GACOS-Assisted InSAR Time Series Technique

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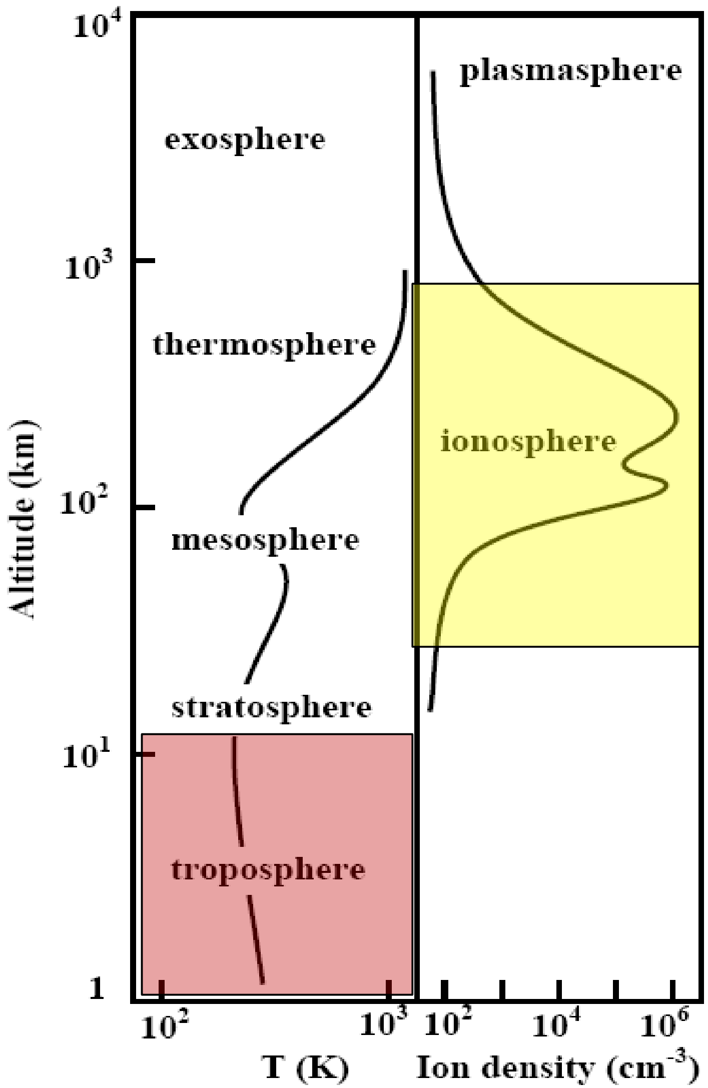
Basic Structure of the Atmosphere



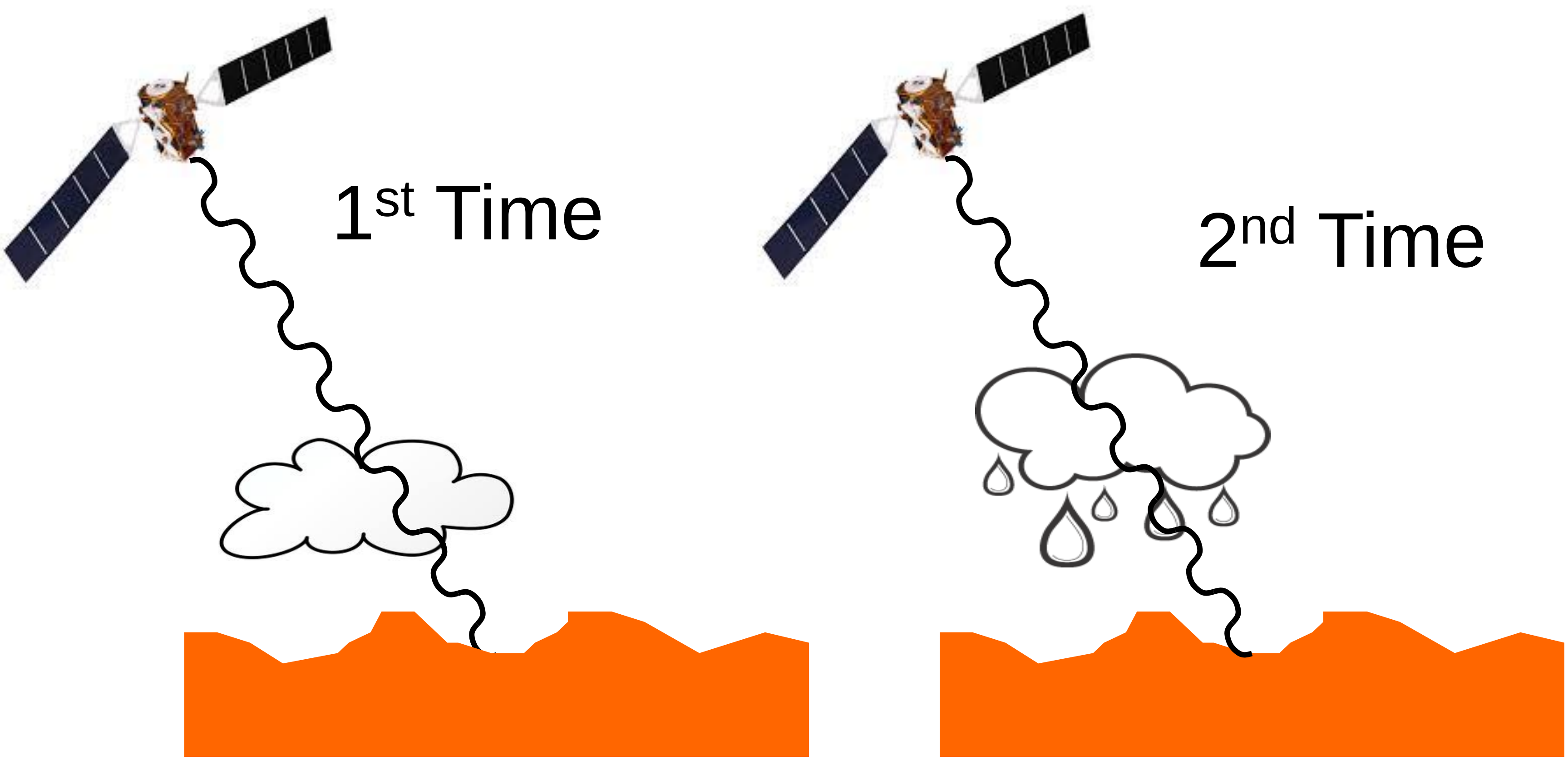
❖ **Troposphere:**

- Contains 80% of air mass
- Contains 99% of water vapour
- Air temperature decreases with altitude
- ~12km thick on average
  ~16 km in the Tropics
  ~9km in the Polar Regions
- Not dispersive (up to 30 GHz)

We focus on **Troposphere** today…

InSAR – atmospheric effects

- **Spatiotemporal variations** in **Troposphere** represent one of the major limitations of repeat-pass InSAR



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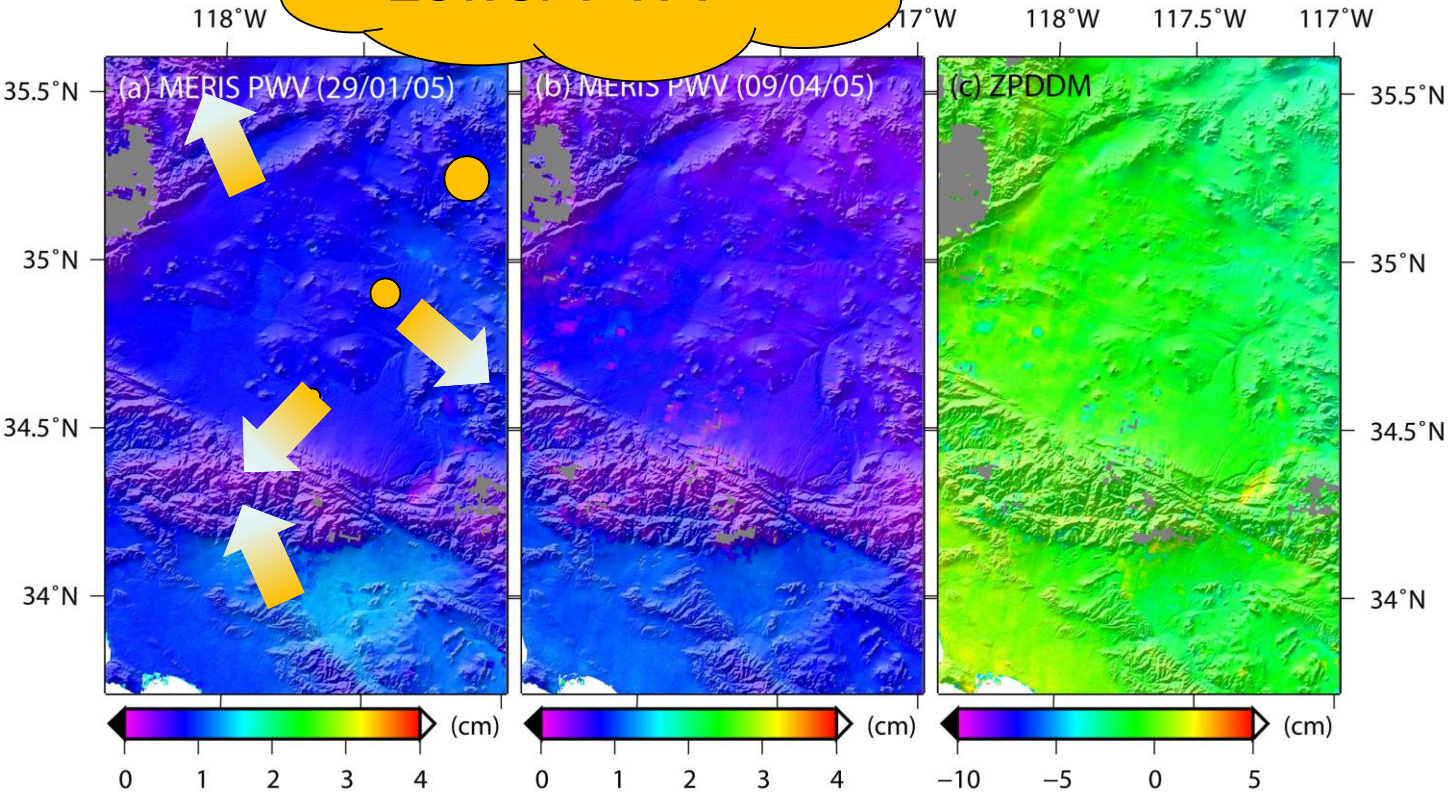
Water vapour effects on InSAR measurements

Higher altitude, Lower PWV

So… n 2005 – 09 Apr 2005)



ZPDDM

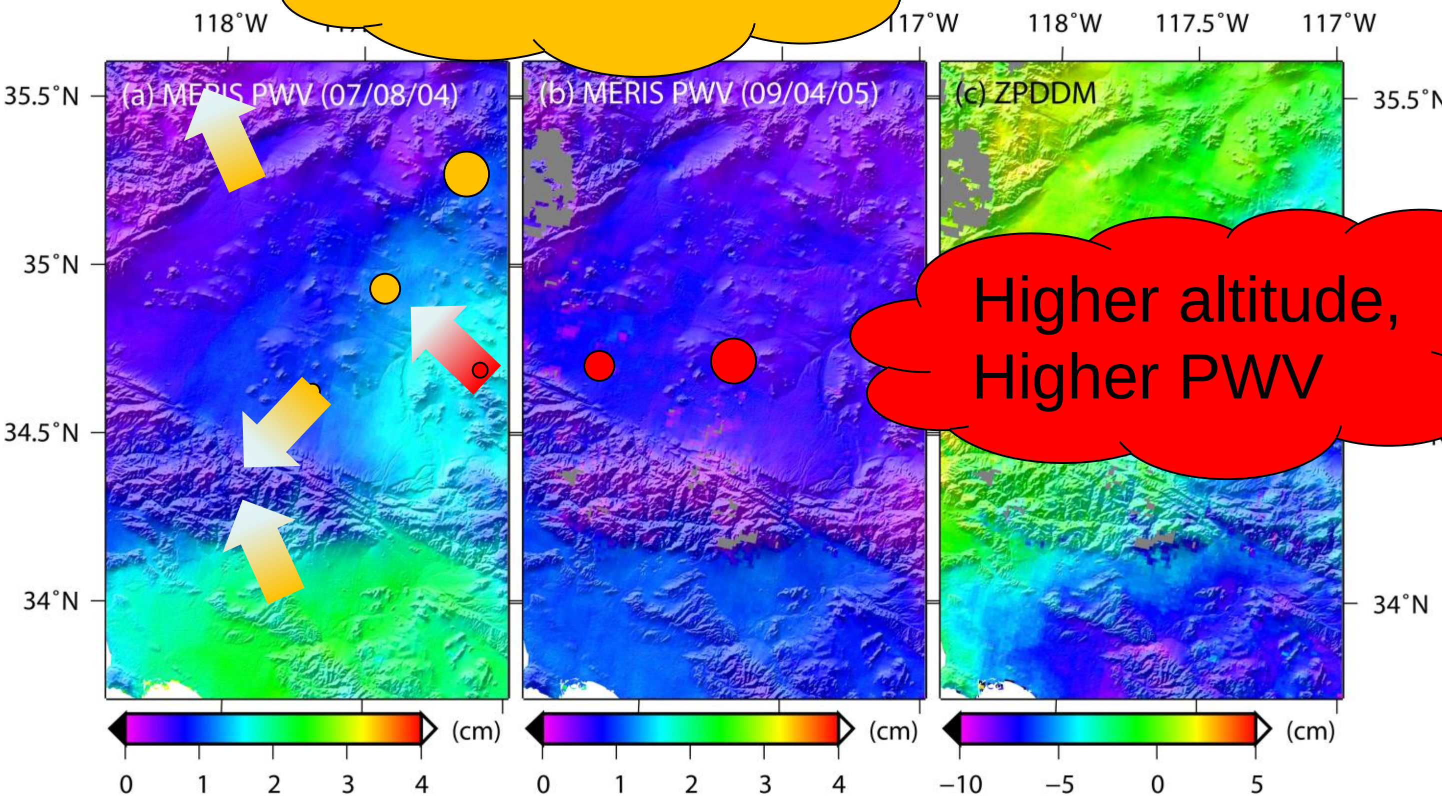
- Max: 7.8 cm
- Min: -5.2 cm
- Mean: -0.9 cm
- StdDev: 1.0 cm

- 1 mm of PWV => ~6.2 mm of ZPD
- ZPDDM: Zenith Path Delay Difference Map

Water vapour effects on InSAR measurements

Higher altitude,
Lower PWV

So g 2004 – 09 Apr 2005)



Higher altitude,
Higher PWV

ZPDDM:

ax: 2.7 cm

n: -12.8cm

Mean: -2.9 cm

StdDev:

2.9 cm

N.B. Strong gradient in Figure (a)

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InSAR Atmospheric Correction Models

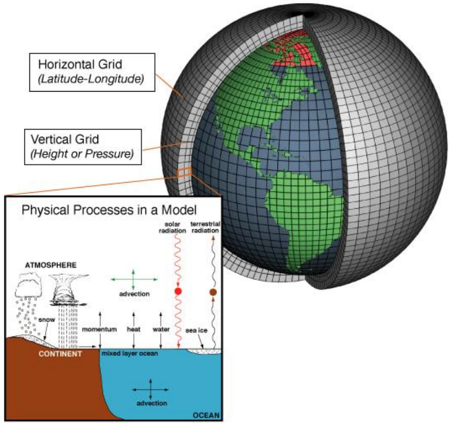
- Space-based water vapour measurements

  \- Limitations: Sensitive to the presence of clouds;
  Available in the daytime only;
  Time differences between radar and PWV data

- Ground-based measurements

  \- Limitations: Coverage + Density + Distribution

- Numerical Weather Models (NWM)
  - ✓ Global/regional/local coverage
  - ✓ High-resolution (relatively)
  - ✓ Non-continuous but regular
  - ✓ Insensitive to the presence of clouds



Key Questions

1. How to generate high resolution (e.g. 90m) and precise (e.g. 1-2 mm) water vapour maps from sparse observations (e.g. GPS derived PWVs)?

2. Which numerical weather model can be used to generate high resolution (e.g. 90m) and precise (e.g. 1-2 mm) water vapour maps?

3. Is it feasible to integrate multiple sources with different resolutions to produce high resolution (e.g. 90m) and precise (e.g. 1-2 mm) water vapour maps?

N.B. 1 mm of PWV => 6.2 mm of Phase Delay

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Basic equations

- Tropospheric delays can be calculated as follows:

$$\Delta S = 10^{-6}\int_S N \cdot ds$$

where *N* is **refractivity**: $N = (n - 1) \times 10^{-6}$

- The **refractivity** of the troposphere is given by

$$N = \underbrace{k_1 \frac{P_d}{T} Z_d^{-1}}_{\text{Density of dry air}} + \underbrace{k_2 \frac{P_w}{T} Z_d^{-1}}_{\text{Density of water vapour}} + \underbrace{k_3 \frac{P_w}{T^2} Z_d^{-1}}_{\text{Dipole compoent of water vapour } \rho/\mathrm{T}}$$

$$k_1 = 77.60 \pm 0.05 \quad \mathrm{K/mbar}$$

$$k_2 = 70.4 \pm 2.2 \quad \mathrm{K/mbar}$$

$$k_3 = (3.739 \pm 0.012) \times 10^5 \quad \mathrm{K^2/mbar}$$

Basic equations

- The refractivity of the troposphere is COMMONLY written as

$$N = N_h + N_w$$

- Assuming a spherically symmetric atmosphere, the zenith tropospheric delay (ZTD) can be expressed as:

$$ZTD = ZHD + ZWD$$

  - *ZHD:* Zenith Hydrostatic Delay
  - *ZWD:* Zenith Wet Delay

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Atmospheric Correction Model:

Iterative Tropospheric Decomposition Model (ITDM)

AGU PUBLICATIONS

JGR

Journal of Geophysical Research: Atmospheres

RESEARCH ARTICLE

10.1002/2016JD025753

Generation of real-time mode high-resolution water vapor fields from GPS observations

Chen Yu[1], Nigel T. Penna[1], and Zhenhong Li[1]

[1]School of Civil Engineering and Geosciences, Newcastle University, Newcastle upon Tyne, UK

Key Points:

- An iterative tropospheric decomposition model for zero differenced ZTD interpolation
- Generation of high-resolution

Tropospheric delays include:

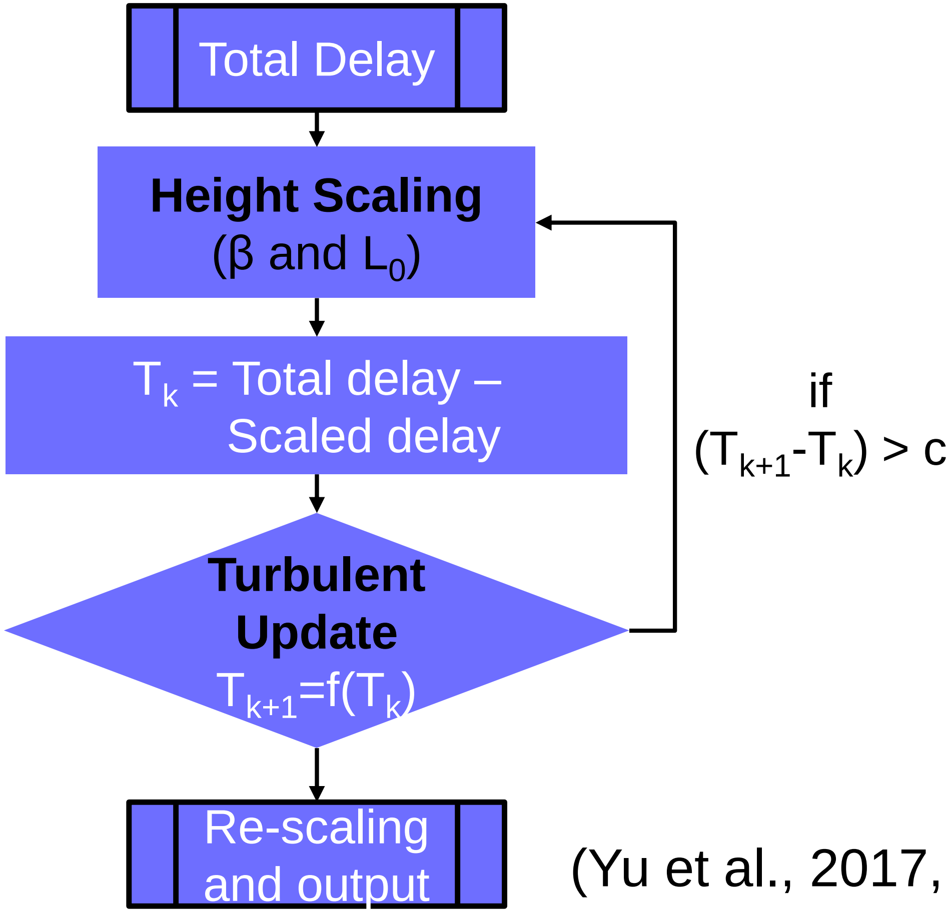
- Stratified: Topography-dependent component
- Turbulent: Topography-independent component resulting from turbulent processes

$$\mathrm{V}L_{ij}^{k} = T(\mathbf{x}^{k}) + L_0 e^{-\beta h^{k}} + \varepsilon$$

Turbulent Stratified Unmodelled error

Atmospheric Correction Model:

Iterative Tropospheric Decomposition Model (ITDM)



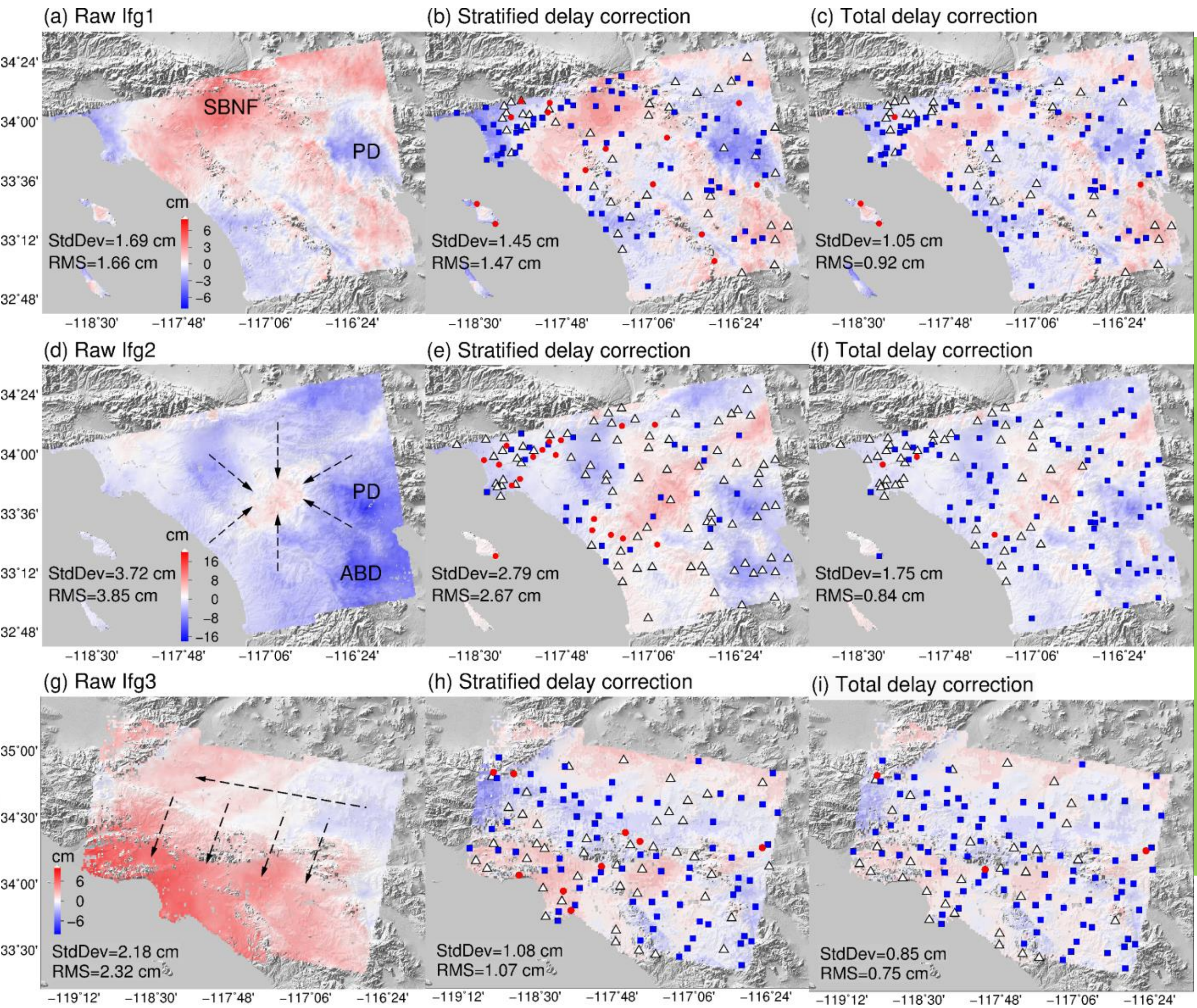
$$
\begin{cases}
T_u = \sum_{i=1}^{n} w_{ui} T_i(\mathbf{x}_i) \\
w_{ui} = d_{ui}^{-2} \Big/ \sum_{k=1}^{n} d_{uk}^{-2}
\end{cases}
$$

$$
\overrightarrow{T_{k+1}} = \begin{pmatrix} 0 & w_{12} & \cdots & w_{1n} \\ w_{21} & 0 & \cdots & w_{2n} \\ \vdots & \vdots & 0 & \vdots \\ w_{n1} & \cdots & w_{n,n-1} & 0 \end{pmatrix} \overrightarrow{T_k}
$$

(Yu et al., 2017, JGR)

- The turbulent and stratified components are modeled with **IDW** and **exponential functions**, respectively
- ITDM reduces the **turbulence effects** on the estimation of height scaling

Atmospheric Correction Model:
Iterative Tropospheric Decomposition Model (ITDM)

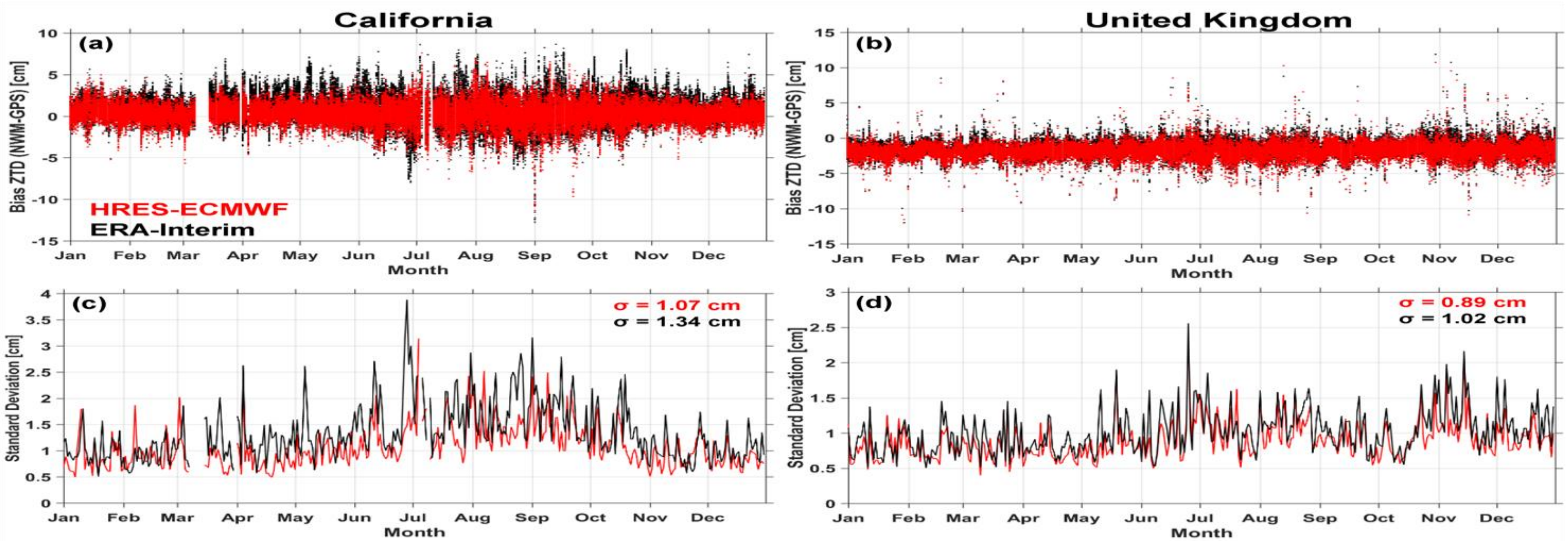


ITDM leads to 45–78% of noise reduction even with a sparse (~50–80 km station spacing) GPS network and/or with strong and non-random tropospheric turbulence.

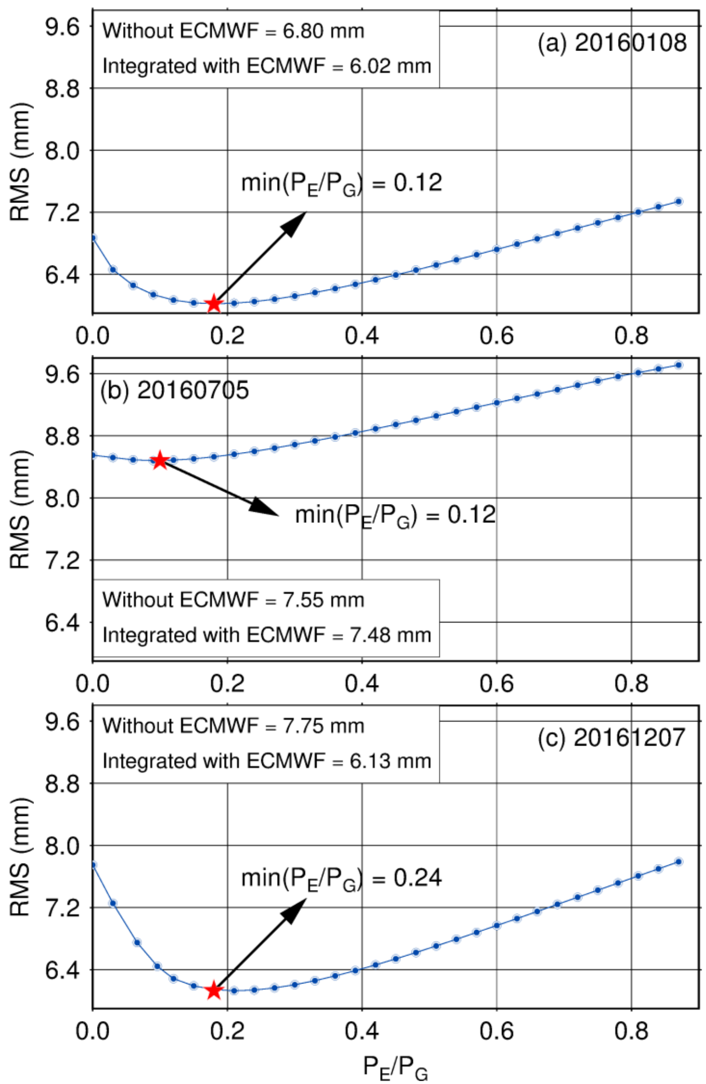
(Yu et al., 2018, RSE)

Comparison between HRES ECMWF and ERA-Interim

	HRES-ECMWF	ERA-Interim
Horizontal Resolution	9~16 km	75 km
Vertical Resolution	137 levels	61 levels
Output frequency	00,06,12,18 UTC	00,06,12,18 UTC
Data availability	Near real-time	Delayed 3-4 months
Data access	Free with authorization	Free



Integration of GPS and HRES-ECMWF



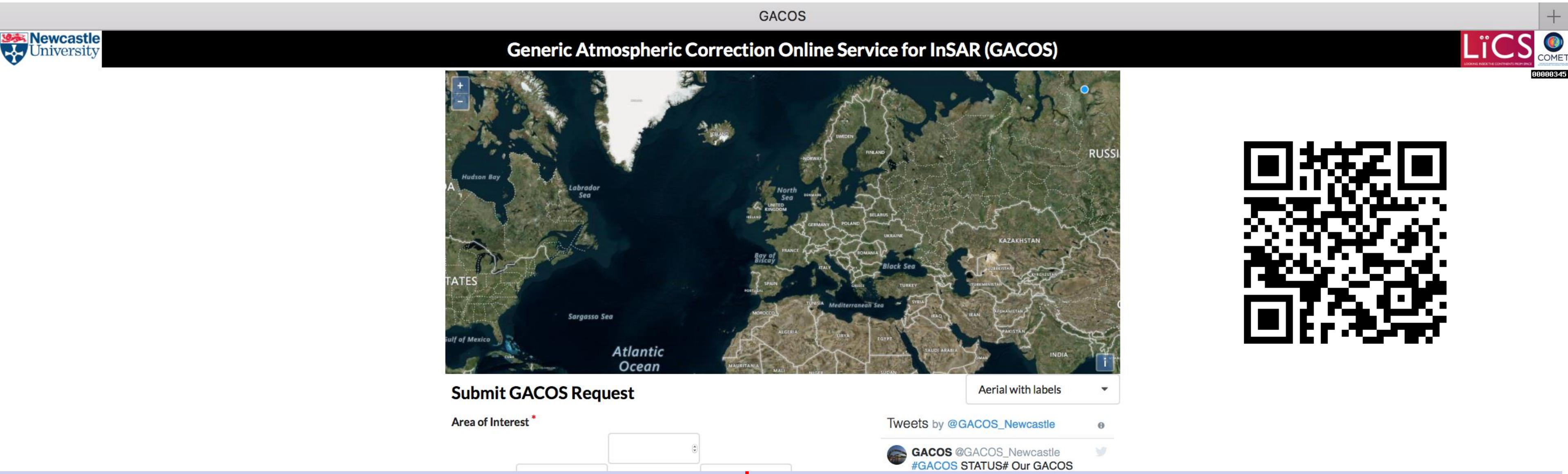
$$S = L_0 e^{-\beta h} \Rightarrow \begin{cases} S_m^G = L_0 e^{-\beta h_m} \\ S_n^E = L_0 e^{-\beta h_n} \end{cases}, \quad \boxed{P_S = \begin{bmatrix} P_G & 0 \\ 0 & P_E \end{bmatrix}}$$

$$T_u = \sum_{i=1}^{n} w_{ui} T(\mathbf{x}_i), \quad w_{ui} = \boxed{p_i} d_{ui}^{-2} \Big/ \sum_{i=1}^{n} p_i d_{ui}^{-2}$$

- GPS and HRES-ECMWF are integrated with proper weighting to generate reliable ZTD correction maps.
- The relative weighting between GPS and HRES-ECMWF are controlled by the precision and station distribution of GPS.

(Yu et al., 2018, in press for JGR)

GACOS: Generic Atmospheric Correction Online Service for InSAR

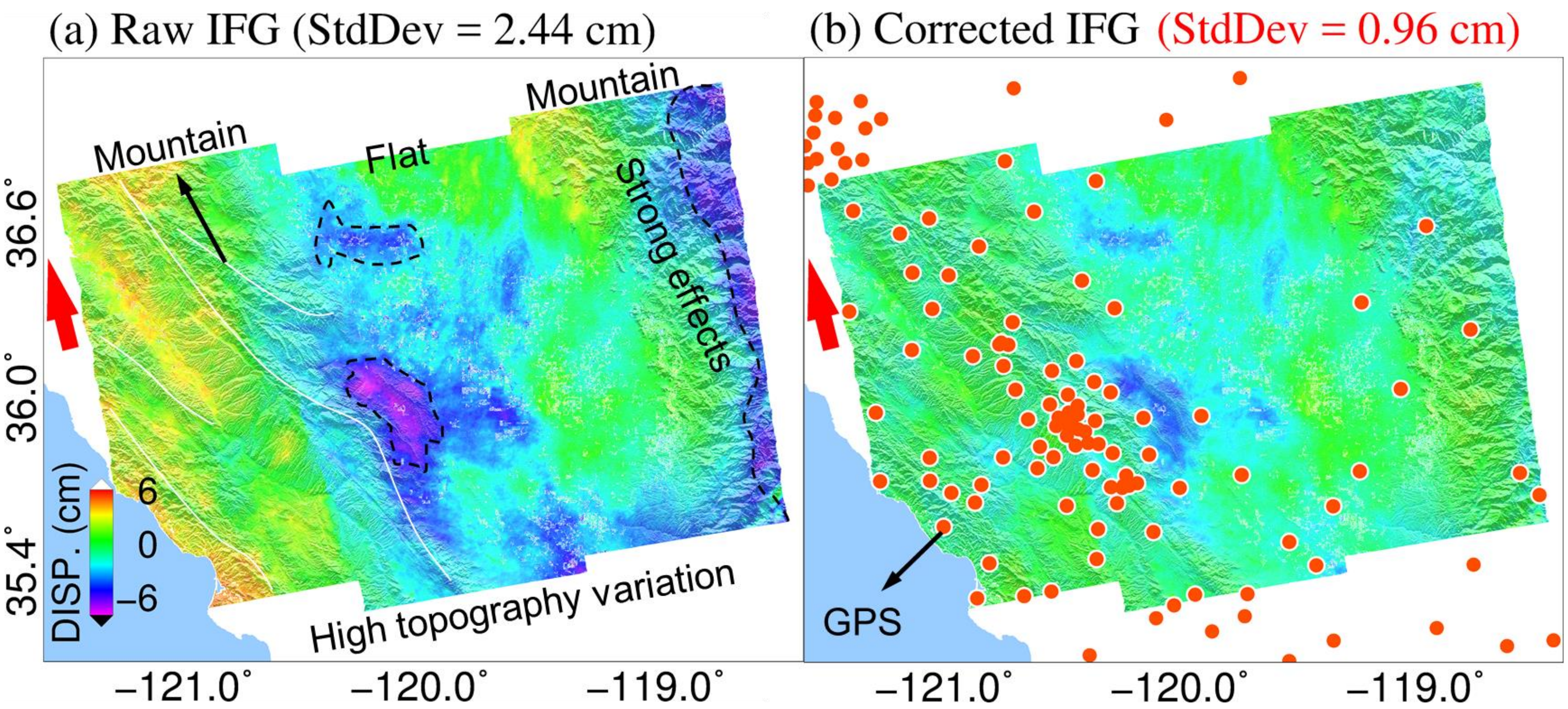


- Global coverage
- Operational in near real time
- Easy to implement
- Performance indicators

- High Resolution ECMWF (0.125, 6 hours);
- GNSS (soon to be released)
- 90m SRTM and ASTER GDEM

Launched in the 2017 Fringe Workshop on 6 Jun 2017

Case study: Central California



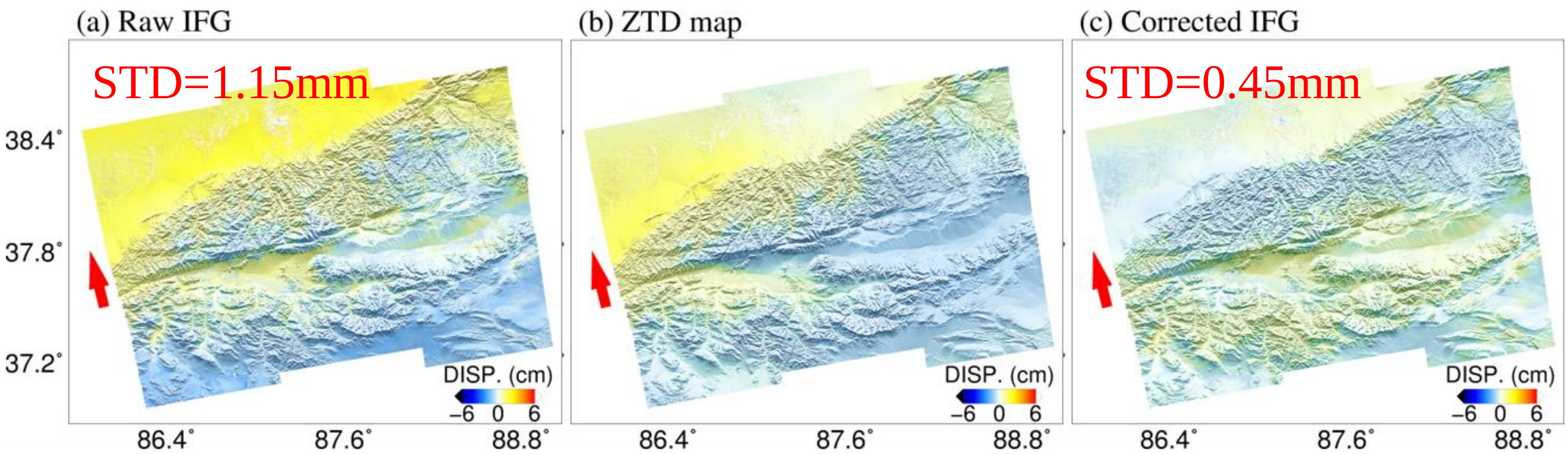
N.B. RMS difference (InSAR vs GPS): 2.43 cm -> 0.72 cm

(Yu et al., 2018, in press for JGR)

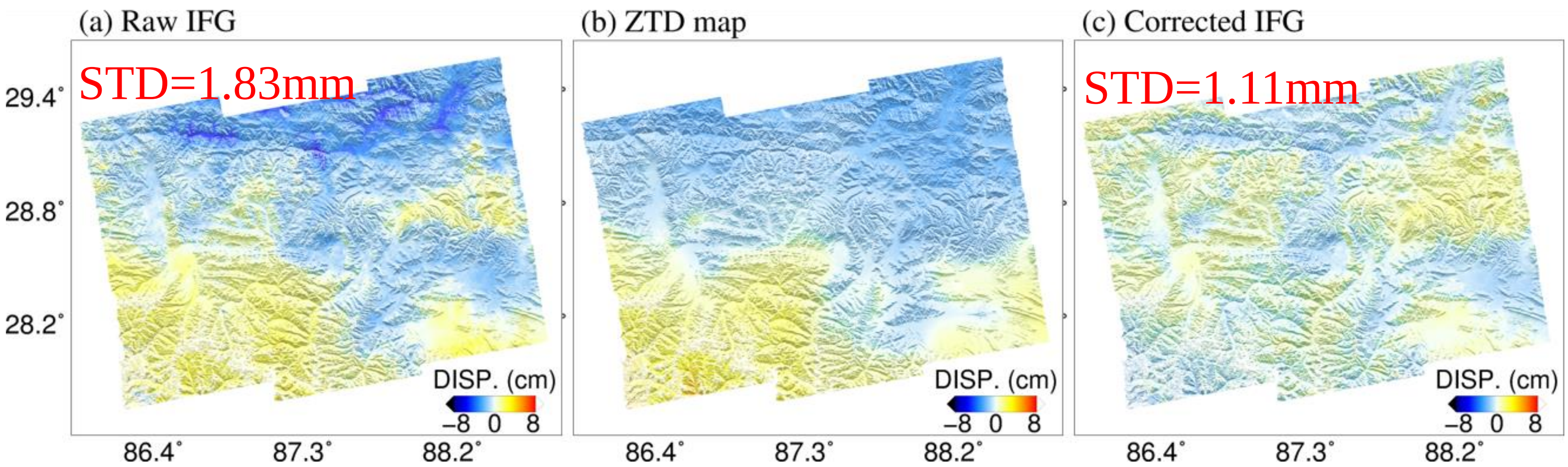
Case studies: Northern Tibet/Nepal

Raw IFGs | ZTD maps | Corrected IFGs

Northern Tibet



Nepal



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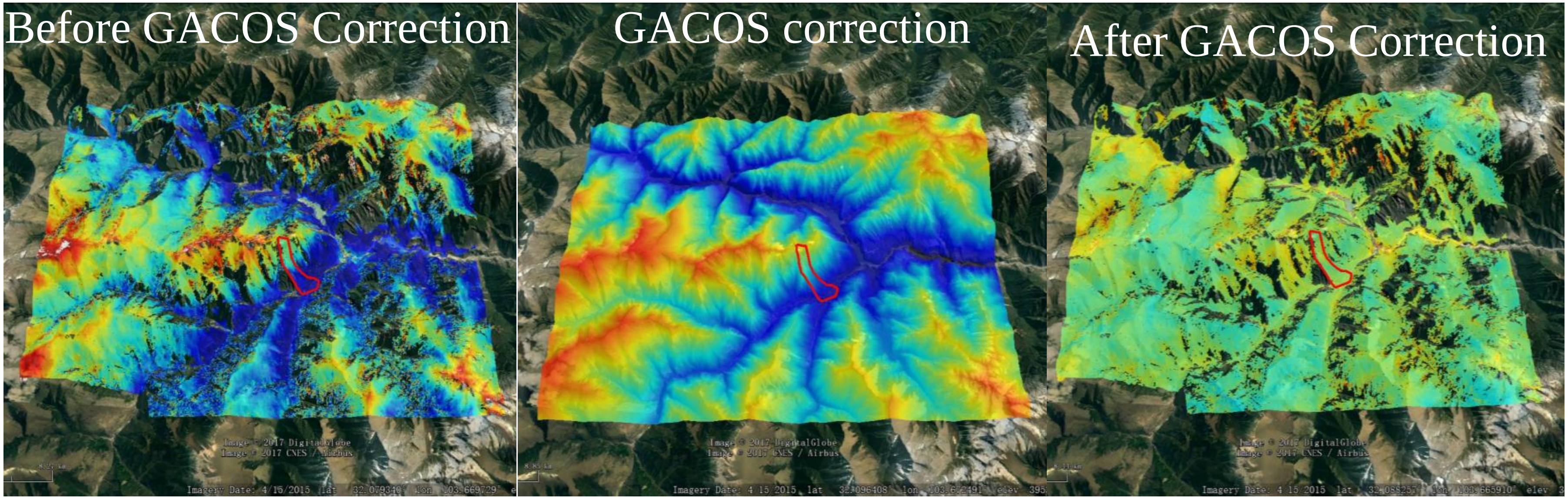
Case study: Maoxian Landslide, China

The 24 June 2017 Maoxian (China) Landslide
(Sentinel-1A 20170131-20170531)



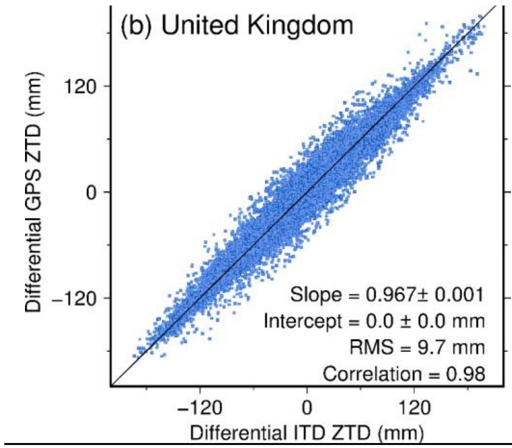
8 km

Performance Matrix (Indicators)

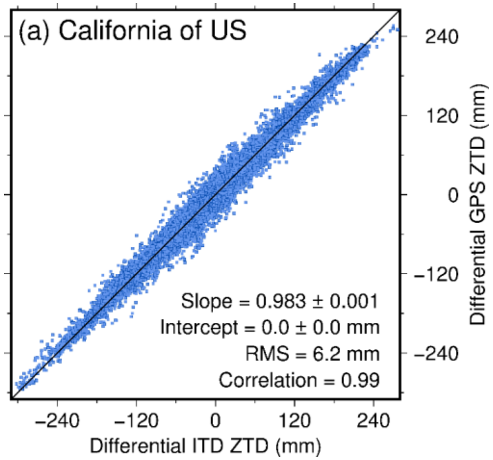
- Cross RMS
- Correlation coefficients
- ECMWF time difference
- Topography variation

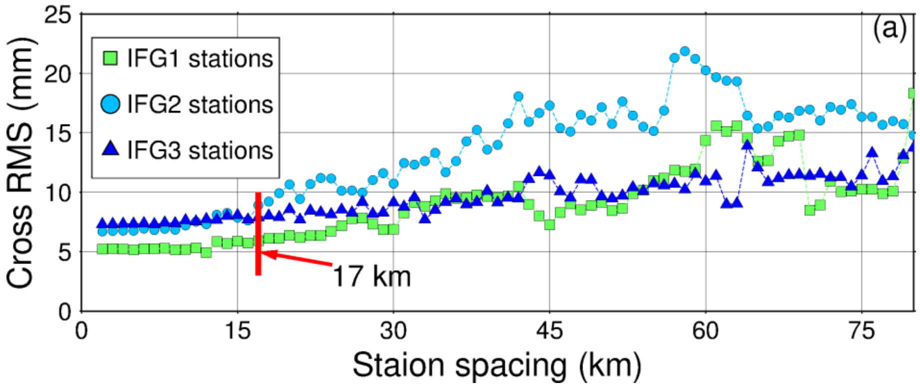
Performance indicator: Cross RMS

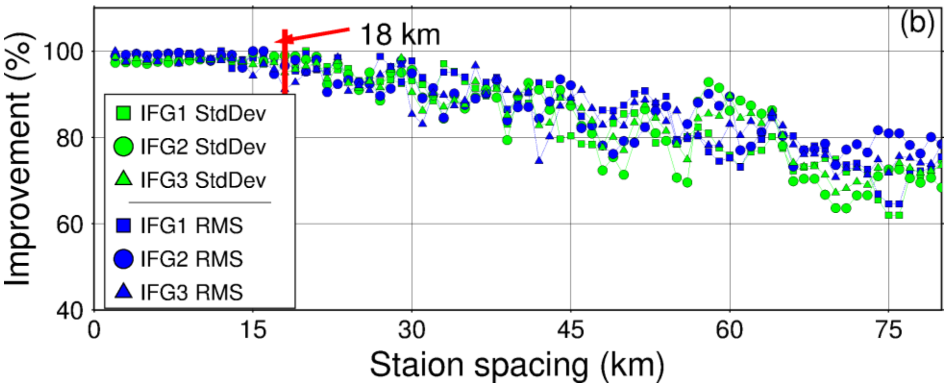
UK Network (> 50 km)
RMS = 9.7 mm



California Network (~ 10 km)
RMS = 6.2 mm



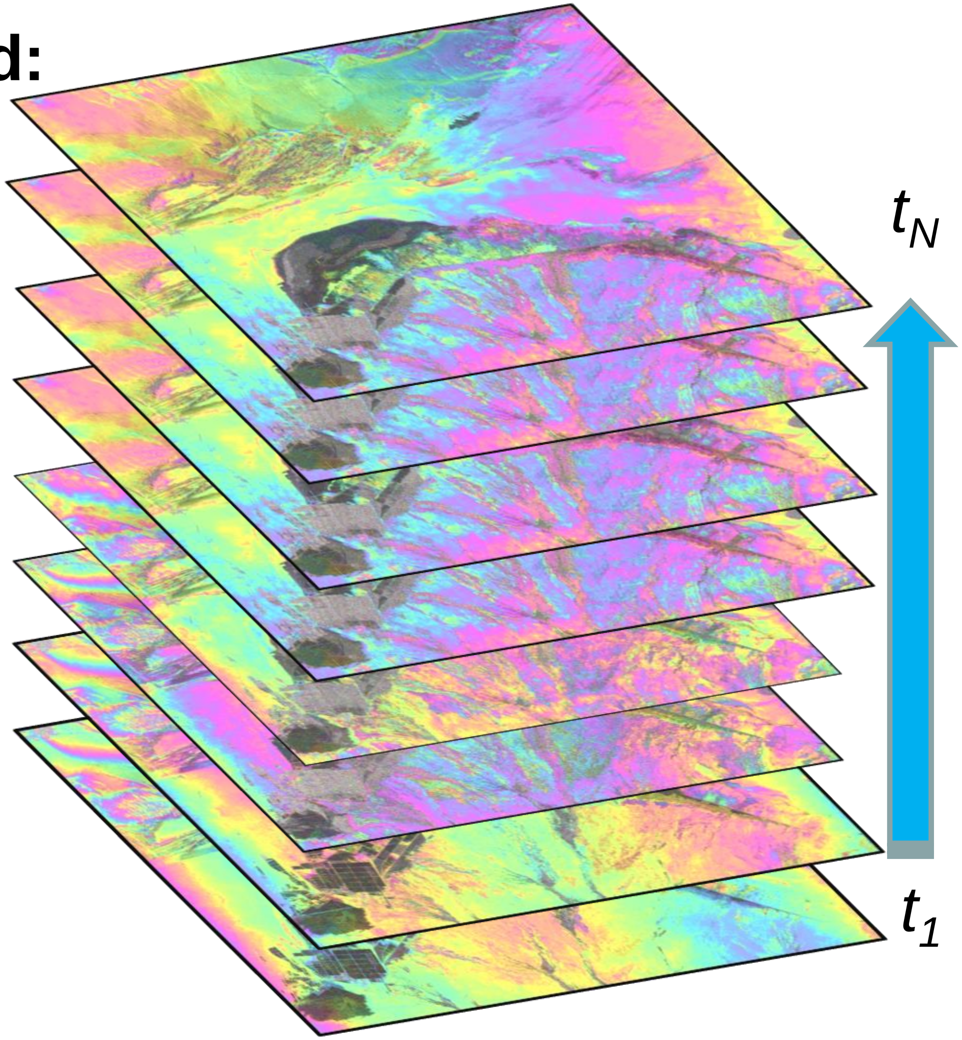




- Model performance decreases whilst Cross RMS increases.

InSAR Time Series Analysis

- **Parameters to be estimated:**
- ✓ Displacement time series
- ✓ Mean velocity
- ✓ DEM error
- ✓ *Orbital ramps + Atmospheric effects (Atmospheric Phase Screen, APS)*



InSAR Time Series Analysis

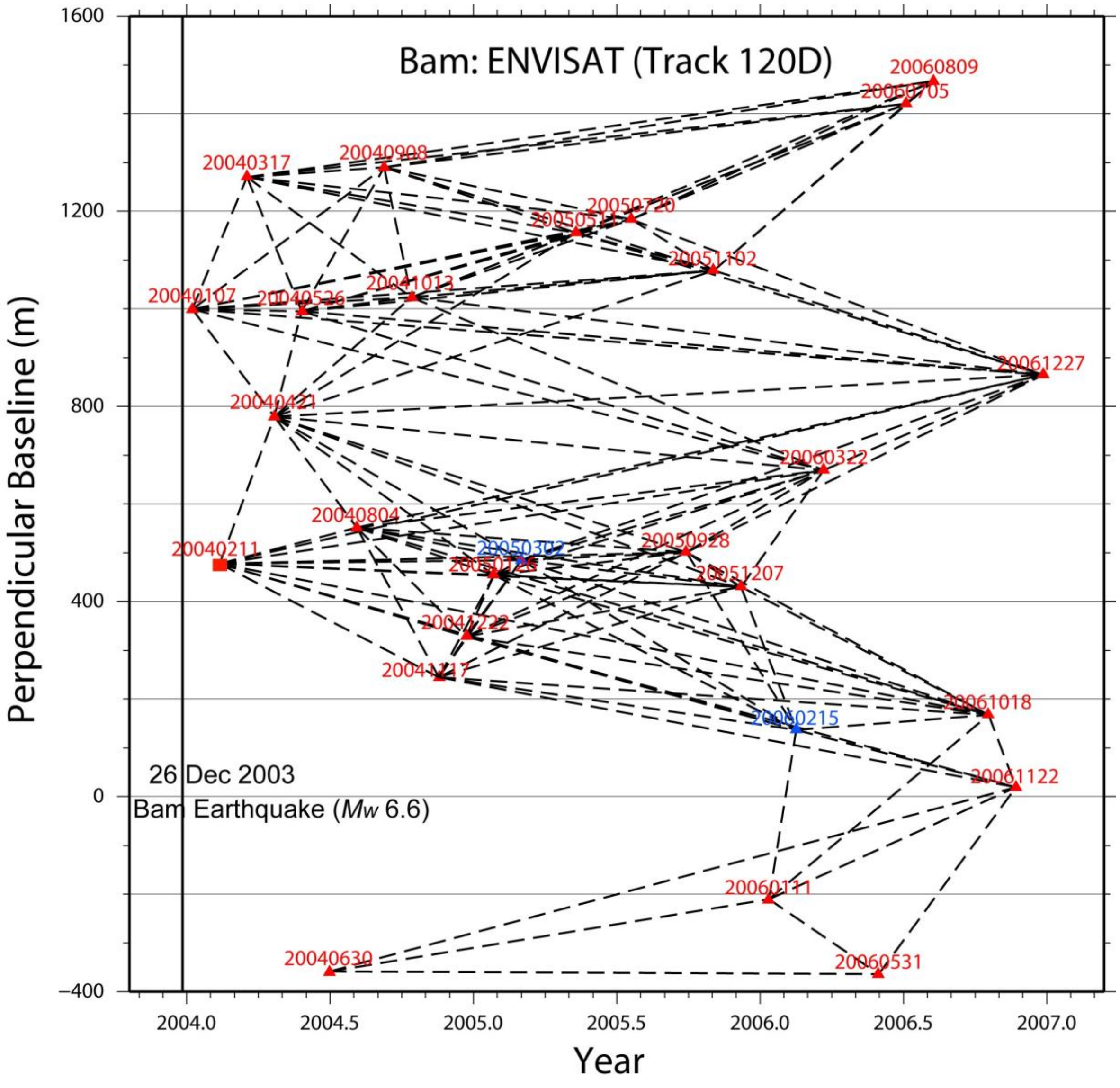
- **Fundamental assumptions:**

- Deformation signals are correlated in time and in space (√)
- APS signals are correlated in space, but **NOT in time** (**?**)

- **Our solution:**

- Apply GACOS correction for every interferogram
- Identify the dates with poor GACOS correction according to GACOS performance indicators
- Estimate APS for those dates using a sub-network approach (Li et al., 2009, IEEE TGRS)
- Perform standard time series inversion…

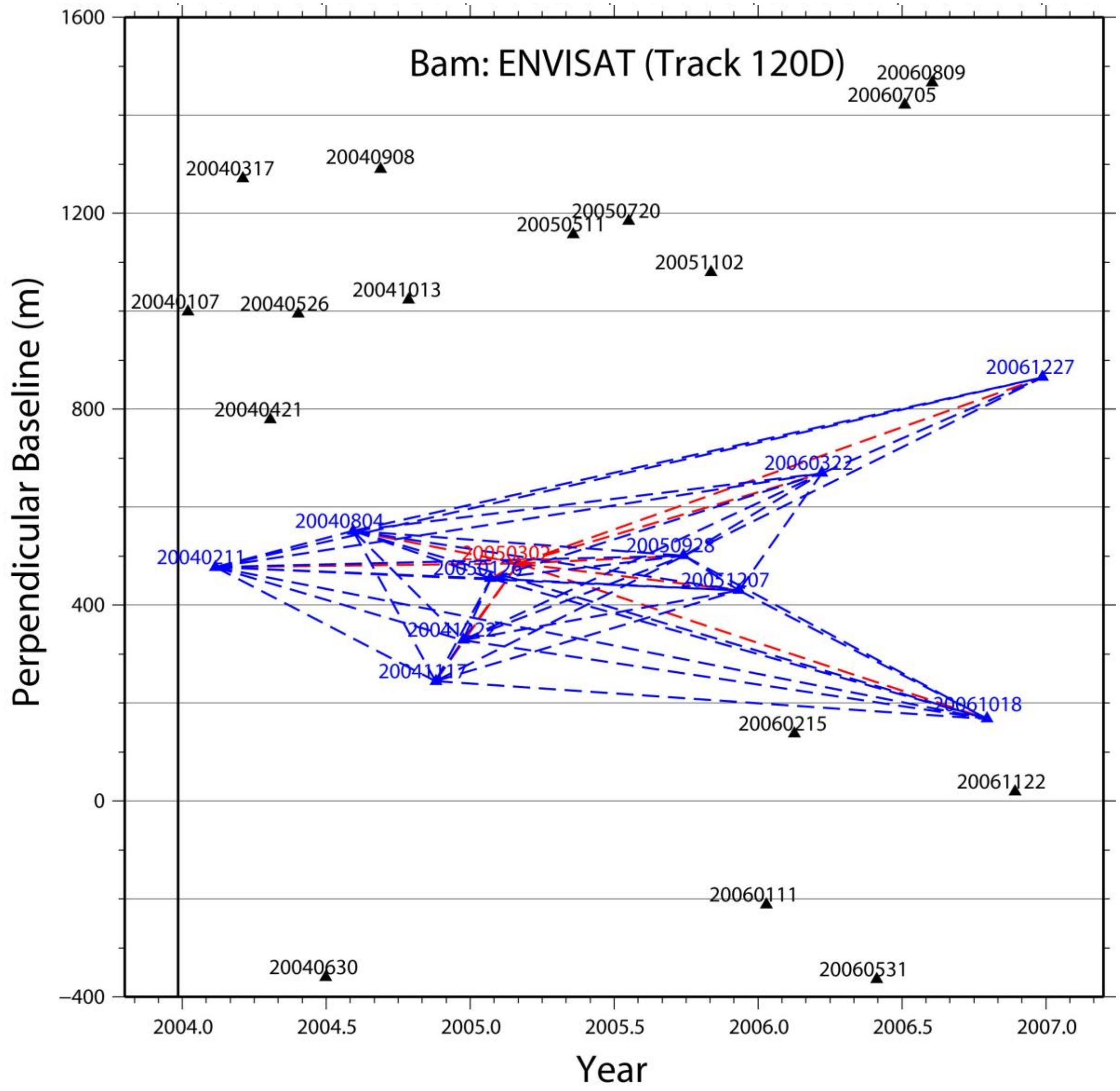
Sub-network for APS Estimation: Envisat over Bam



- Descending track 120
- 27 images: (2004.01–2006.12)
- 25 dates: APS OK
- 2 dates: APS to be estimated
- 130 interferograms
- Small Perp baseline: < 400 m
- Network inversion:
- 109 cloud-free pairs

(Li et al., 2009)

Sub-network for APS Estimation: Envisat over Bam



Date: 050503

Perp baseline:

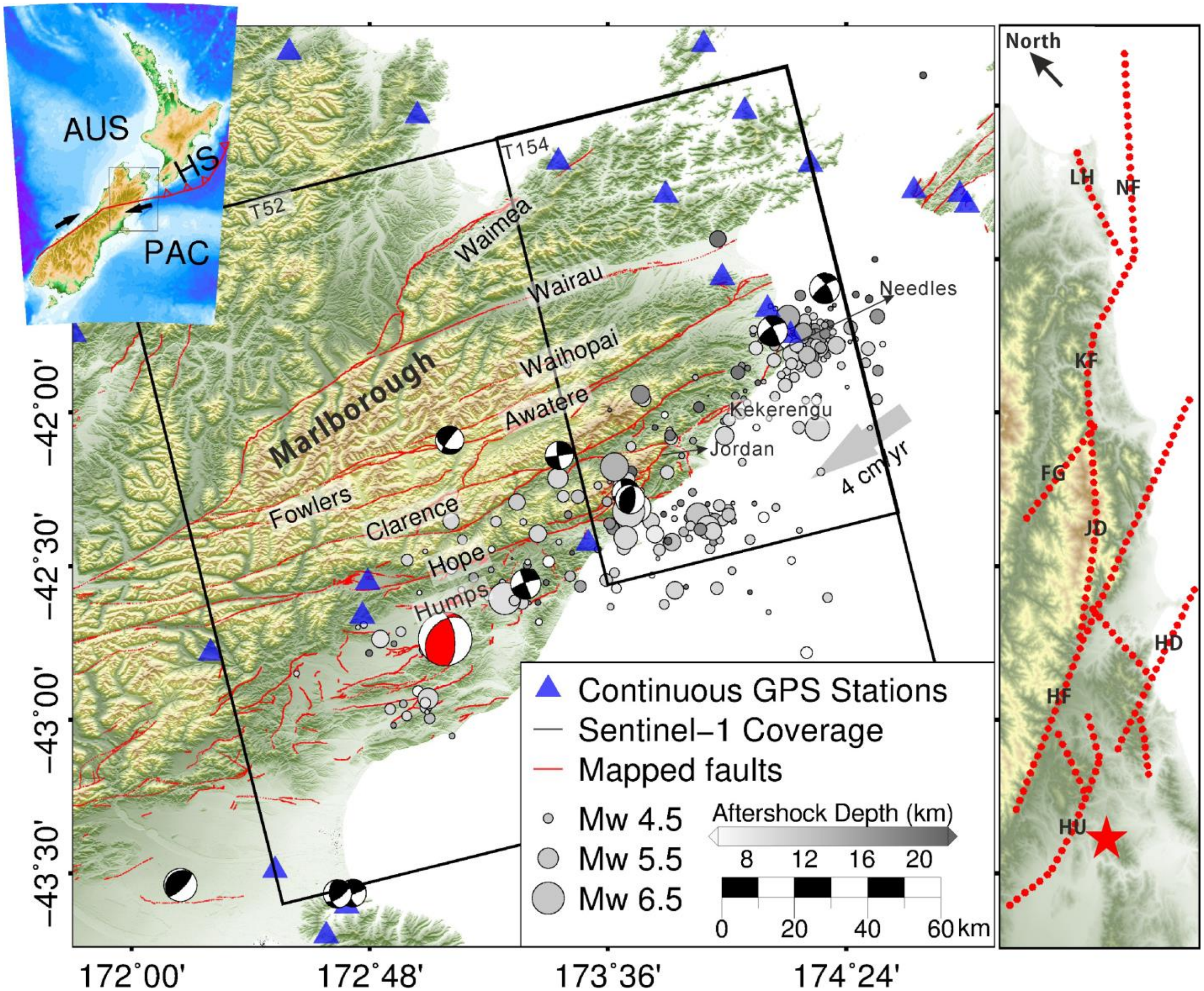
< 400 m

Red: 10 Single-PWV-corrected Infms

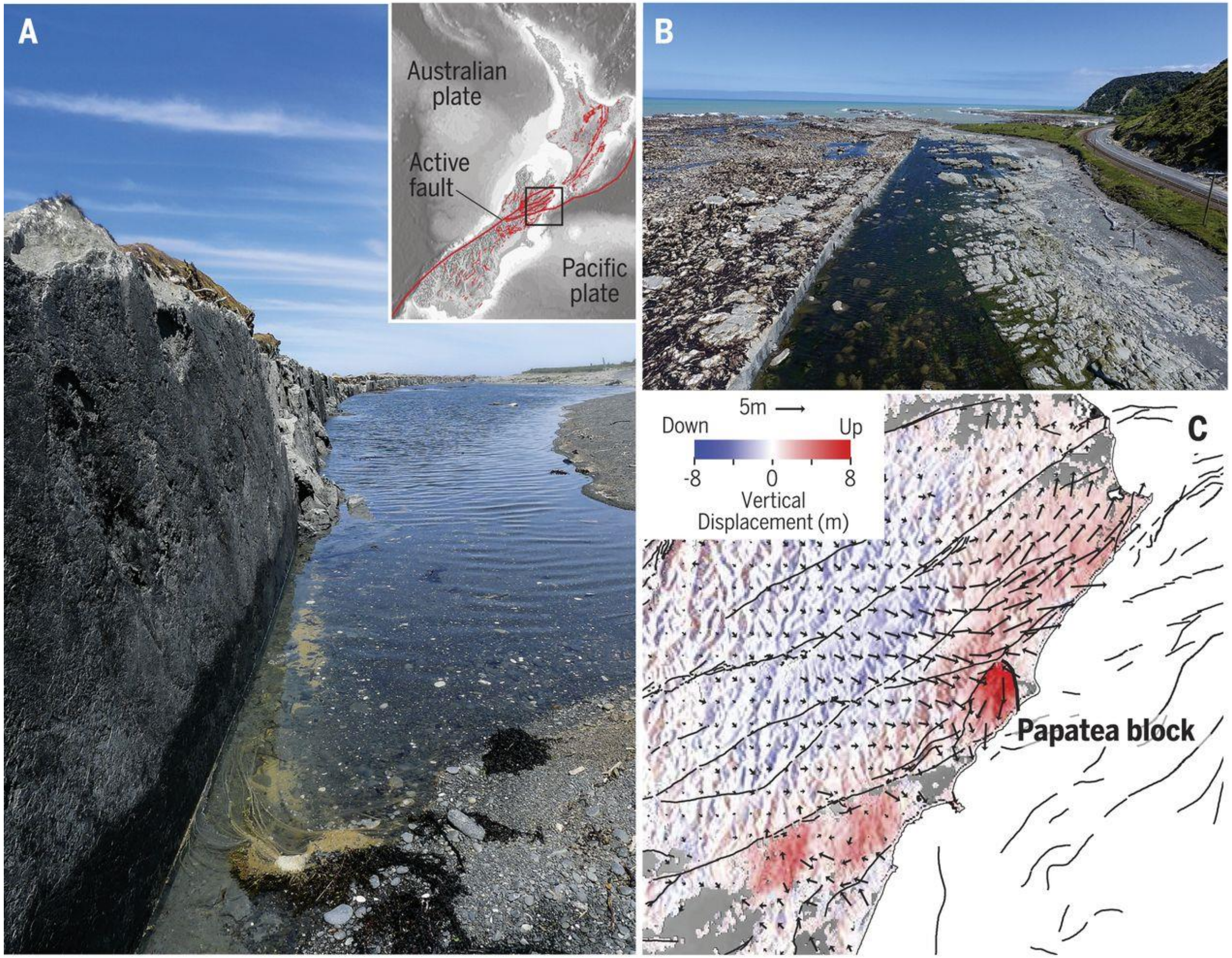
Blue: 38 ZPDDM-corrected Infms

(Li et al., 2009, IEEE TGRS)

Postseismic motion after the 2016 Kaikōura, New Zealand, earthquake

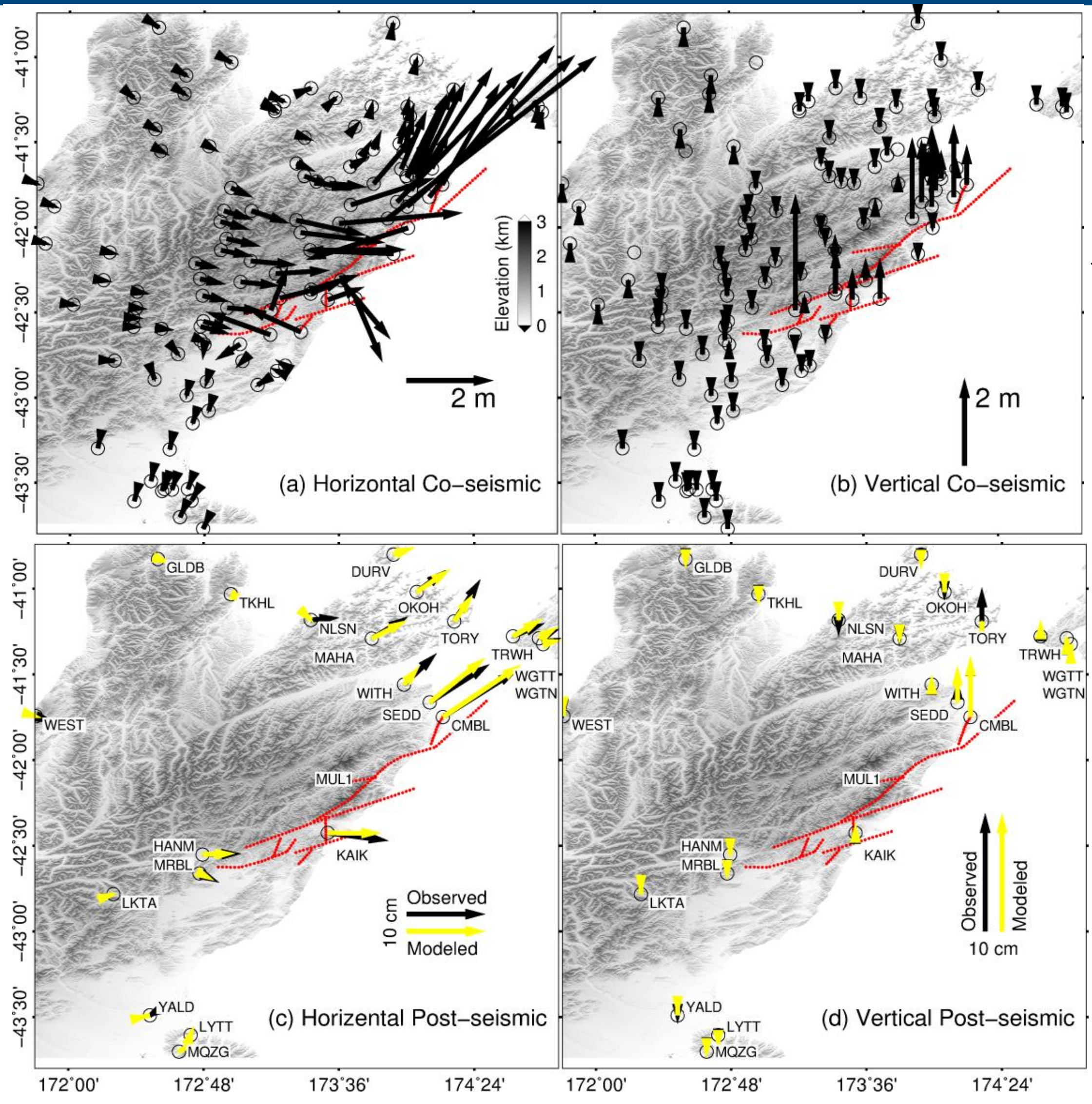


Co-seismic displacements



(Ian J. Hamling et al. Science 2017)

Co- & Post-seismic displacements From GPS

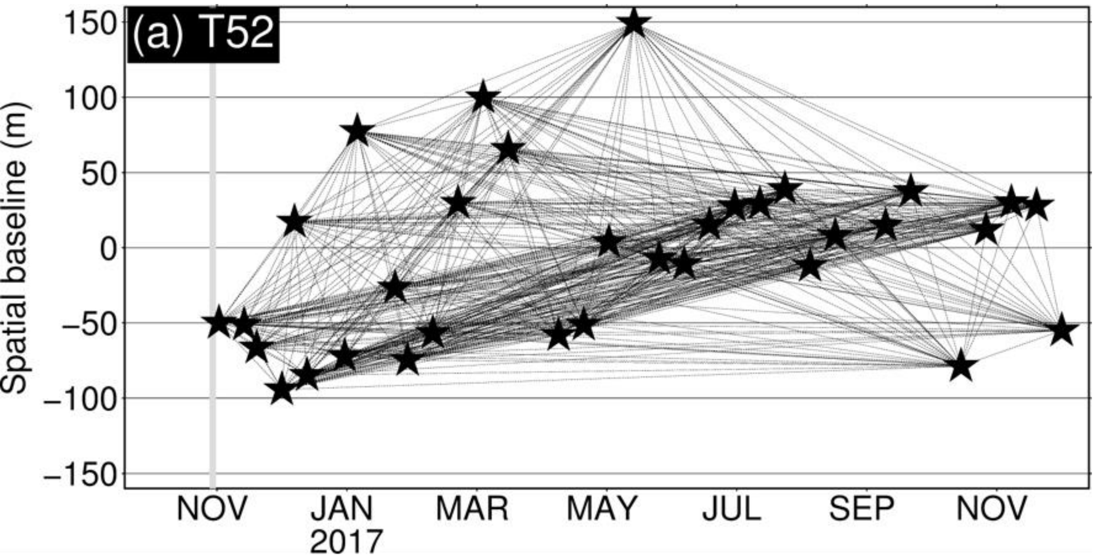


Co-seismic

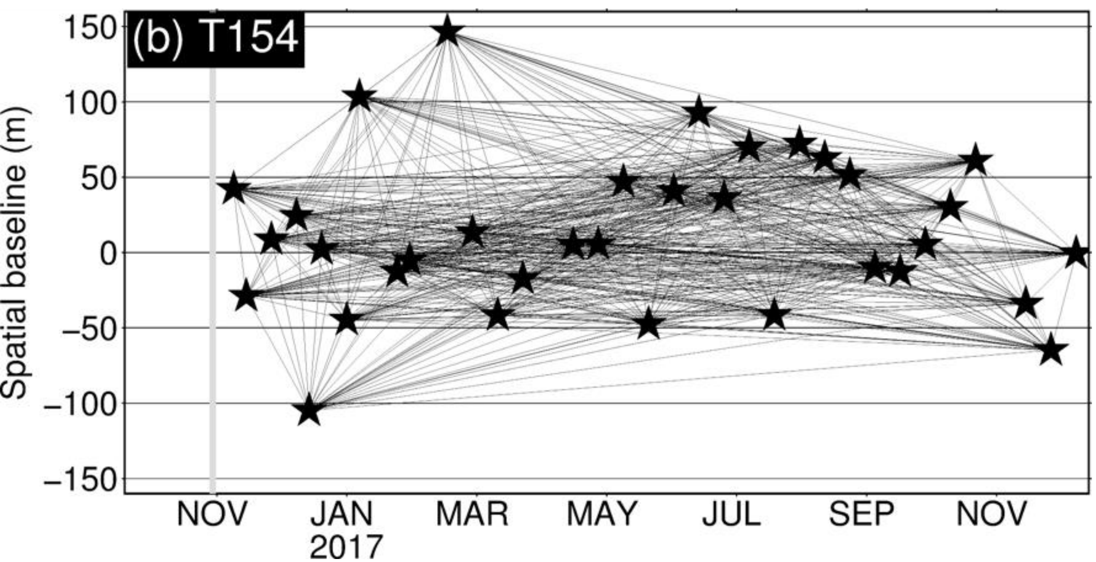
(Horiz. + Vert.)

Post-seismic

New Zealand Post-seismic time series

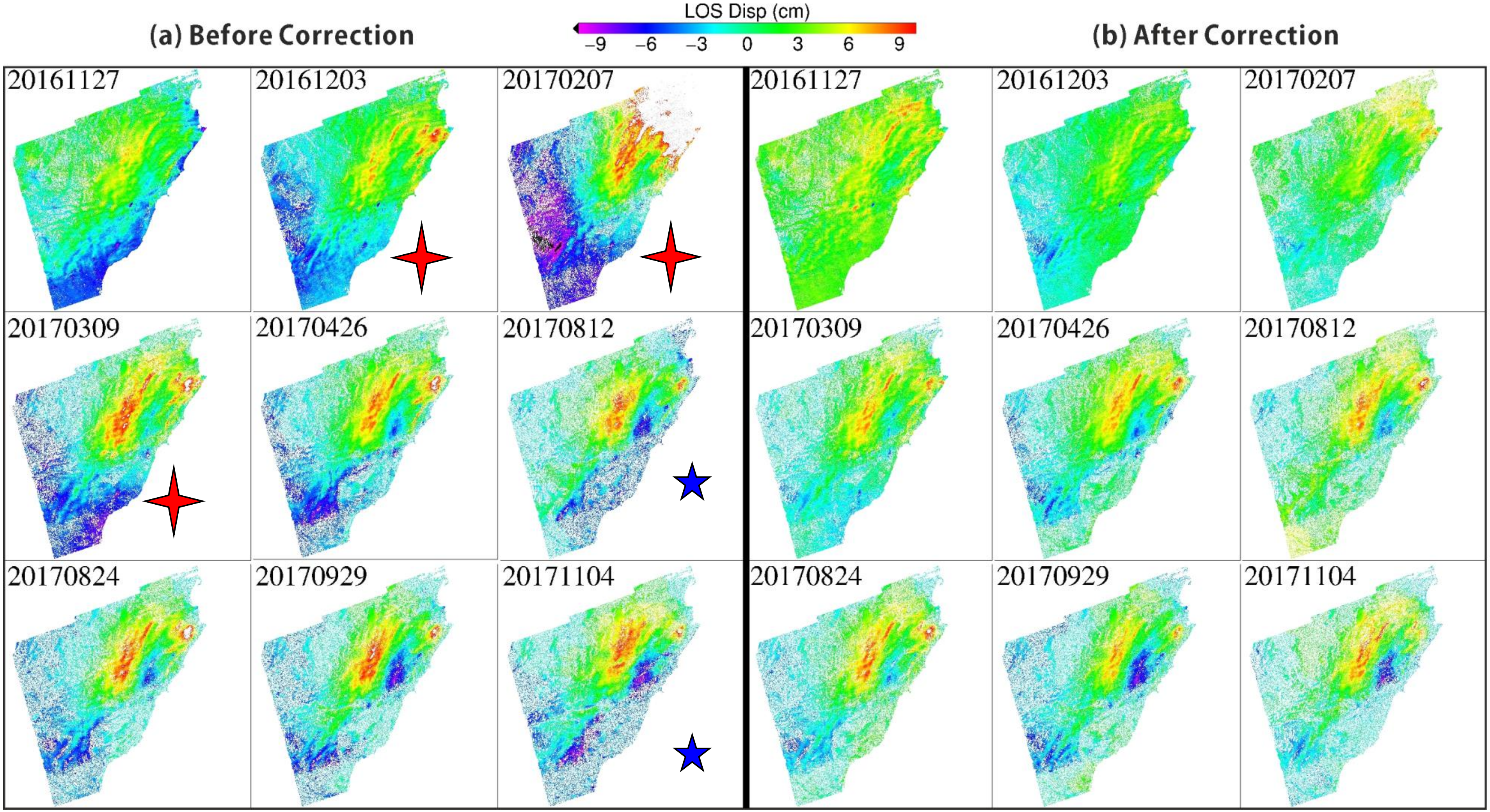


Ascending
33 images
(2016.11–2017.12)
550 interferograms
Small Perp baseline:<200m
200 km by 200 km

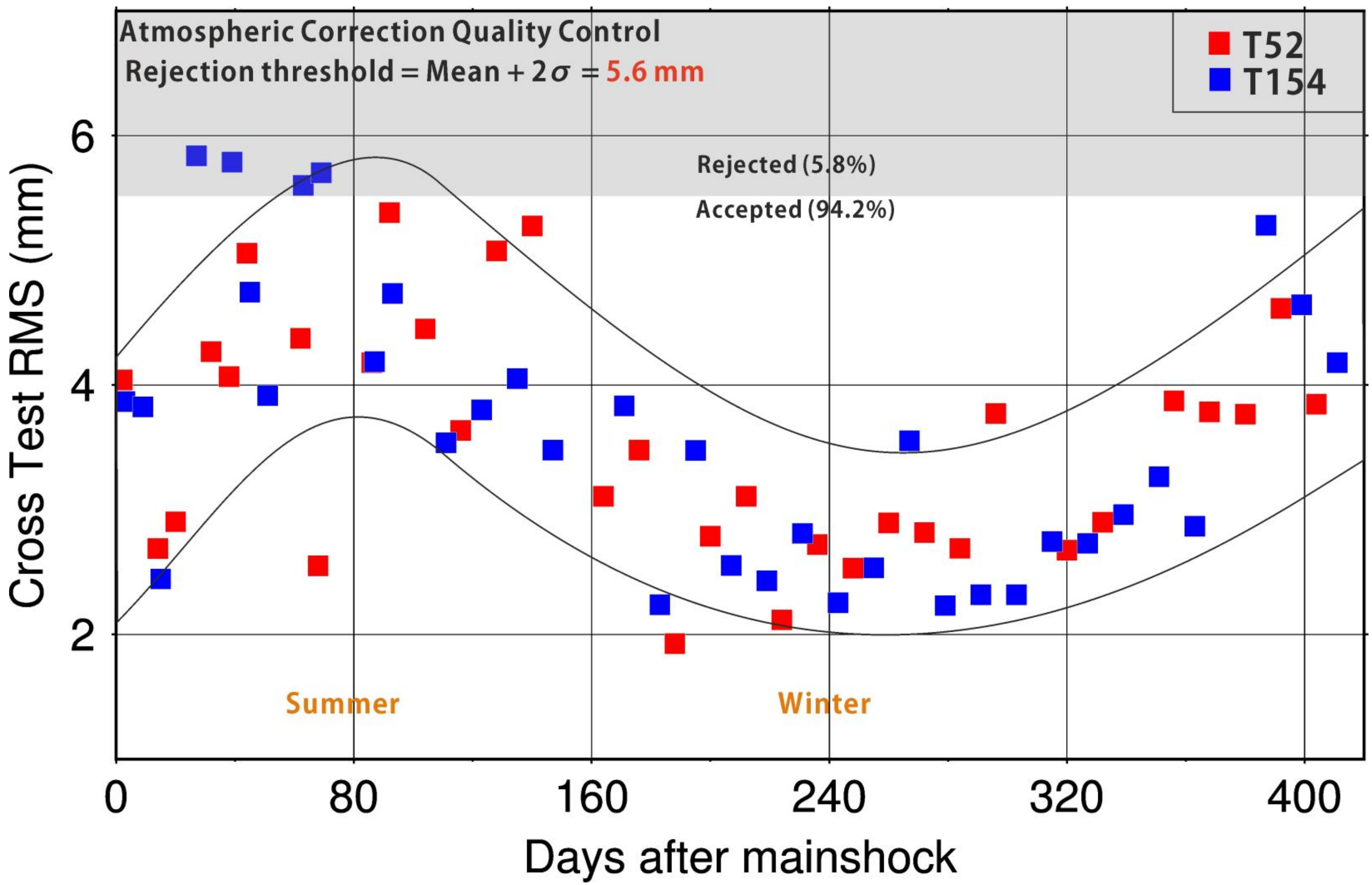


Ascending
35 images
(2016.11–2017.12)
559 interferograms
Small Perp baseline:<200m
150 km by 100 km

S-1 Inteferograms with or without GACOS correction

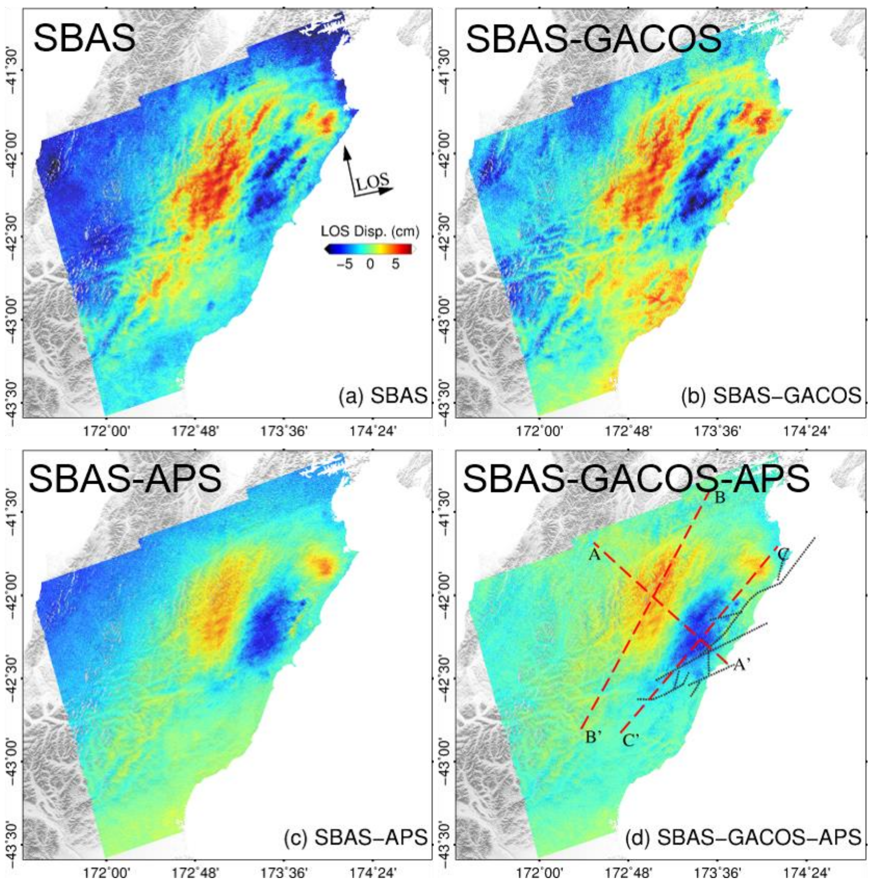


GACOS Performance Indicator(s)

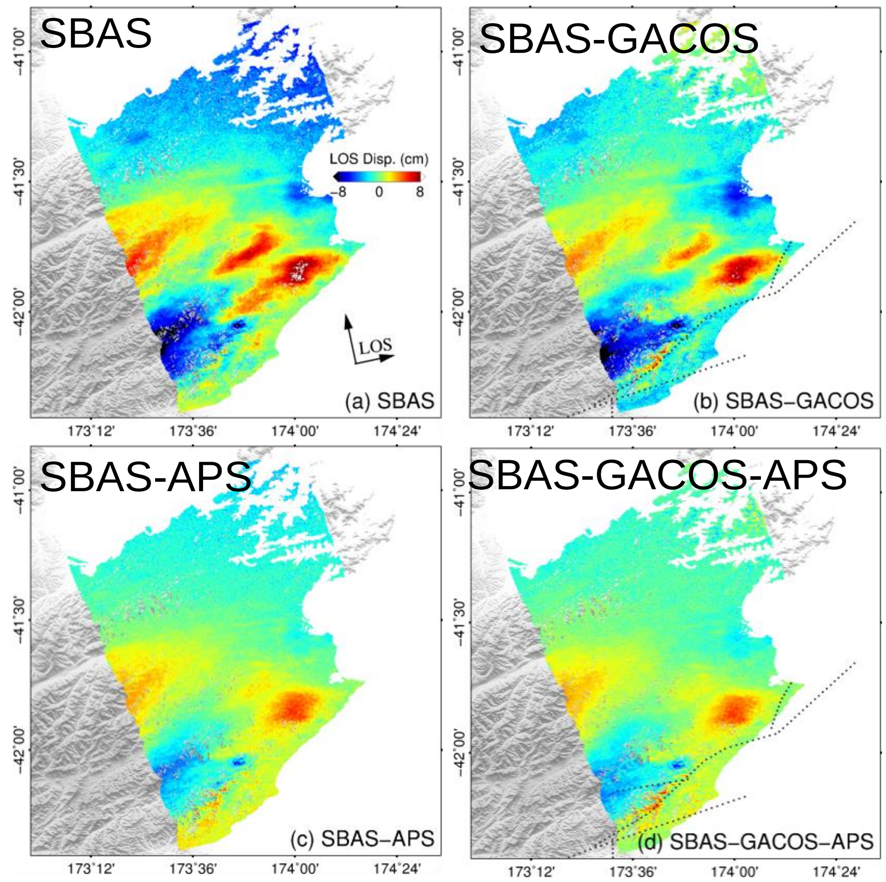


InSAR time series results

T52



T154



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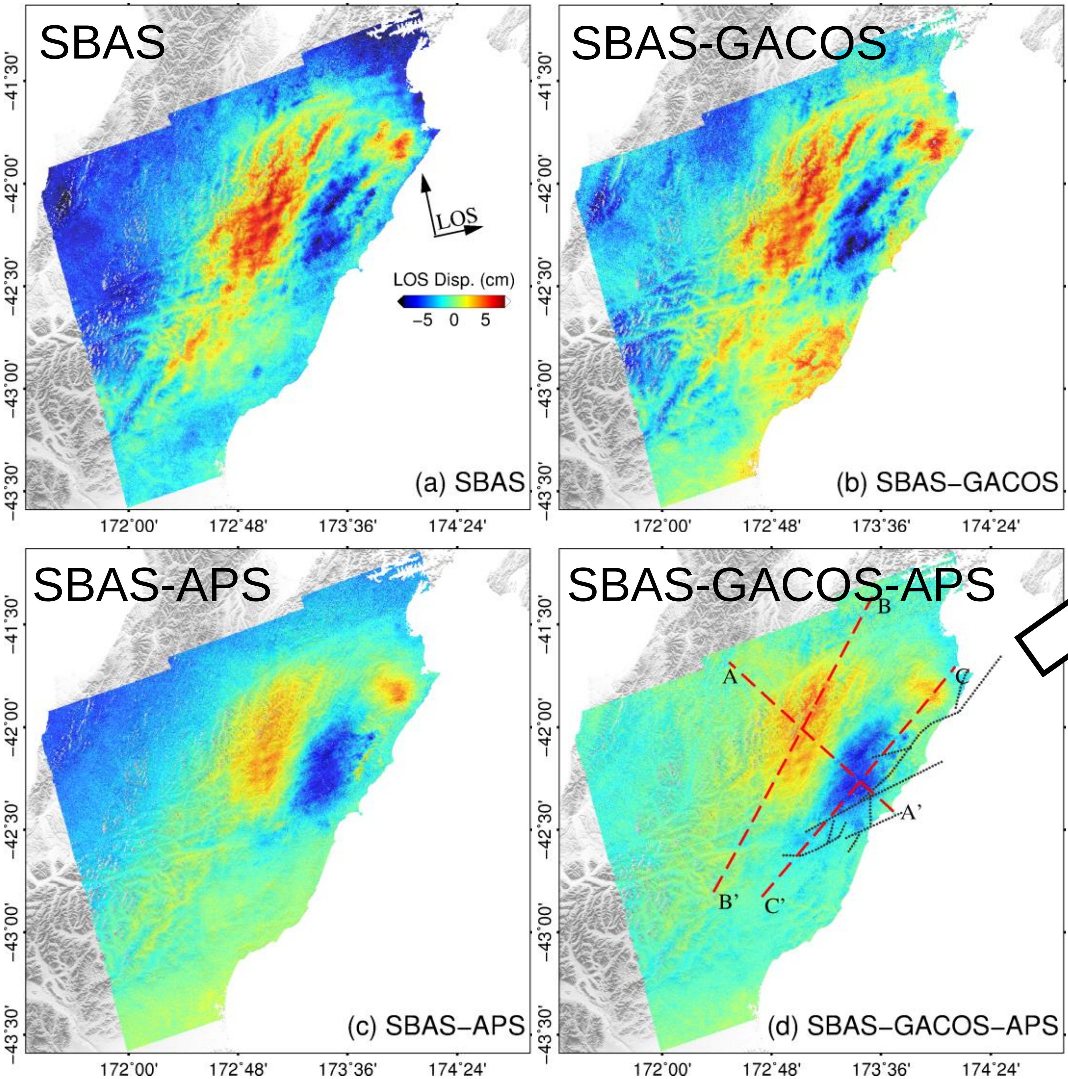
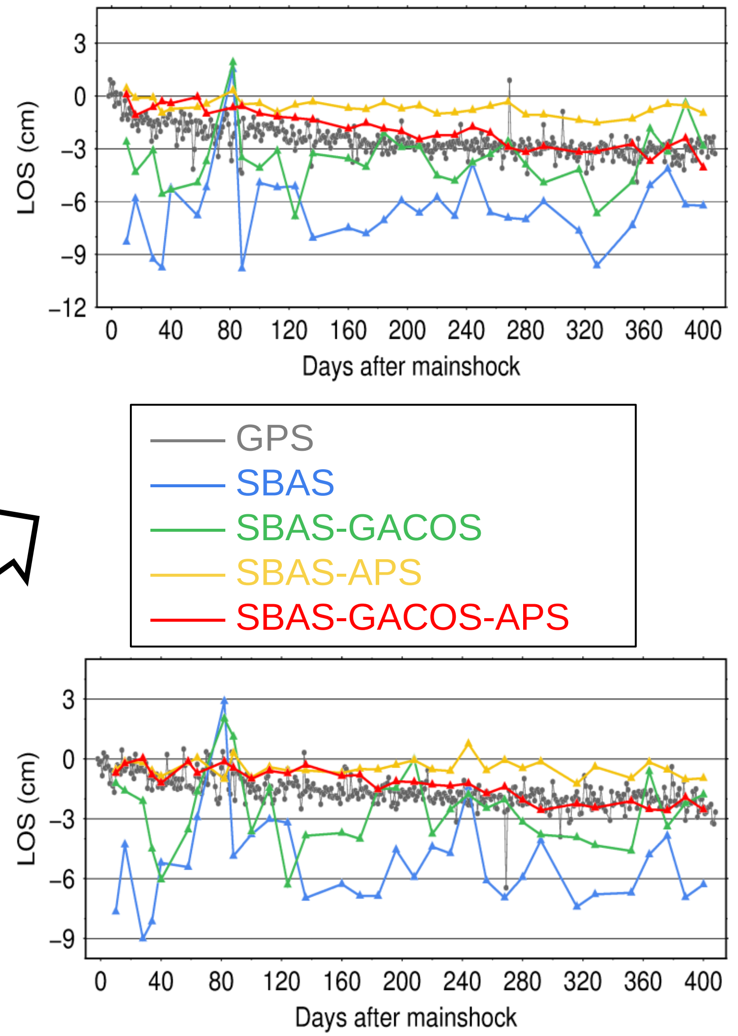
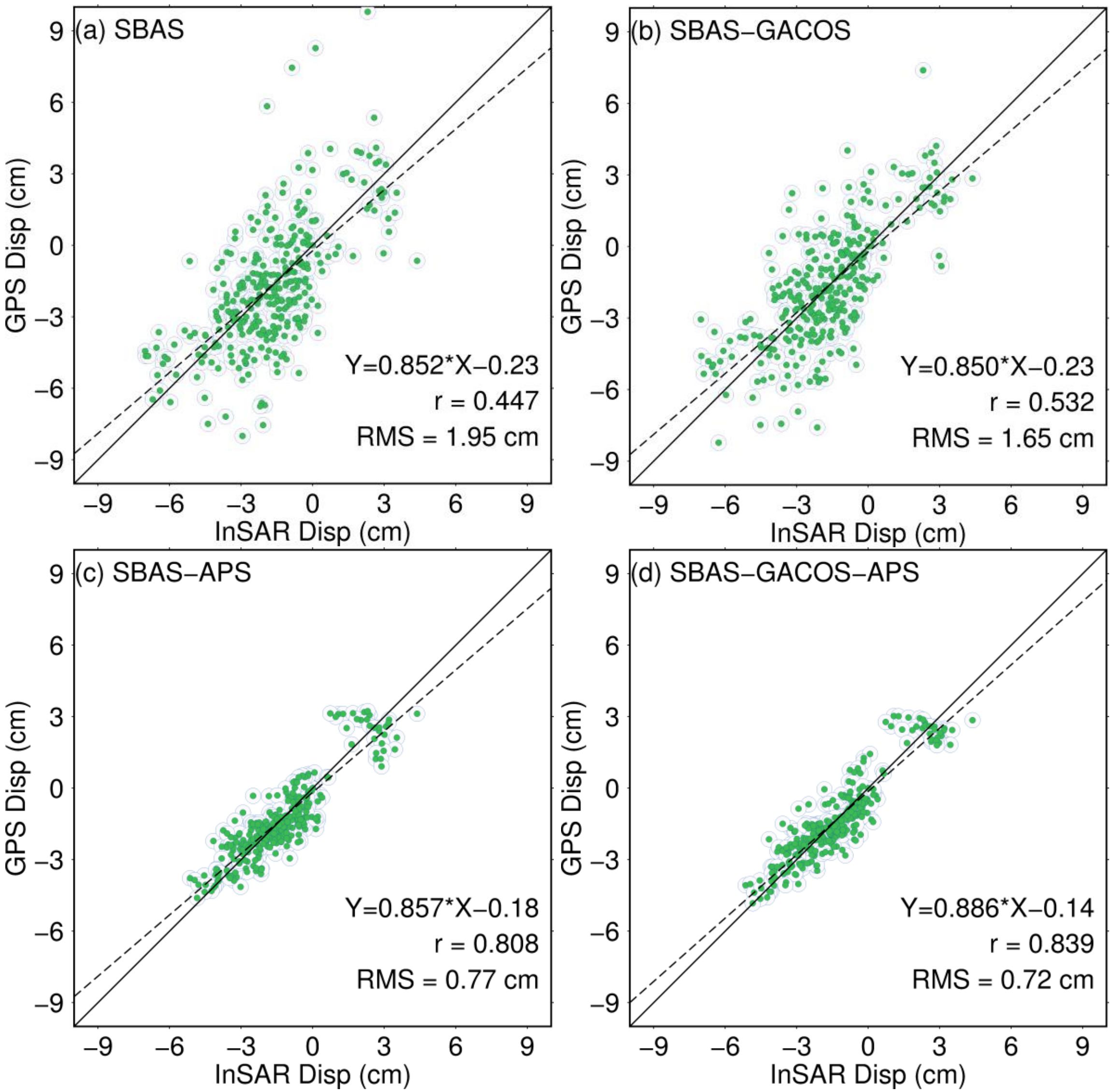
Cumulative Displacements





InSAR vs GPS displacements



RMS Difference

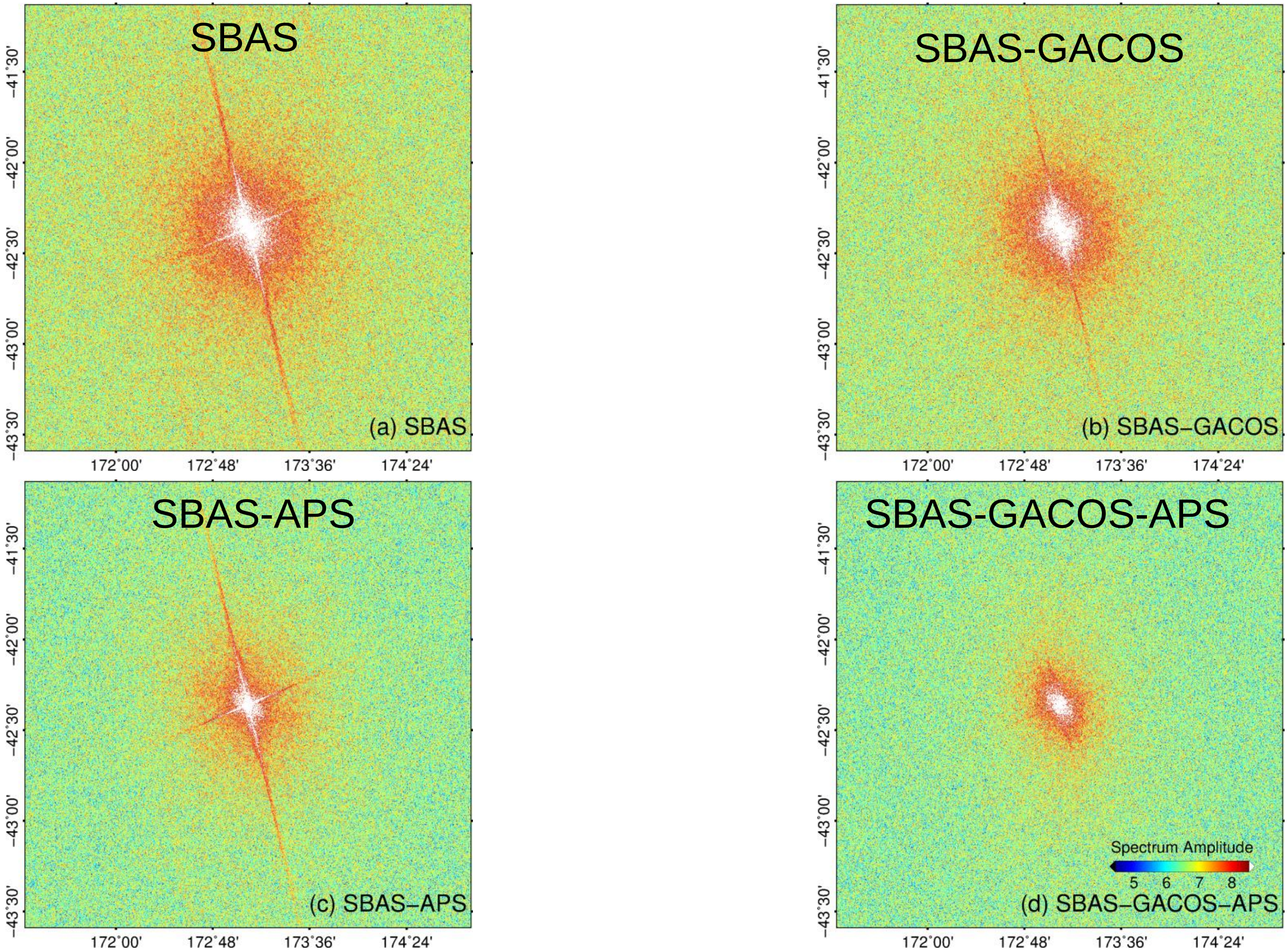
(a) 1.95 cm

(b) 1.65 cm

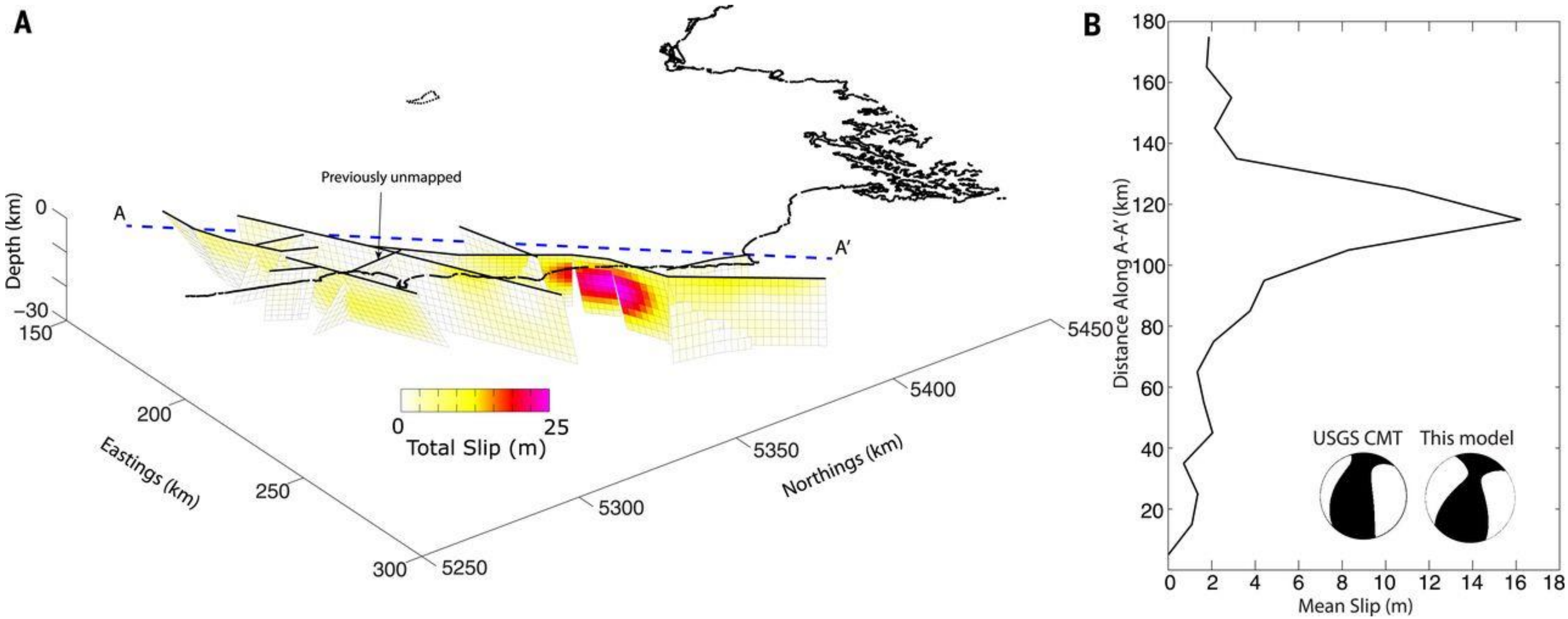
(c) 0.77 cm

(d) 0.72 cm

2D spectral analysis

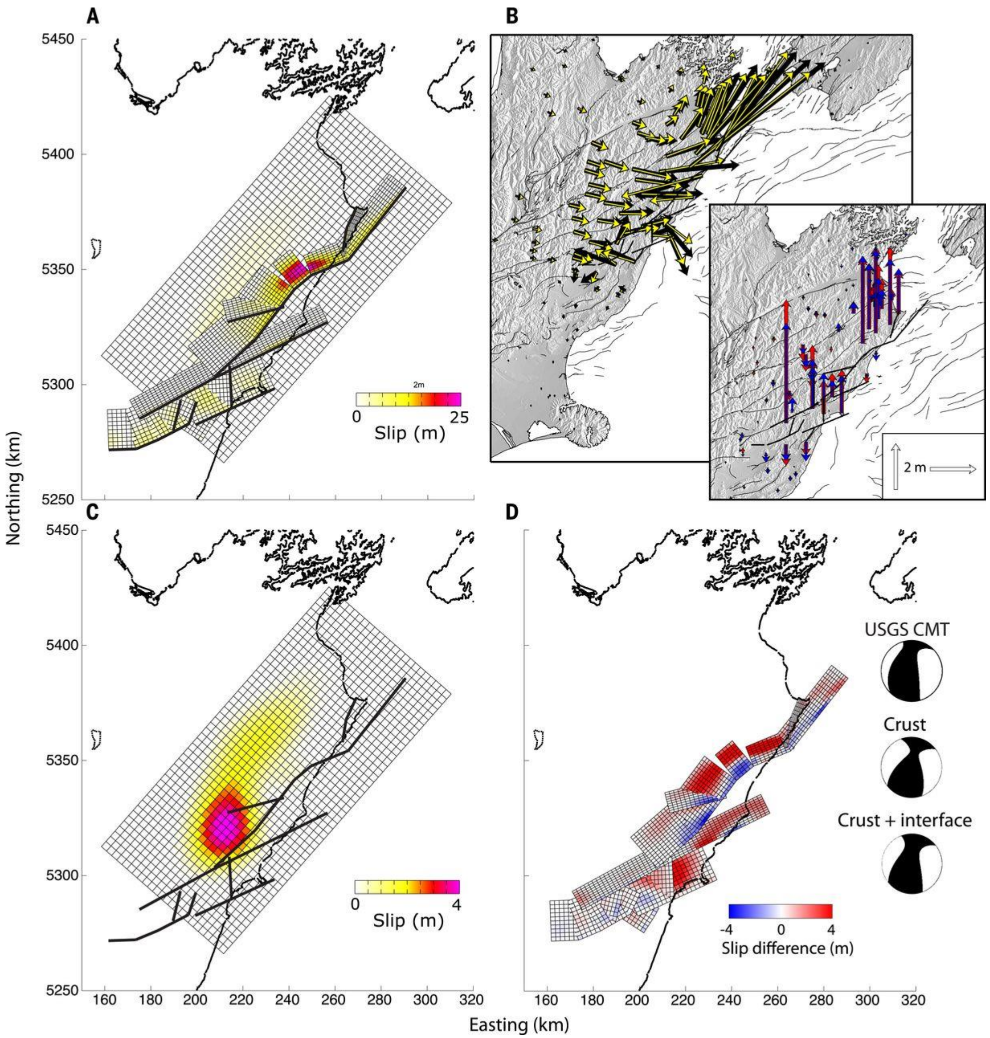


Model 1: Best-fitting crustal fault model



(Ian J. Hamling et al. Science 2017)

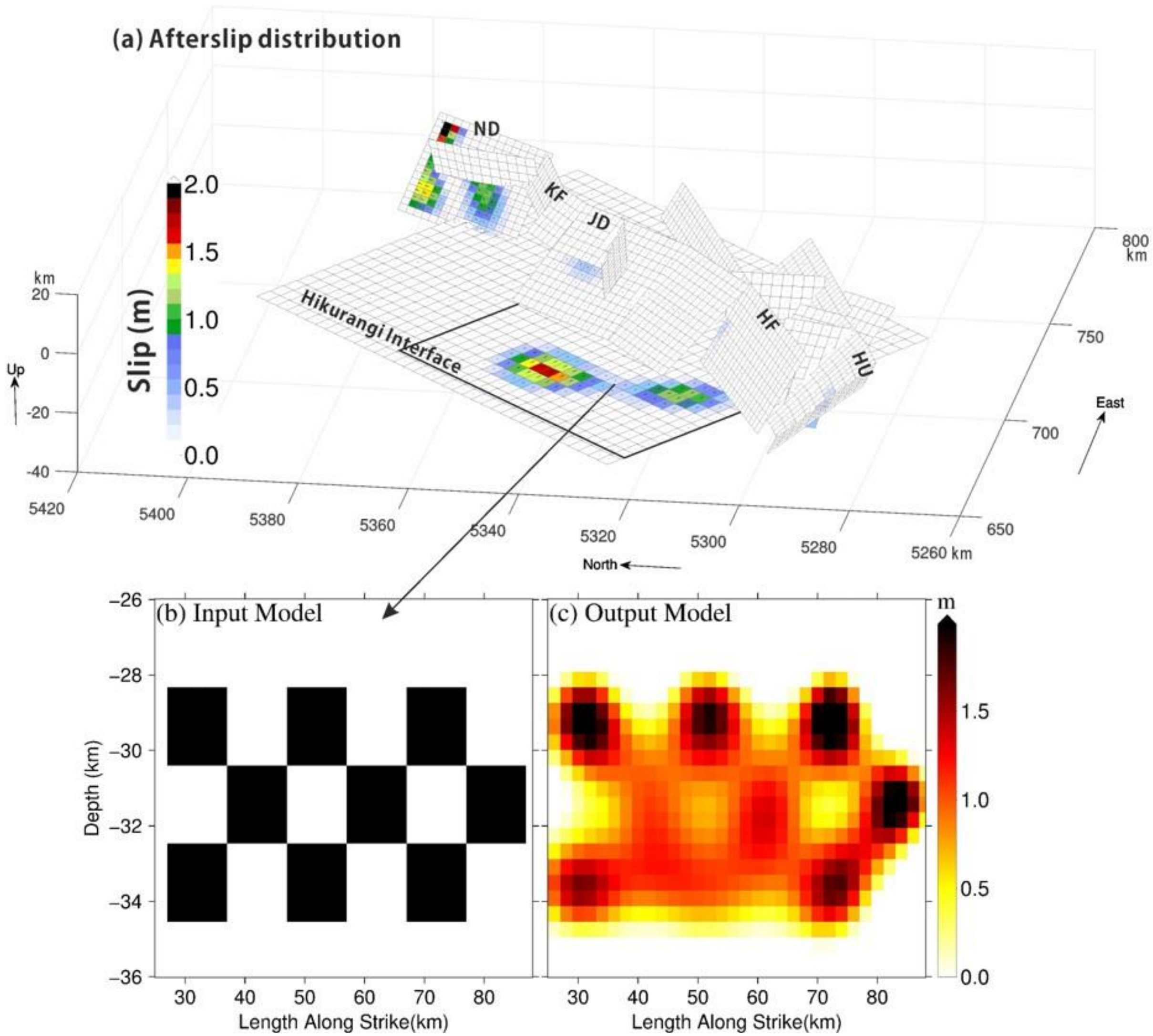
Model 2: Best-fitting slip model including an interface source



NB. Given the proximity of the event and the location of the southern end of the Hikurangi subduction zone, an interface was introduced in Model 2

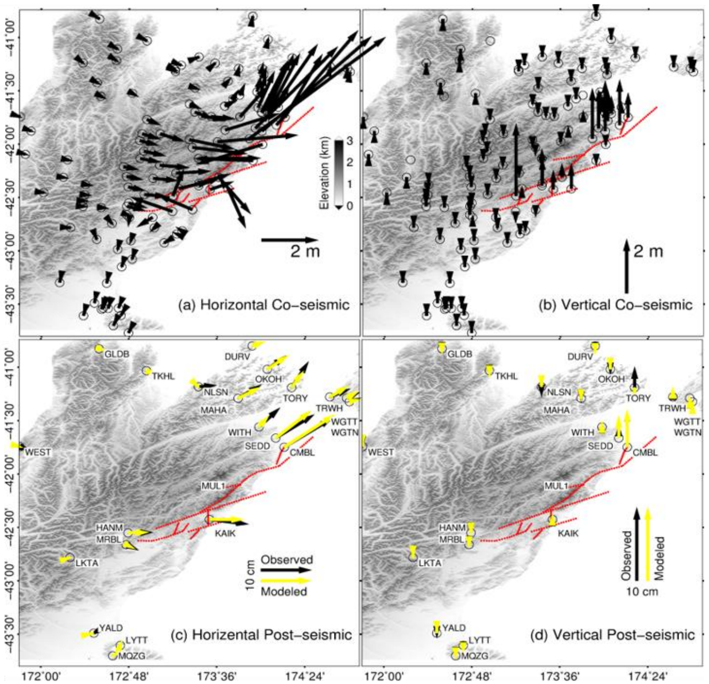
(Ian J. Hamling et al. Science 2017)

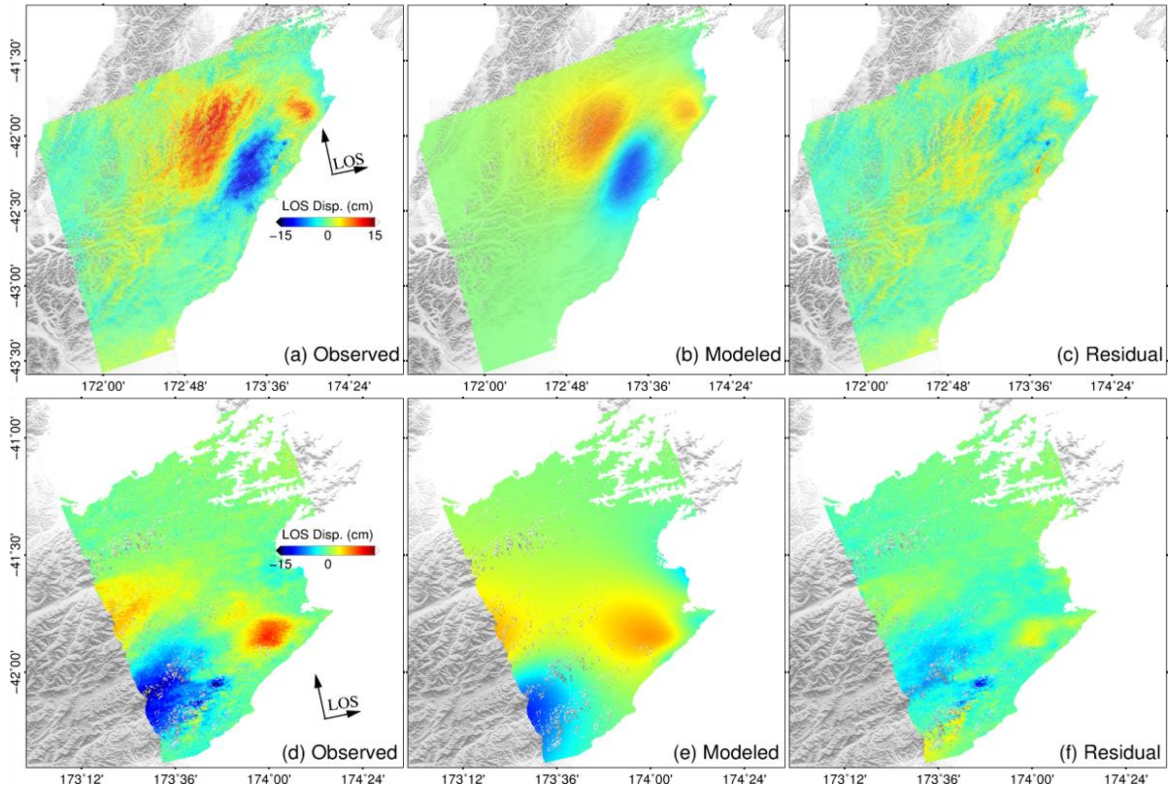
Best-fitting afterslip model



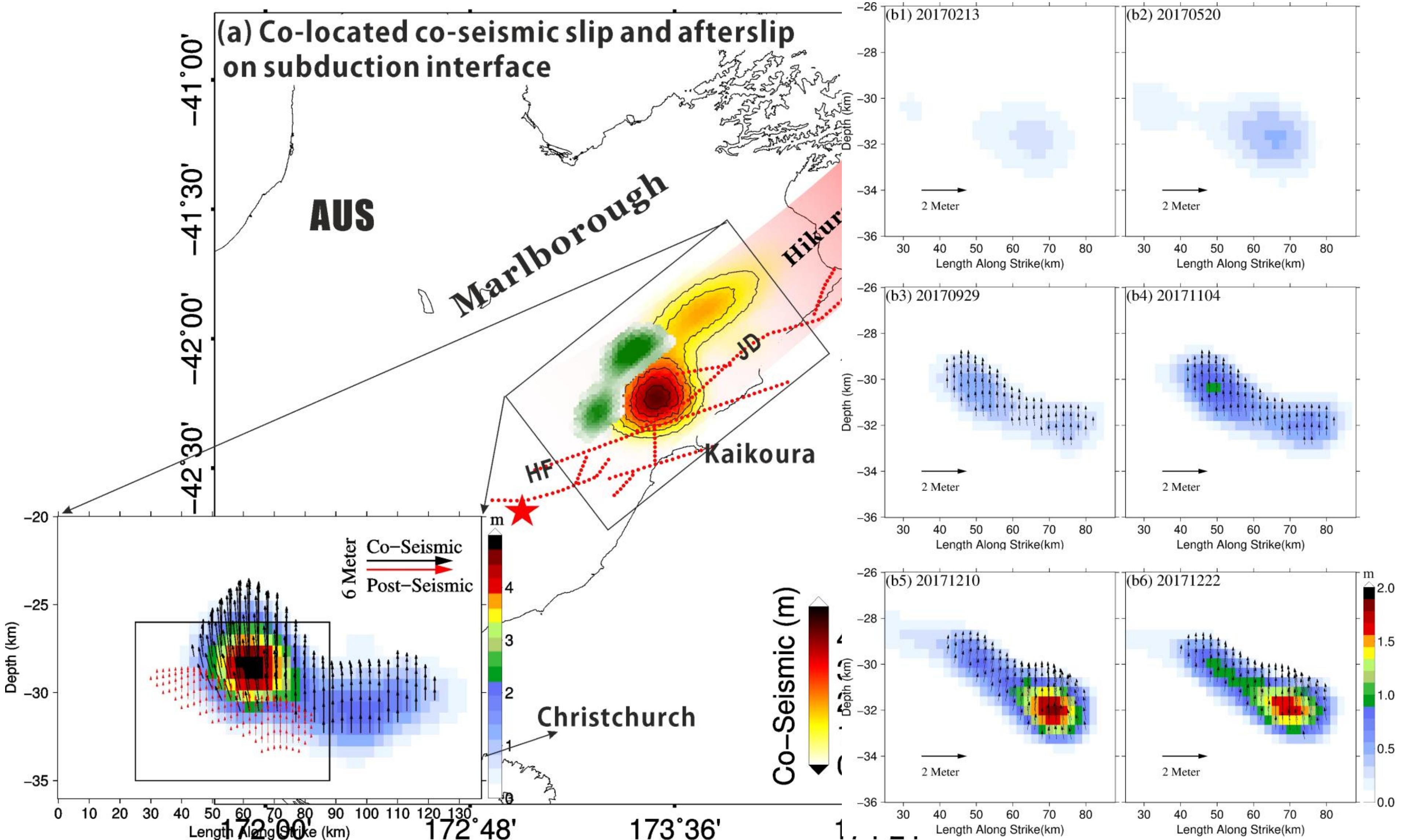
Best-fitting afterslip model

Observed **Modeled** **Residual**





Afterslip time series



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Conclusions

- GACOS is freely available for the InSAR research community (http://ceg-research.ncl.ac.uk/v2/gacos/ Version 2 will be released in Oct 2018.

- The assumption on APS being uncorrelated in time does not hold.

- GACOS-assisted InSAR TS is demonstrated, and outperform other TS techniques.

- Our preliminary afterslip model suggests that the 2nd co-seismic model including an interface source is preferred, i.e. ***the subduction slab moved during the co-seismic period and continues to move afterwards***