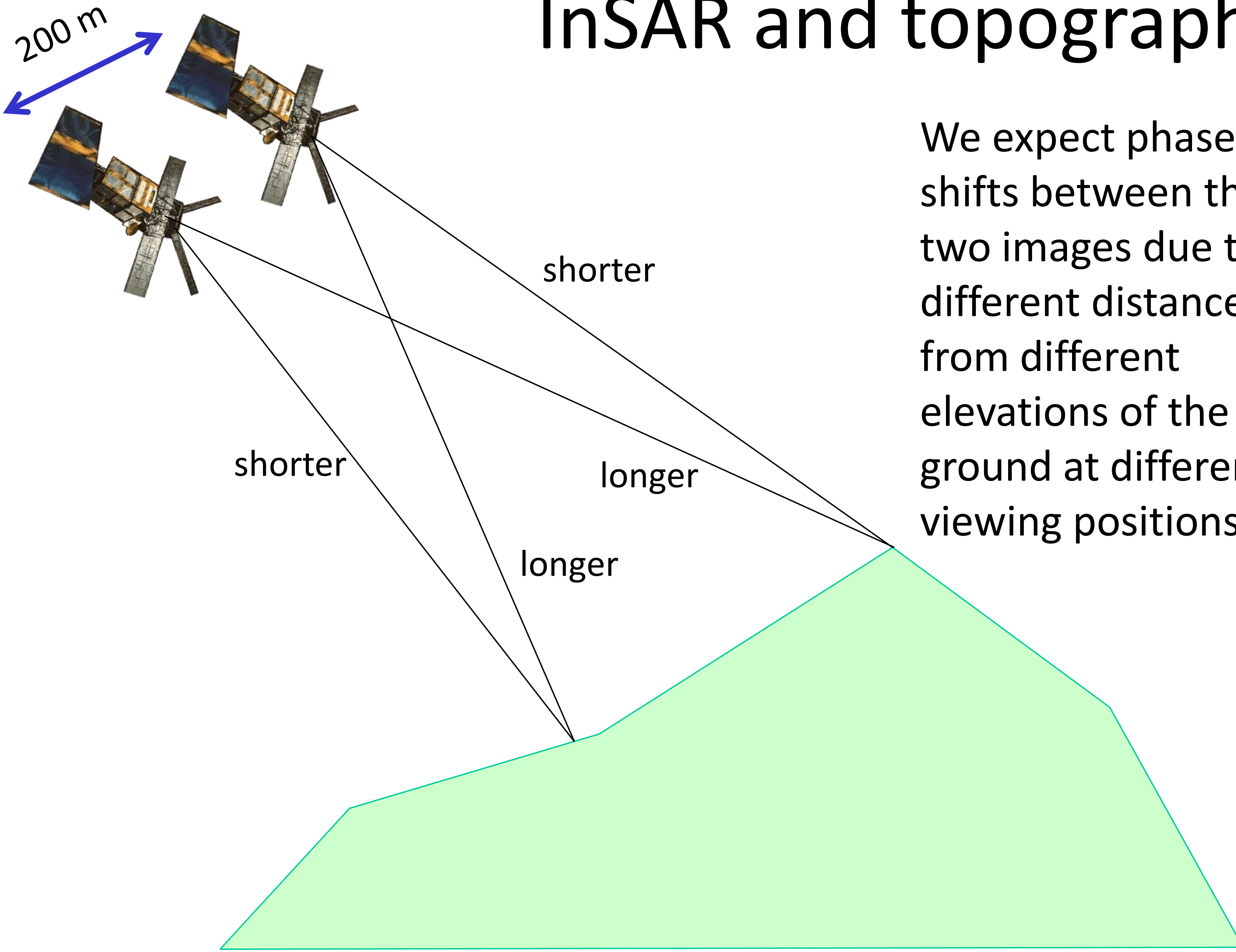
Orbital phase (3)

The orbital phase component is usually the largest contributor to an interferogram

ERS-1, baseline varies between 121 m at the top and 136 m at the bottom



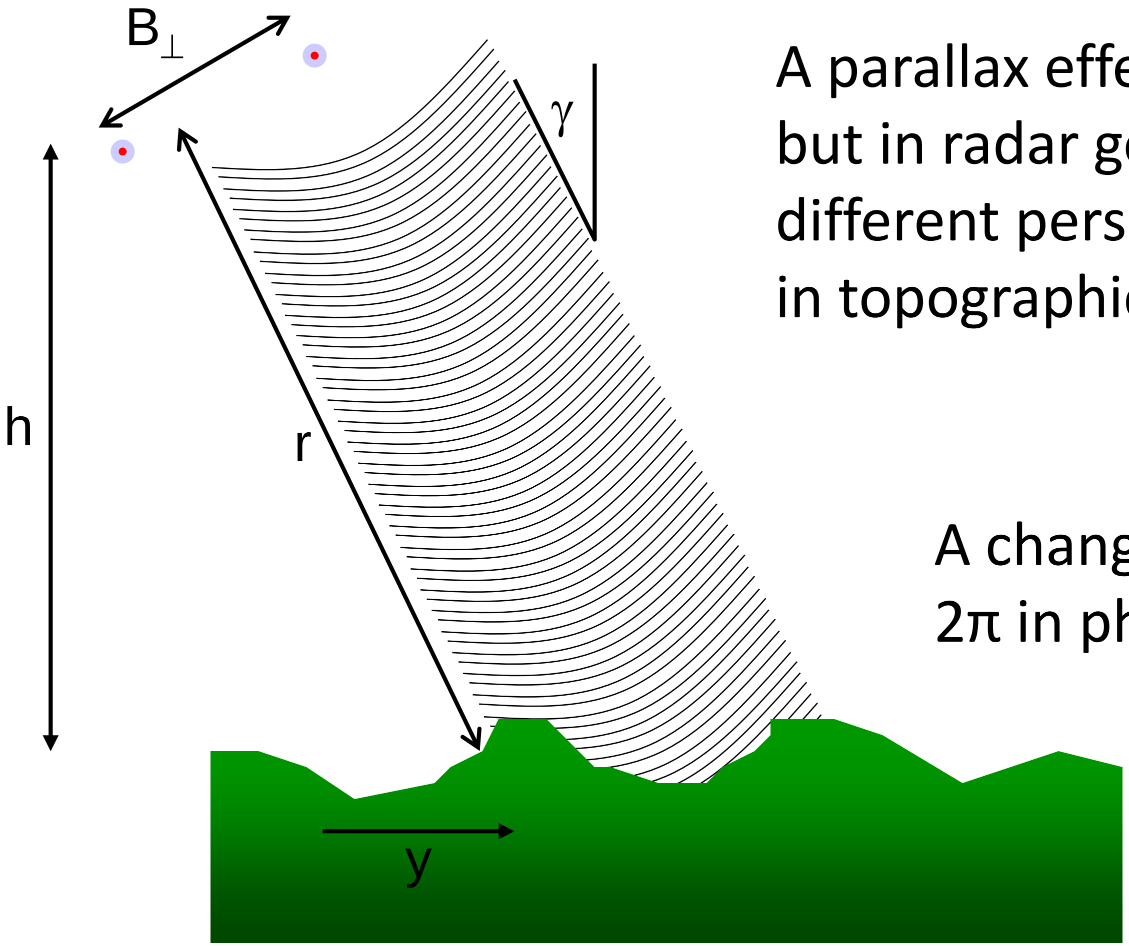
InSAR and topography



We expect phase shifts between the two images due to different distances from different elevations of the ground at different viewing positions

Topographic phase (1)

$$\boxed{\Delta\phi_{int} = \Delta\phi_{orb} + \Delta\phi_{topo} + \Delta\phi_{atm} + \Delta\phi_{pixel} + \Delta\phi_{def}}$$



A parallax effect (like stereoscopy, but in radar geometry) gives different perspective on changes in topographic height

A change in height, h_a, equals 2π in phase change

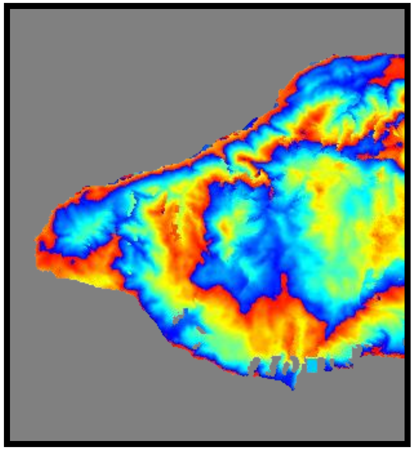
$$h_a = \frac{r\lambda \sin\gamma}{2B_\perp} \approx \frac{10{,}000}{B_\perp}$$

Topographic phase (2)

$$\boxed{\Delta\phi_{\text{int}} = \Delta\phi_{\text{orb}} + \Delta\phi_{\text{topo}} + \Delta\phi_{\text{atm}} + \Delta\phi_{\text{pixel}} + \Delta\phi_{\text{def}}}$$

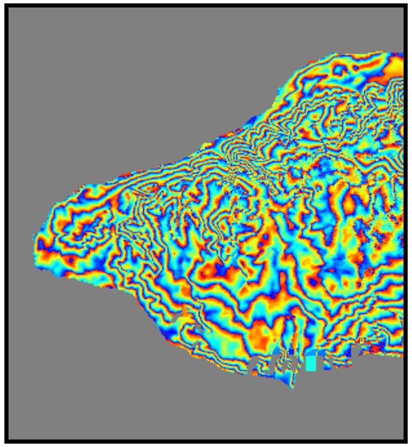
$h_a = 500$ m

$B_\perp = 20$ m



$h_a = 100$ m

$B_\perp = 100$ m



- Parallax effect $\Rightarrow$ topographic fringes
- 1 fringe for each change in elevation h_a

$$h_a = \frac{r\lambda \sin\gamma}{2B_\perp} \approx \frac{10{,}000}{B_\perp}$$

- Remove $\Delta\phi_{\text{topo}}$ using a pre-existing DEM
- Quality of DEM required $f(h_a)$

Height error = ε_h

$\Rightarrow$ phase error = $2\pi(\varepsilon_h / h_a)$

Registering the master to the DEM

In order to apply a topographic correction, we need to register the interferogram to the DEM

In older software, a simulated amplitude image is made by combining the DEM with orbit information, and projecting it into the radar viewing geometry

Assuming uniform backscatter, the simulated amplitude depends on the slope distribution within the SAR image frame

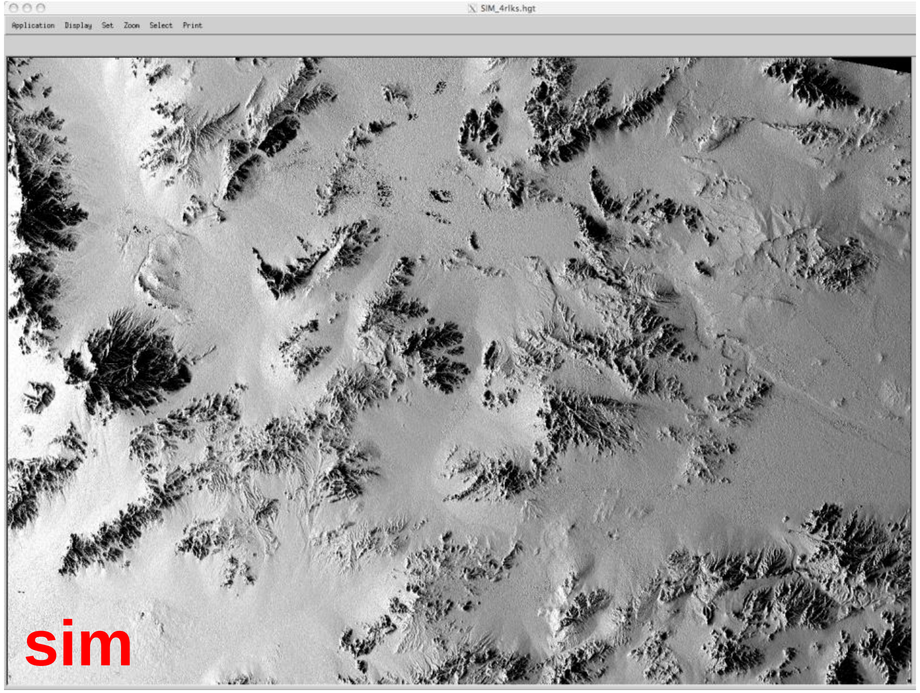
Never packages use a DEM and orbit information to estimate range (distance) to each pixel of a SAR image

Simulated vs real amplitude

These are matched in the same way as the two SLCs

The end result can be used to associate a DEM height/phase correction with each interferogram pixel

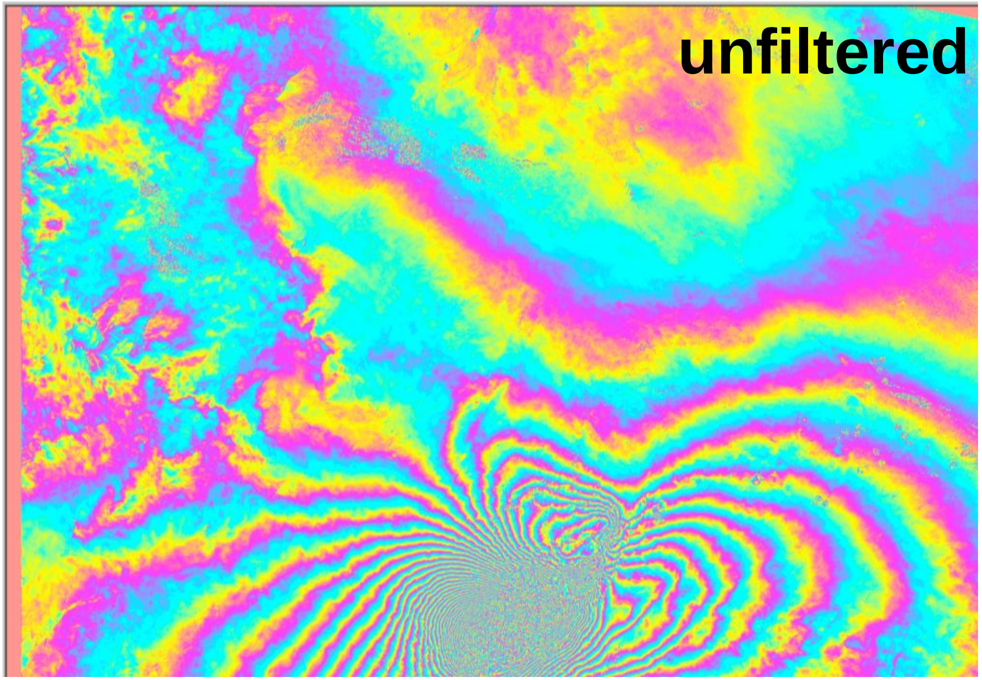
It is also used in geocoding

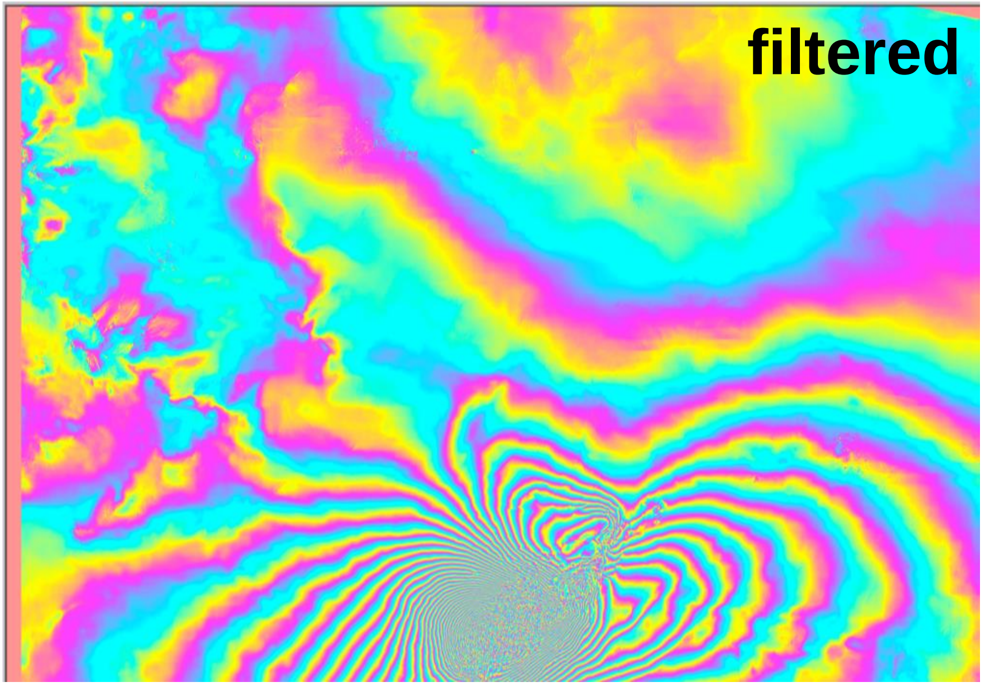


Filtering

To boost the signal over the noise, a power spectrum filter is applied

This increases the power of the most coherent information in the interferogram

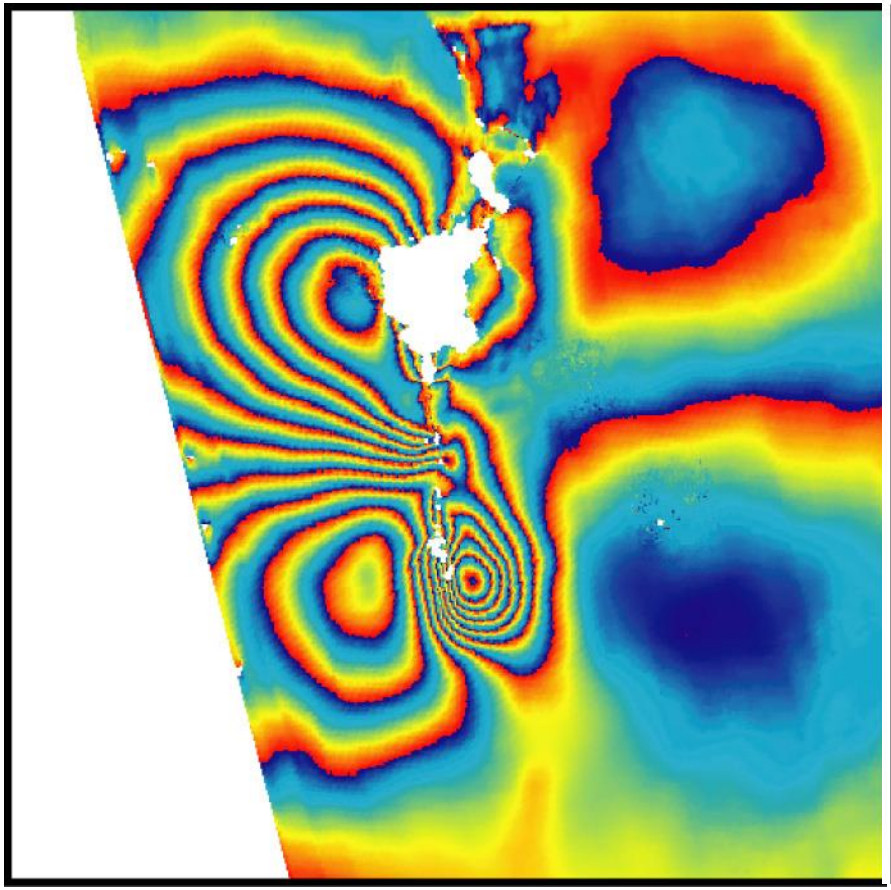




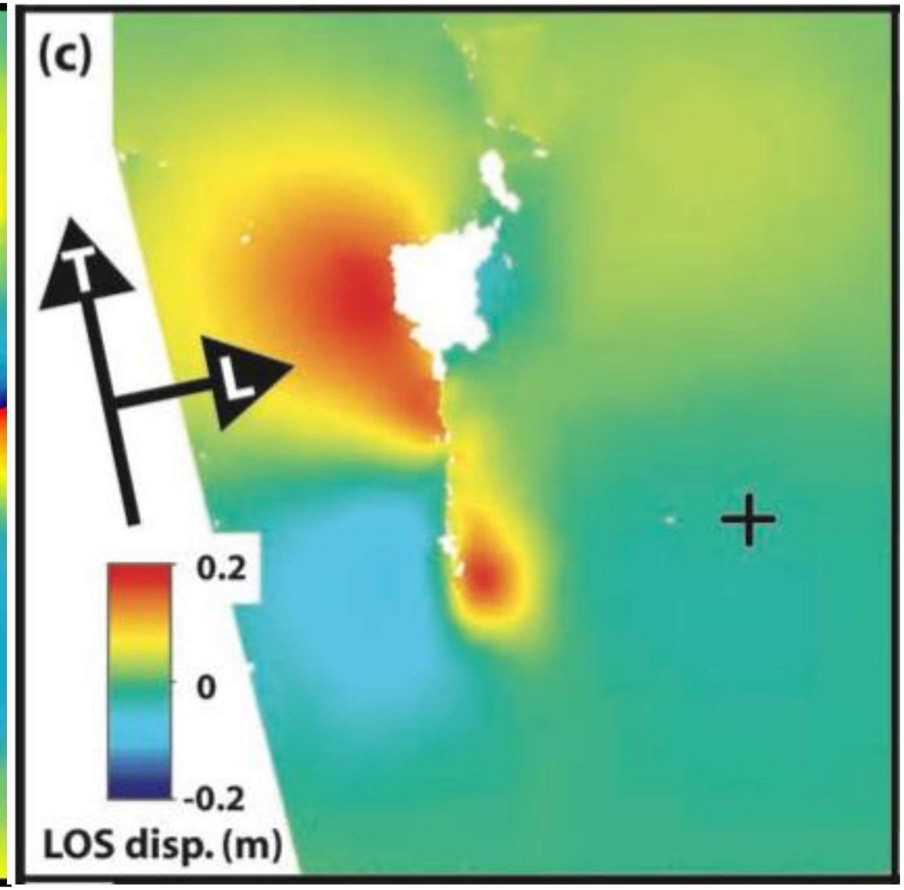
Unwrapping

'Unwrapping' is the process of converting the cyclical (modulo 2π) phase signal of an interferogram into a continuous phase signal

It is usually preferable to use unwrapped phase for deformation or topography estimation “wrapped”



“unwrapped”



Unwrapping

Several different algorithms exist for unwrapping. Although they differ in detail, they typically do similar things:

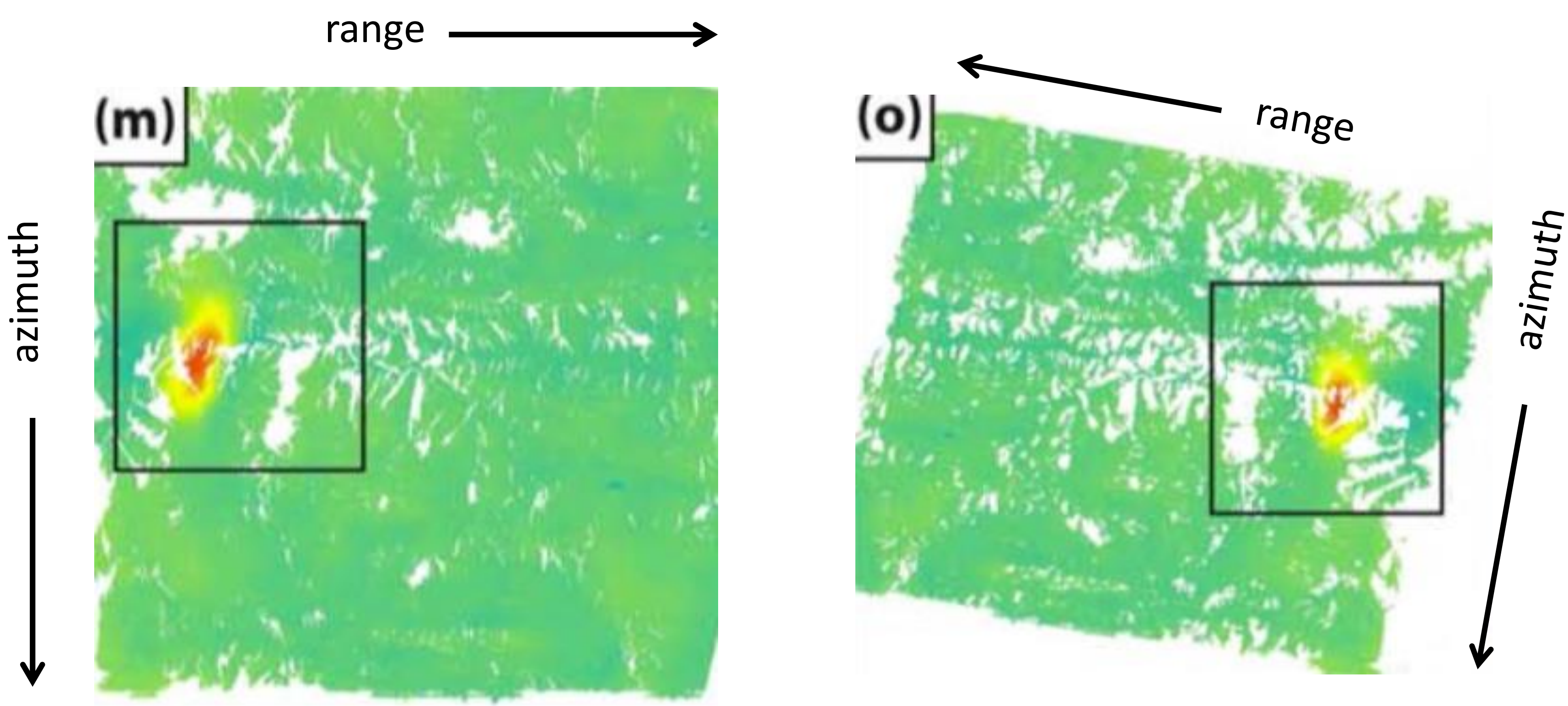
1) Find the connected components of an interferogram (e.g. by integrating around closed loops)

2) Estimate (manually or statistically) the adjustment between neighboring connected areas

These algorithms can produce false results (incorrect estimates of phase differences between neighbors), so always check the results!

Geocoding

Final stage of processing, converts the data from 'radar geometry' (left) to geographical coordinates (right)



Funning, 2005

Processing software

ROI_PAC (Repeat Orbit Interferometry Package): 2000s era software from JPL/NASA (free, but defunct)

GAMMA: Commercial package from one of the original ROI_PAC developers (up to date, but expensive)

GMTSAR: Developed at Scripps, built on top of GMT (free, up to date)

ISCE (InSAR Scientific Computing Environment): Next generation JPL/NASA software (free, up to date)

SNAP (Sentinel Application Platform): ESA-supported software (free, up to date, easy to install but clunky)

Processing software

UNAVCO/WInSAR currently support annual summer training courses in the ISCE and GMTSAR packages

https://www.unavco.org/education/professional-development/short-courses/2018/2018.html