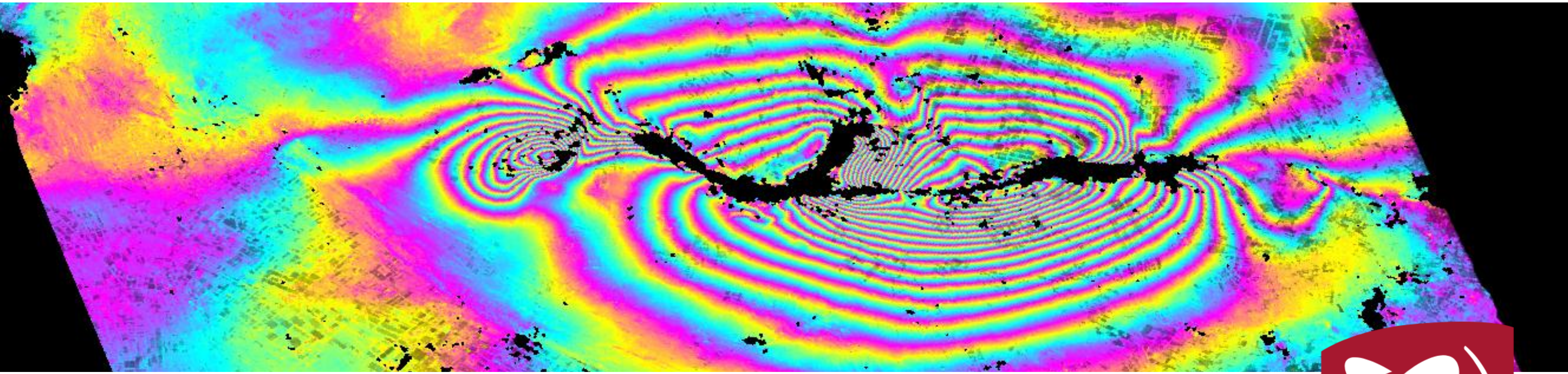
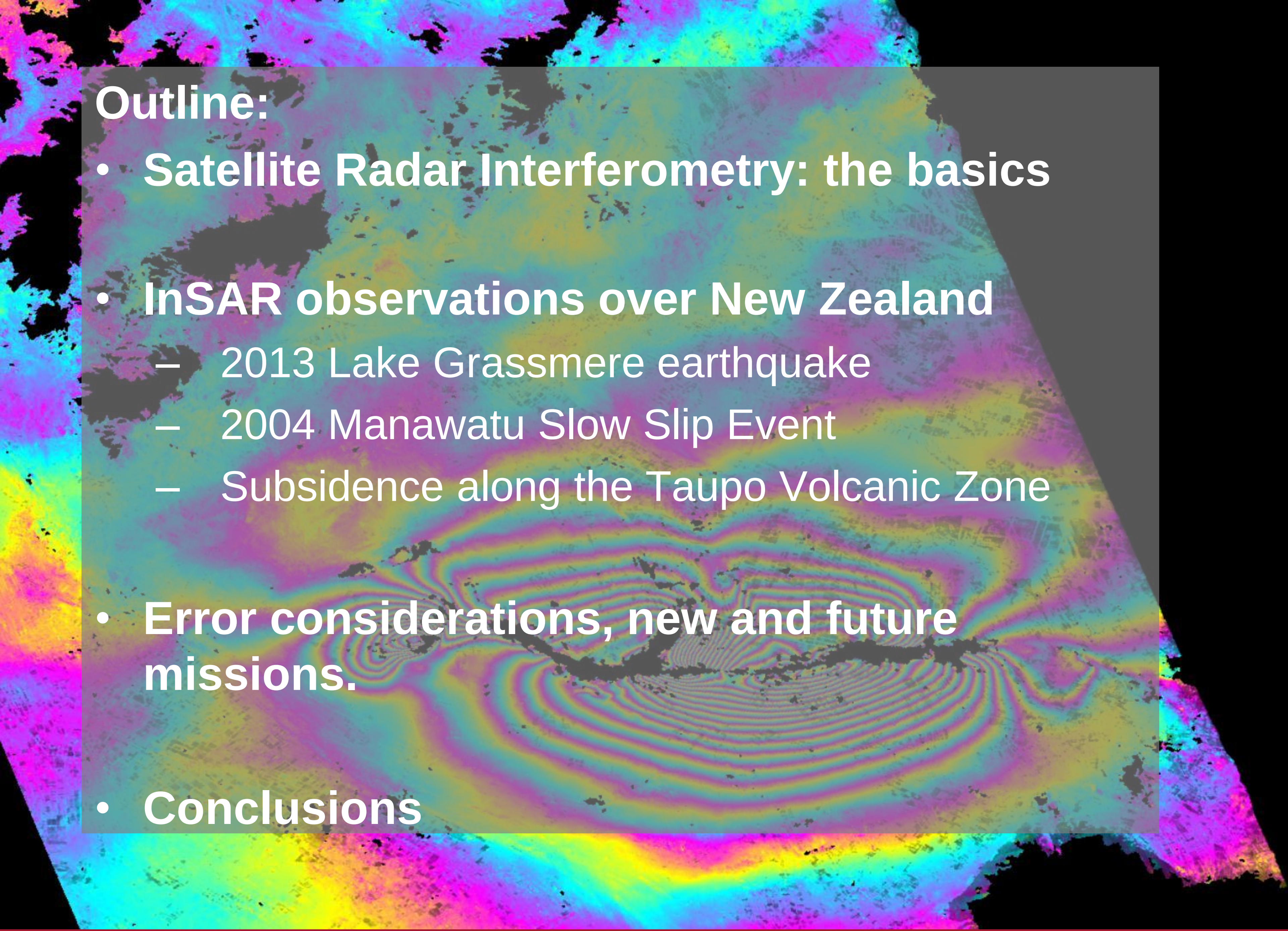
InSAR observations of New Zealand Deformation: Past, Present and Future



Ian Hamling, Sigrún Hreinsdóttir, Laura Wallace, Nico Fournier and others



Outline:

- **Satellite Radar Interferometry: the basics**
- **InSAR observations over New Zealand**
  - 2013 Lake Grassmere earthquake
  - 2004 Manawatu Slow Slip Event
  - Subsidence along the Taupo Volcanic Zone
- **Error considerations, new and future missions.**
- **Conclusions**

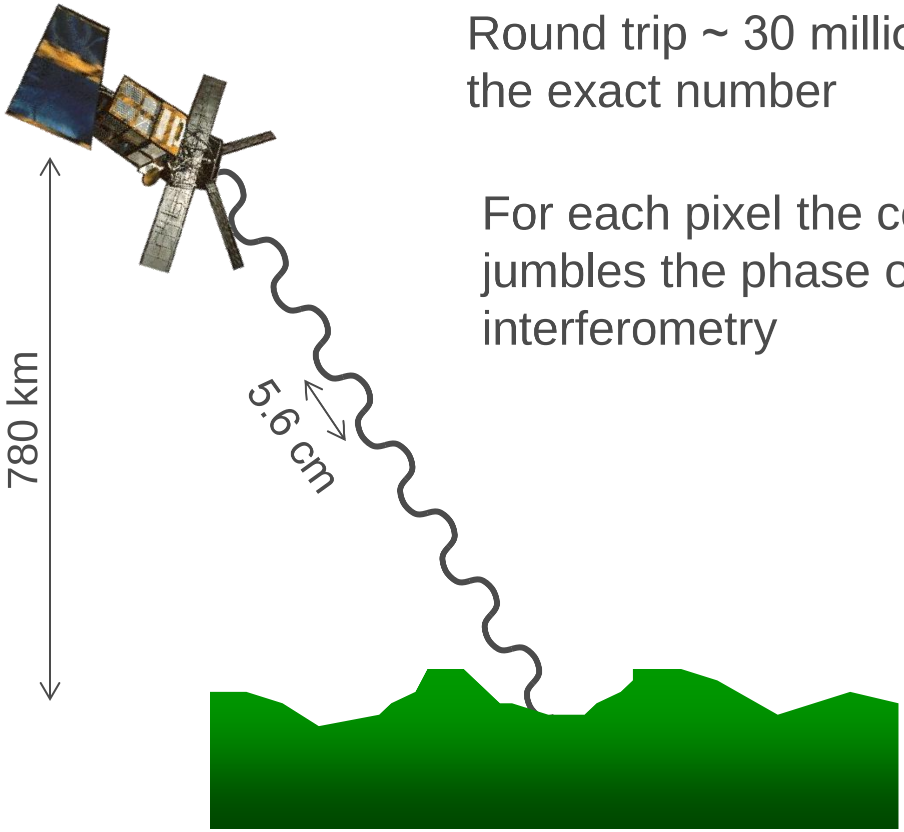
InSAR – how it works

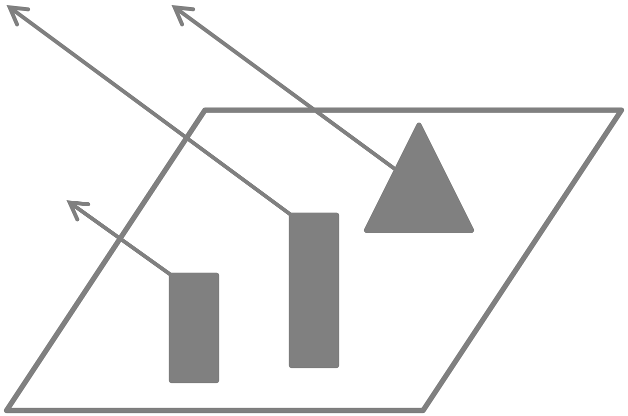
The phase of the radar signal is the number of cycles of oscillation that the wave executes between the radar and the surface and back again.

The total phase is two-way range measured in wave cycles + random component from the surface

Round trip ~ 30 million wavelengths, BUT we don’t know the exact number

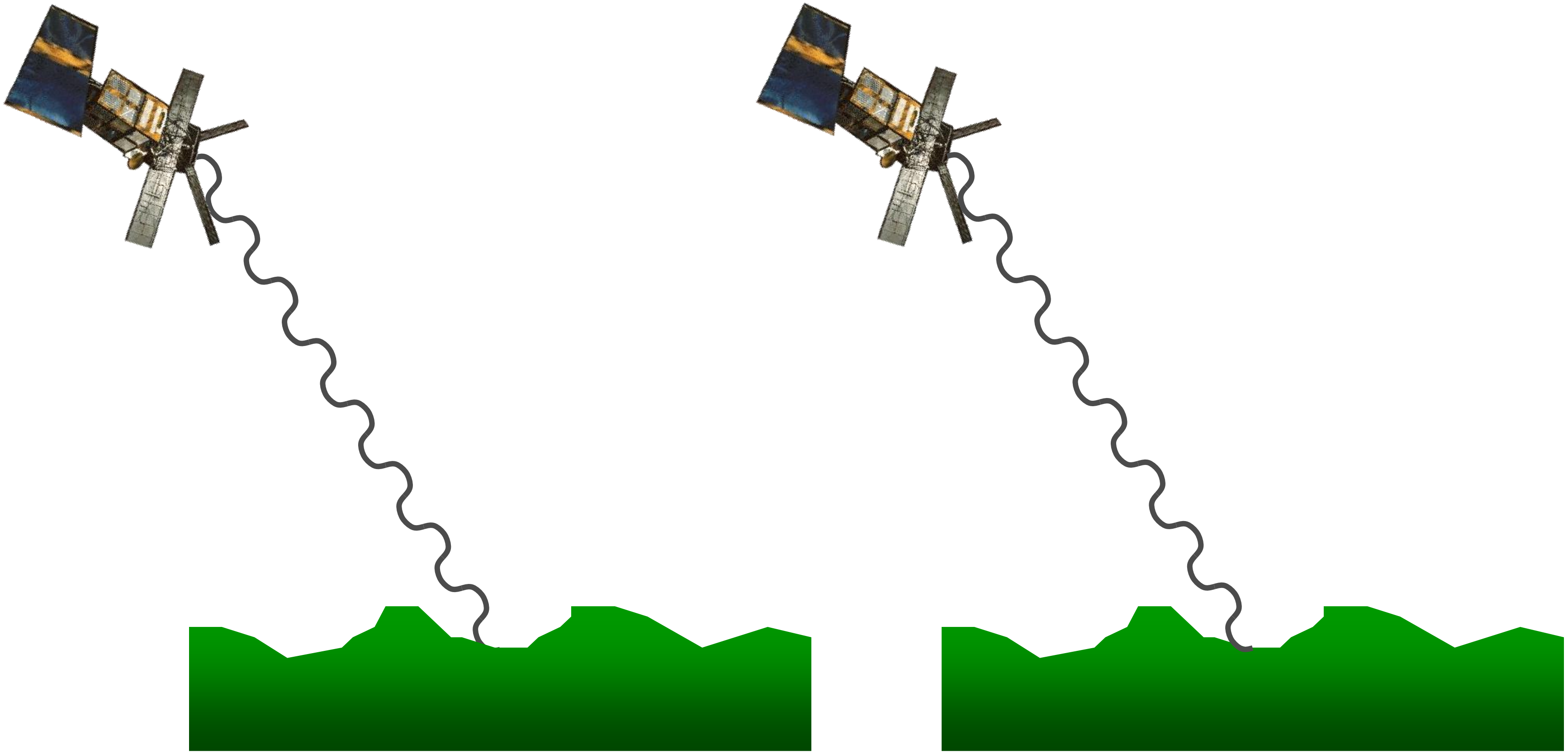
For each pixel the collection of random path lengths jumbles the phase of the echo – solved by interferometry





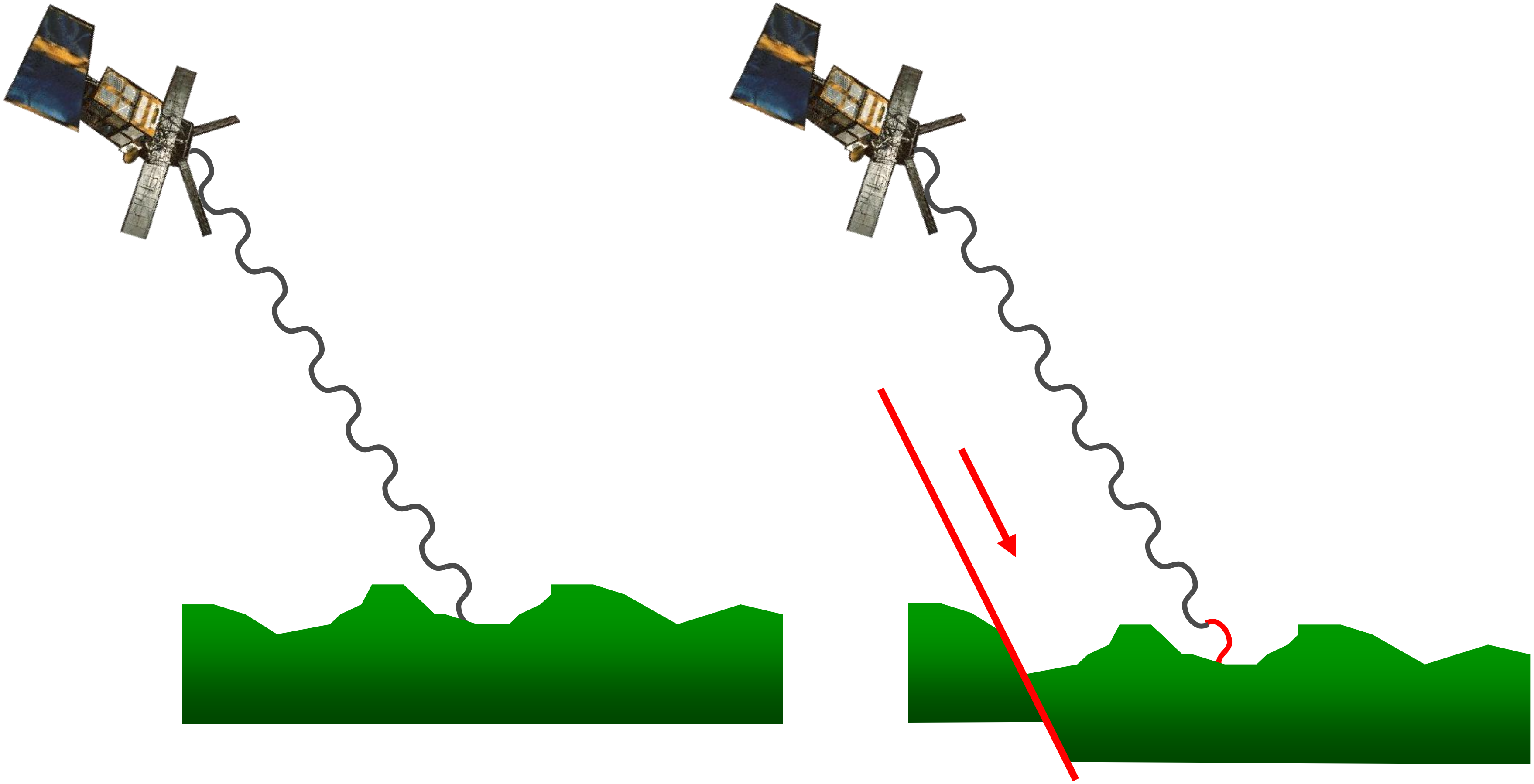
InSAR – how it works

Two radar images taken at times t_1 and t_2

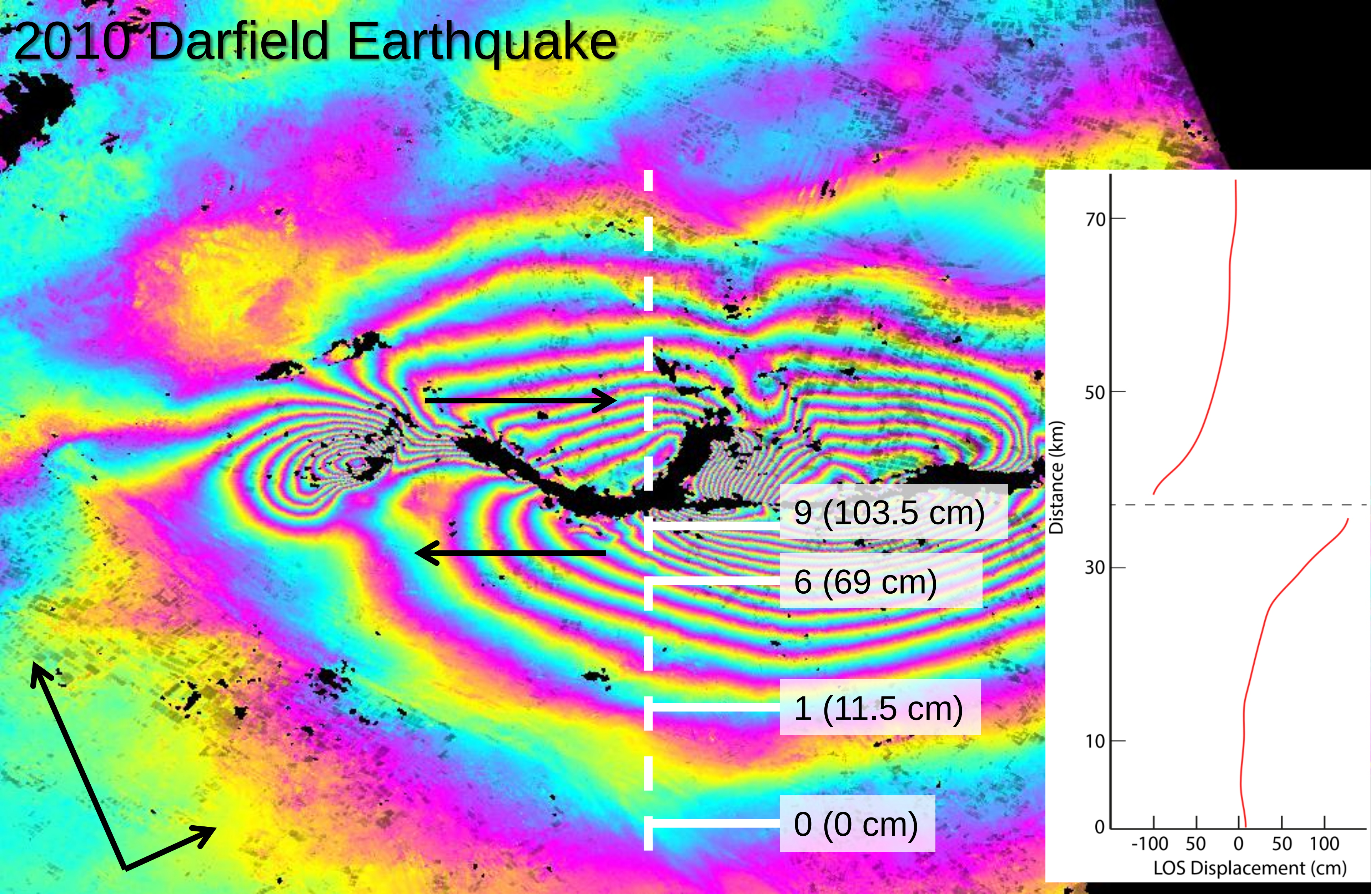


InSAR – how it works

Another two radar images taken at times t_1 and t_2 (after an earthquake)



2010 Darfield Earthquake



ALOS interferogram 13th August – 28th September

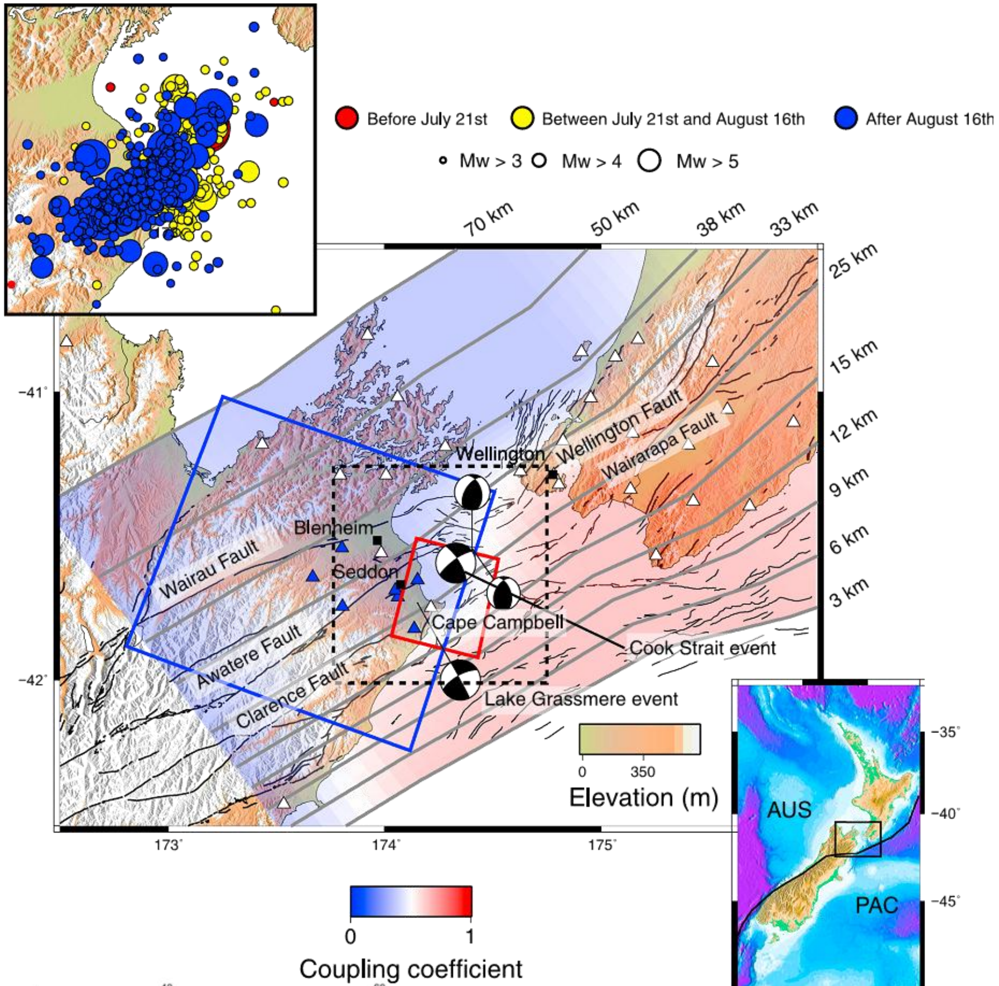
Each fringe represents 11.5 cm (half a wavelength) of motion towards or away from the satellite.

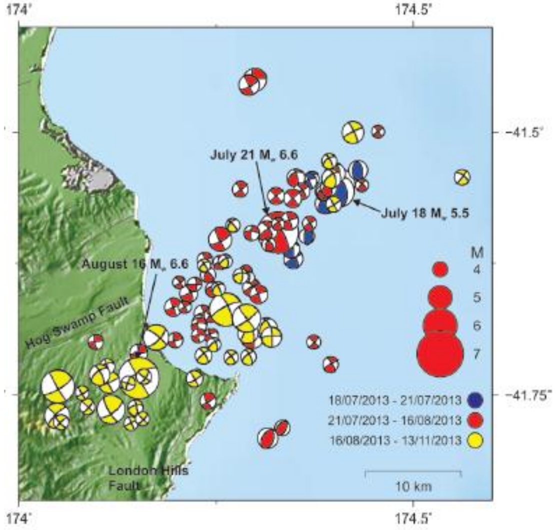
InSAR observations over New Zealand

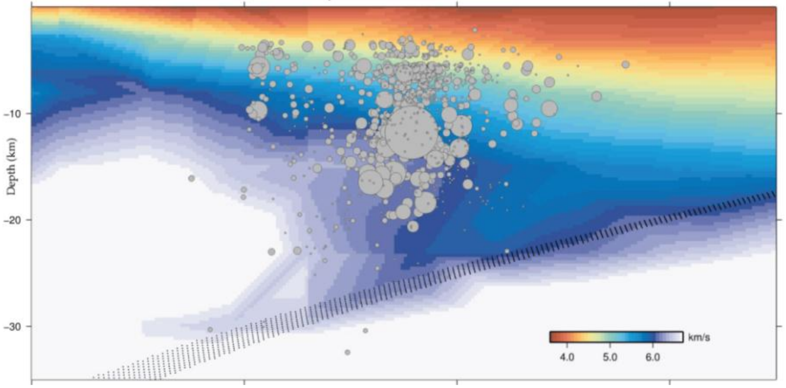
2013 Lake Grassmere earthquake

Cook Strait and Lake Grassmere Earthquakes

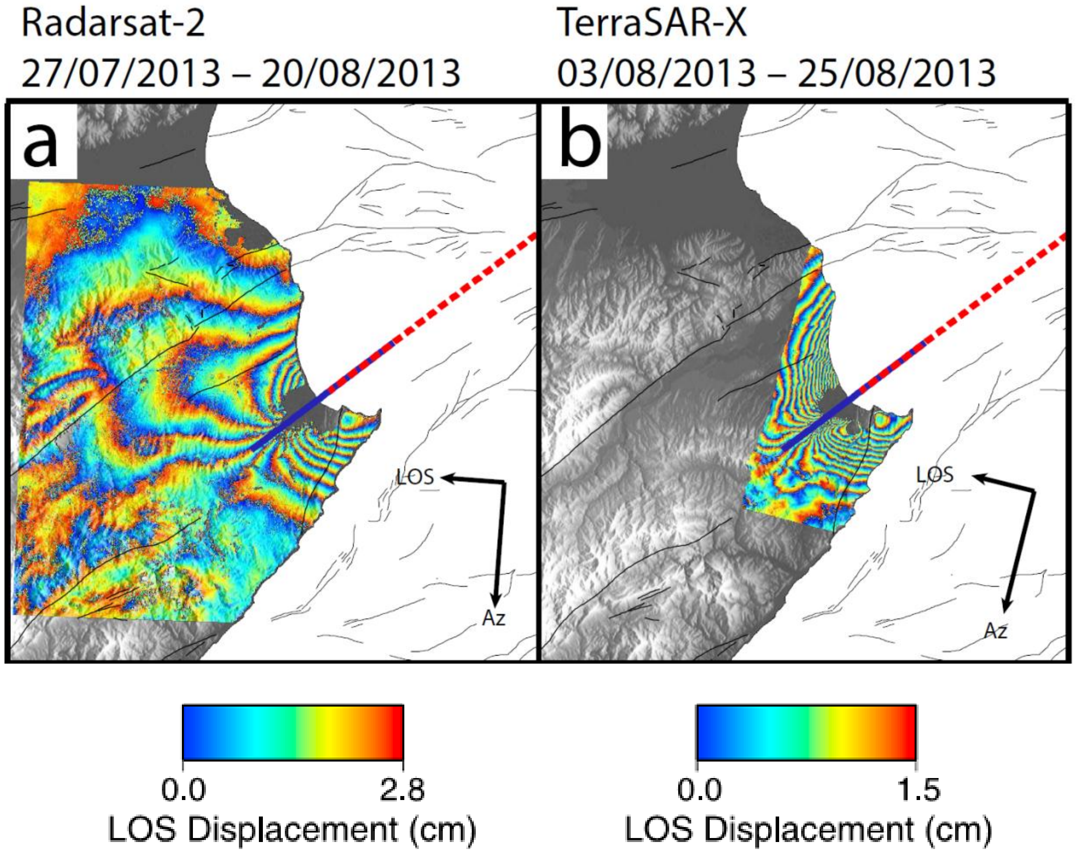
- **Sequence began with 2 foreshocks with Mw 5.7 and 5.8.**
- **Mw 6.6 Cook Strait event occurred on 21st July and was followed by > 2500 Mw 2+ earthquakes**
- **16th August a second Mw 6.6 event occurred beneath Lake Grassmere.**





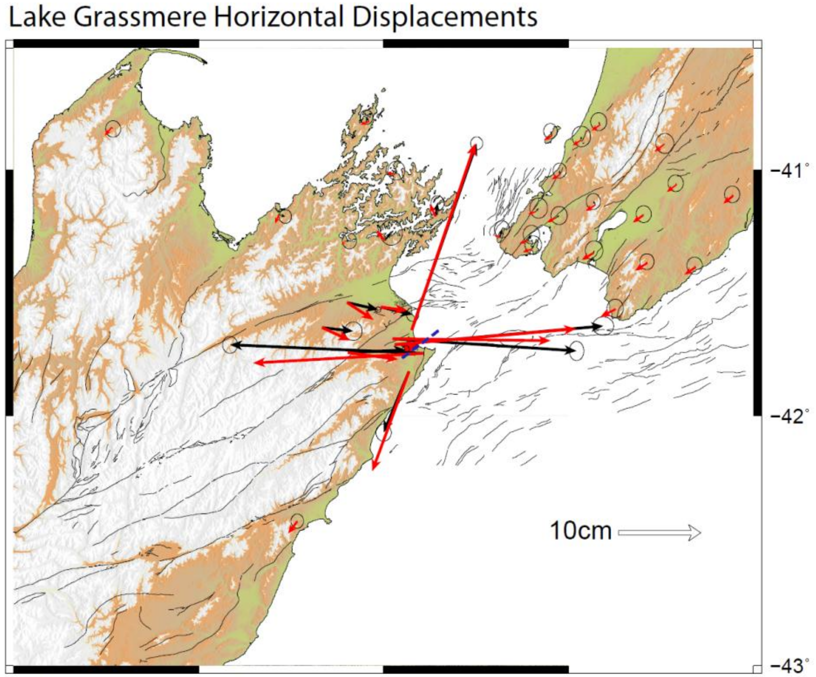


Lake Grassmere event

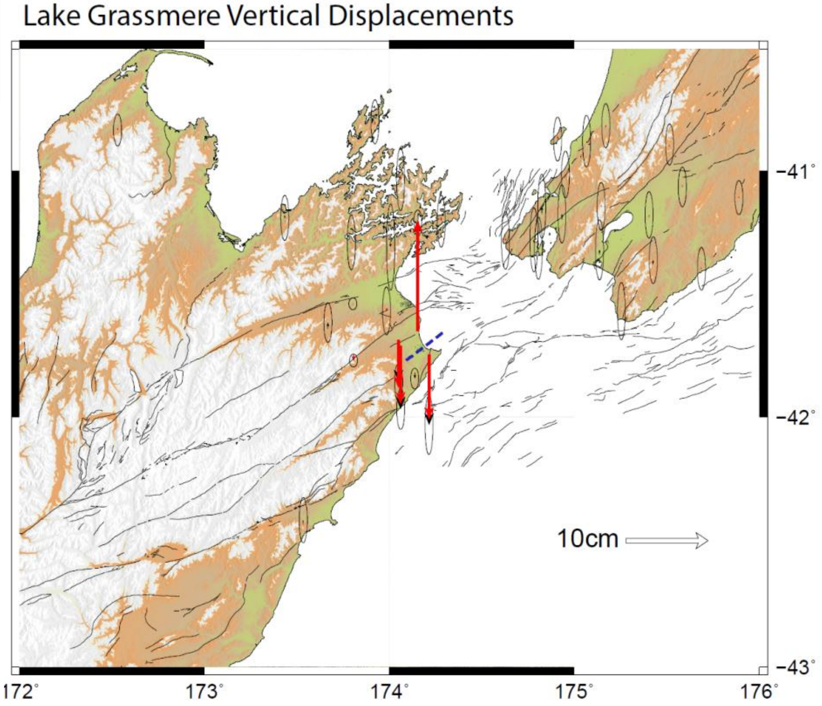


Radarsat-2
27/07/2013 – 20/08/2013

TerraSAR-X
03/08/2013 – 25/08/2013



Lake Grassmere Horizontal Displacements

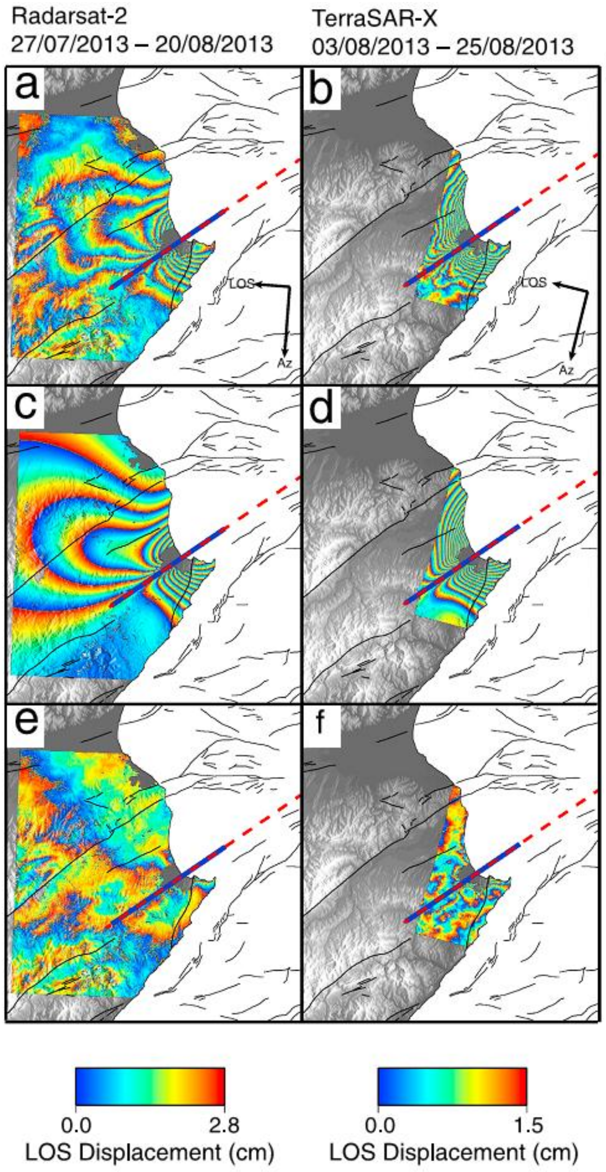


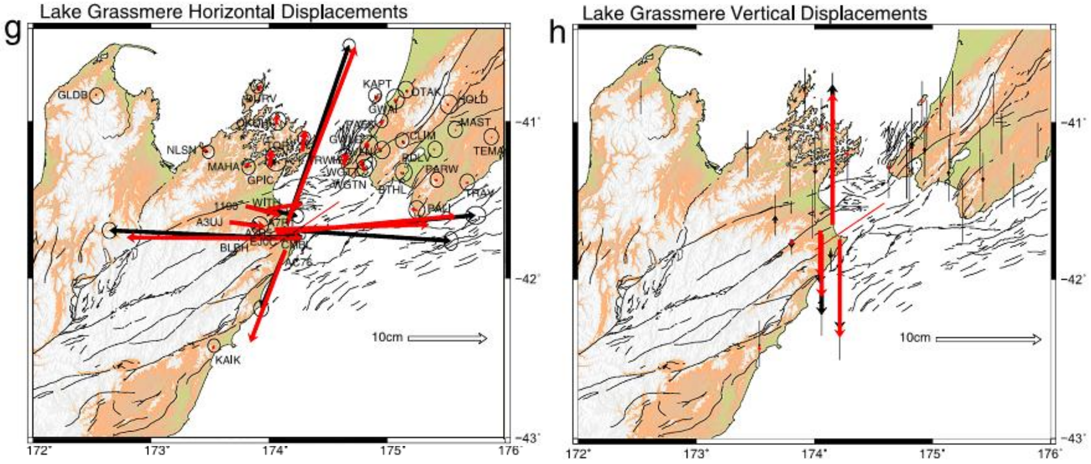
Lake Grassmere Vertical Displacements

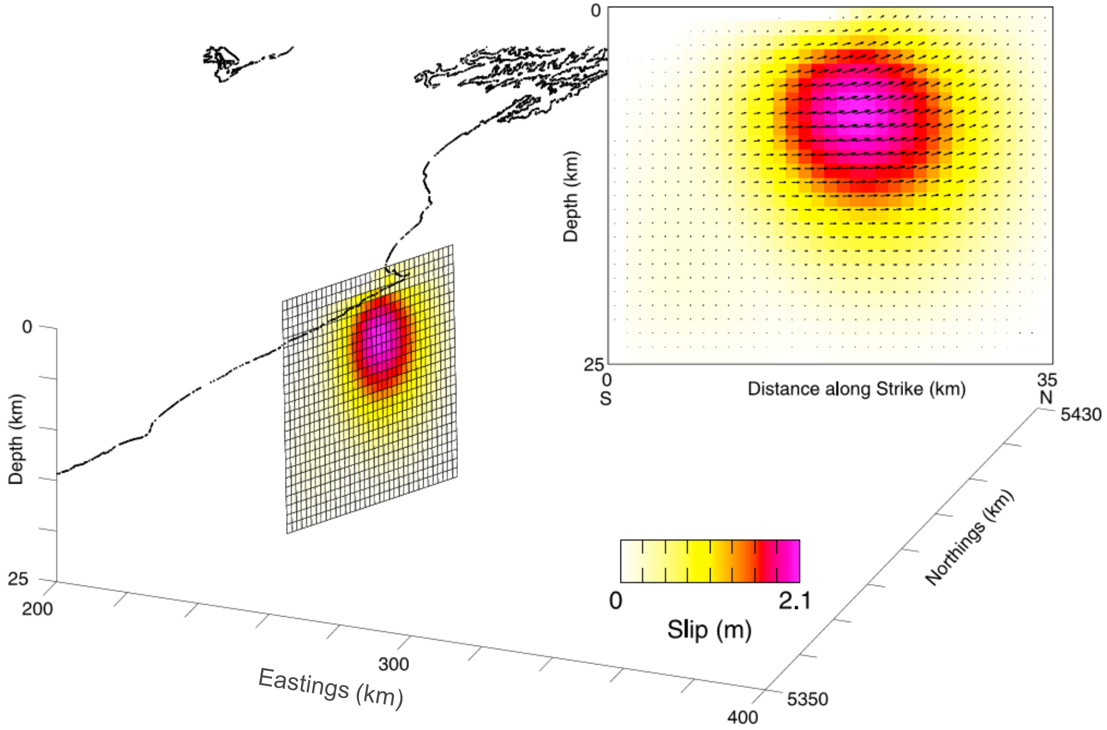
Up to 26 cm of eastward and 15 cm uplift at campaign GPS near Lake Grassmere

InSAR shows up to 25 cm of LOS change at Cape Campbell

Lake Grassmere event



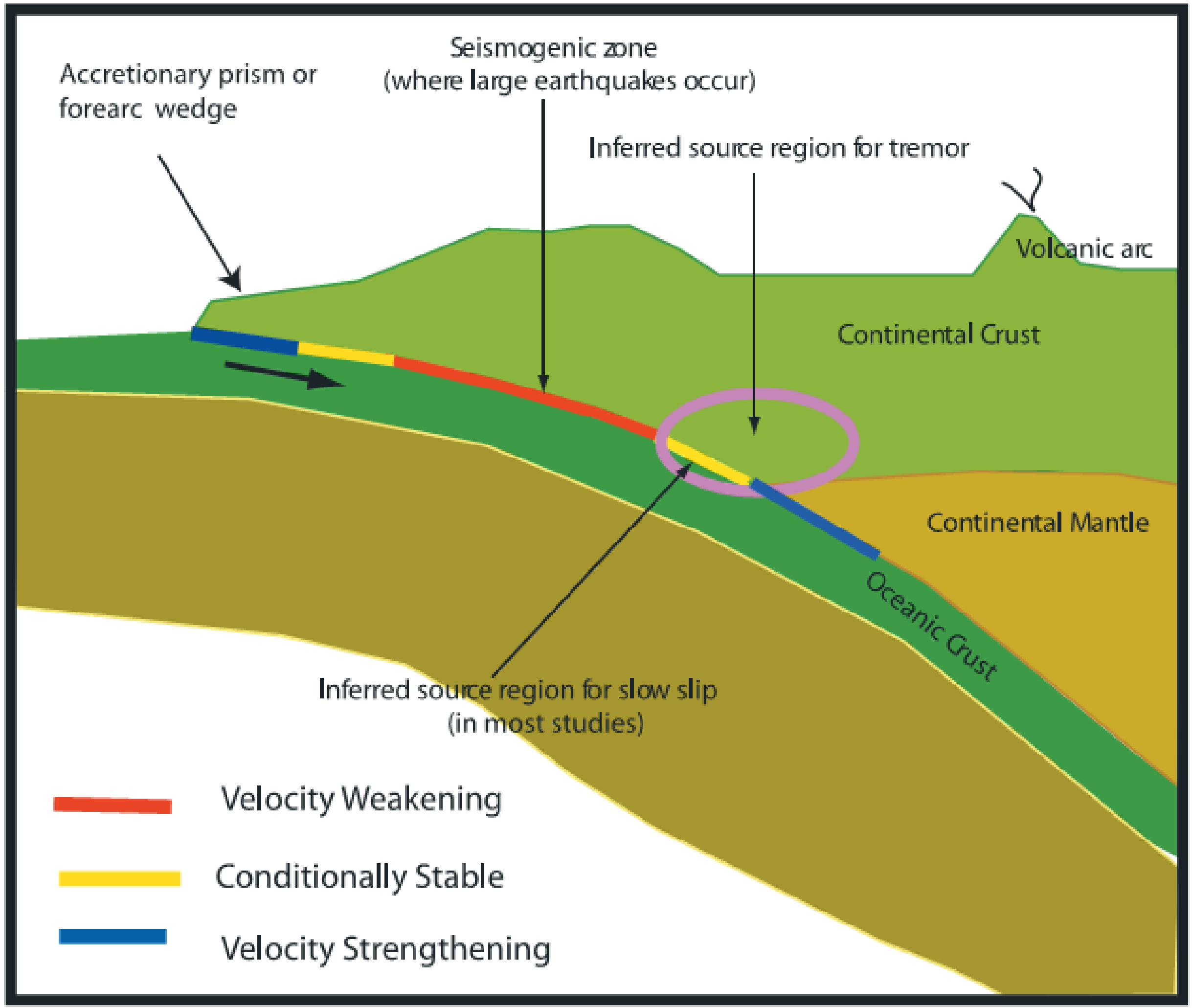




InSAR observations over New Zealand

2004 Manawatu Slow Slip Event

Slow Slip Events

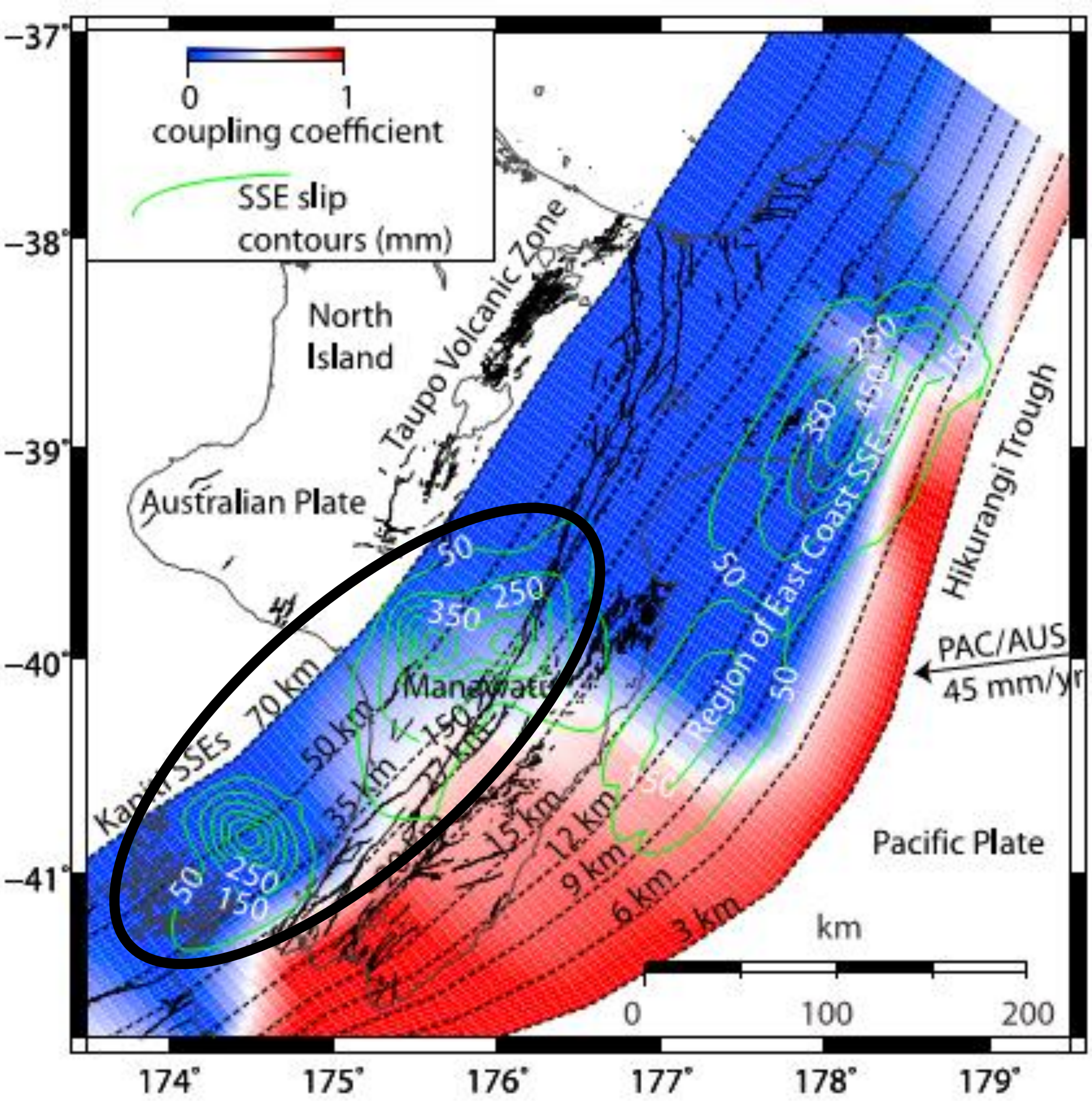


- SSEs have been observed on many subduction margins including Japan, Cascadia, New Zealand and Mexico
- In most regions displacements are too small to observe with InSAR.

Schwartz et al. 2007

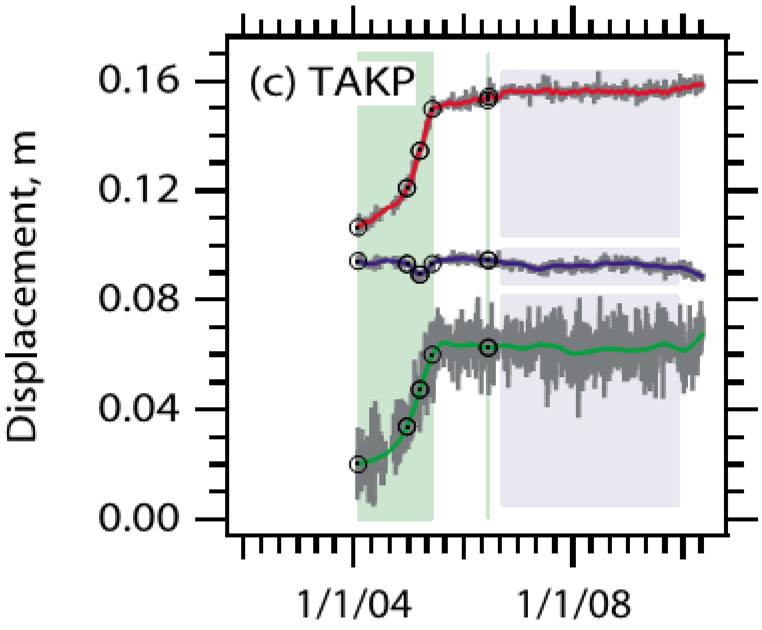
Deep Hikurangi SSEs

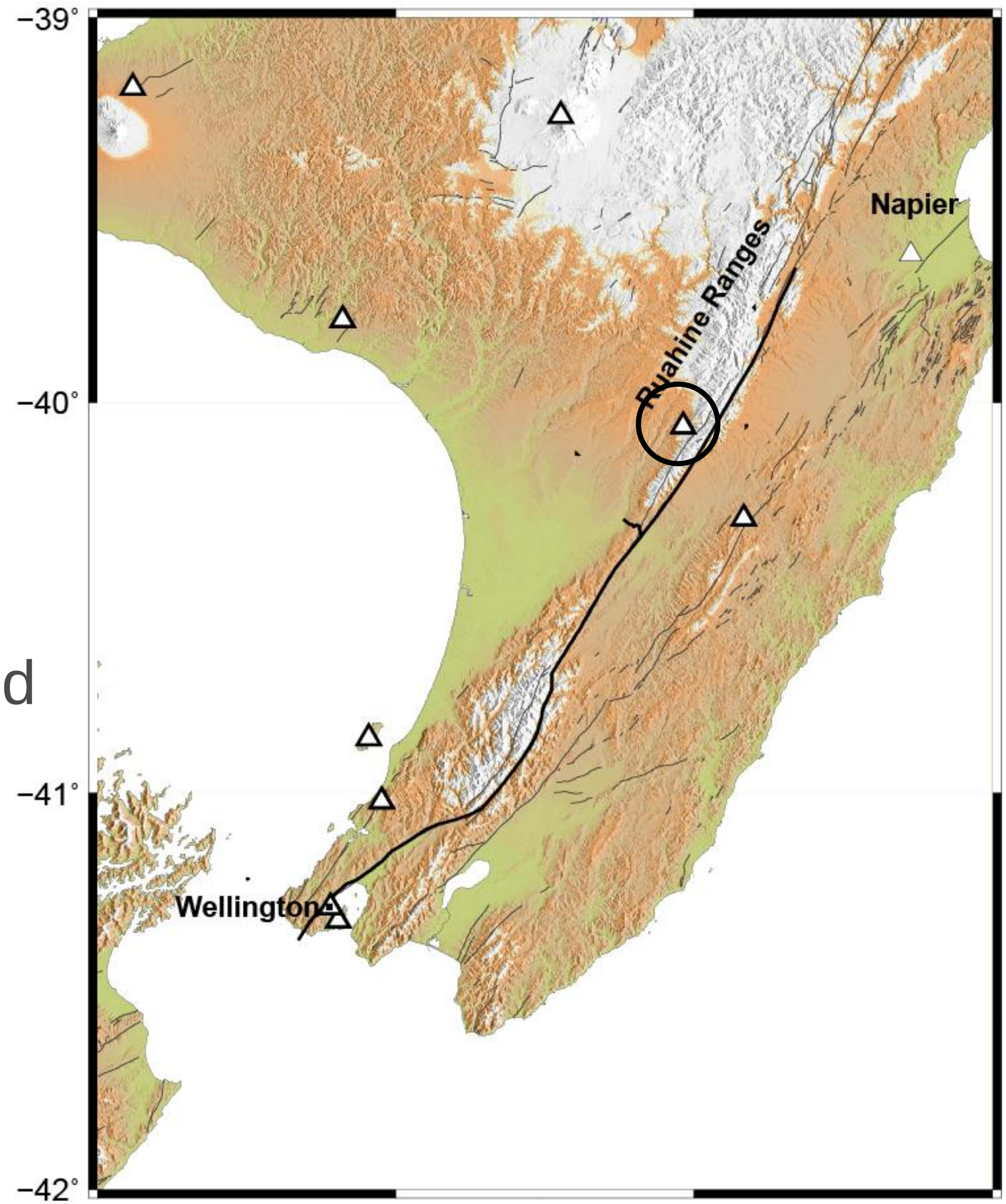
- Deep (25–60 km) slow slip is observed adjacent to the deeply locked portion of the Hikurangi subduction thrust
- These deep SSEs last 1–1.5 years, release moment equivalent to M_w ~7.0, and occur approximately every 5 years..



Wallace et al. 2012

The 2004 Manawatu SSE

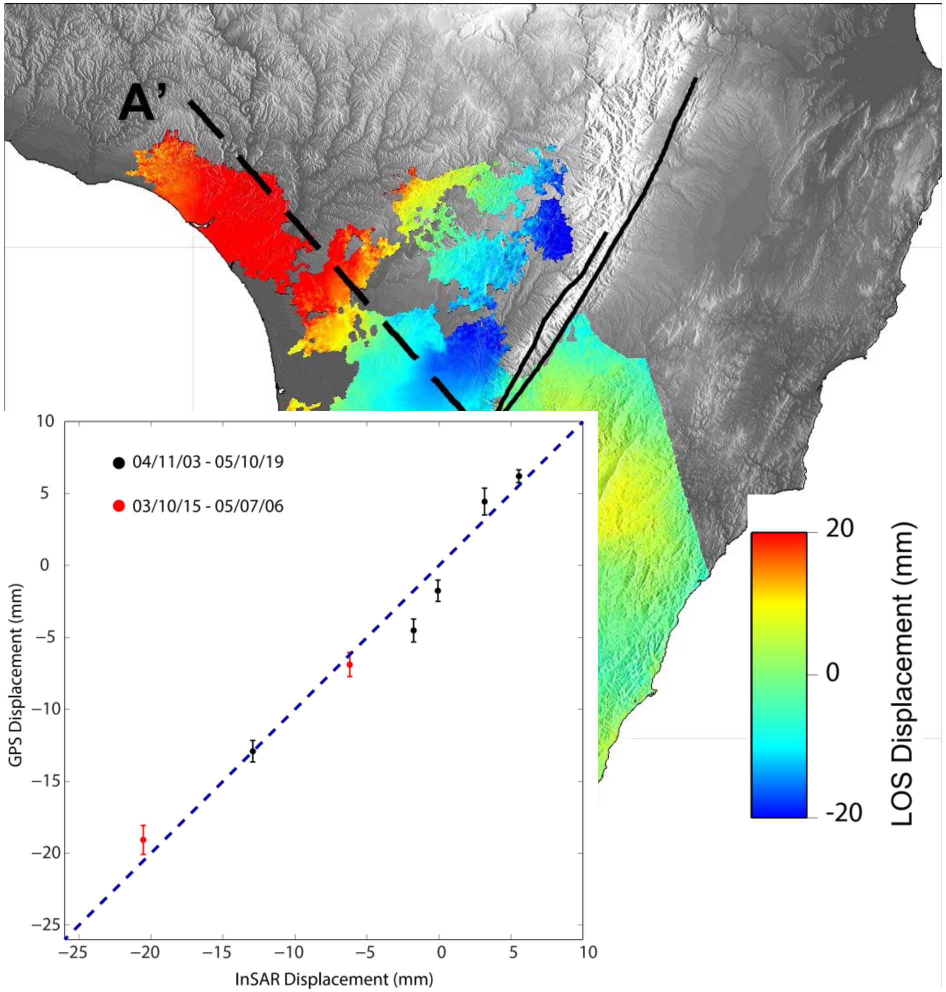




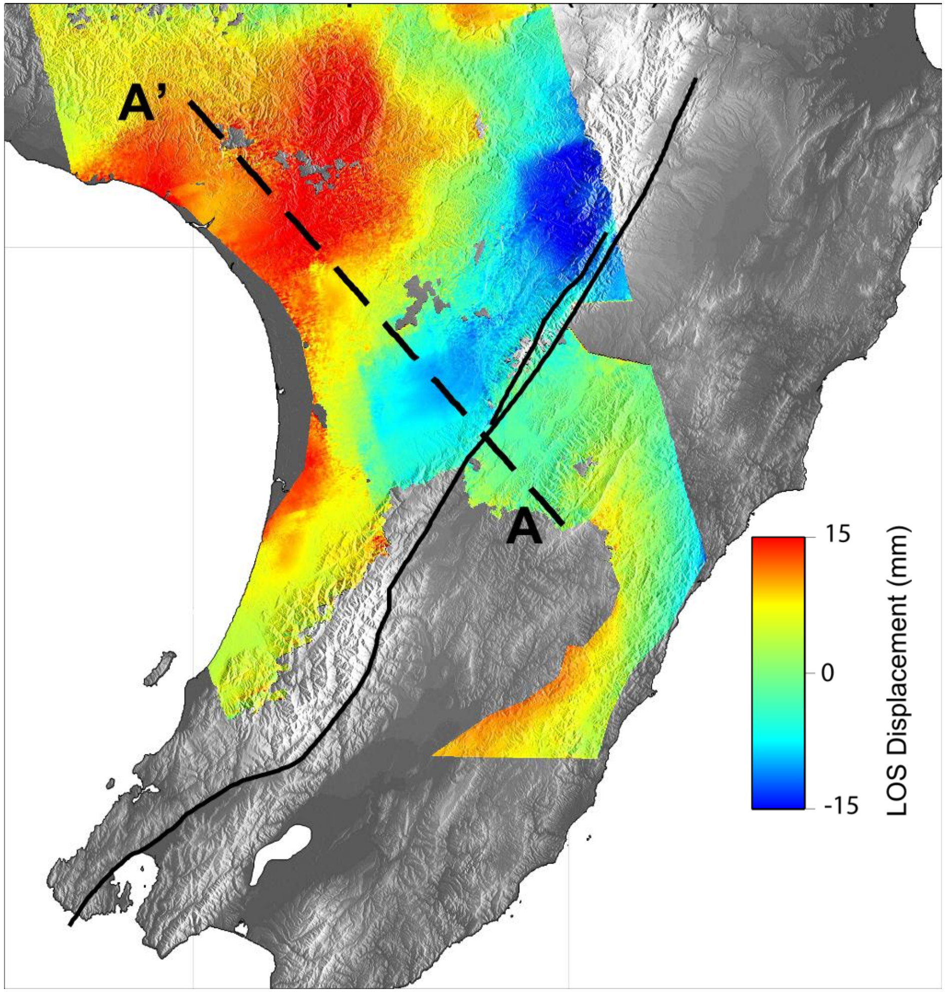
- Began in February 2004 and lasted until June 2005

- Largest offsets recorded at TAKP with up to 40 mm of uplift and eastward motion.

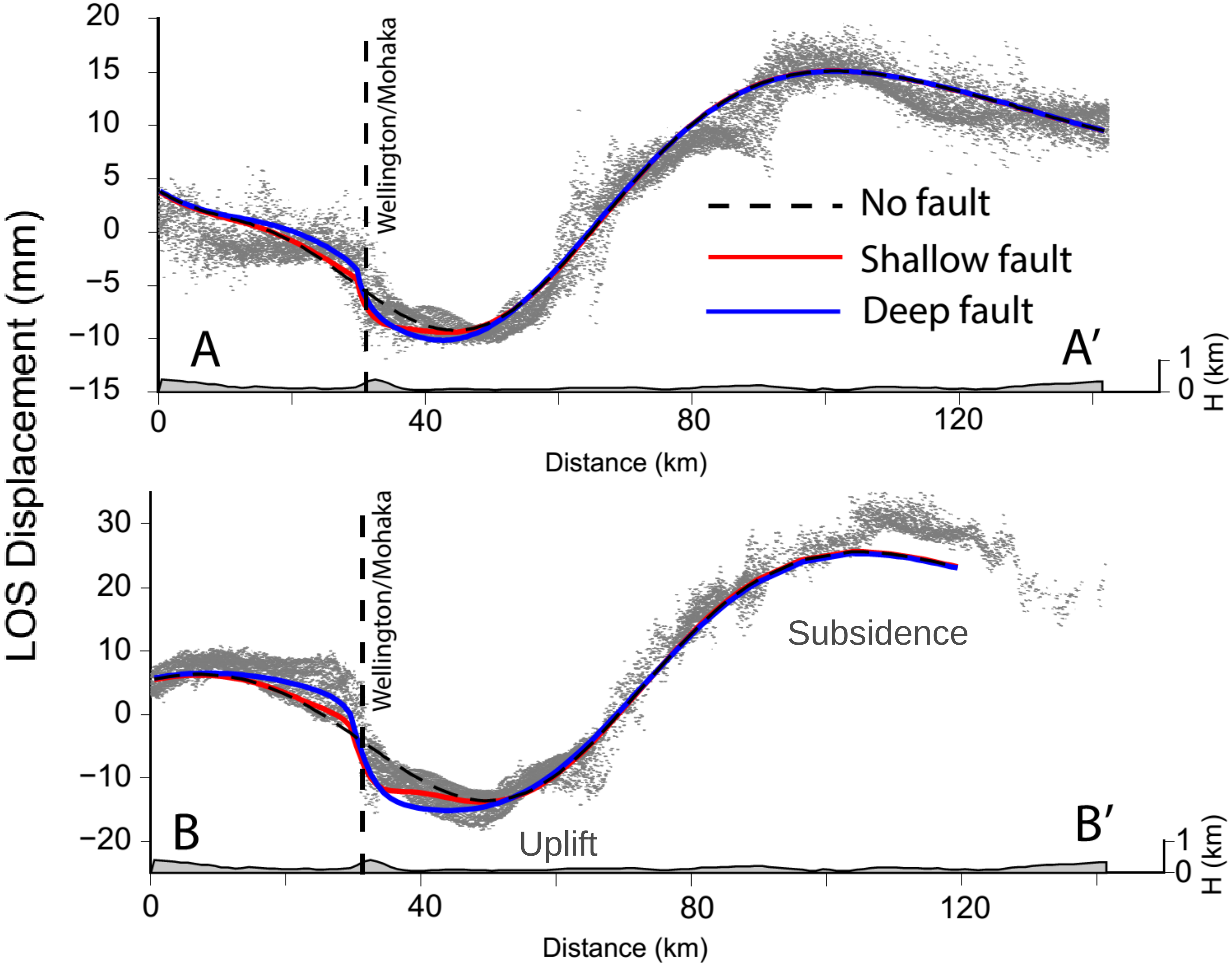
Data availability



15/10/2003-06/07/2005



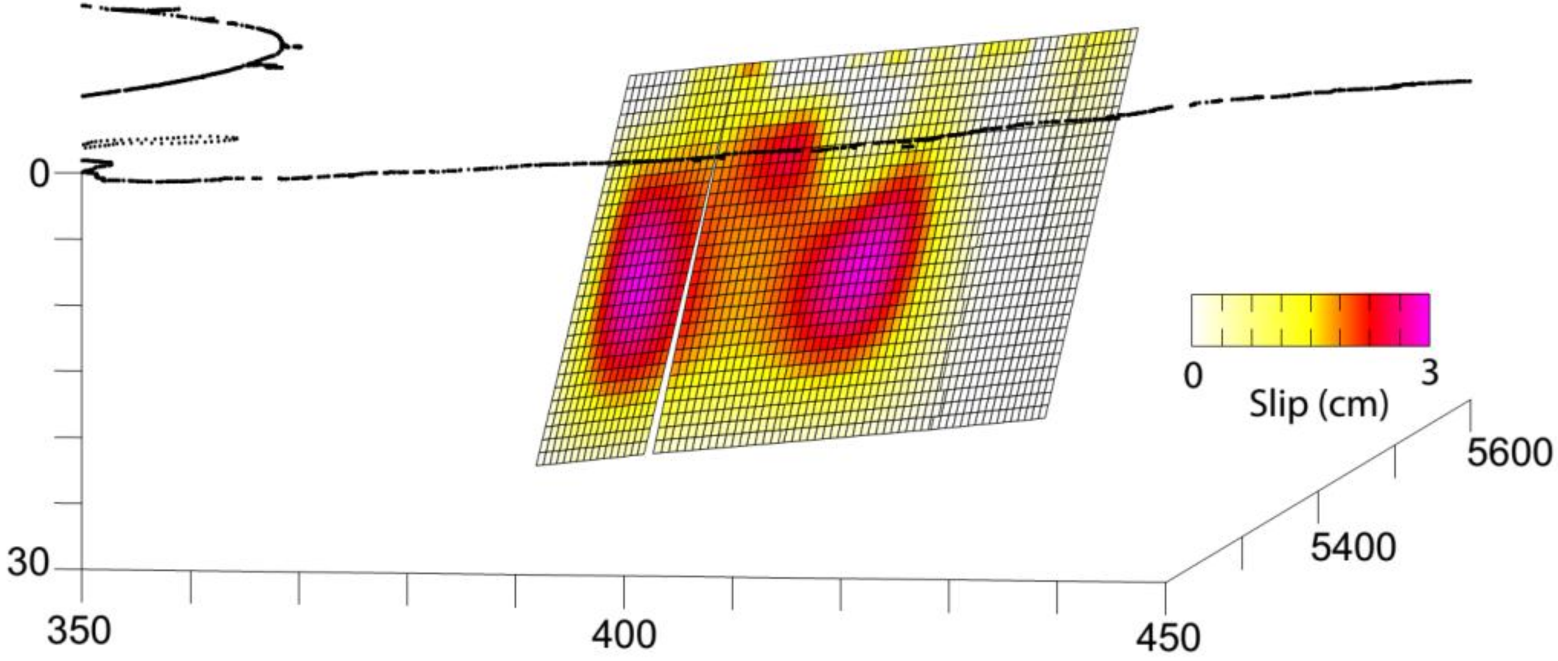
03/11/2004-19/10/2005


LOS Displacement (mm)
20
15
10
5
0
−5
−10
−15
Wellington/Mohaka
No fault
Shallow fault
Deep fault
A
A′
1
0
H (km)
0
40
80
120
Distance (km)
30
20
10
0
−10
−20
Wellington/Mohaka
Subsidence
Uplift
B
B′
1
0
H (km)
0
40
80
120
Distance (km)

Implications

- The 1855 Wairarapa earthquake is thought to have initiated on the subducting slab before “jumping” onto overlying fault.

- Stress analysis suggests that a rupture of the deep portion of the margin would promote failure of an event on the Wellington fault.

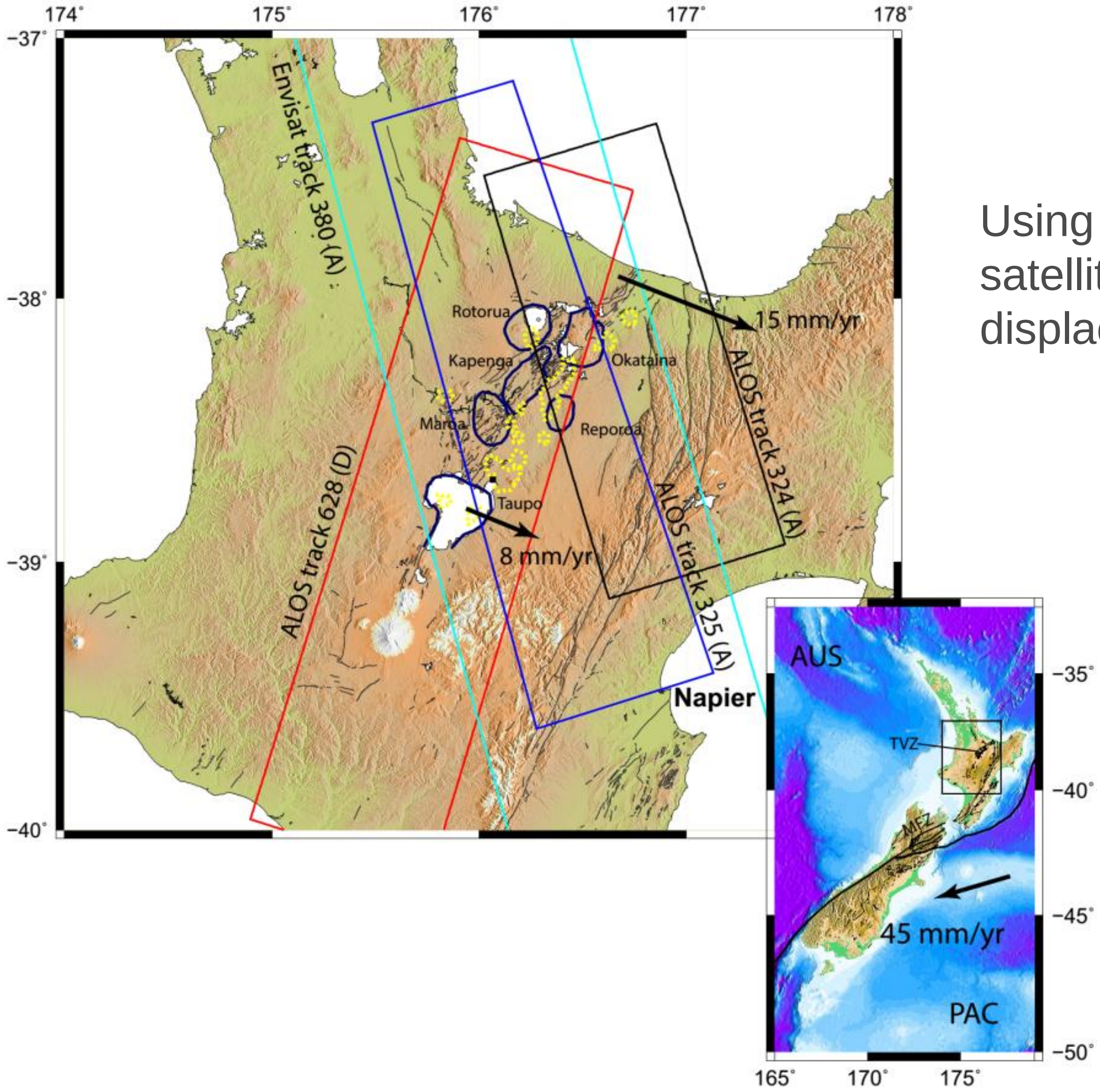


InSAR observations over New Zealand

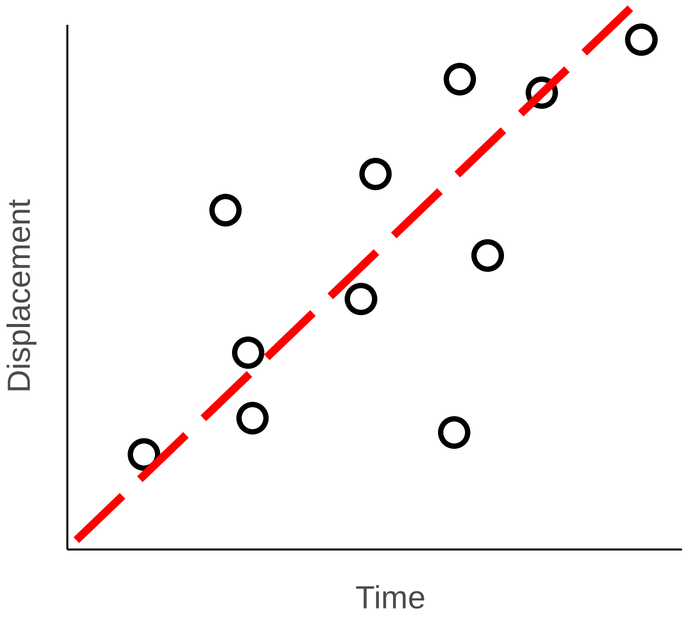
Subsidence along the TVZ

The ups and downs of the TVZ: Geodetic observations of ground deformation along the Taupo Volcanic Zone

Ian Hamling, Sigrún Hreinsdóttir, Nico Fournier

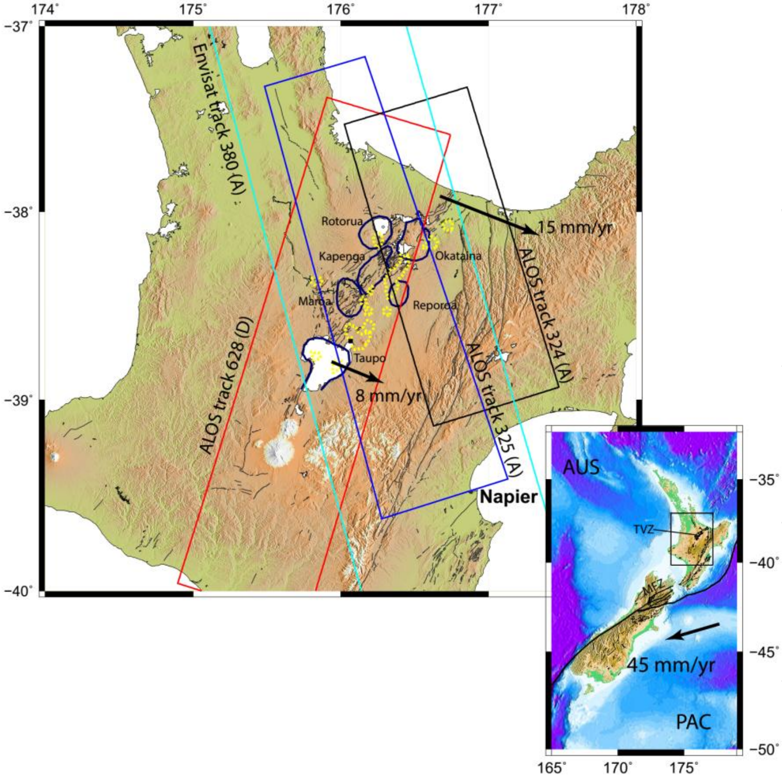


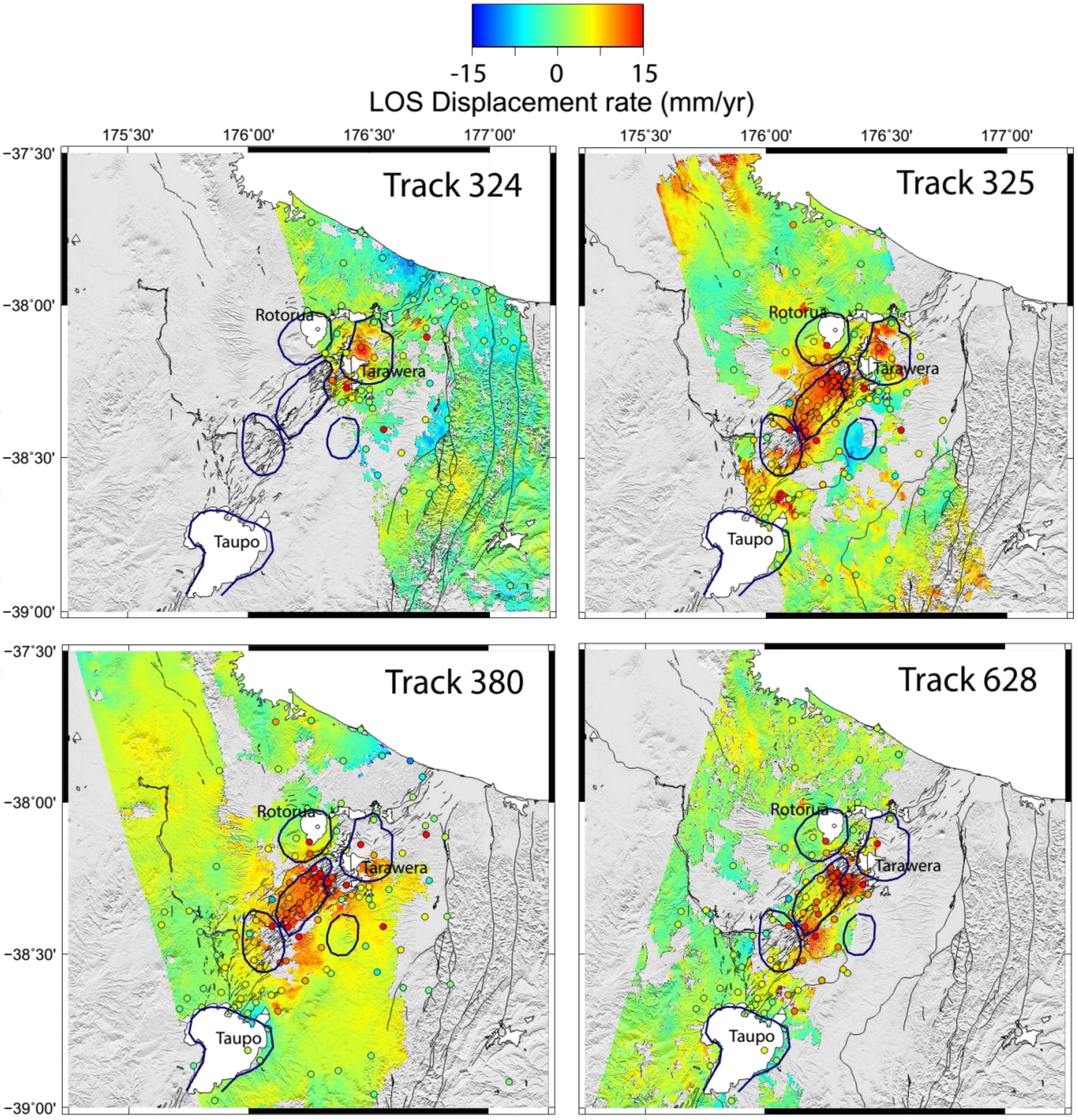
Using ~80 interferograms across 4 satellite tracks we solve for best fitting displacement rate for each pixel.



The ups and downs of the TVZ: Geodetic observations of ground deformation along the Taupo Volcanic Zone

Ian Hamling, Sigrún Hreinsdóttir, Nico Fournier

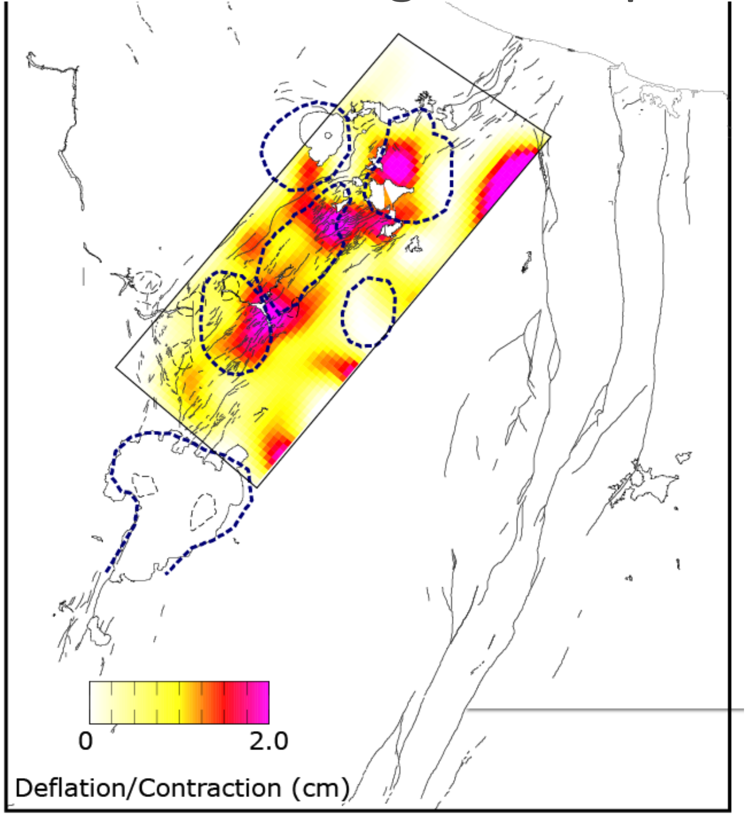


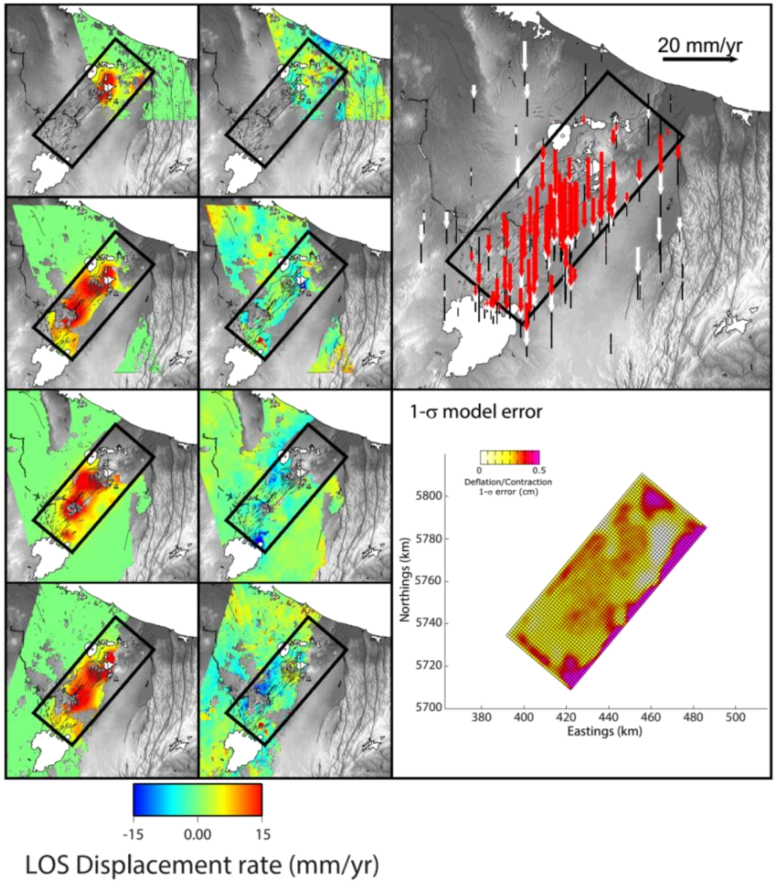


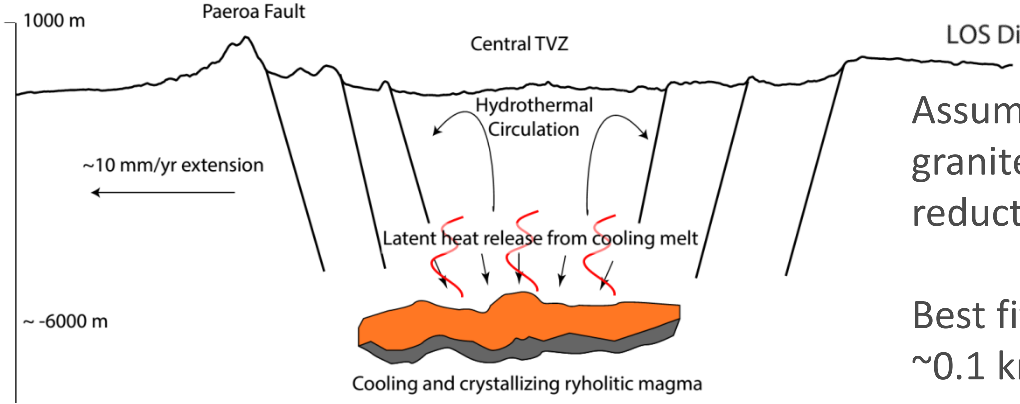
InSAR and GPS show up to 25 mm/yr of subsidence along the length of the TVZ between 2003 and 2011.

Up to 50 mm/yr of subsidence at Wairakei geothermal field.

The ups and downs of the TVZ: Geodetic observations of ground deformation along the Taupo Volcanic Zone







Assuming cooling of rhyolitic melt (2200 km/m^3) into granite (2700 kg/m^3) would result in a ~20% volume reduction.

Best fitting model suggests cooling and contraction of ~0.1 km^3 of ryholite at 6 km depth

What strain rate can we resolve from InSAR?

How do we achieve 1 mm/100km/yr??

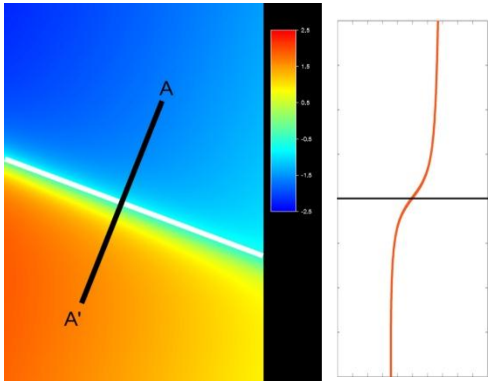
Error Considerations

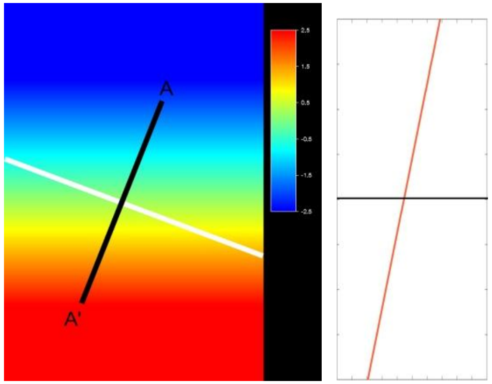
$$\sigma^2 = \sigma_{geom}^2 + \sigma_{topo}^2 + \sigma_{atmos}^2 + \sigma_{coh}^2 + \sigma_{sys}^2 + \sigma_{unw}^2$$

- Orbital errors lead to long wavelength ramps across scene - can mask interseismic signals

- Can be removed by tying to GPS on ground

- Should be minimal with new satellites with more tightly controlled GPS orbits





Error Considerations

$$\sigma^2 = \sigma_{geom}^2 + \boxed{\sigma_{topo}^2} + \sigma_{atmos}^2 + \sigma_{coh}^2 + \sigma_{sys}^2 + \sigma_{unw}^2$$

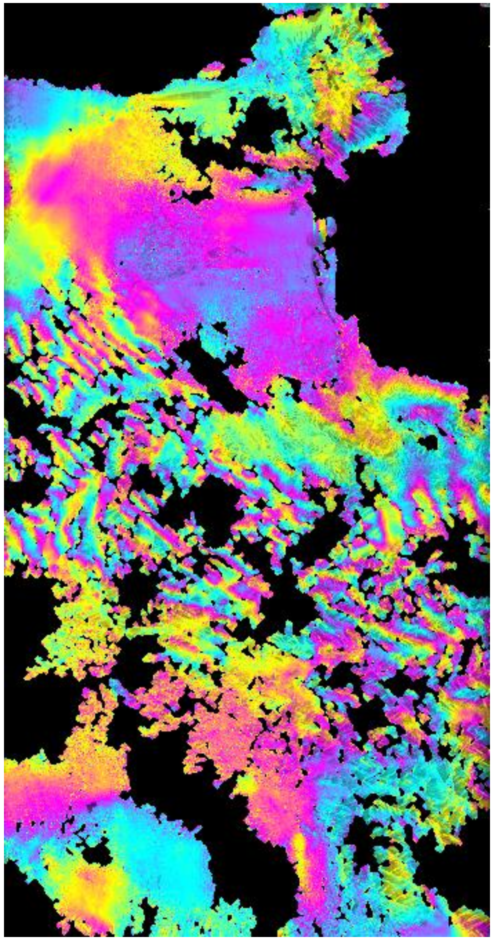
$$\sigma_{topo} = \frac{B_\perp}{R_{slant}\sin\theta}\sigma_{dem}$$

Absolute σ_{dem} for SRTM in New Zealand ~ 5 m, 2.5 m of which is not spatially correlated.

B_{perp}	σ_{topo} (40˚incidence)
50 m	0.5 mm
500 m	5 mm
1500 m	16 mm

Error Considerations

$$\sigma^2 = \sigma^2_{geom} + \sigma^2_{topo} + \boxed{\sigma^2_{atmos}} + \sigma^2_{coh} + \sigma^2_{sys} + \sigma^2_{unw}$$



Large source of error caused by distribution of water vapour in the troposphere

Can be corrected using weather models but these can introduce additional error.

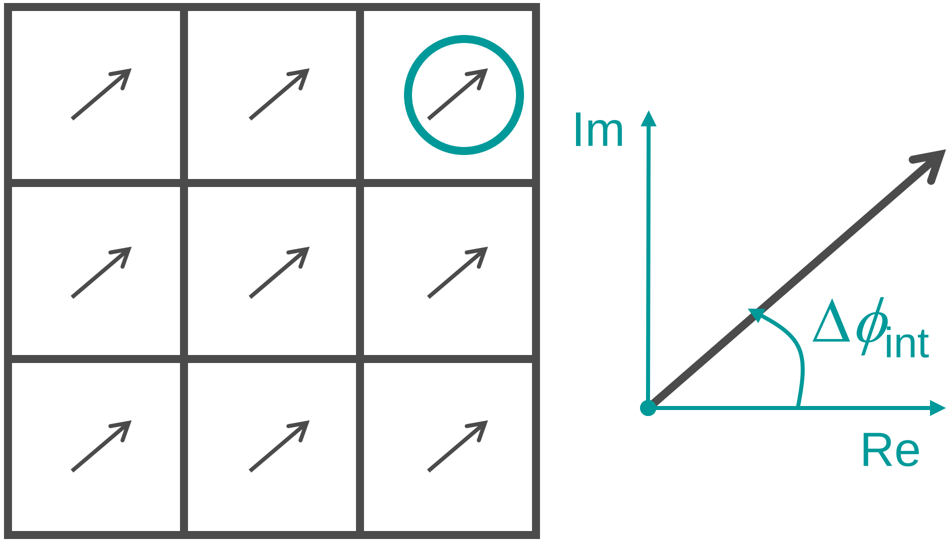
Typically 25 mm over 100 km wavelength but can be larger.

Error Considerations

$$\sigma^2 = \sigma^2_{geom} + \sigma^2_{topo} + \sigma^2_{atmos} + \sigma^2_{coh} + \sigma^2_{sys} + \sigma^2_{unw}$$

- Biggest source of noise is due to changing ground surface
- Worse at short wavelengths but can be averaged by multilooking
- *Coherence* is convenient measure

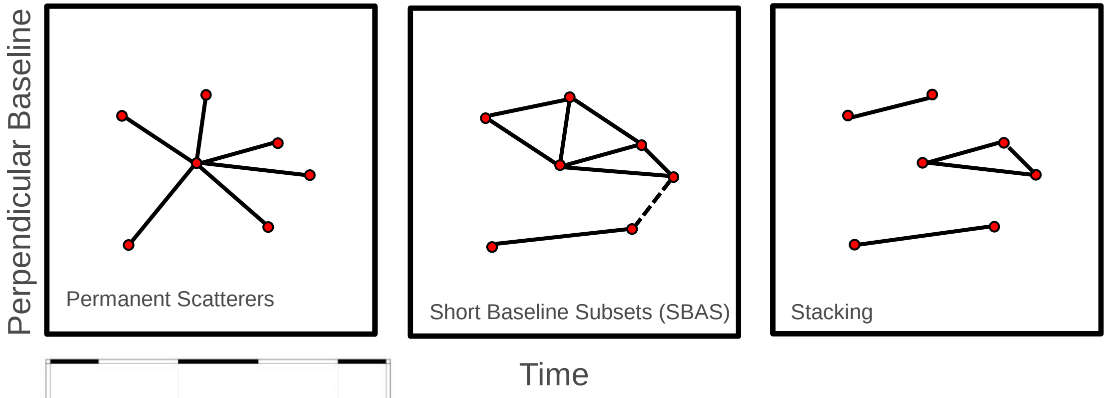
$$\hat{\gamma} = \frac{\sum_{i=1}^{N} u_{1i} u_{2i}^{*}}{\sqrt{\sum_{i=1}^{N} |u_{1i}|^2} \sqrt{\sum_{i=1}^{N} |u_{2i}|^2}}$$

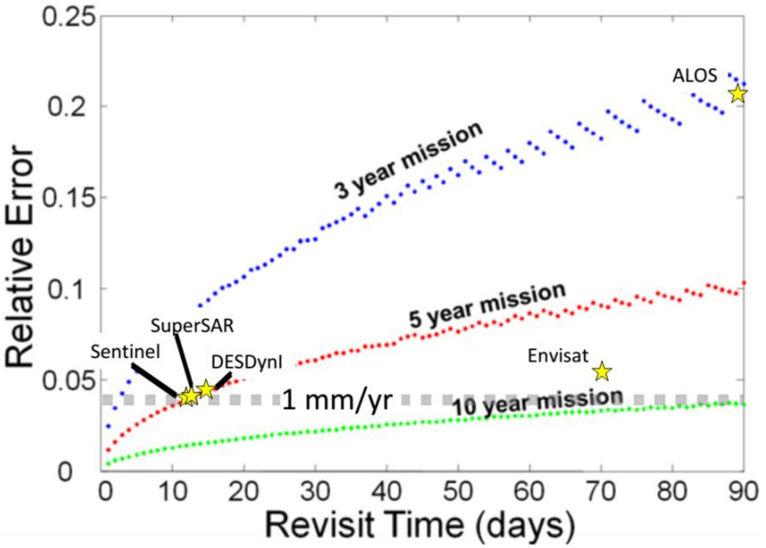


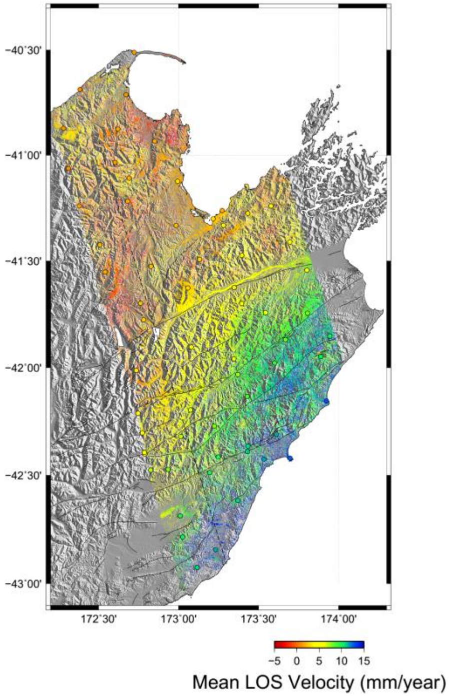
$$\sigma_{coh} = \left(\frac{\lambda}{4\pi}\right) \frac{1}{\sqrt{N_L}} \frac{\sqrt{1-\gamma^2}}{\gamma}$$

How do we achieve 1 mm/100km/yr??

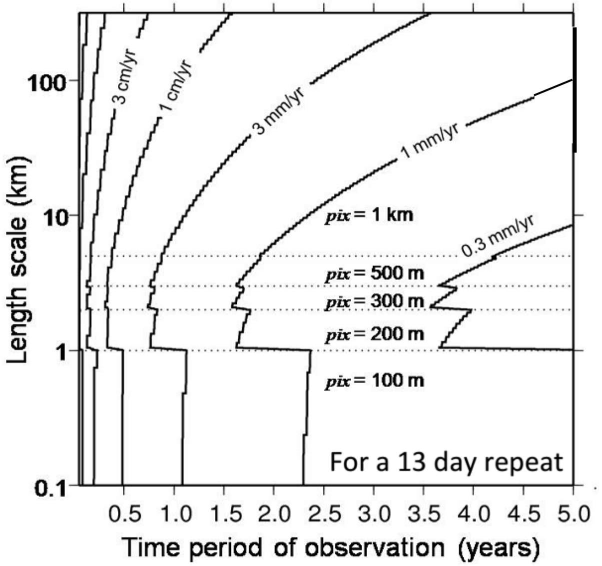
- Need to combine lots of observations in timeseries analysis, stacking is not enough!







- Assuming perfect coherence (unlikely), need at least 5 years of observations.
- New missions should make this achievable in the future but it will take some time.

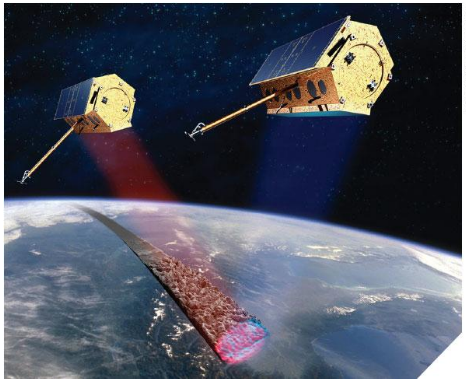


Wright, Fringe 2011

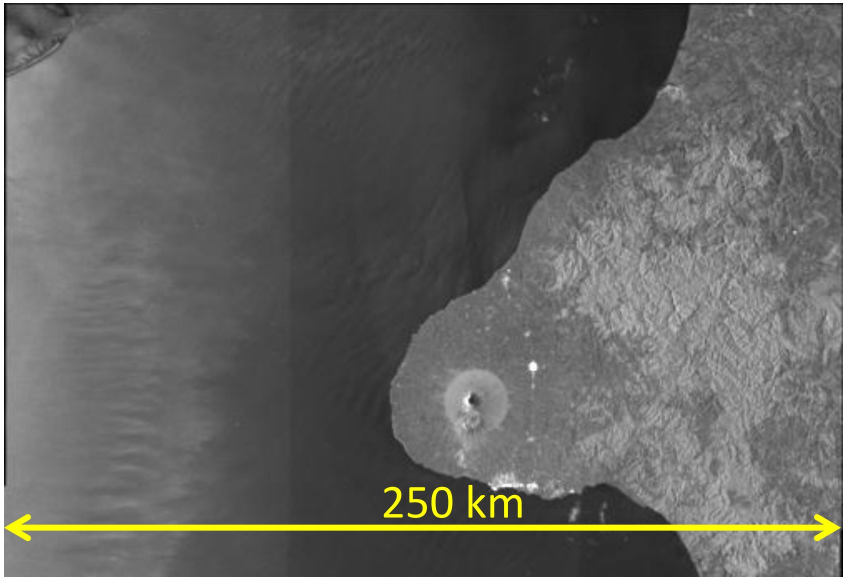
InSAR Current and future missions:

- TerraSAR-X and TanDEM-X launched in 2007 and 2010 .
- X-Band mission with resolutions varying from 0.25 – 40 m, revisit time of 11 days.
- Mission will be continued with TerraSAR-X2.

JAXA lauched ALOS-2 (L-Band) earlier this year. Started releasing data 25th November.

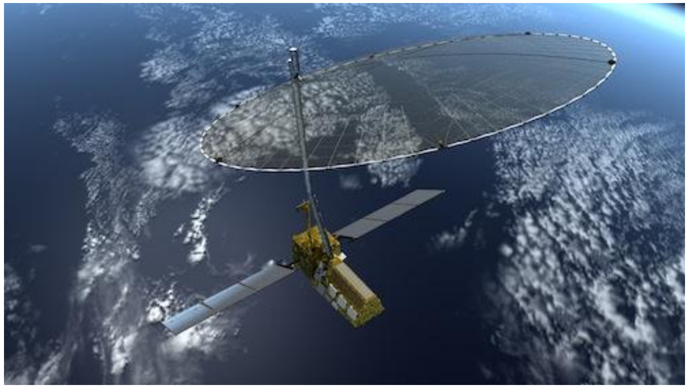


Courtesy www.astrium-geo.com



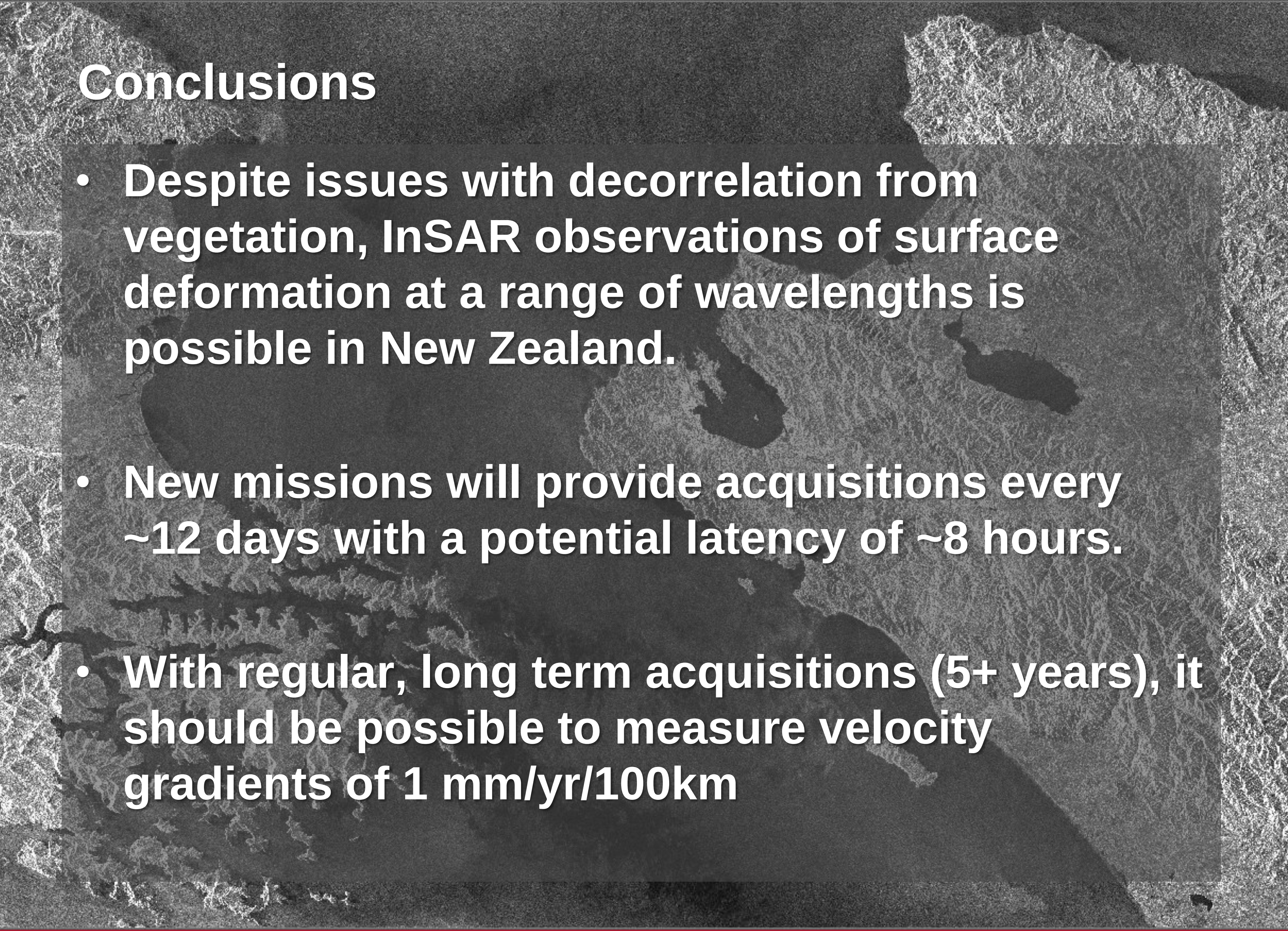
ESA’s Sentinel-1a mission began data dissemination in early October. Will provide radar data over NZ every 6-12 days.

Radarsat-2 launched in 2007



Artiste's concept of the Nisar satellite. Courtesy NASA

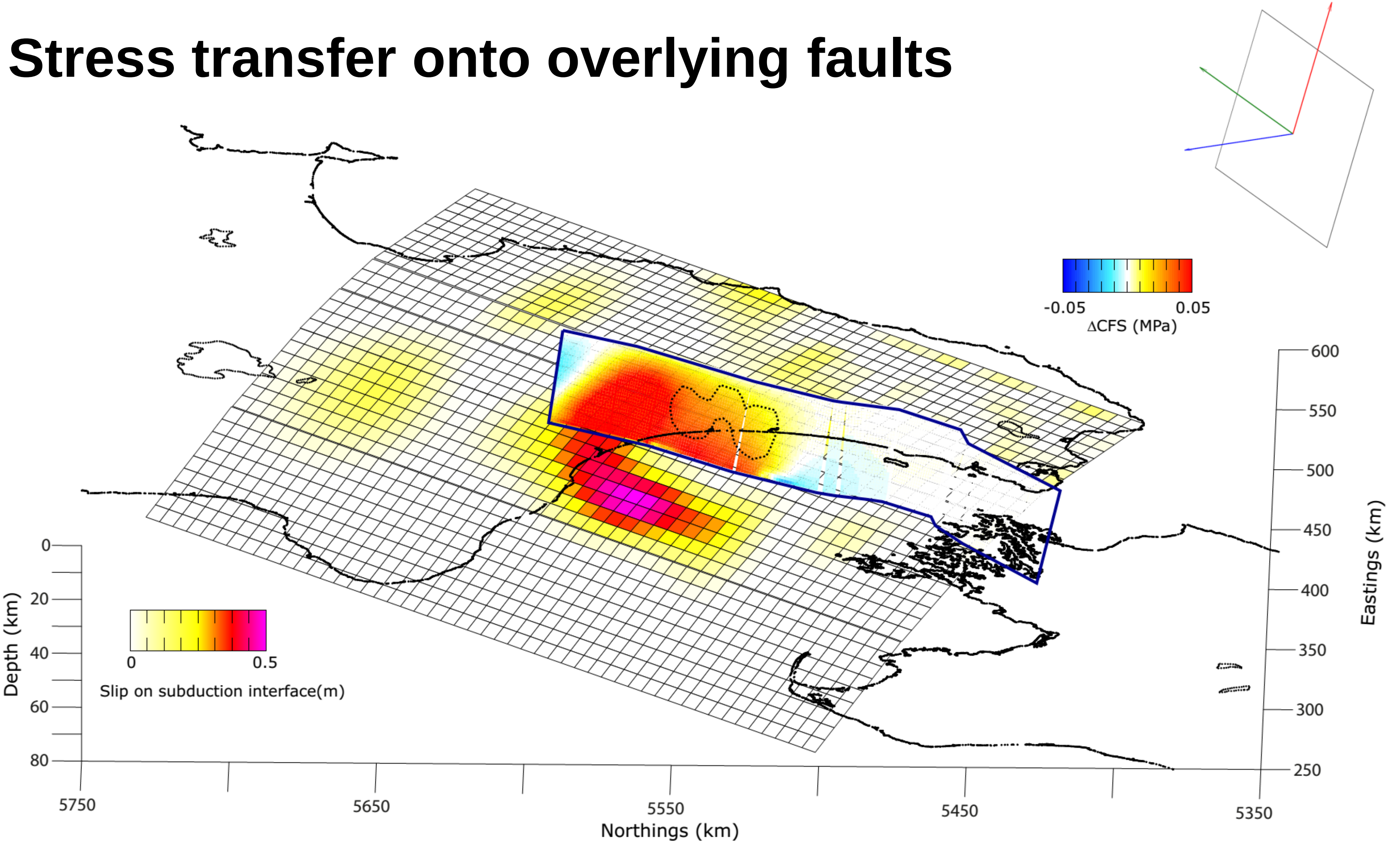
NASA plan an L-Band/S-Band mission in 2020: NISAR



Conclusions

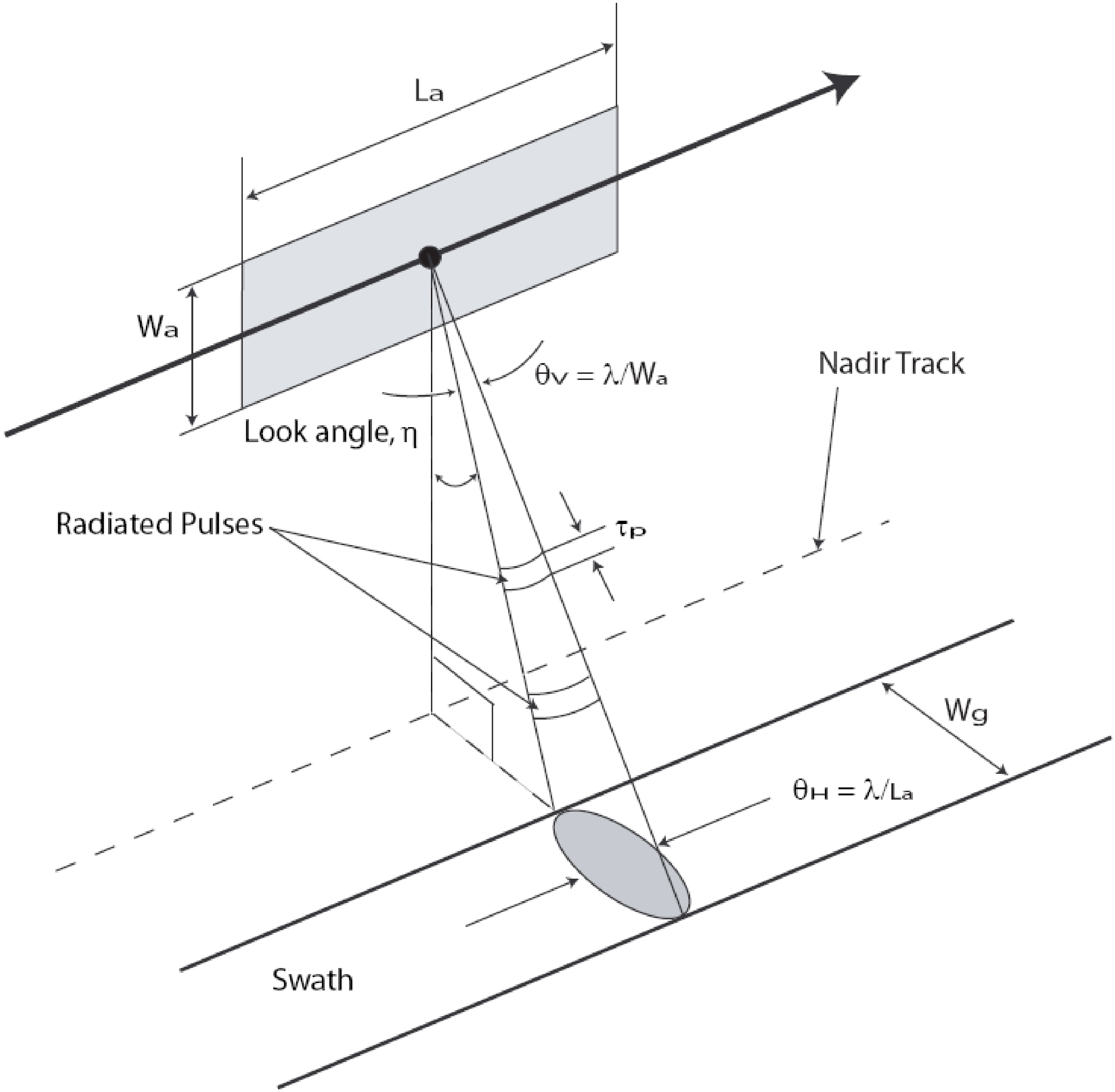
- Despite issues with decorrelation from vegetation, InSAR observations of surface deformation at a range of wavelengths is possible in New Zealand.
- New missions will provide acquisitions every ~12 days with a potential latency of ~8 hours.
- With regular, long term acquisitions (5+ years), it should be possible to measure velocity gradients of 1 mm/yr/100km

Stress transfer onto overlying faults



- At base of fault (25-30 km) stresses are > 0.075 Mpa
- 95% of slip > 1 cm slip falls in regions where the coulomb stress change is > 0.01 Mpa.

Side-Looking Airborne Radar



$\theta \sim \lambda / L$

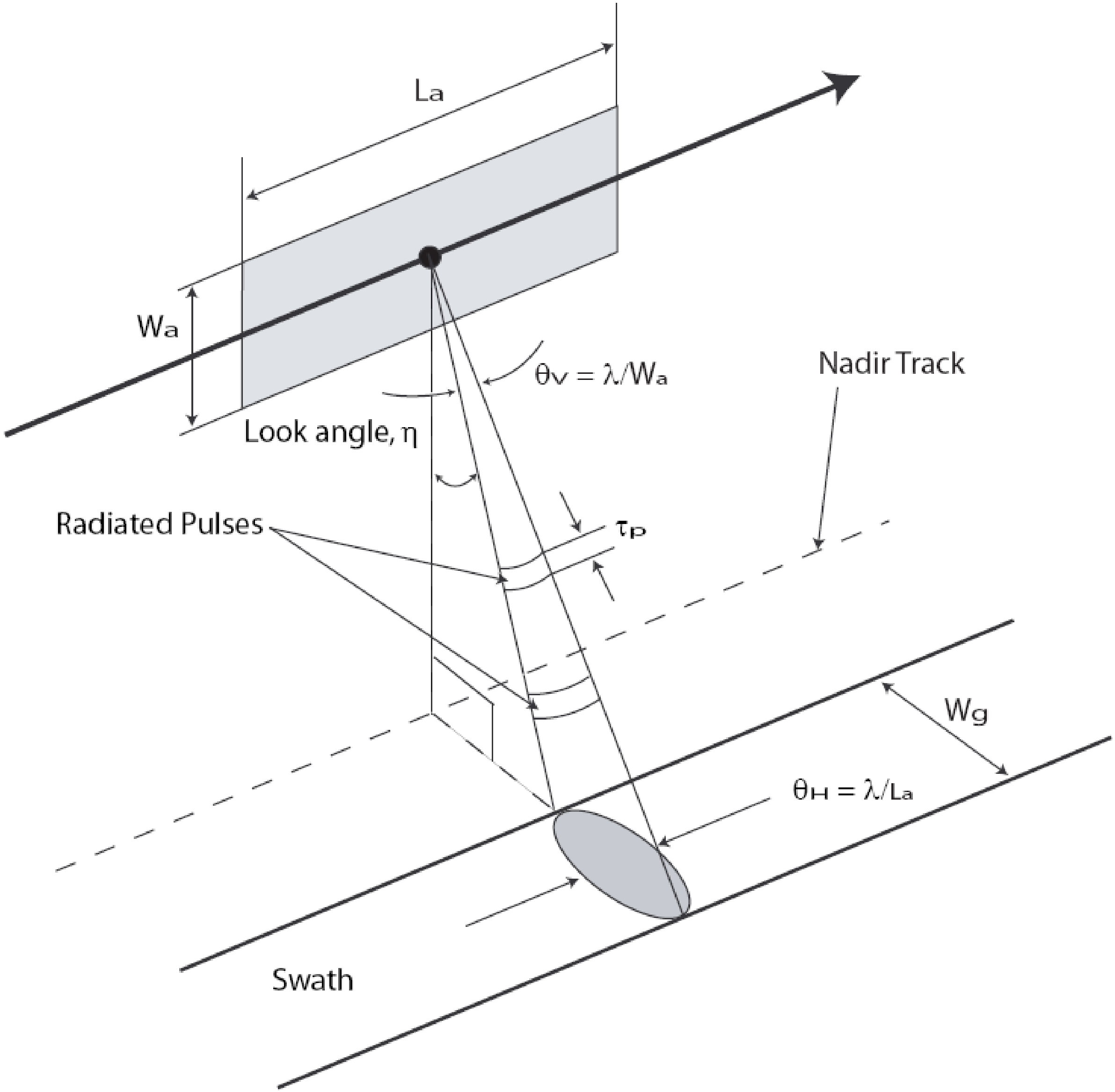
e.g. $\lambda = 0.05$ m

W = 10 m

$\theta \sim 0.005$ radians

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

Side-Looking Airborne Radar



Points on the ground can only be resolved if they are not within the same beamwidth

So ...

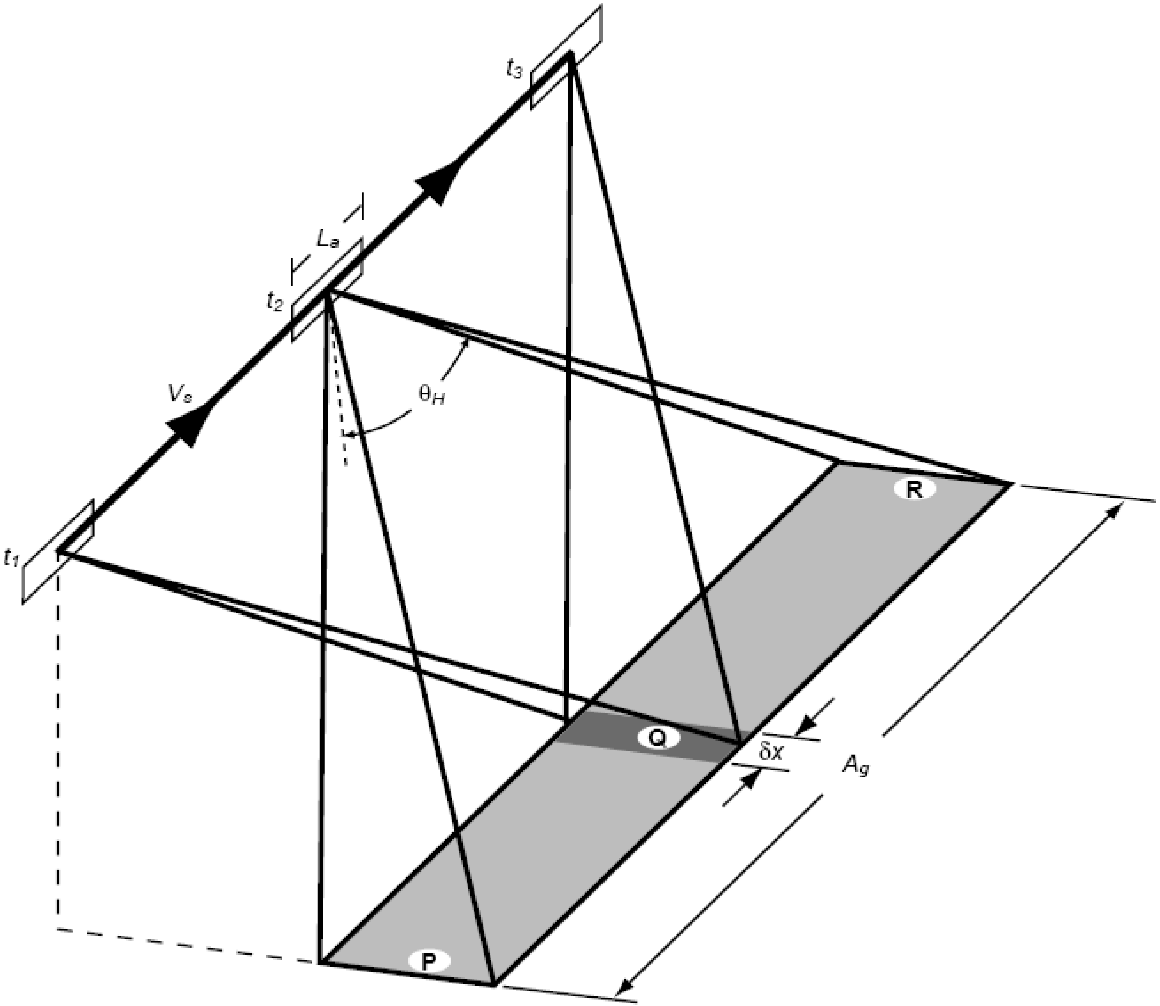
$R_a = s\lambda/L$

Where ***s*** is the slant range from the antenna to the scattering point on the ground.

Therefore for a satellite where s ~850 km and L = 10 m the azimuthal resolution is ~4 km!

How do we get 20 m resolution?

Trick – the Synthetic Aperture



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

Point Q is illuminated throughout time interval t_1-t_3. Distance travelled over this time is equal to beam width of real aperture radar.

Synthetic Aperture Radar (SAR)

- Phase of a wave is invariant with reference frame. As a result, the frequency in a moving frame must adjust to compensate for relative velocity
- 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.