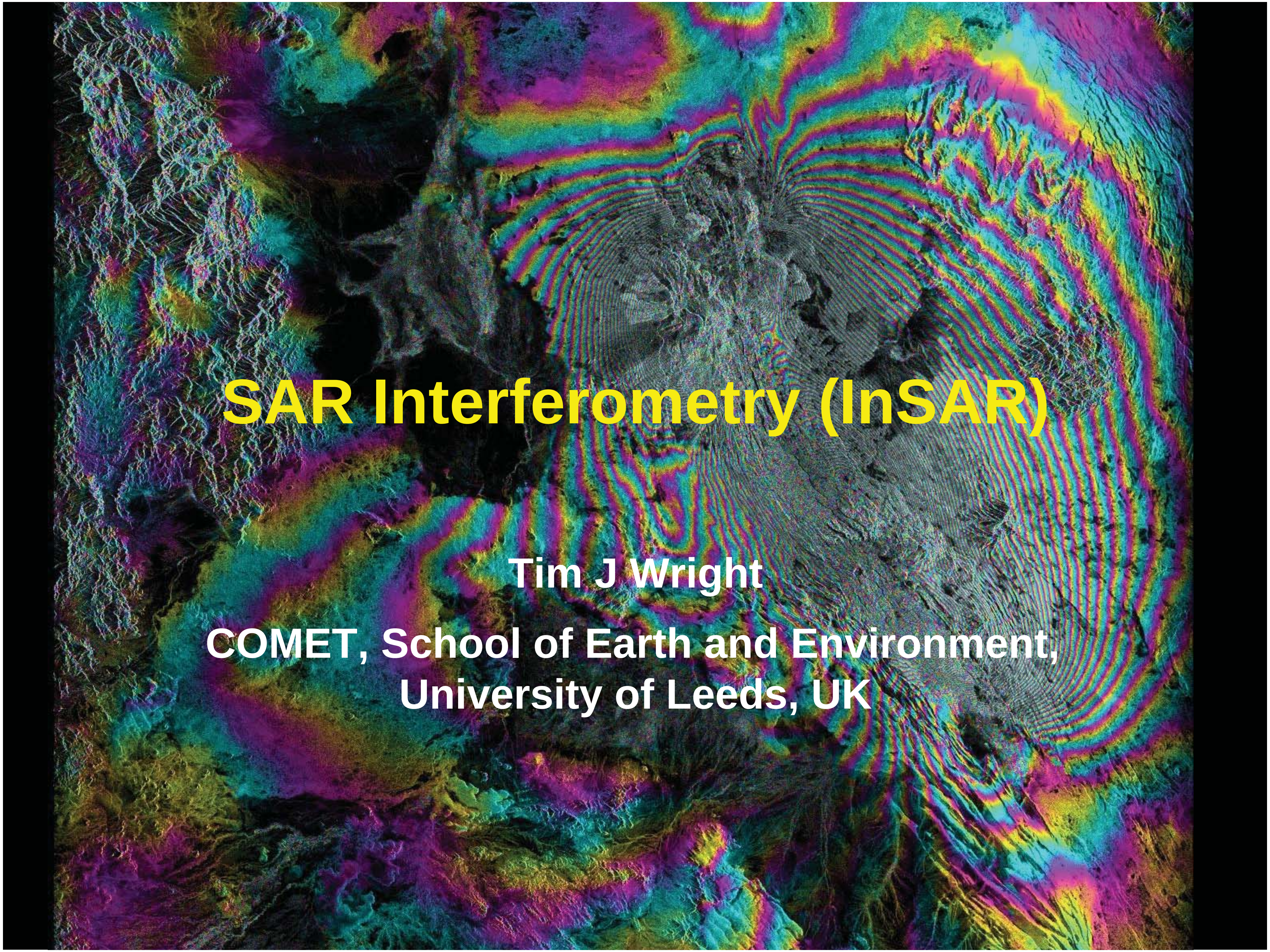
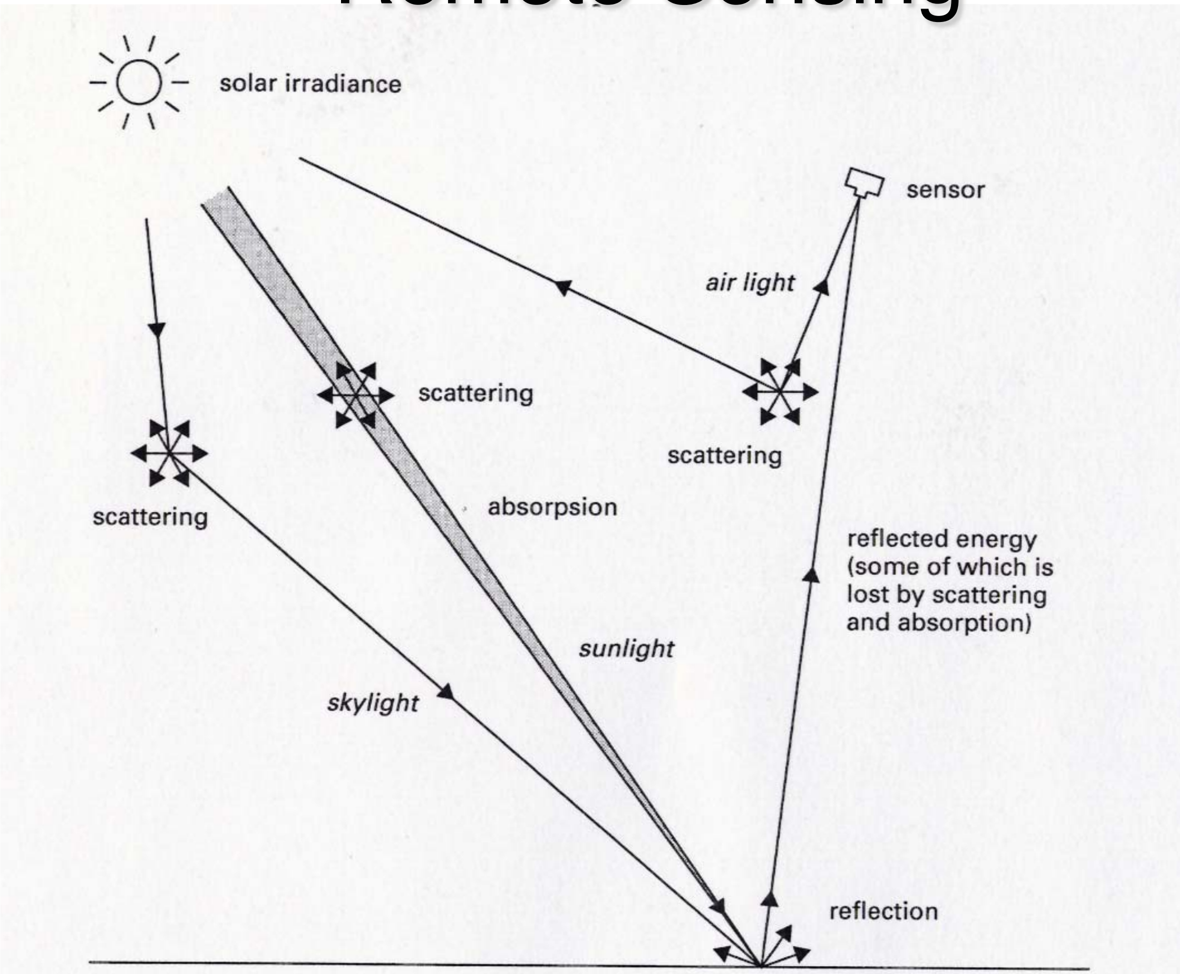


SAR Interferometry (InSAR)

Tim J Wright

COMET, School of Earth and Environment,
University of Leeds, UK

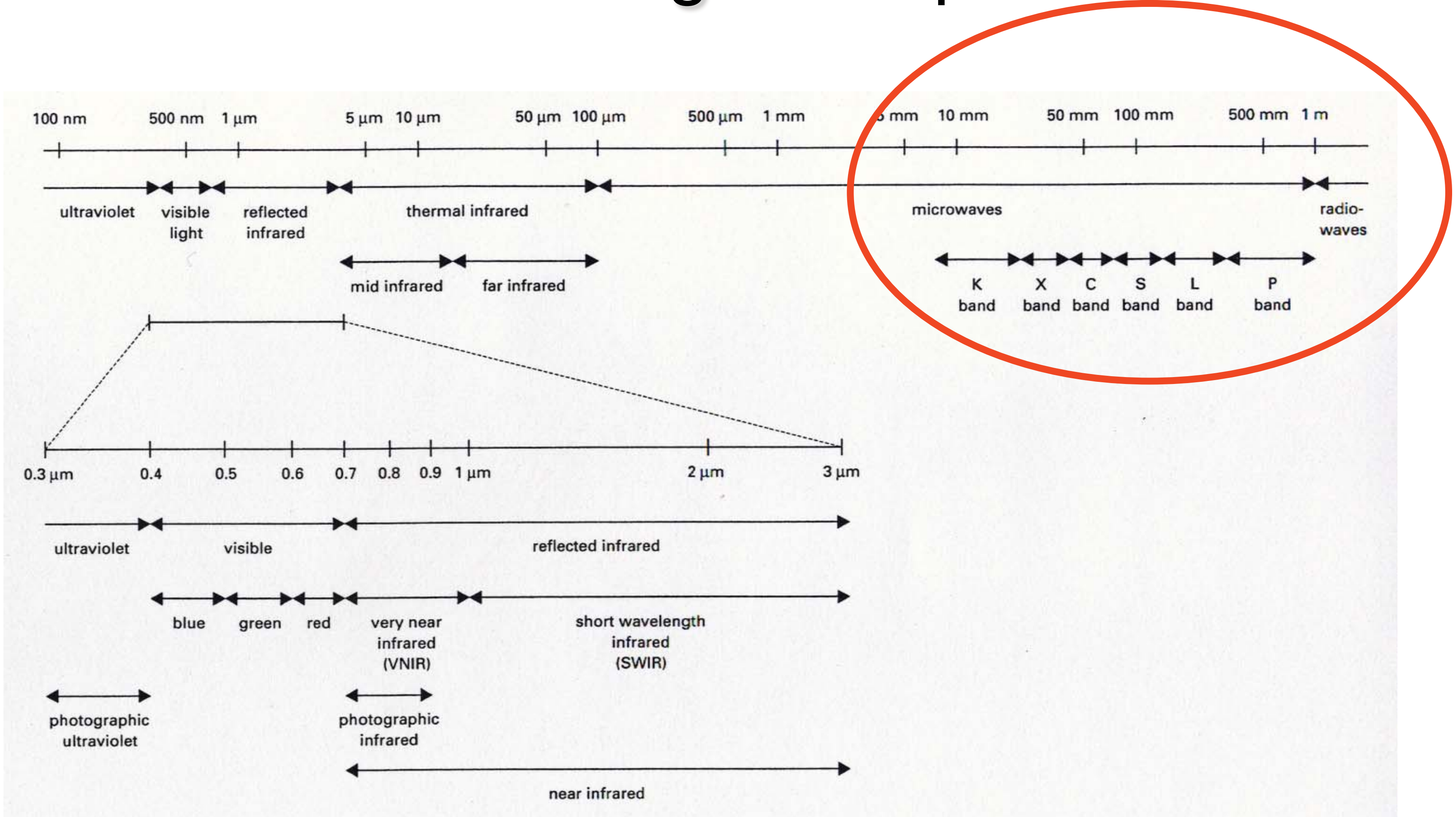
Remote Sensing



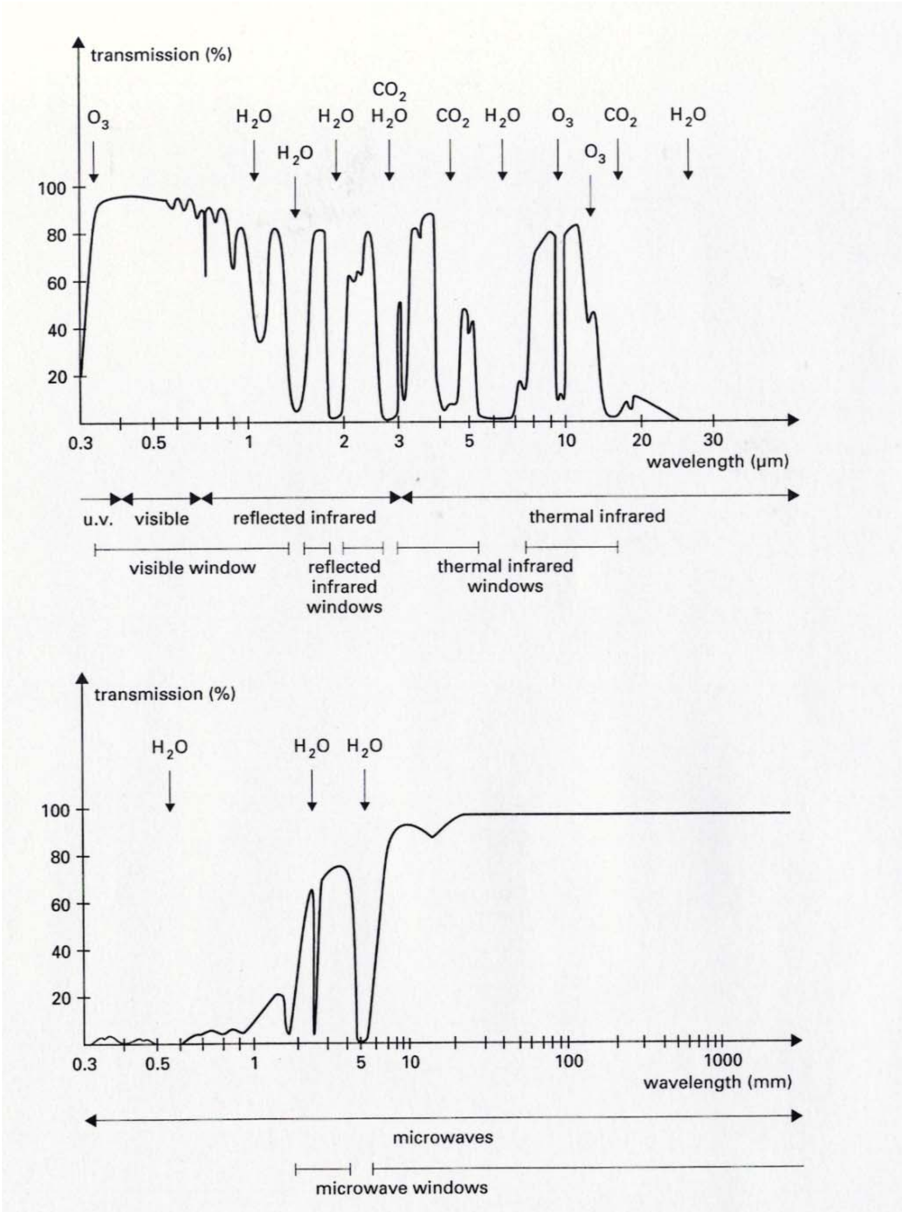
This is **passive** remote sensing where the Sun provides a natural source of illumination.

Active remote sensing involves illuminating the ground from the observing platform in some way, e.g. with radar or lasers.

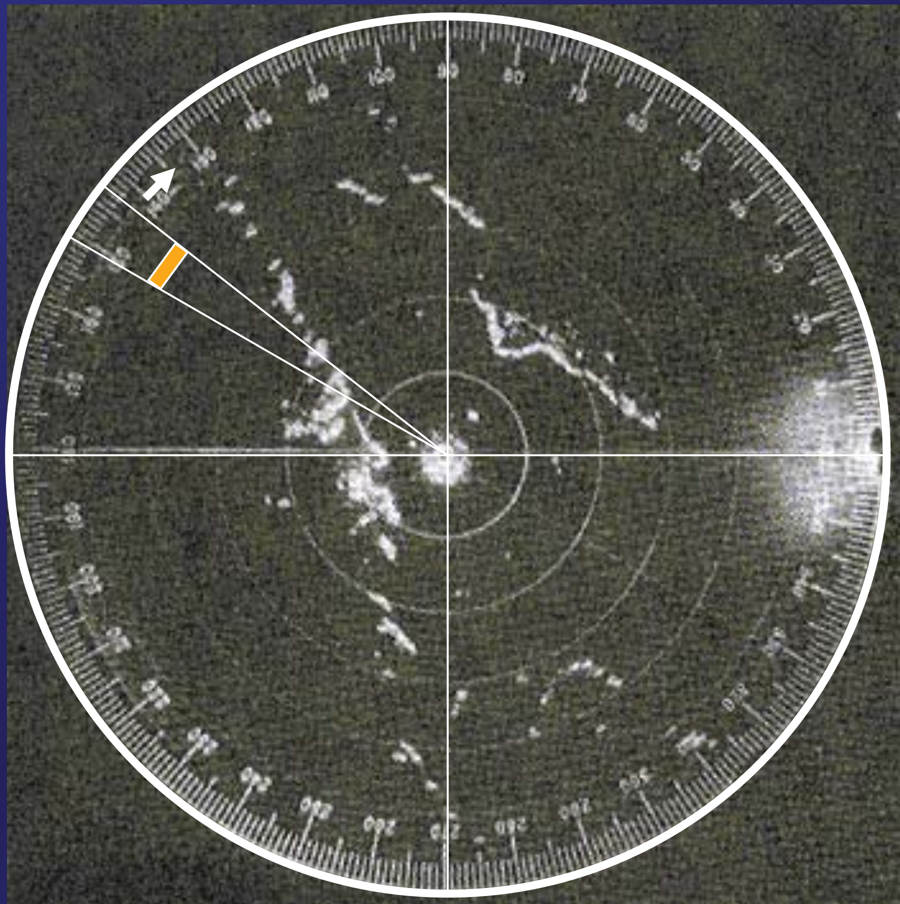
The Electromagnetic Spectrum



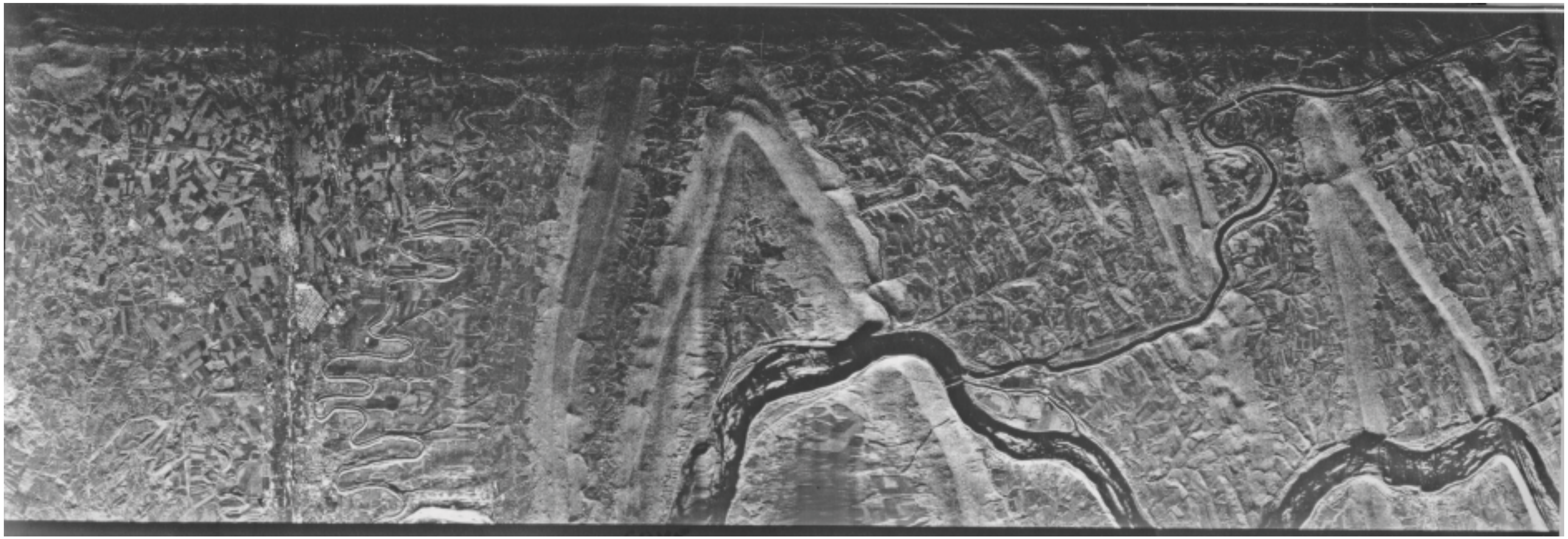
Active Remote Sensing with Microwaves



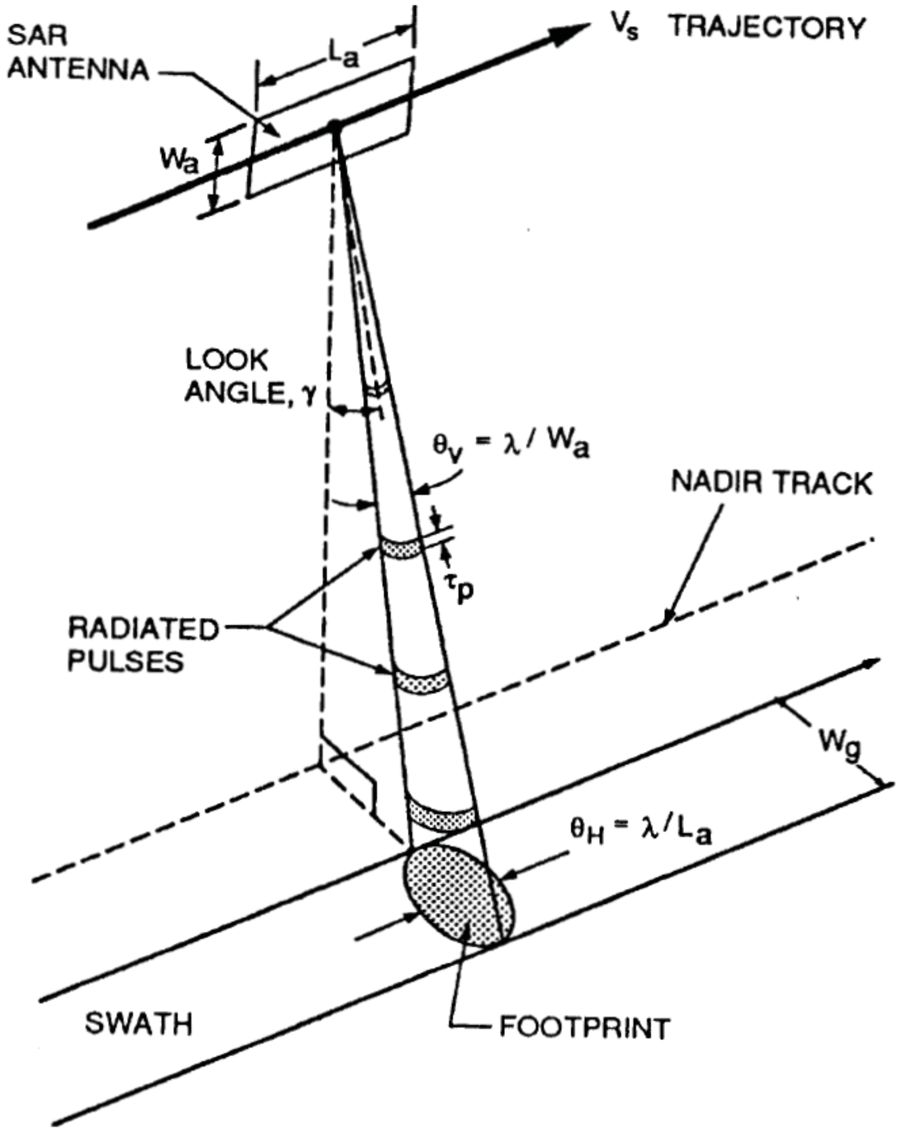
Radar = RAdio Detection And Ranging



Side-Looking Airborne Radar



Side-Looking Airborne Radar



$$\theta \sim \lambda / W$$

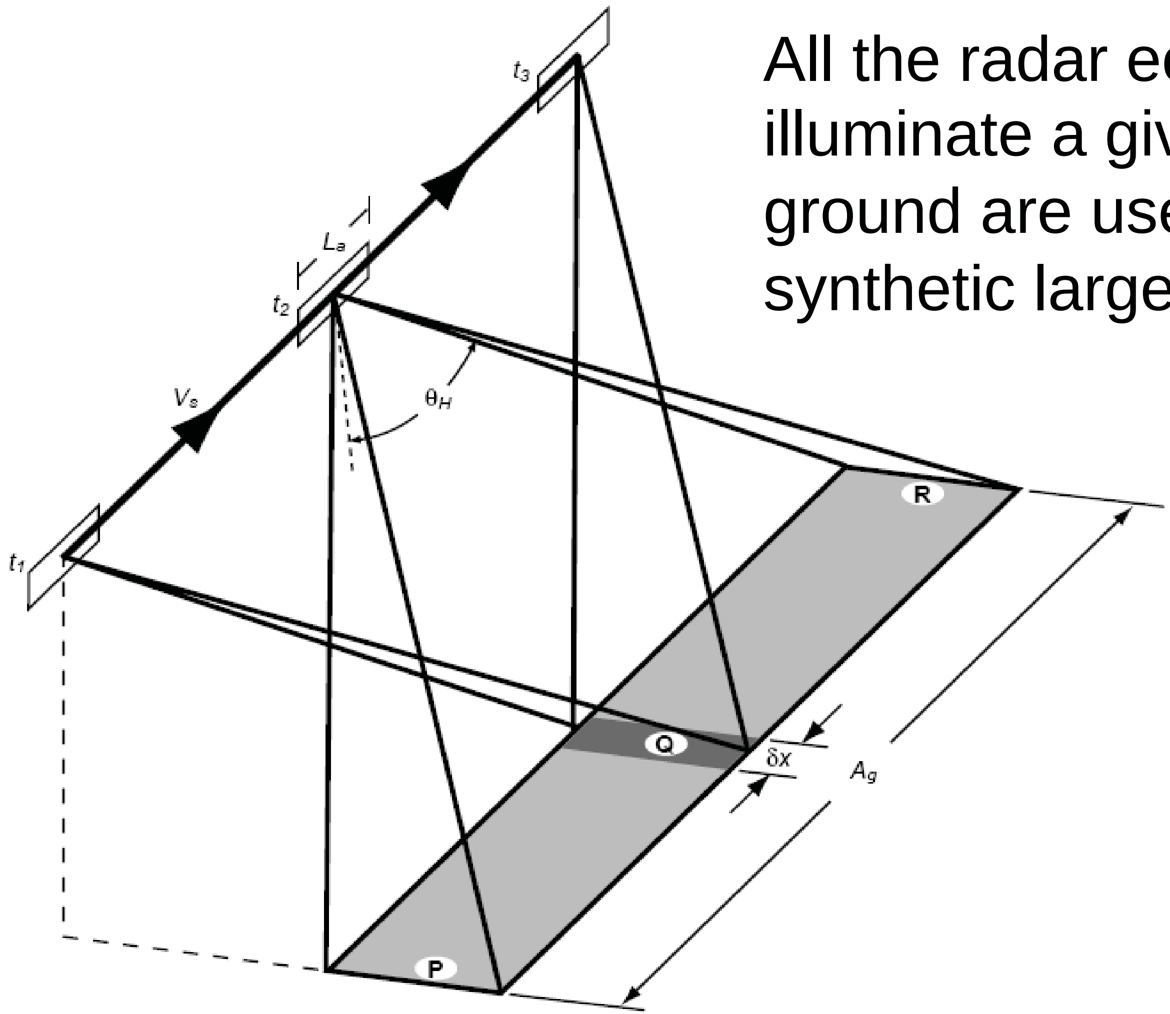
e.g. λ = 0.05 m

W = 10 m

θ ~ 0.005 radians

If at 800 km height, along-track footprint ~ 4 km

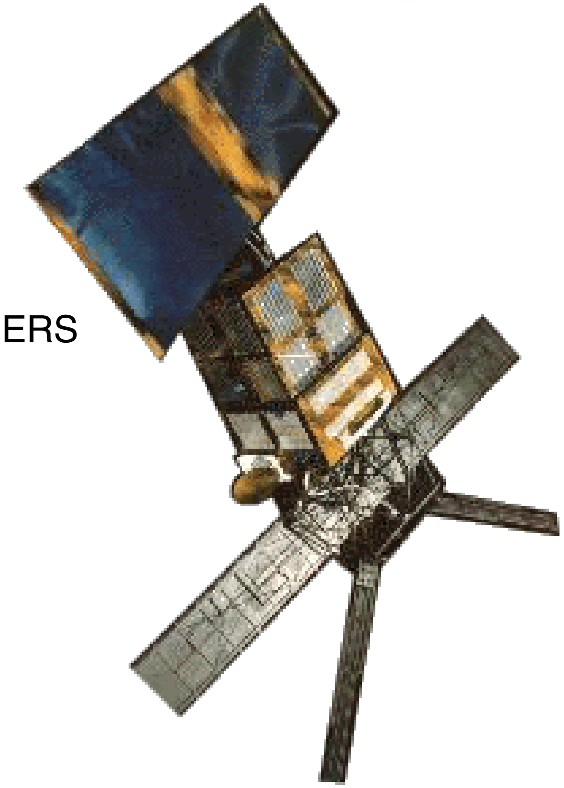
Trick – the Synthetic Aperture

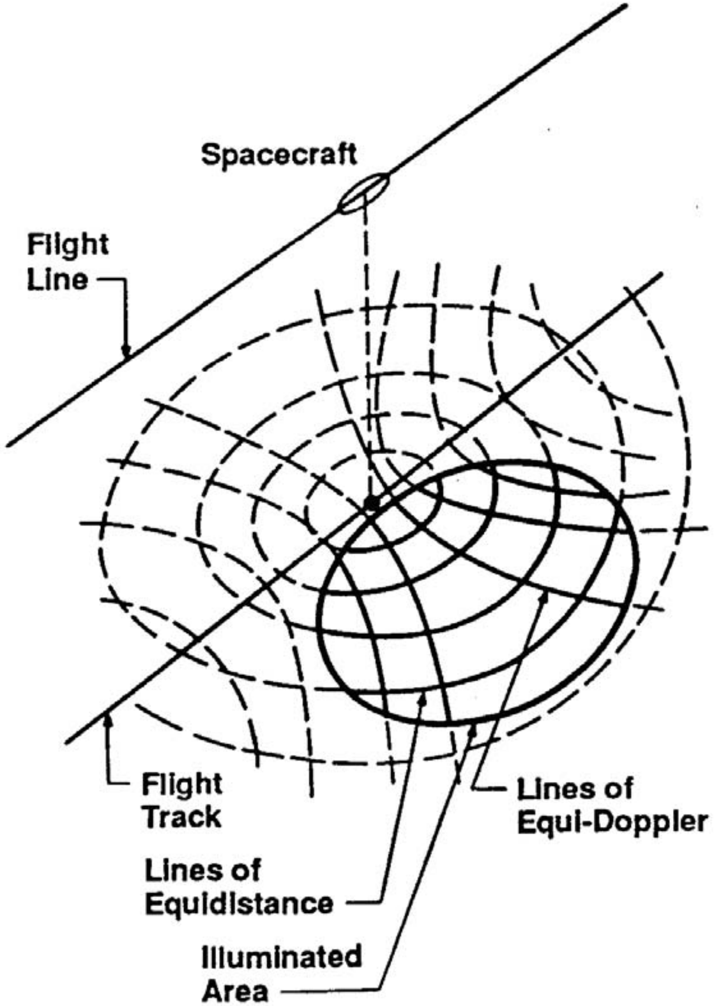


All the radar echoes that illuminate a given patch of ground are used to construct a synthetic larger antenna

Synthetic Aperture Radar (SAR)

ERS





A SAR makes use of measurements of the range and Doppler shift of the radar returns to locate ground points. The signals from many returns are analysed together to image ground elements ~5x20m in size, much smaller than would be possible with a stationary antenna of the same size - hence the Synthetic Aperture.

InSAR – how it works

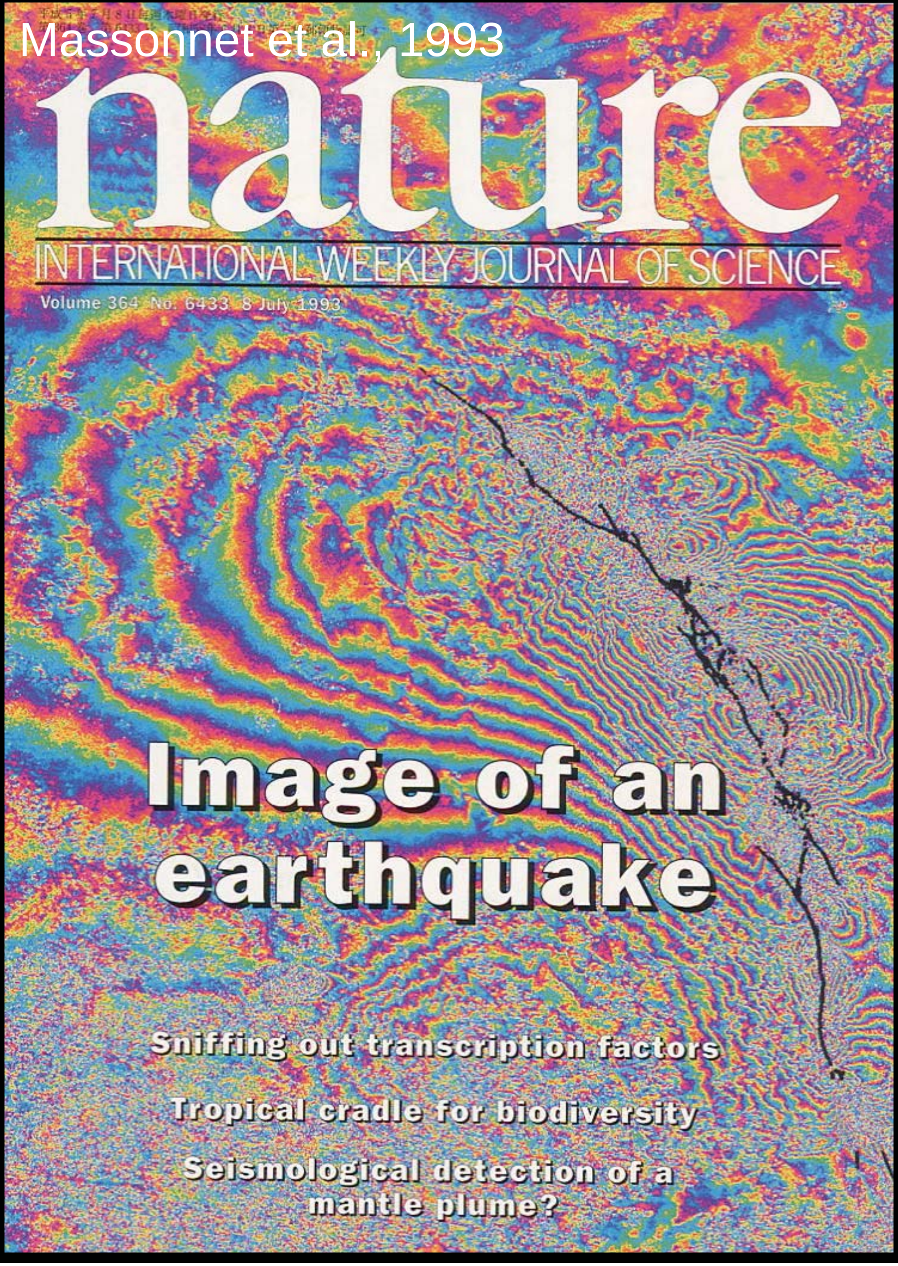
• Actively illuminate ground with radar waves.

• Operates day and night, can see through clouds

• ERS, Envisat (1991): very stable orbits and pointing ⇨ InSAR

• Followed by ERS-2 (1995) and Envisat (2003) for ~ 20 year time series

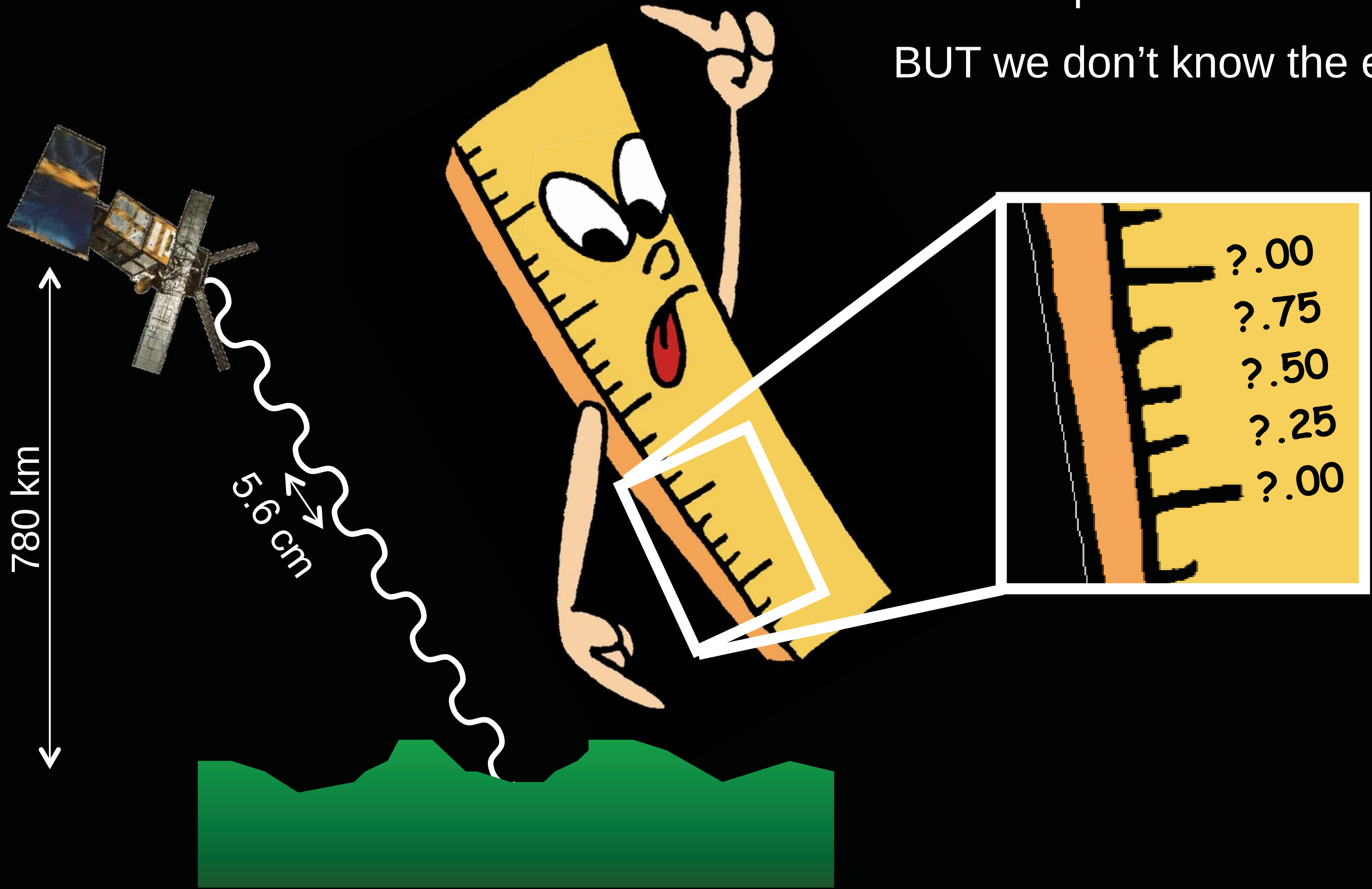
Massonnet et al., 1993



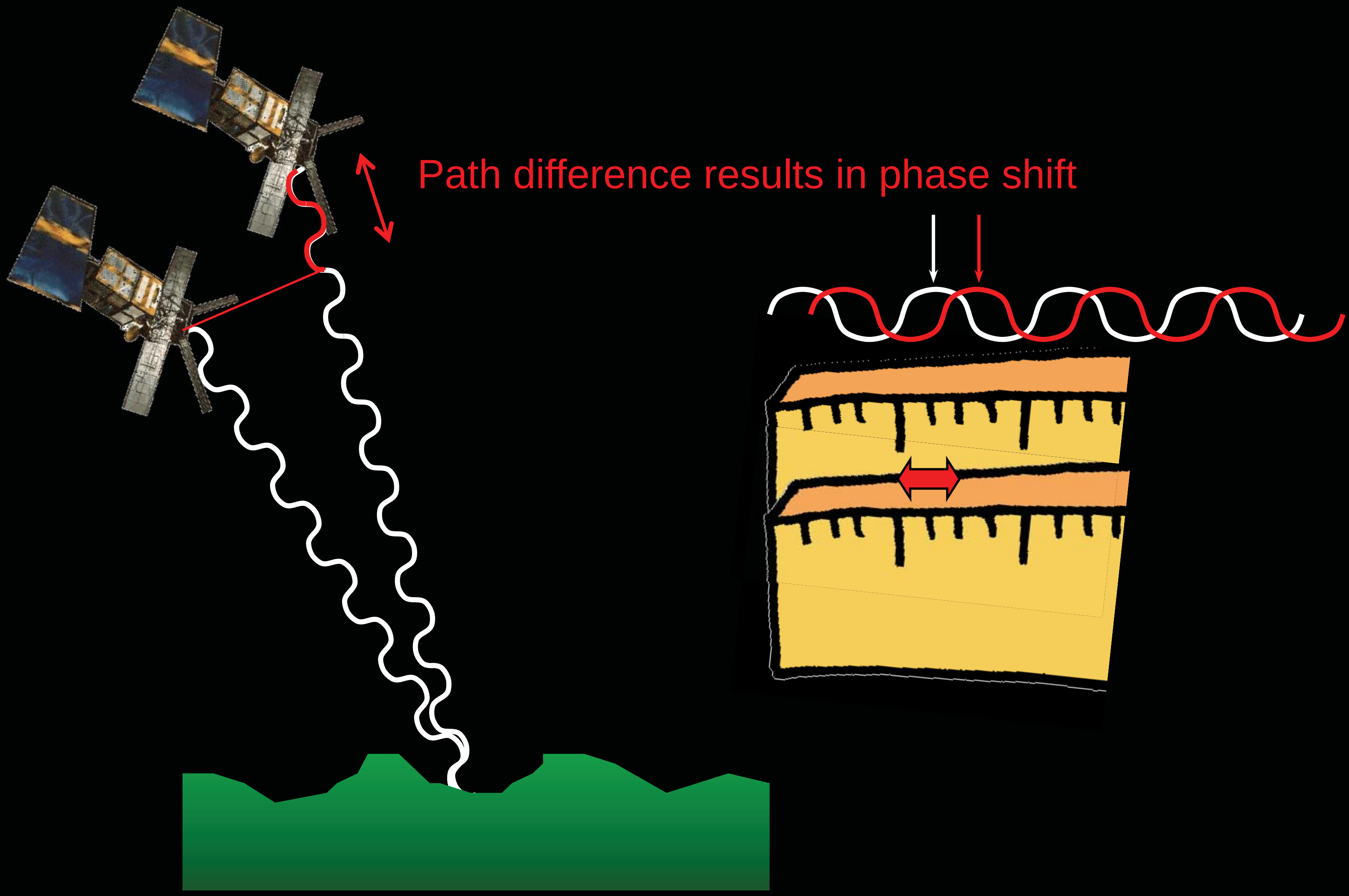
InSAR – how it works

Round trip ~ 30 million wavelengths

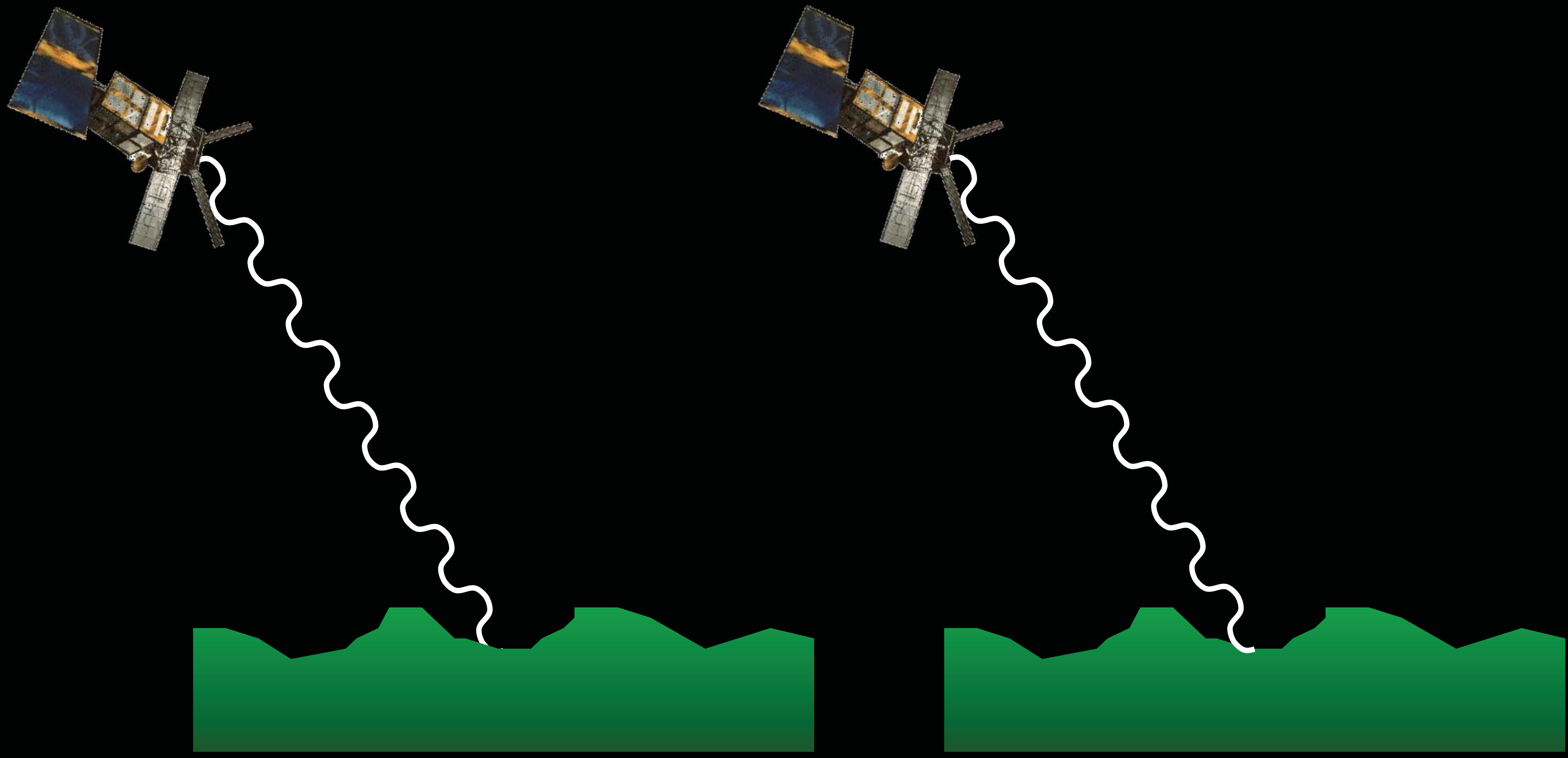
BUT we don't know the exact number



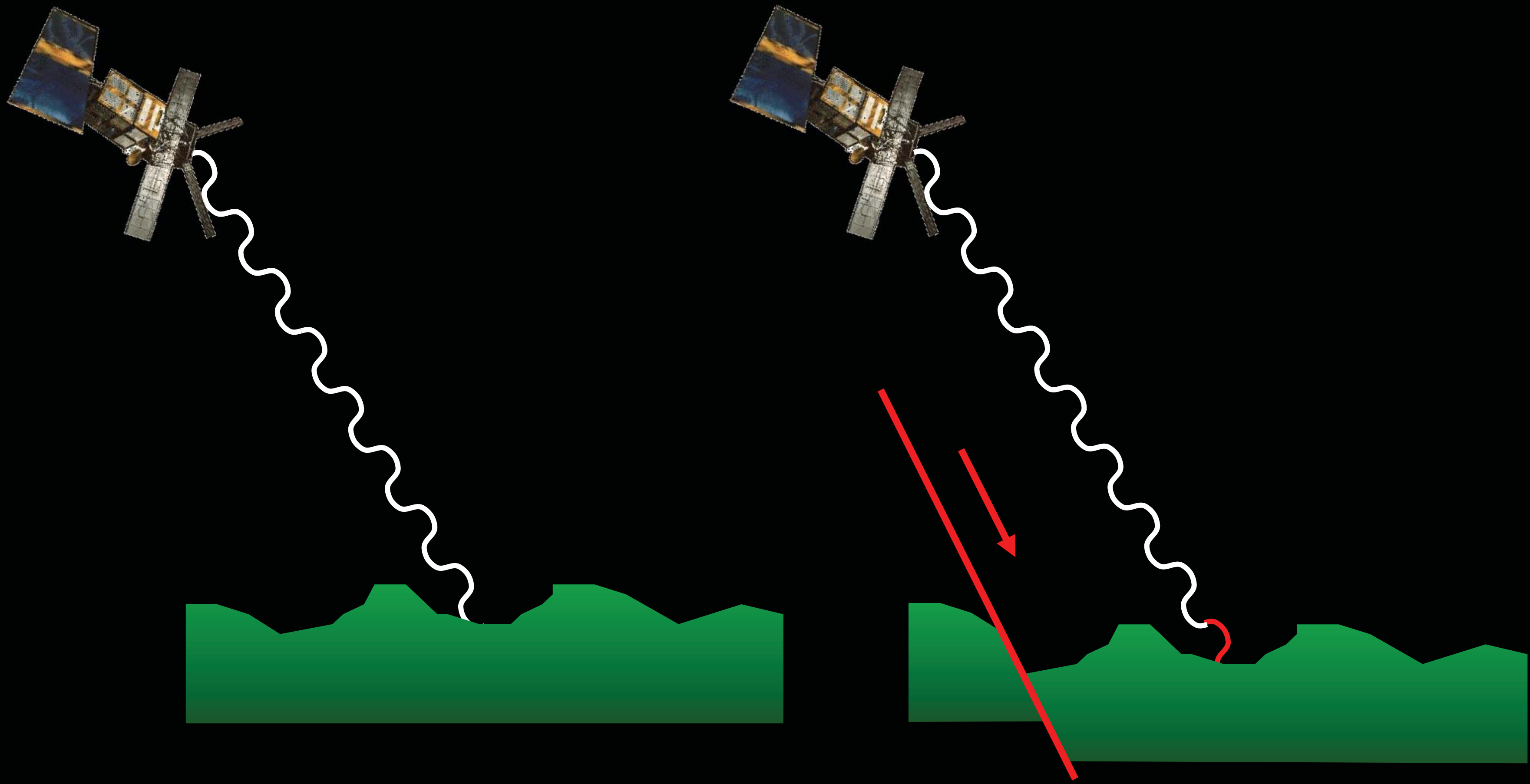
InSAR – how it works



InSAR – how it works



InSAR – how it works



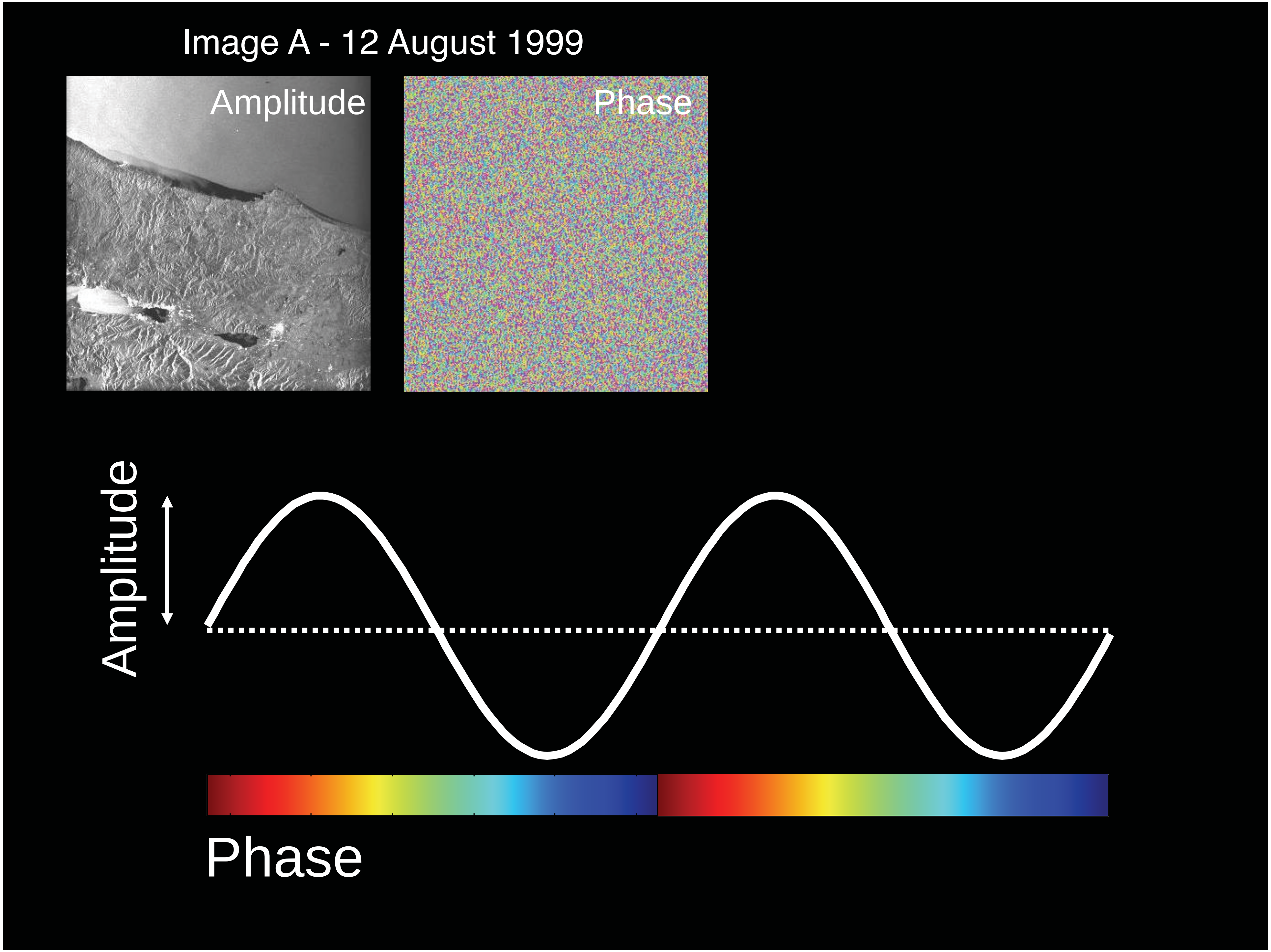


Image A - 12 August 1999
Amplitude
Phase
Amplitude
Phase

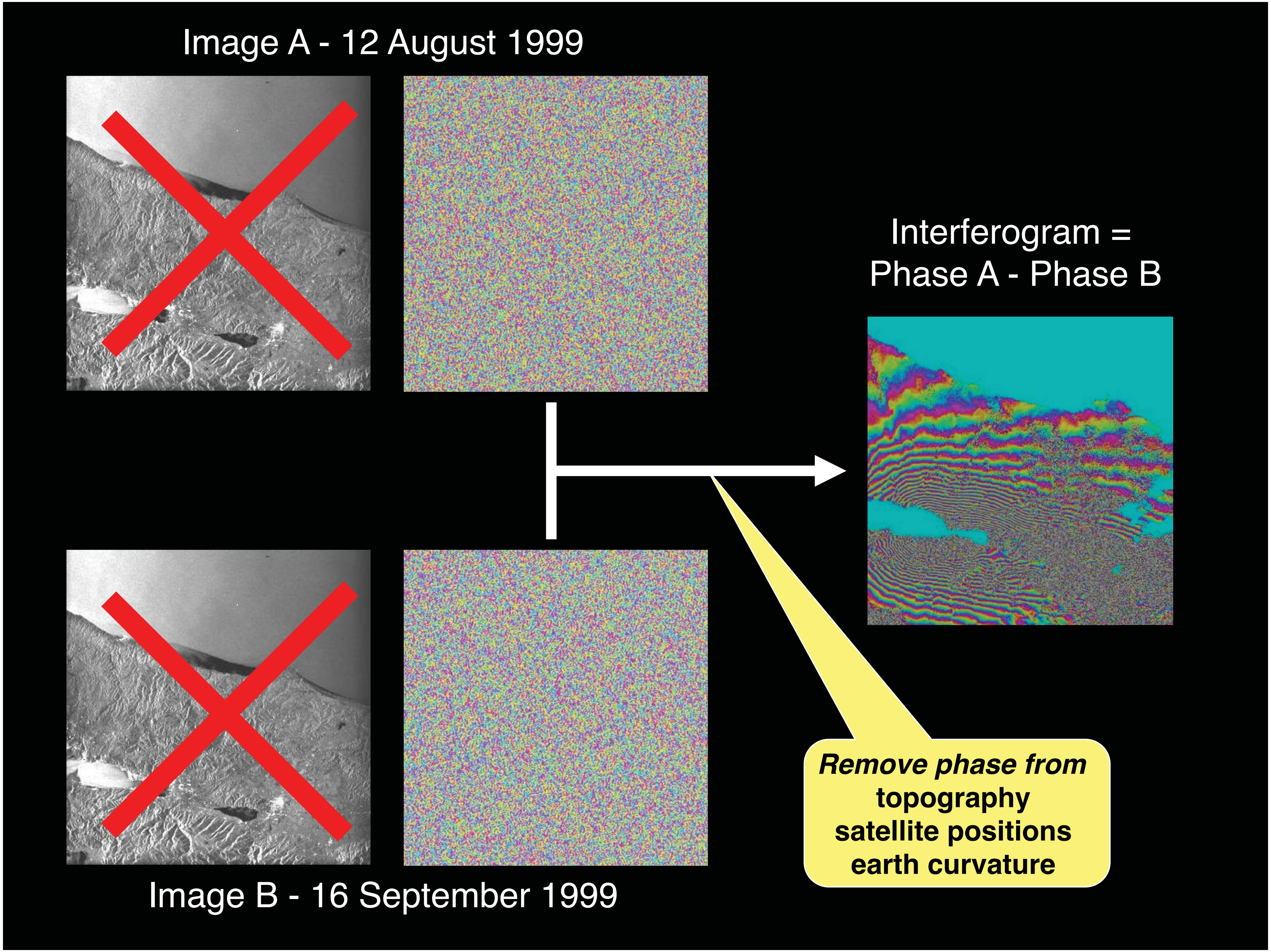
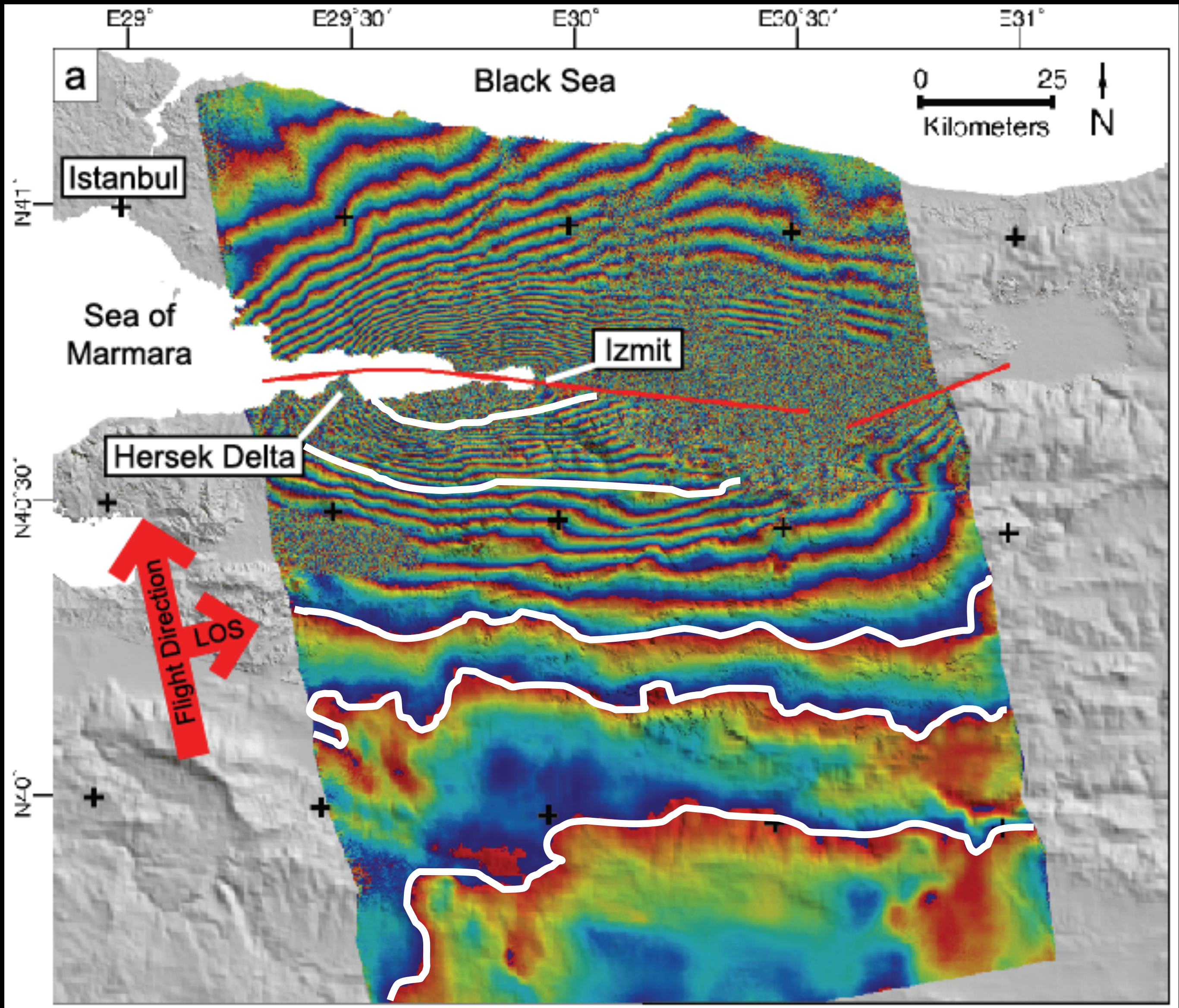


Image A - 12 August 1999
Interferogram =
Phase A - Phase B
Remove phase from
topography
satellite positions
earth curvature
Image B - 16 September 1999



(-20) 567 mm range decrease

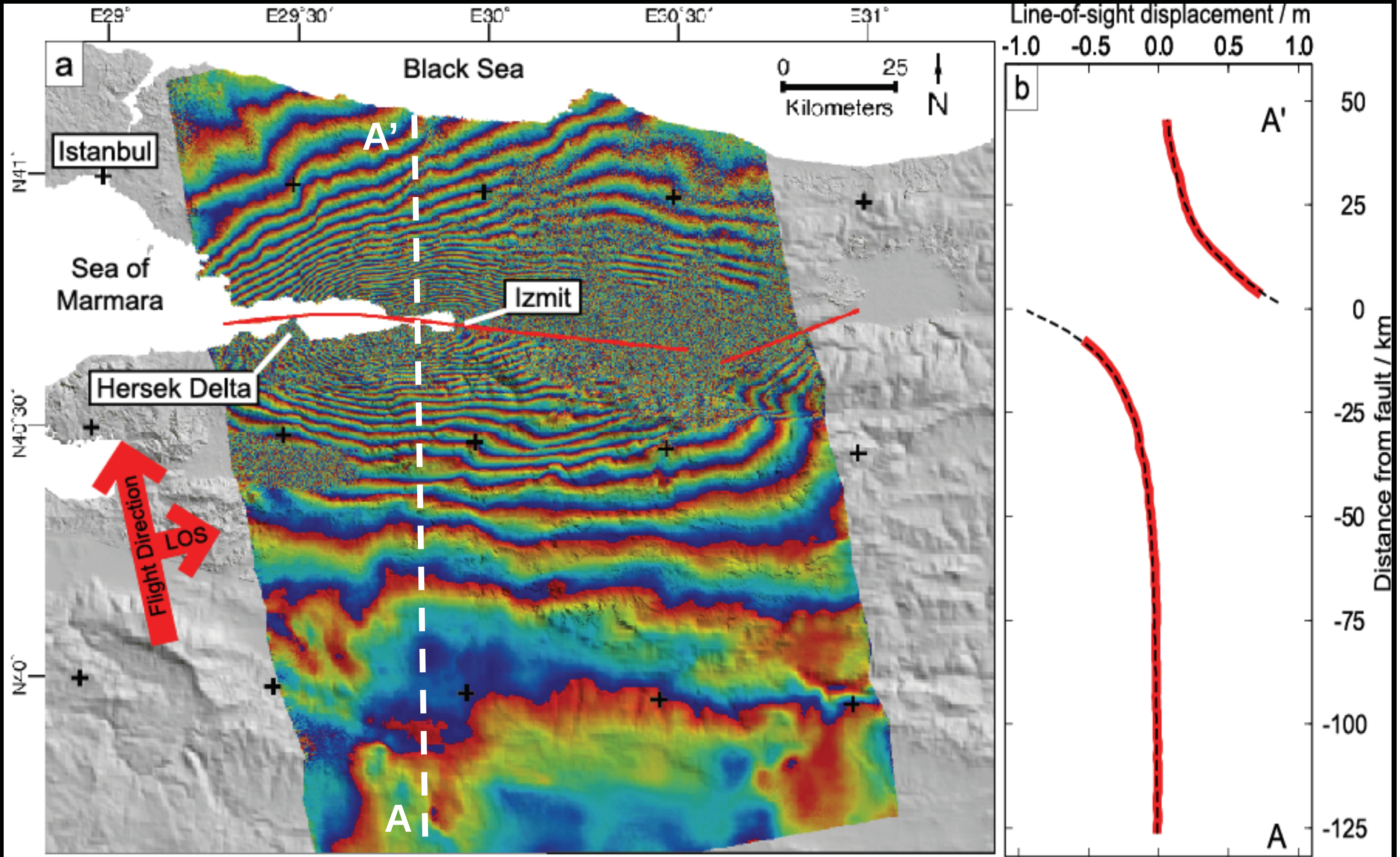
(-10) 283 mm range decrease

(-2) 57 mm range decrease

(-1) 28 mm range decrease

(0) 0 mm range change

17 August 1999, Izmit earthquake (Turkey)



17 August 1999, Izmit earthquake (Turkey)

Components of interferometric phase

$$\Delta\phi_{int} = \Delta\phi_{geom} + \Delta\phi_{topo} + \Delta\phi_{atm} + \Delta\phi_{noise} + \Delta\phi_{def}$$

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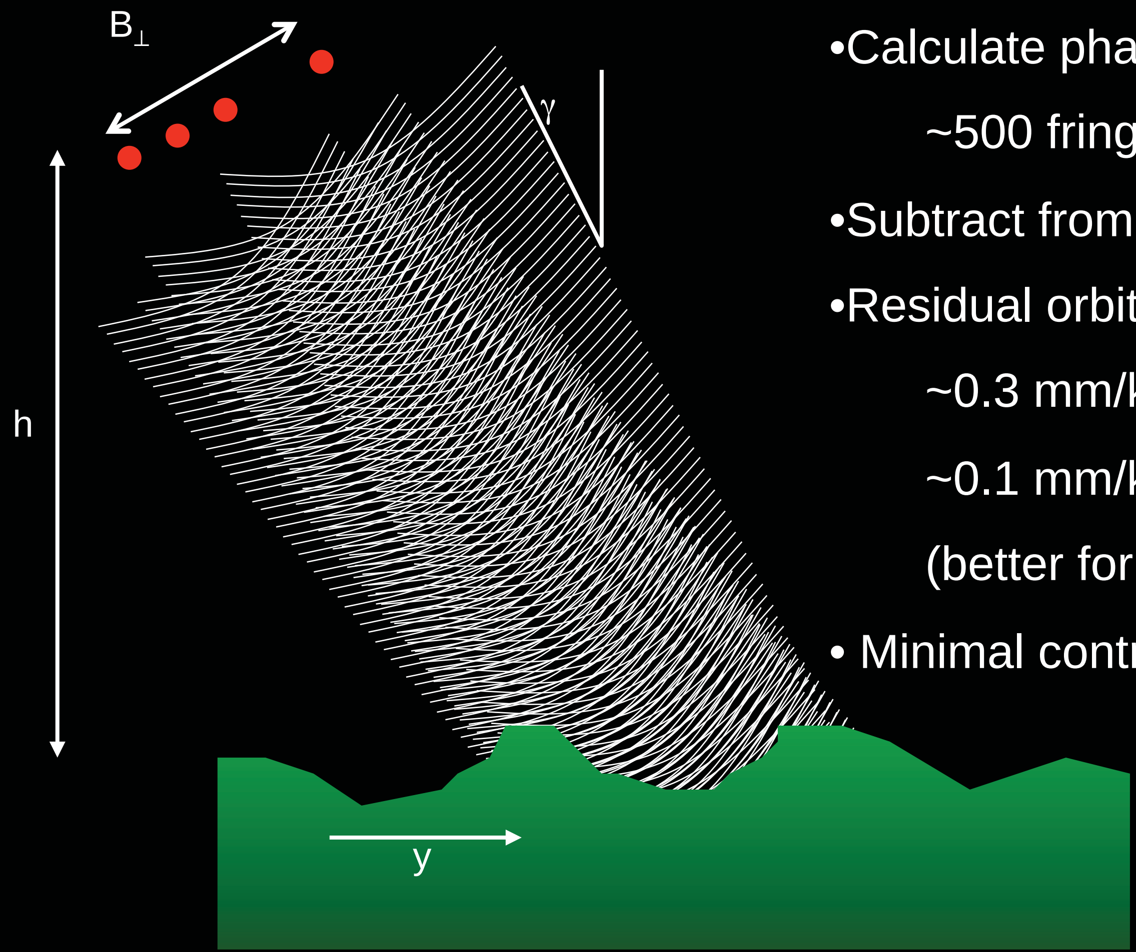
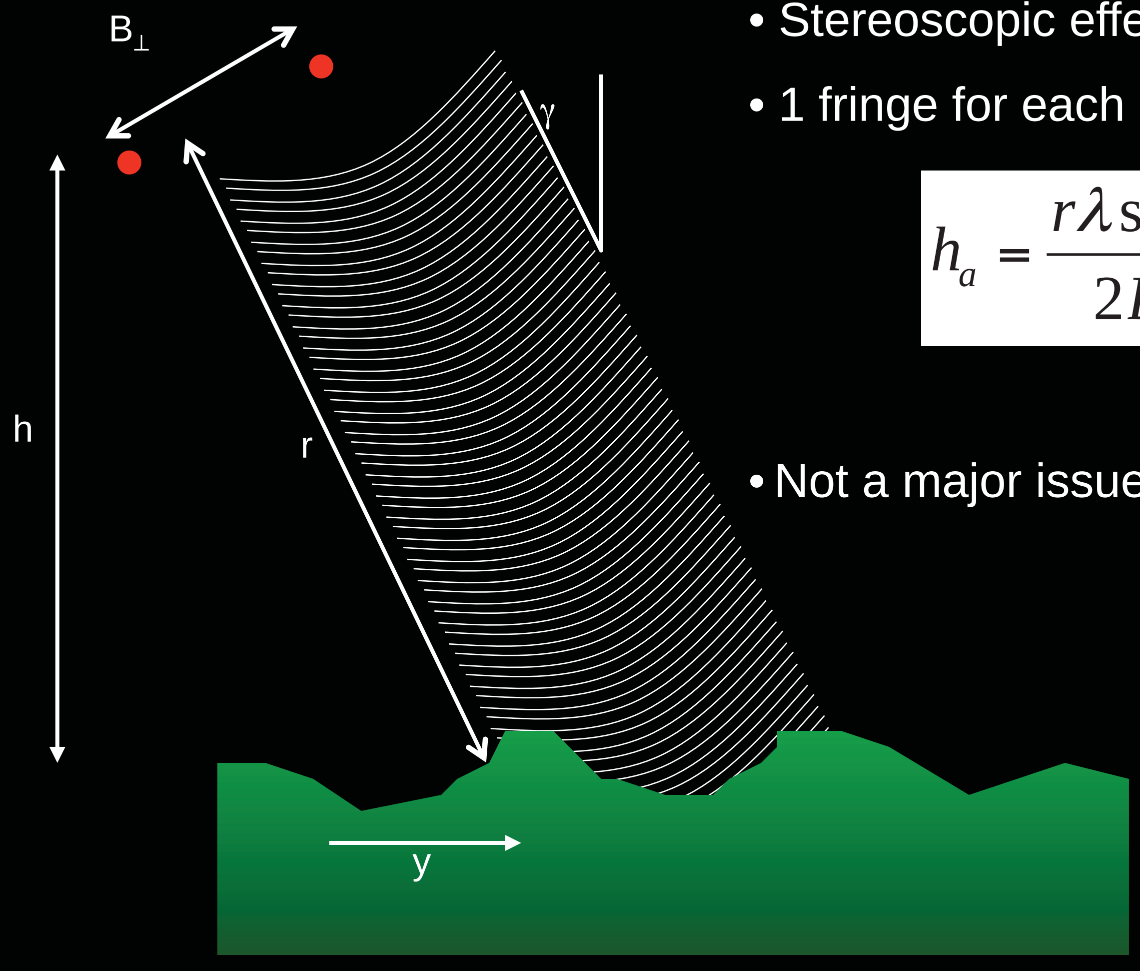


- Calculate phase ramp from satellite orbits
  - ~500 fringes across typical frame
- Subtract from interferogram
- Residual orbital errors:
  - ~0.3 mm/km (north, ERS)
  - ~0.1 mm/km (east, ERS)
  - (better for Envisat)
- Minimal control on v. long wavelength

Components of interferometric phase

$$\Delta\phi_{int} = \Delta\phi_{geom} + \Delta\phi_{topo} + \Delta\phi_{atm} + \Delta\phi_{noise} + \Delta\phi_{def}$$



- Stereoscopic effect ⇒ topographic fringes
- 1 fringe for each change in elevation h_a

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

- Not a major issue since SRTM

Components of interferometric phase

$$\Delta\phi_{int} = \Delta\phi_{geom} + \Delta\phi_{topo} + \Delta\phi_{atm} + \Delta\phi_{noise} + \Delta\phi_{def}$$

A foggy morning,

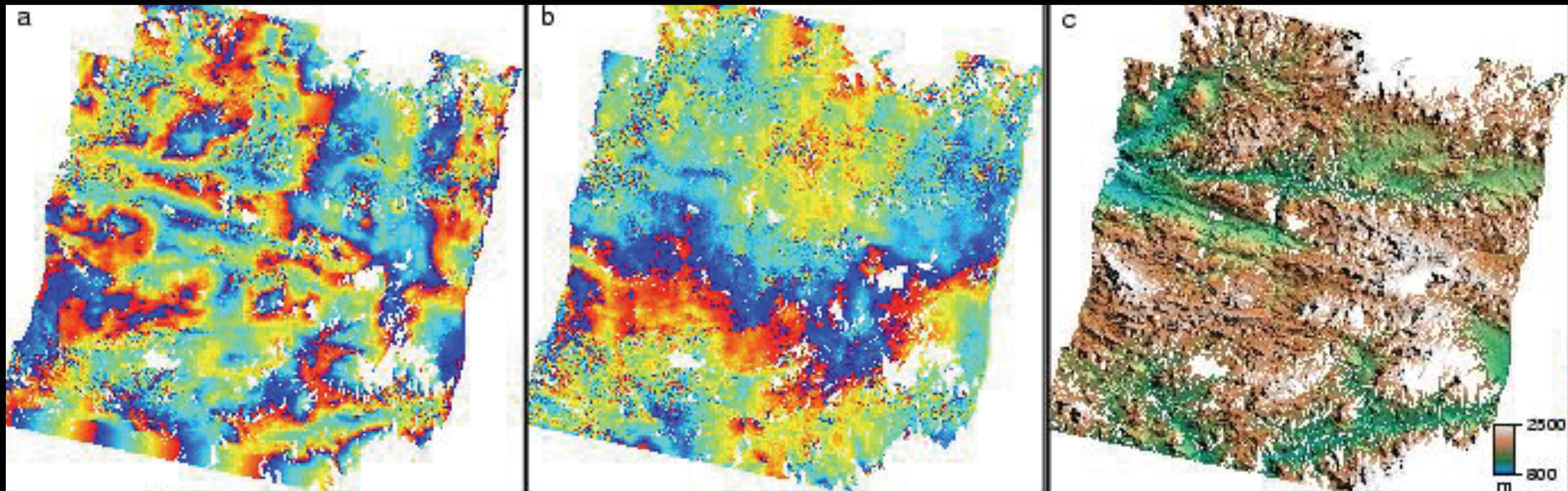
near ancient Mycenae,

Greece

Components of interferometric phase

$$\Delta\phi_{int} = \Delta\phi_{geom} + \Delta\phi_{topo} + \Delta\phi_{atm} + \Delta\phi_{noise} + \Delta\phi_{def}$$

Layered atmosphere

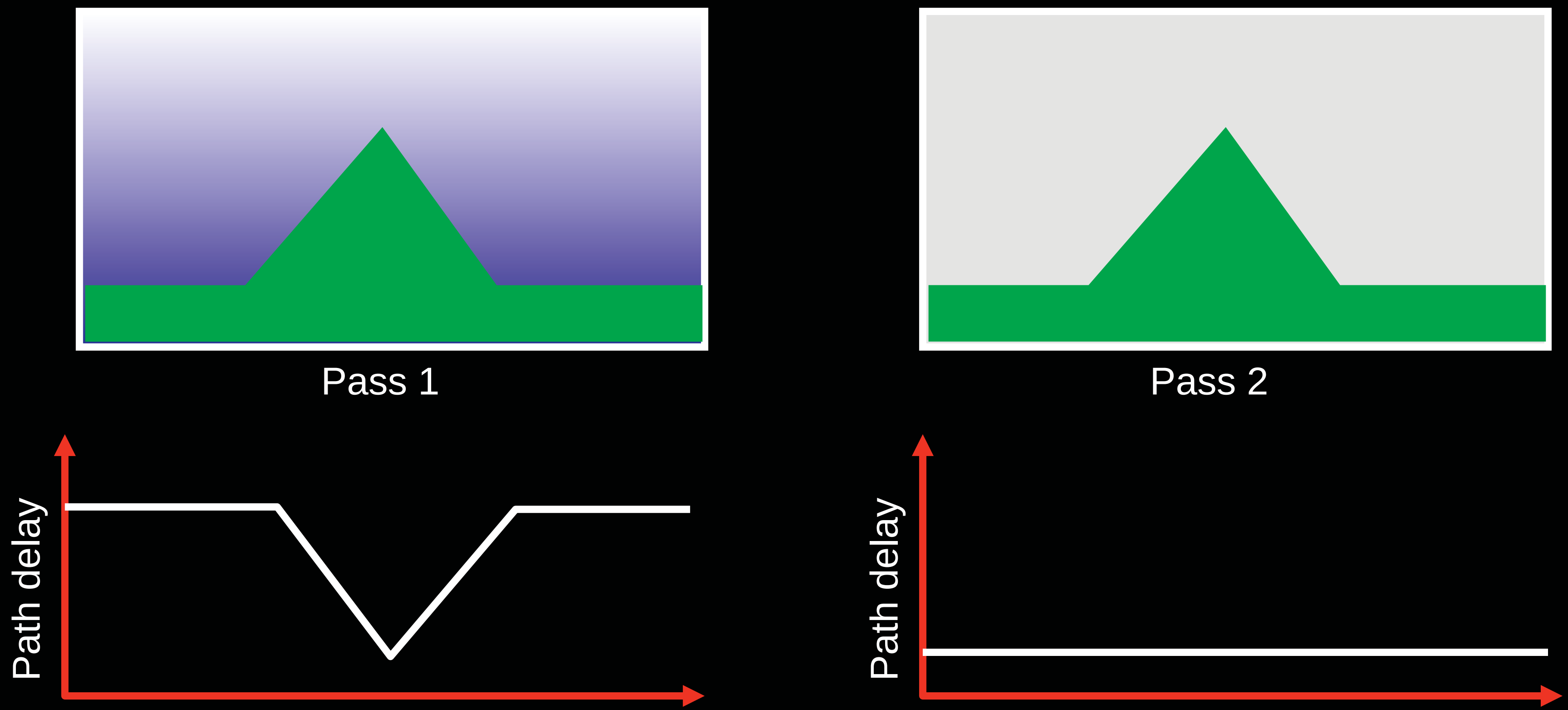


29/8/1995 to 29/7/1997 — 30/8/1995 to 29/7/1997 — Topography

Components of interferometric phase

$$\Delta\phi_{\mathrm{int}} = \Delta\phi_{\mathrm{geom}} + \Delta\phi_{\mathrm{topo}} + \Delta\phi_{\mathrm{atm}} + \Delta\phi_{\mathrm{noise}} + \Delta\phi_{\mathrm{def}}$$

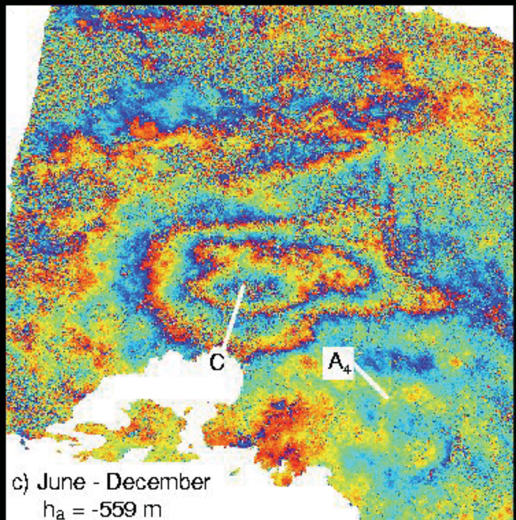
Layered atmosphere



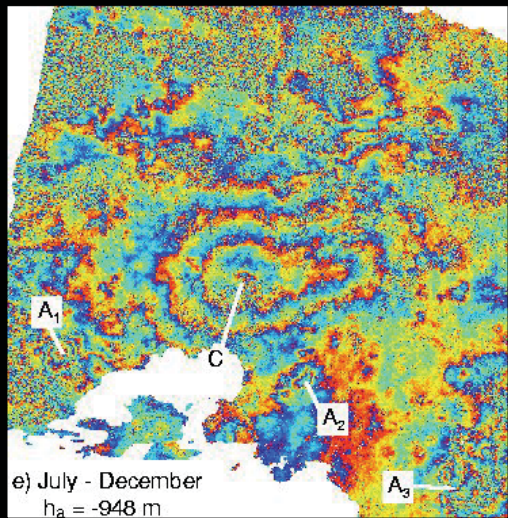
Components of interferometric phase

$$\Delta\phi_{int} = \Delta\phi_{geom} + \Delta\phi_{topo} + \Delta\phi_{atm} + \Delta\phi_{noise} + \Delta\phi_{def}$$

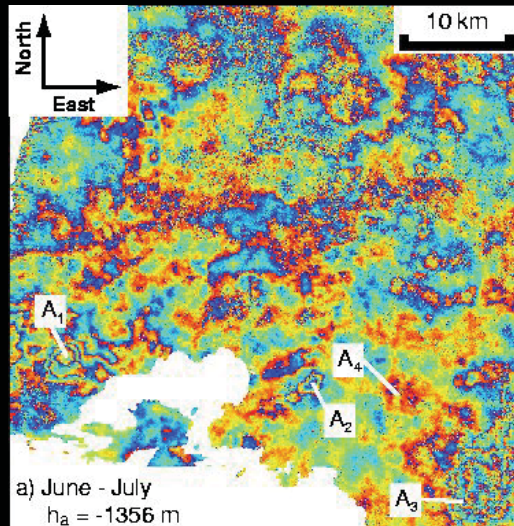
Turbulent atmosphere



June to December



July to December



June to July

Athens Earthquake – September 1999

Components of interferometric phase

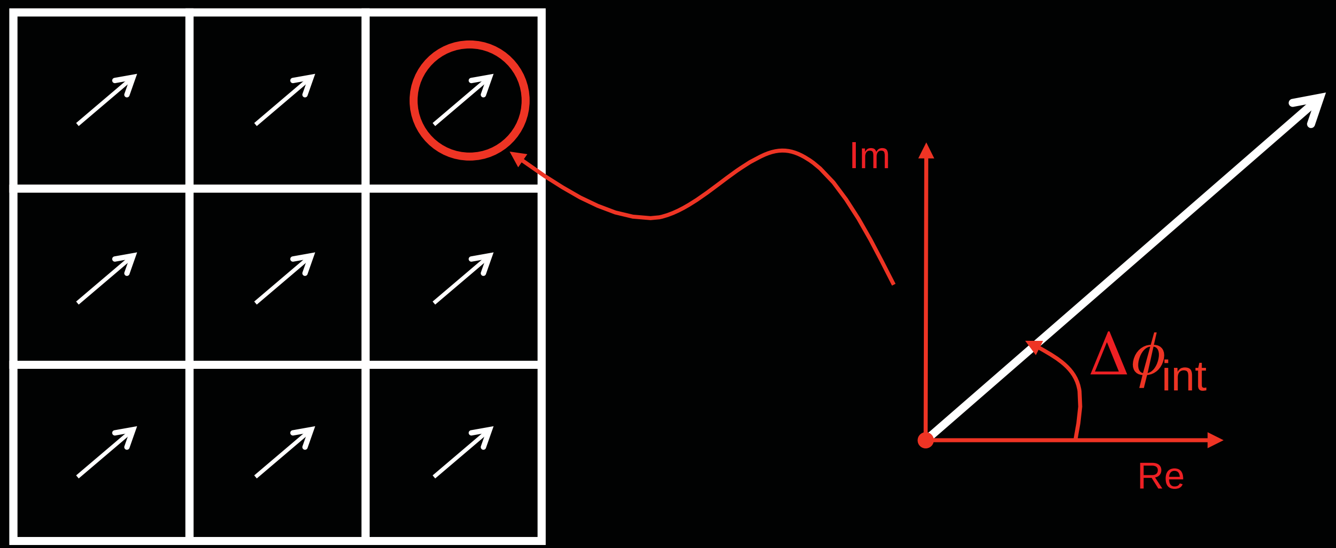
$$\Delta\phi_{int} = \Delta\phi_{geom} + \Delta\phi_{topo} + \Delta\phi_{atm} + \Delta\phi_{noise} + \Delta\phi_{def}$$

- Size of $\Delta\phi_{atm}$ (at sea level) scales with distance, but can be +/- 10 cm or more.
- Methods for dealing with $\Delta\phi_{atm}$
  - Ignore (most common)
  - Quantify
  - Model based on other observations (e.g. GPS, meteorology…)
  - Increase SNR by stacking or time series analysis

Components of interferometric phase

$$\Delta\phi_{\text{int}} = \Delta\phi_{\text{geom}} + \Delta\phi_{\text{topo}} + \Delta\phi_{\text{atm}} + \Delta\phi_{\text{noise}} + \Delta\phi_{\text{def}}$$

- Biggest source of noise is due to changing ground surface (*Coherence*)
- Spatial *Correlation* can be used to estimate *Coherence*



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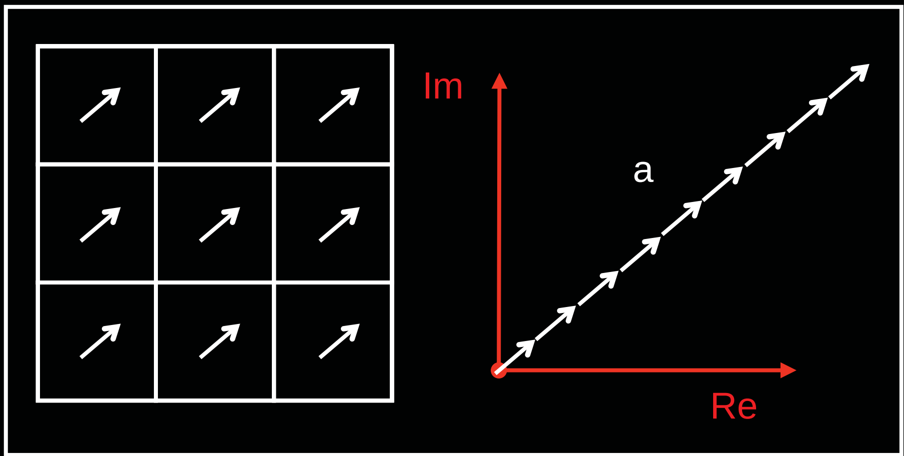
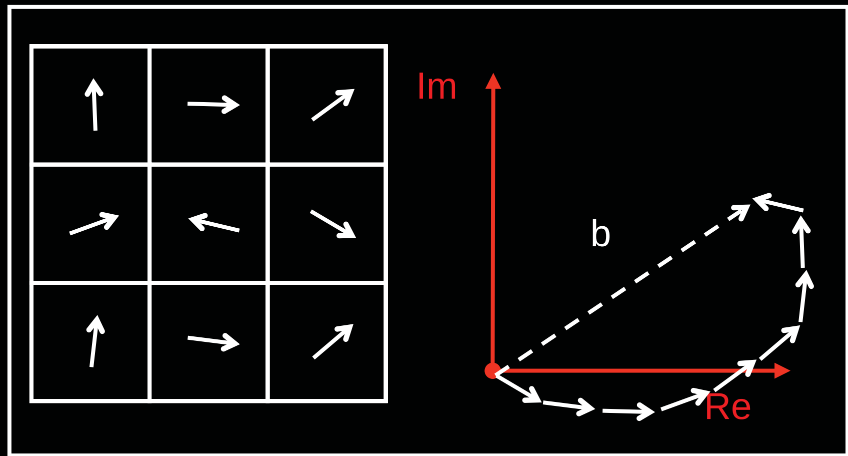
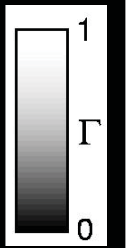


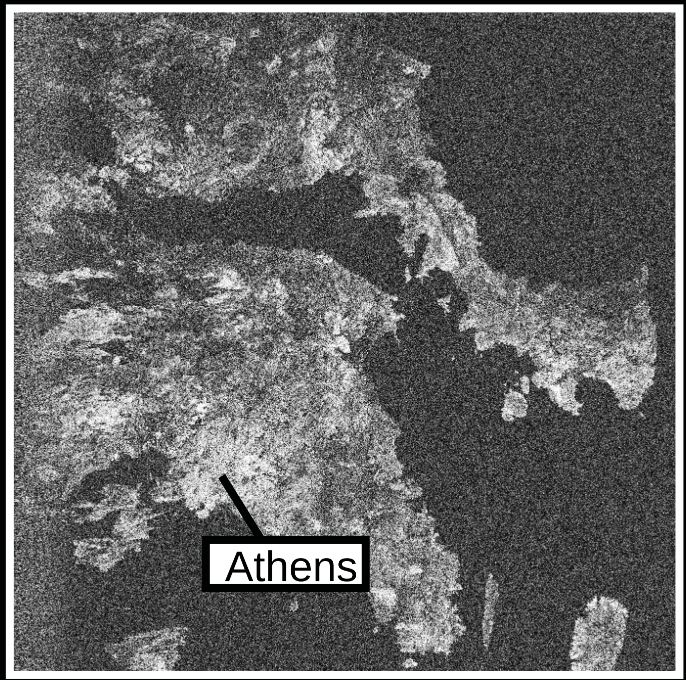


Coherence = b / a

Components of interferometric phase

$$\Delta\phi_{int} = \Delta\phi_{geom} + \Delta\phi_{topo} + \Delta\phi_{atm} + \Delta\phi_{noise} + \Delta\phi_{def}$$





Coherent surface types

- Bare Rock
- Buildings esp. towns/cities

- Grassland
- Agricultural fields
- Ice

Incoherent surface types

- Leafy Trees
- Water

Components of interferometric phase

$$\Delta\phi_{\text{int}} = \Delta\phi_{\text{geom}} + \Delta\phi_{\text{topo}} + \Delta\phi_{\text{atm}} + \Delta\phi_{\text{noise}} + \Delta\phi_{\text{def}}$$

1. incoherence

- Changes in the ground cover cause a random phase shift for each pixel
- Large baselines

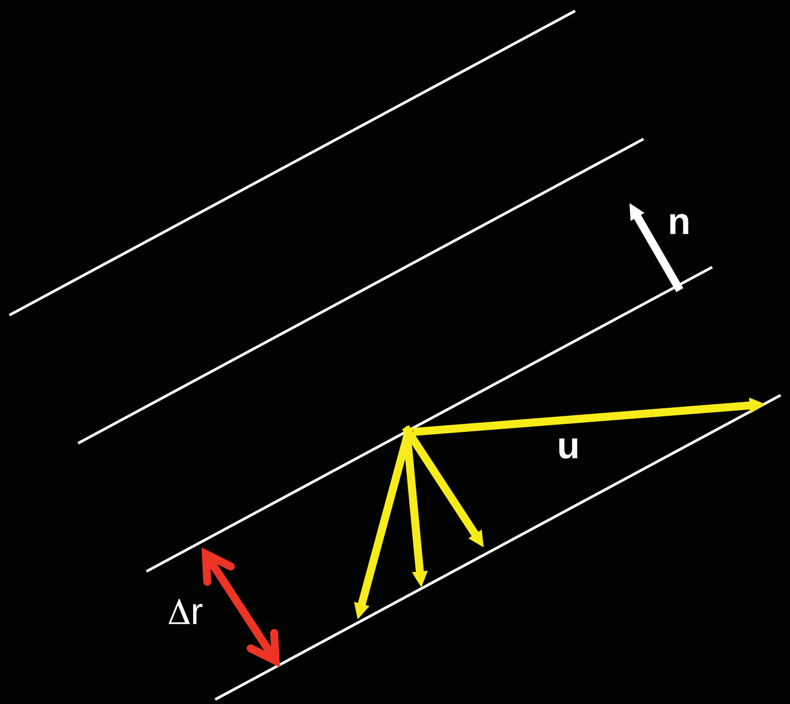
2. Unwrapping errrors

- Phase in interferograms is wrapped (each fringe is 2 π radians).
- Discontinuities or data gaps can cause phase unwrapping errors

Components of interferometric phase

$$\Delta\phi_{int} = \Delta\phi_{geom} + \Delta\phi_{topo} + \Delta\phi_{atm} + \Delta\phi_{noise} + \Delta\phi_{def}$$

InSAR ONLY MEASURES THE COMPONENT OF SURFACE DEFORMATION IN THE SATELLITE'S LINE OF SIGHT



$$\Delta r = - \mathbf{n.u}$$

where n is a unit vector pointing from the ground to the satellite

$$\Delta\phi_{def} = (4\pi / \lambda)\, \Delta r$$

i.e. 1 fringe = 28.3 mm l.o.s. deformation for ERS

Error Budget (1)
Single interferogram

$$\sigma_{def}^2 = \sigma_{gm}^2 + \sigma_{topo}^2 + \sigma_{atm}^2 + \sigma_{coh}^2 + \sigma_{sys}^2 + \sigma_{unw}^2$$

- Orbital errors ⇨ long-wavelength ramps.
- Envisat: ~0.3 mm/km (across-track) and 0.1 mm/km (along-track) [Wang, Wright and Biggs, GRL 2009].
- Can correct by processing long strips and tying to GPS **(see. Fringe presentations by Wang, Pagli and Hamlyn)**
- Should be negligible for future missions with onboard GPS receivers.

Error Budget (1)
Single interferogram

$$\sigma_{def}^2 = \sigma_{gm}^2 + \sigma_{topo}^2 + \sigma_{atm}^2 + \sigma_{coh}^2 + \sigma_{sys}^2 + \sigma_{unw}^2$$

$$\sigma_{topo} = \frac{\bar{r}_{slant} B_{\perp}}{\sin \theta_{inc}} \sigma_{DEM}$$

- SRTM error ~ 4 m absolute, of which 2.5 m is not spatially correlated [Rodriguez et al., PERS 2006]

B_{perp}	σ_{topo} (40° incidence)
150 m	1.1 mm
300 m	2.3 mm
1000 m	7.8 mm

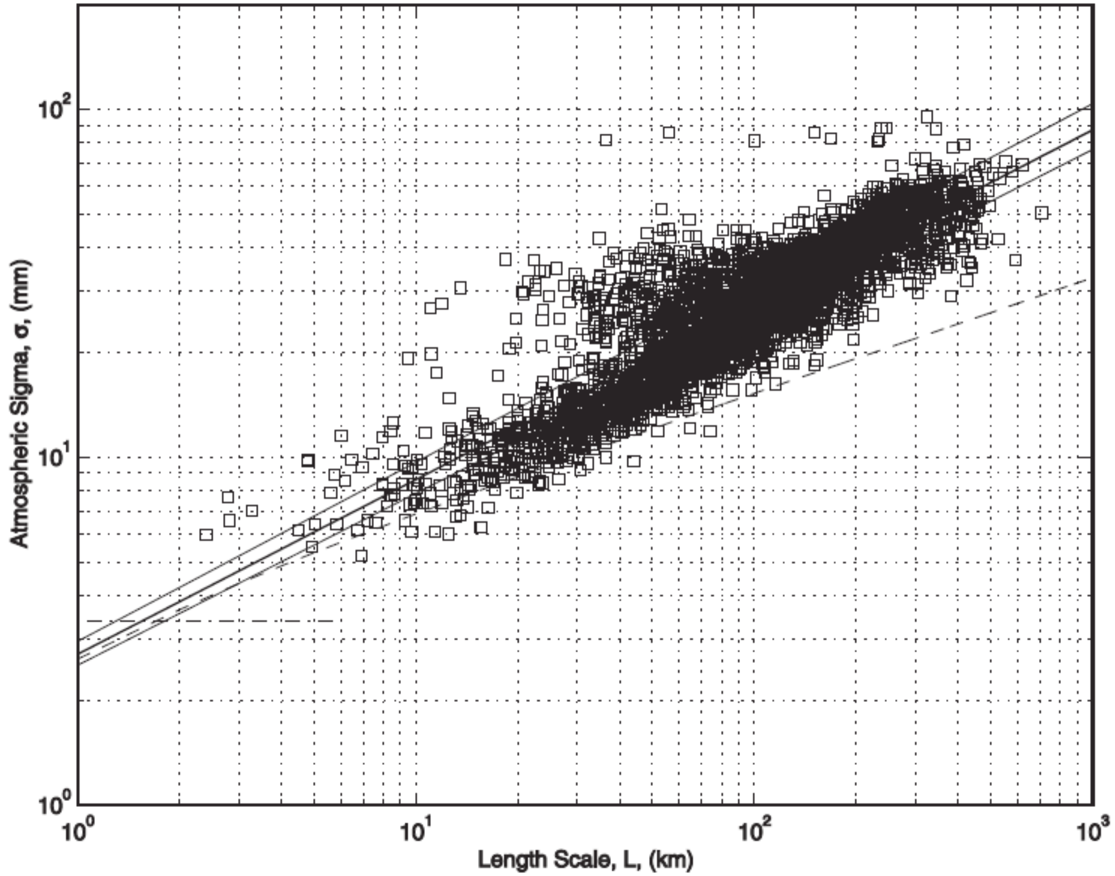
Error Budget (1)
Single interferogram

$$\sigma^2_{def} = \sigma^2_{gm} + \sigma^2_{topo} + \sigma^2_{atm} + \sigma^2_{coh} + \sigma^2_{sys} + \sigma^2_{unw}$$

- Troposhere

Emardson et al., 2003:
$\sigma = cL^{\alpha}$ [c~2.5, α~0.5]
σ= 25 mm at 100 km

(assume no corrections)



Error Budget (1)
Single interferogram

$$\sigma^2_{def} = \sigma^2_{gm} + \sigma^2_{topo} + \sigma^2_{atm} + \sigma^2_{coh} + \sigma^2_{sys} + \sigma^2_{unw}$$

- Ionosphere ($1/f^2$ dependence). Important at L-band, but not at C-band.
- Can correct with split band processing (e.g. 1200 and 1260 MHz) in future missions
- Ionospheric error on 100 km wavelength ~ 1mm after spatial averaging

Error Budget (1)
Single interferogram

$$\sigma_{def}^2 = \sigma_{gm}^2 + \sigma_{topo}^2 + \sigma_{atm}^2 + \sigma_{coh}^2 + \sigma_{sys}^2 + \sigma_{unw}^2$$

- Coherence, γ
  - important at short wavelengths, but can be averaged through multilooking to < 1 mm for most ground cover types

Error Budget (1) Single interferogram

$$\sigma_{def}^2 = \sigma_{gm}^2 + \sigma_{topo}^2 + \sigma_{atm}^2 + \sigma_{coh}^2 + \sigma_{sys}^2 + \sigma_{unw}^2$$

- Coherence, γ
  - important at short wavelengths, but can be averaged through multilooking to < 1 mm for most ground cover types
- System (thermal) - modifies coherence
  - reduces effective coherence, but still insignificant after spatial averaging.

$$\sigma_{coh} = \left(\frac{\lambda}{4\pi}\right)\frac{1}{\sqrt{N_L}}\frac{\sqrt{1-\gamma^2}}{\gamma}$$

$$\gamma_c = \frac{\gamma}{1+SNR^{-1}}$$

Error Budget (1)
Single interferogram

$$\sigma_{def}^2 = \sigma_{gm}^2 + \sigma_{topo}^2 + \sigma_{atm}^2 + \sigma_{coh}^2 + \sigma_{sys}^2 + \sigma_{unw}^2$$

- Unwrapping errors difficult to quantify.
- Assume = 0 in this analysis (probably OK for L-band missions or missions with short revisits).

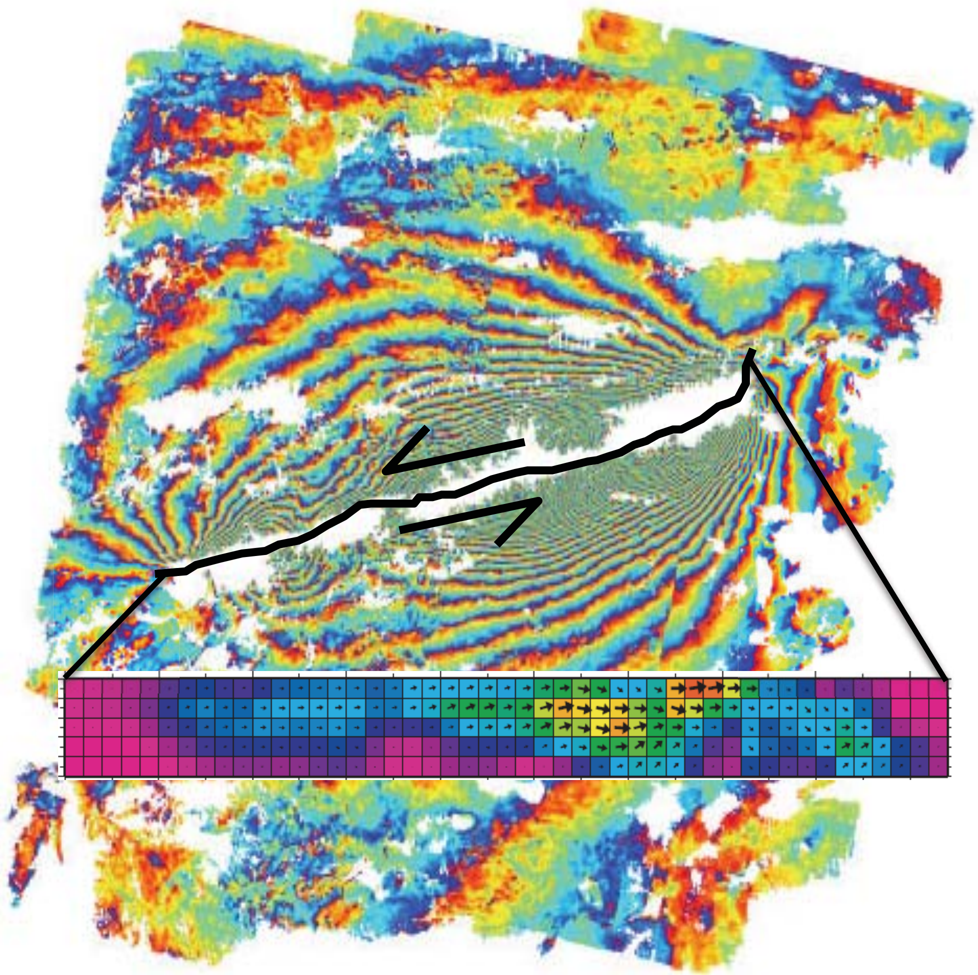
Error Budget (1)
Single interferogram

$$\sigma_{def}^2 = \sigma_{gm}^2 + \sigma_{topo}^2 + \sigma_{atm}^2 + \sigma_{coh}^2 + \sigma_{sys}^2 + \sigma_{unw}^2$$

Atmospheric (tropospheric) error dominates at 100 km length scales, at which single interferograms have error of ~25 mm.

Earthquakes

1. Coseismic Deformation



Current Capability

• Map deformation fields for most damaging earthquakes.
• Identify responsible faults
• Estimate slip models.
• Assess impact on future hazard .

What could be done?

• Routine analysis of **ALL** damaging earthquakes, c.f. Harvard CMT.
• Real-time assessment of causative fault and likely damage area.
• Near-real time assessment of future hazard (aftershocks + triggered quakes).

Why are we not doing this already?

• Data.
• Method Development.
• Manpower.

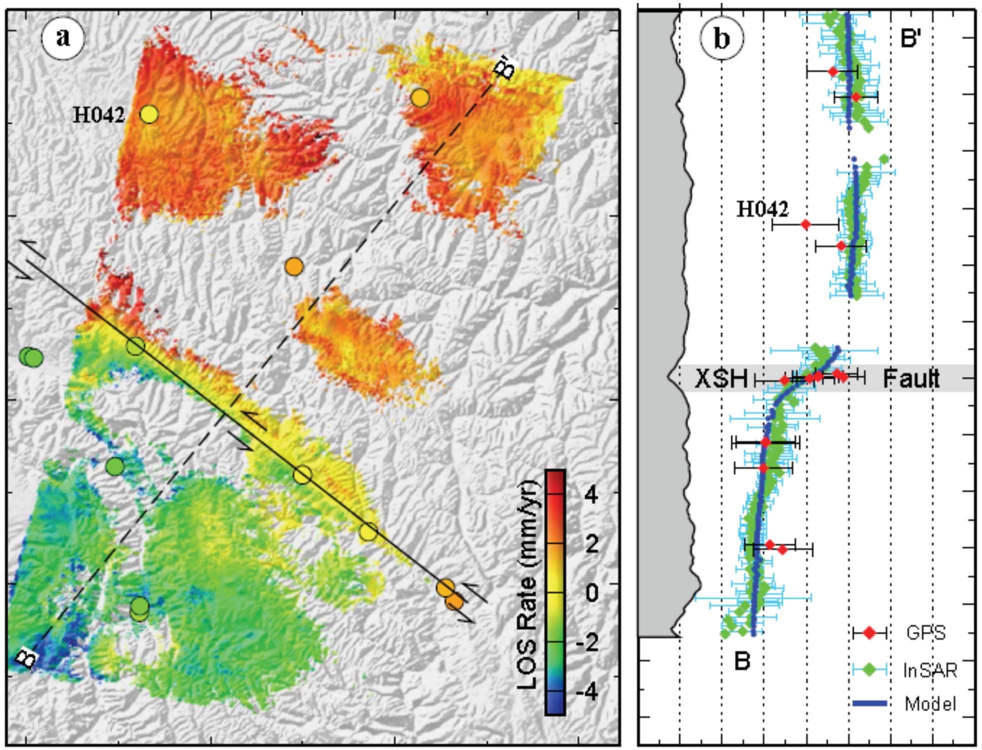
Earthquakes

2. Interseismic Strain

Current Capability
- Measure interseismic strain rates on suitable, targeted faults.
- Use these to constrain slip rate and hence assess future hazard.

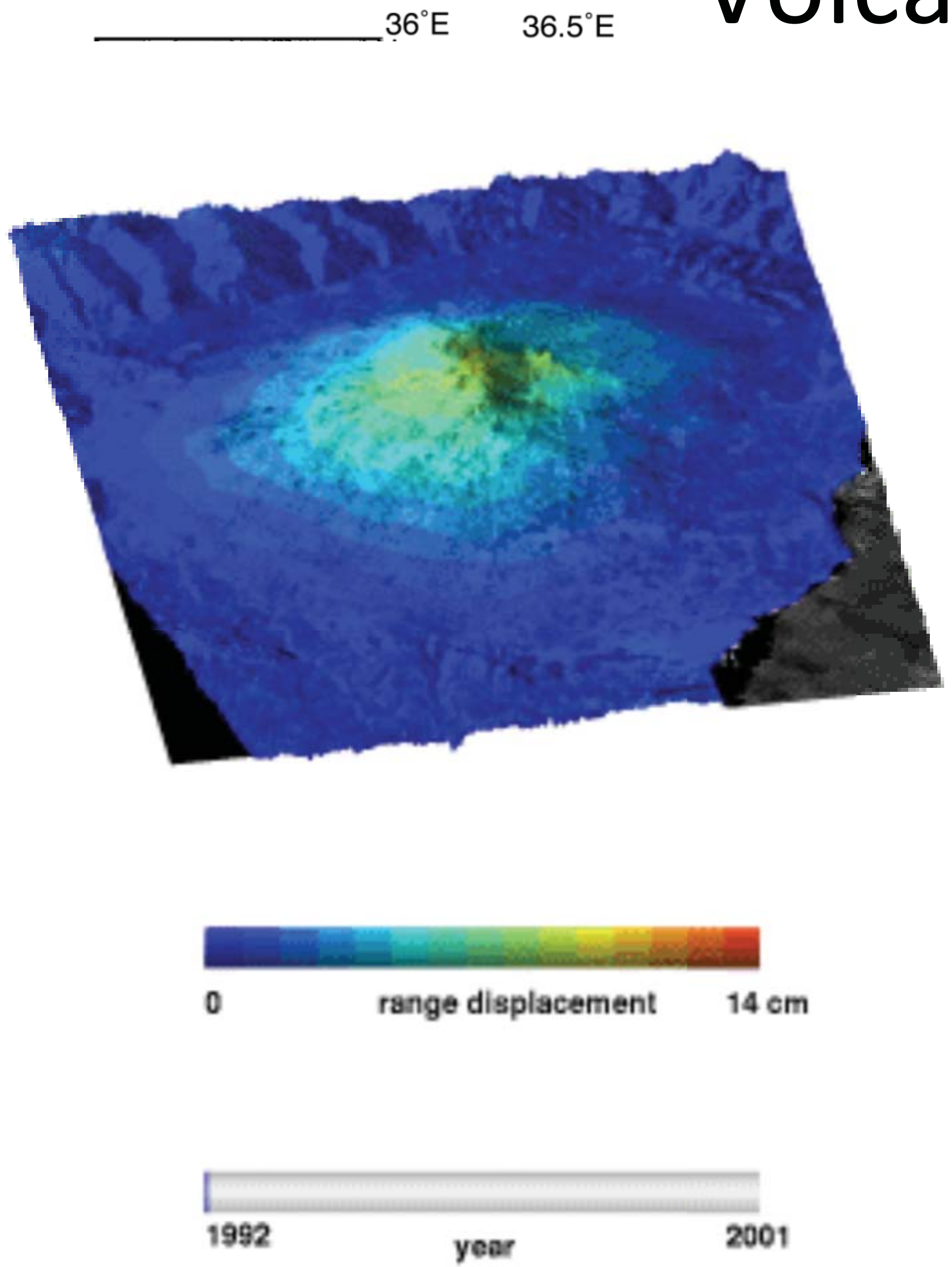
What could be done?
- Routine measurement of strain across whole regions.
- Assessment of slip rates and relative hazard of multiple faults (including unidentified faults).

Why are we not doing this already?
- Data.
- Method Development.
- Manpower.



Wang, Wright and Biggs., GRL 2009

Volcanoes



Current Capability

- Time-series analysis for suitable, targeted volcanoes .
- Snapshot regional surveys.
- Integration with other data sets.

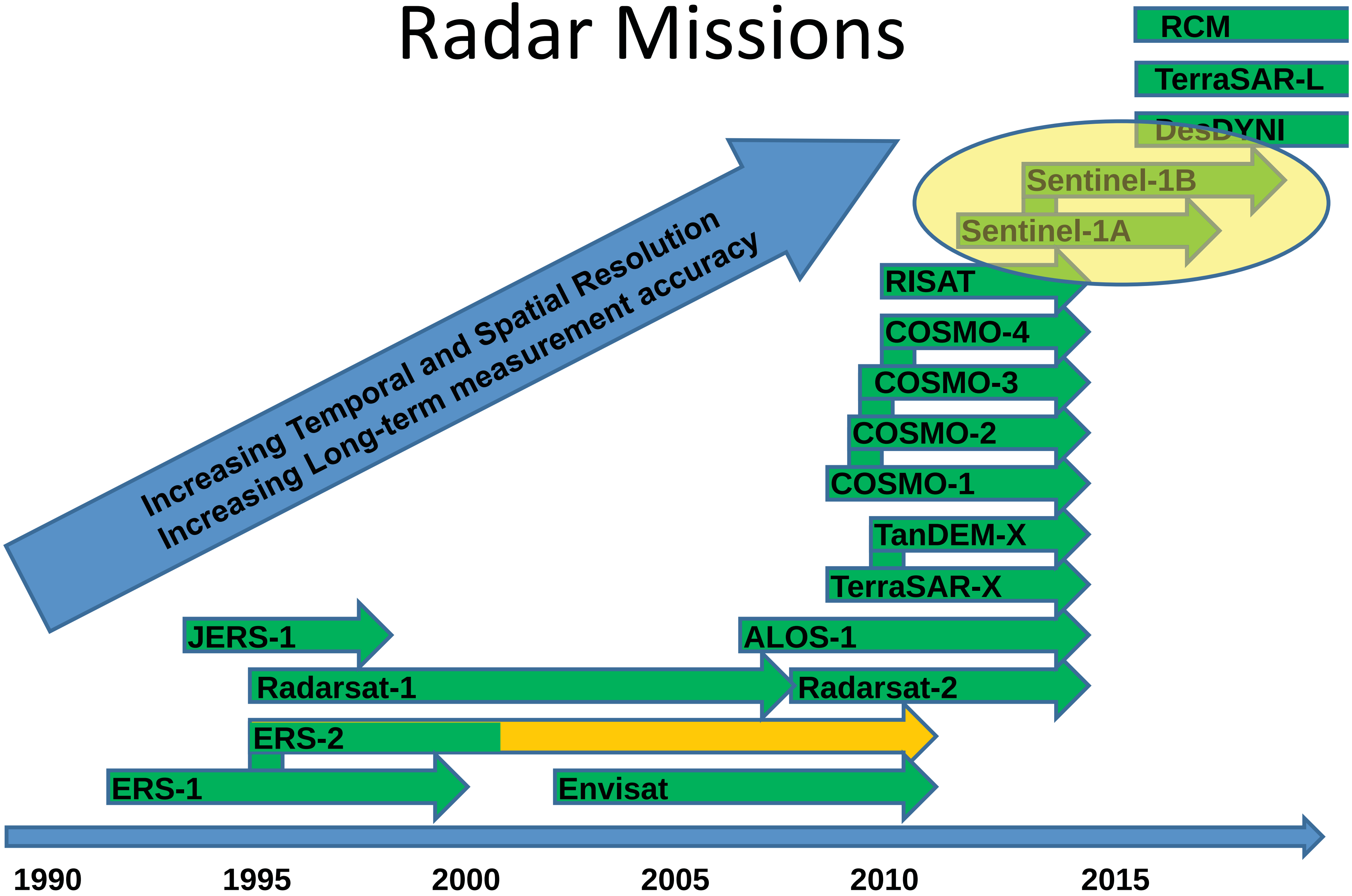
What could be done?

- Routine monitoring of ALL volcanoes worldwide (or in a region).
- Target application of ground monitoring in countries where resources are limited.

Why are we not doing this already?

- Data.
- Method Development.
- Manpower.

Radar Missions



The Future

Sentinel-1 (ESA, GMES)

- “Operational” C-band InSAR
- 12 day repeat, 2 satellites ⇨ 3 day revisit
- Funded for 20 years, Launch early 2014

Conclusions

- InSAR is a powerful, low-cost tool for monitoring Earth deformation
- Capability improving continuously (smaller rates, bigger areas…)
- Future missions and method development will ensure InSAR is a standard technique


SUPERVOLCANO
bbc.co.uk/supervolcano