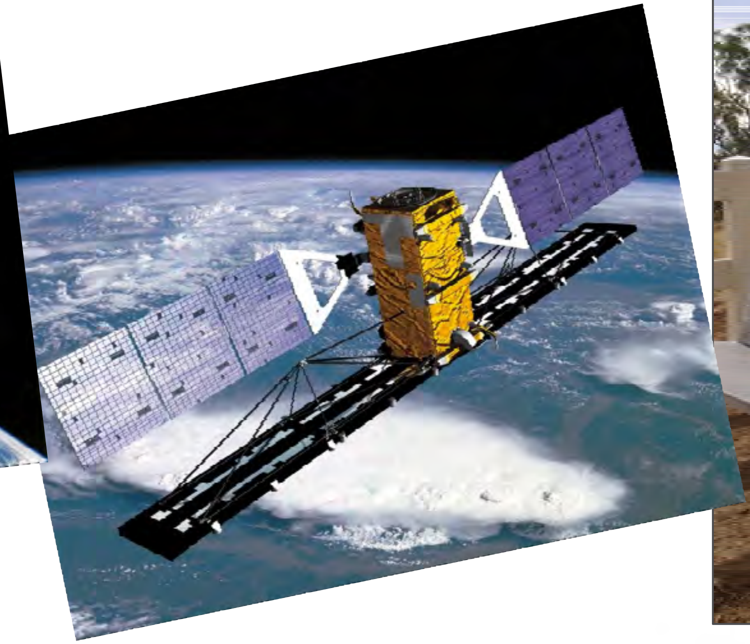
Australian Government
Geoscience Australia

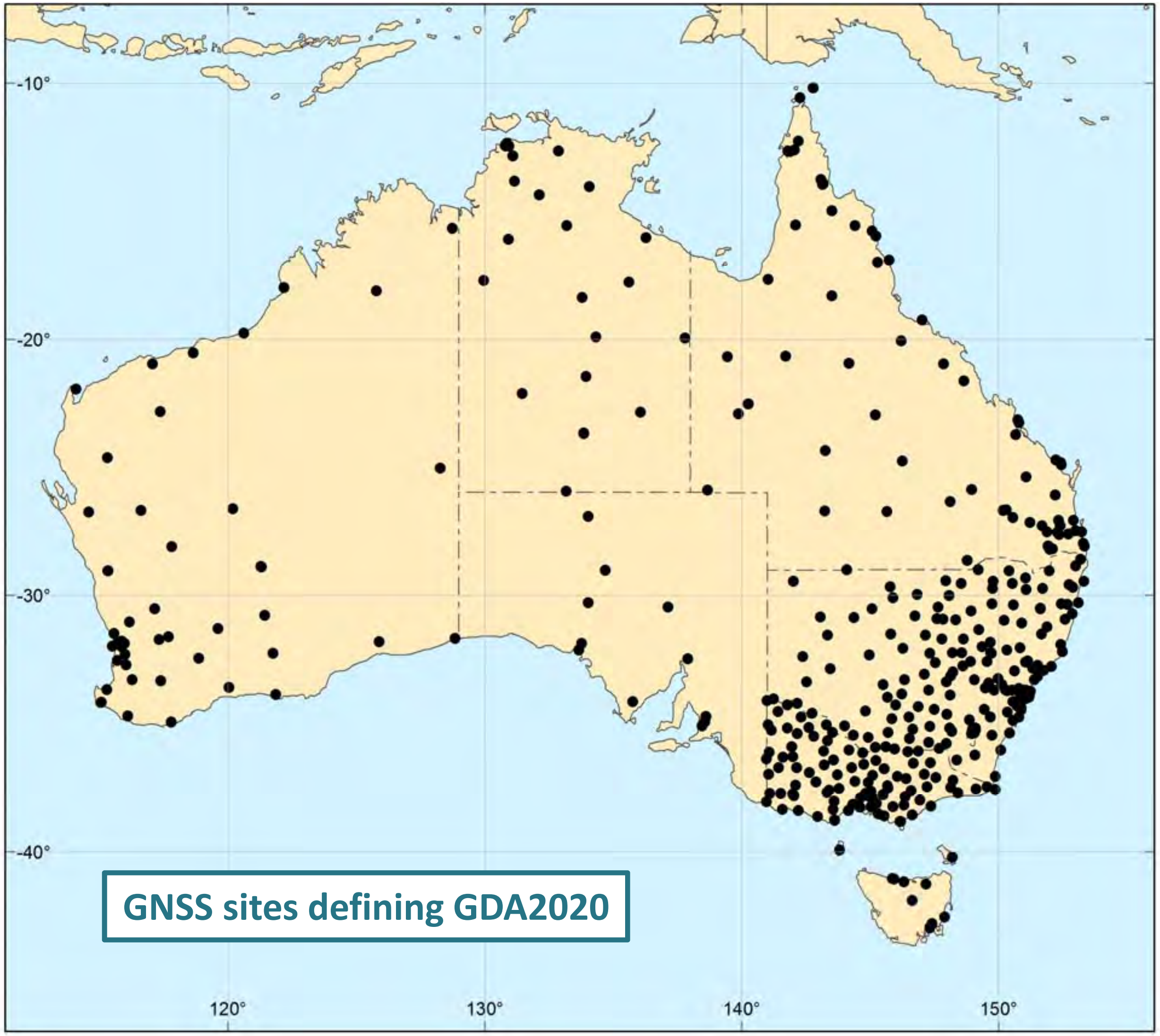
Combination of GNSS and InSAR for Future Australian Datums

Interferometric Synthetic Aperture Radar

Thomas Fuhrmann, Matt Garthwaite, Sarah Lawrie, Nick Brown



Motivation



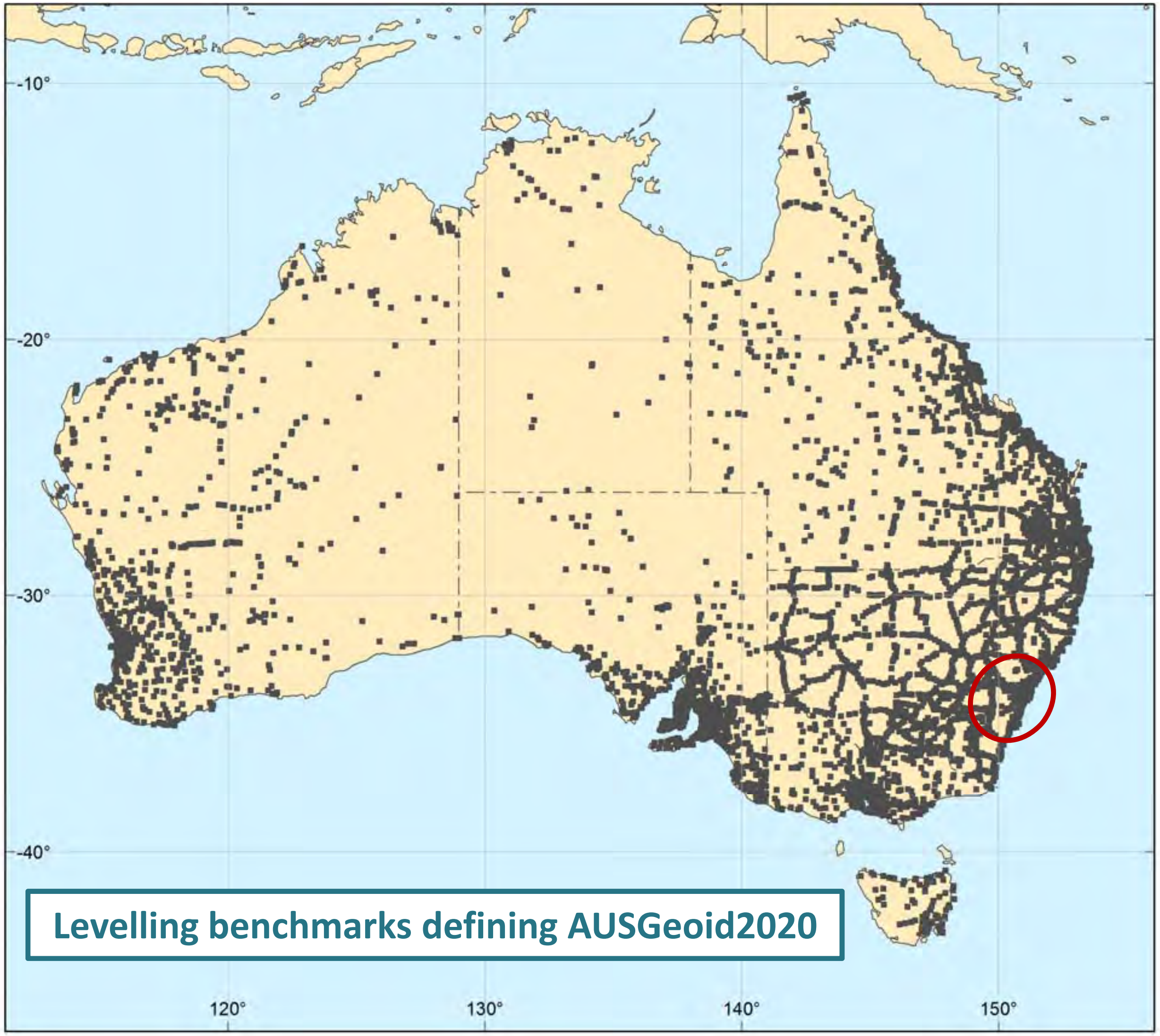
Current situation

- Static Datum: fixed coordinates
- Plate Motion model accounting for general movement trend of the entire Australian Plate (~7cm/yr)

Future realisations

- Dynamic Datum: coordinate + velocity for each site or benchmark

Motivation



Current situation

- Static Vertical Datum: fixed height values

Local Deformation?

Movements of several cm/yr may occur in some areas, e.g. related to mining or groundwater changes

Motivation

Why consider local deformation?

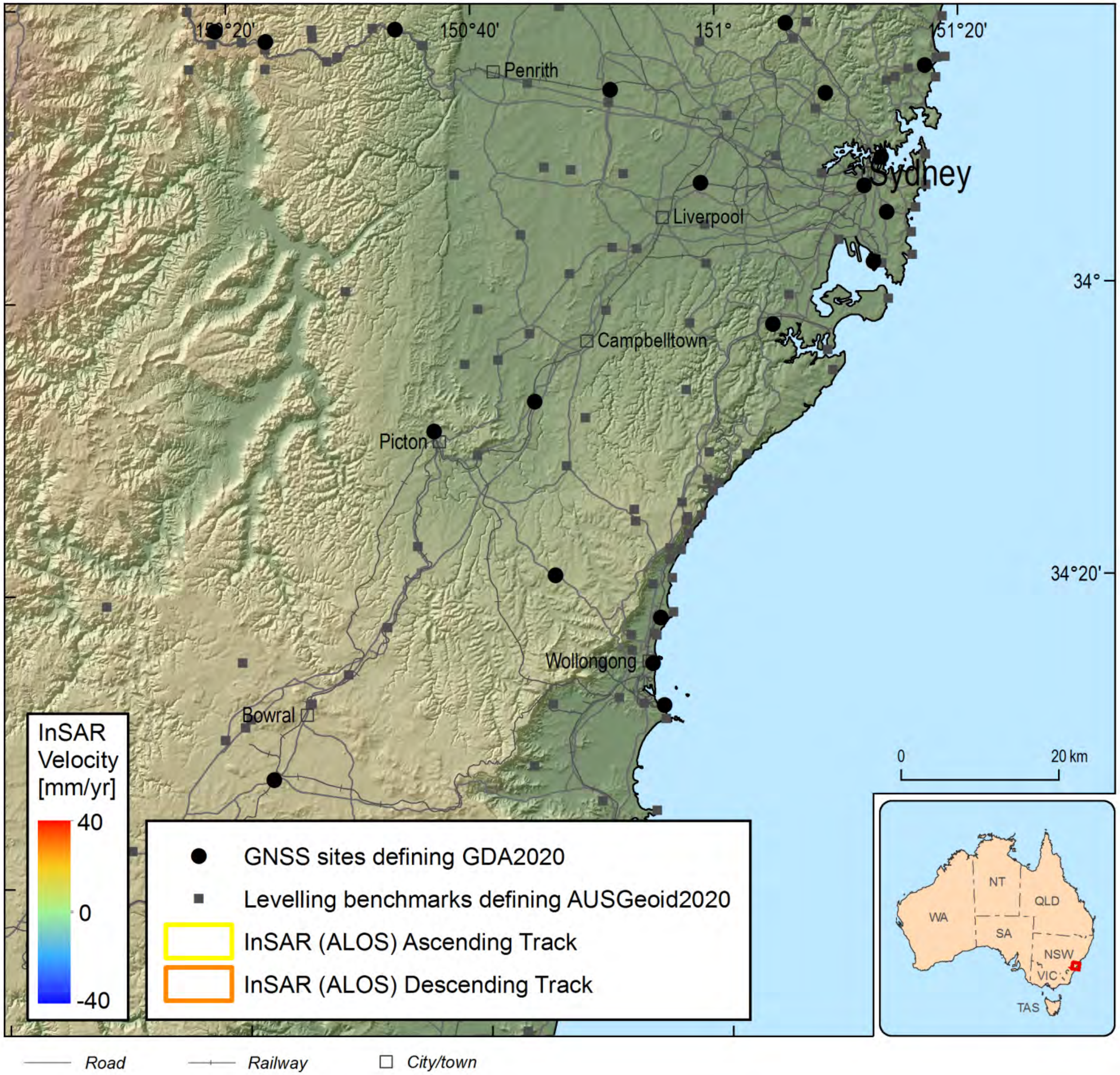
- Keep benchmark/site coordinates up to date
- Detect potential hazards (natural or anthropogenic)

How to measure local deformation?

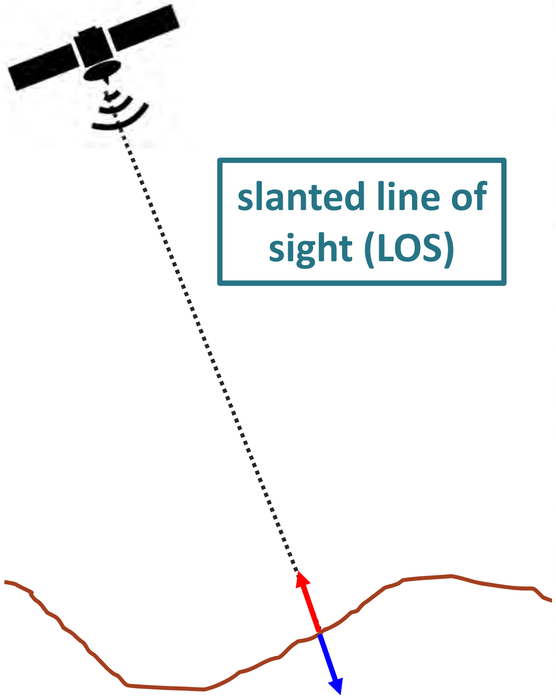
- Perform many local surveys

  or

- **Use InSAR!**

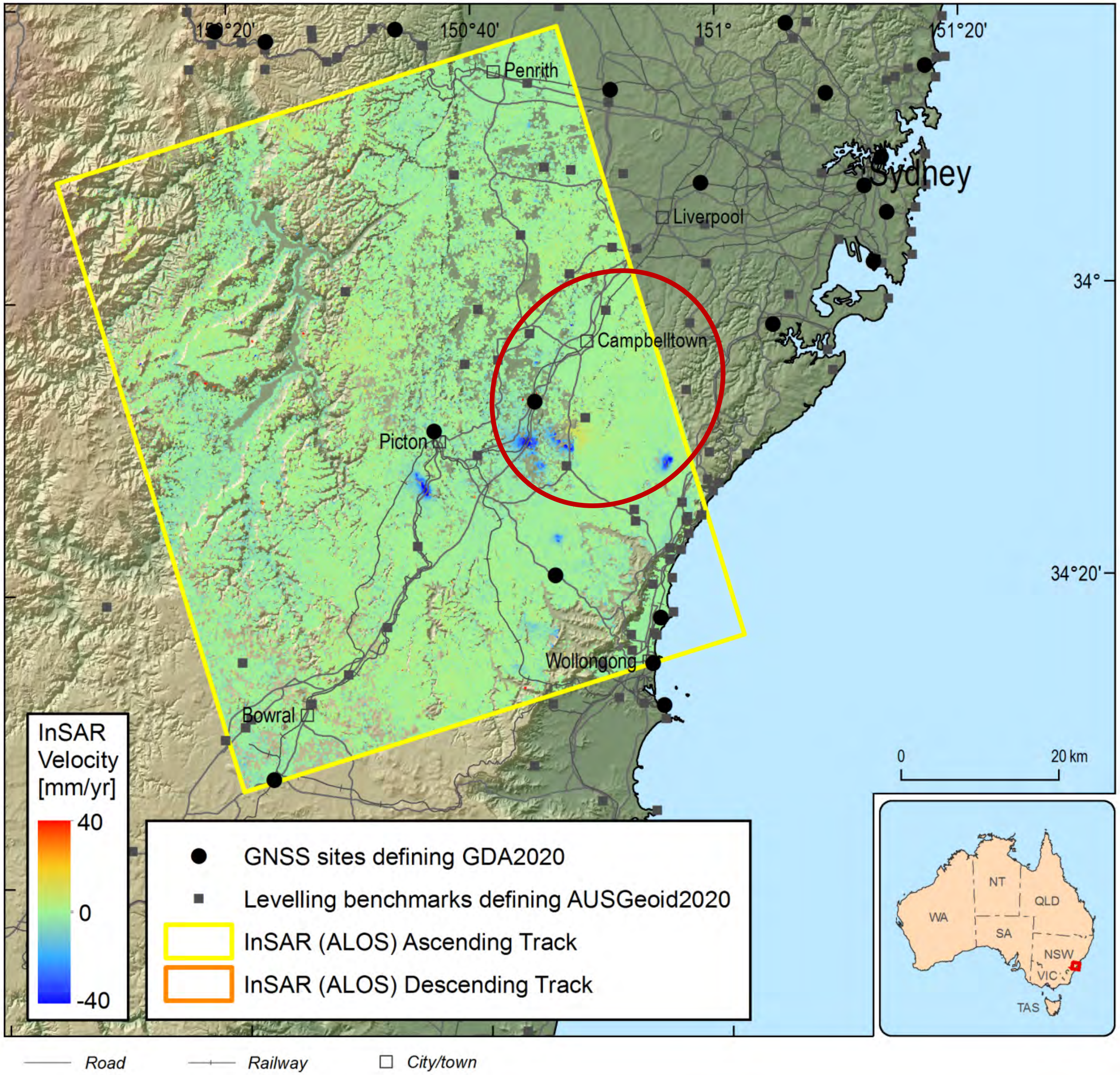


Motivation



slanted line of sight (LOS)

Movements towards the sensor: **positive,** movements away from the sensor: **negative**

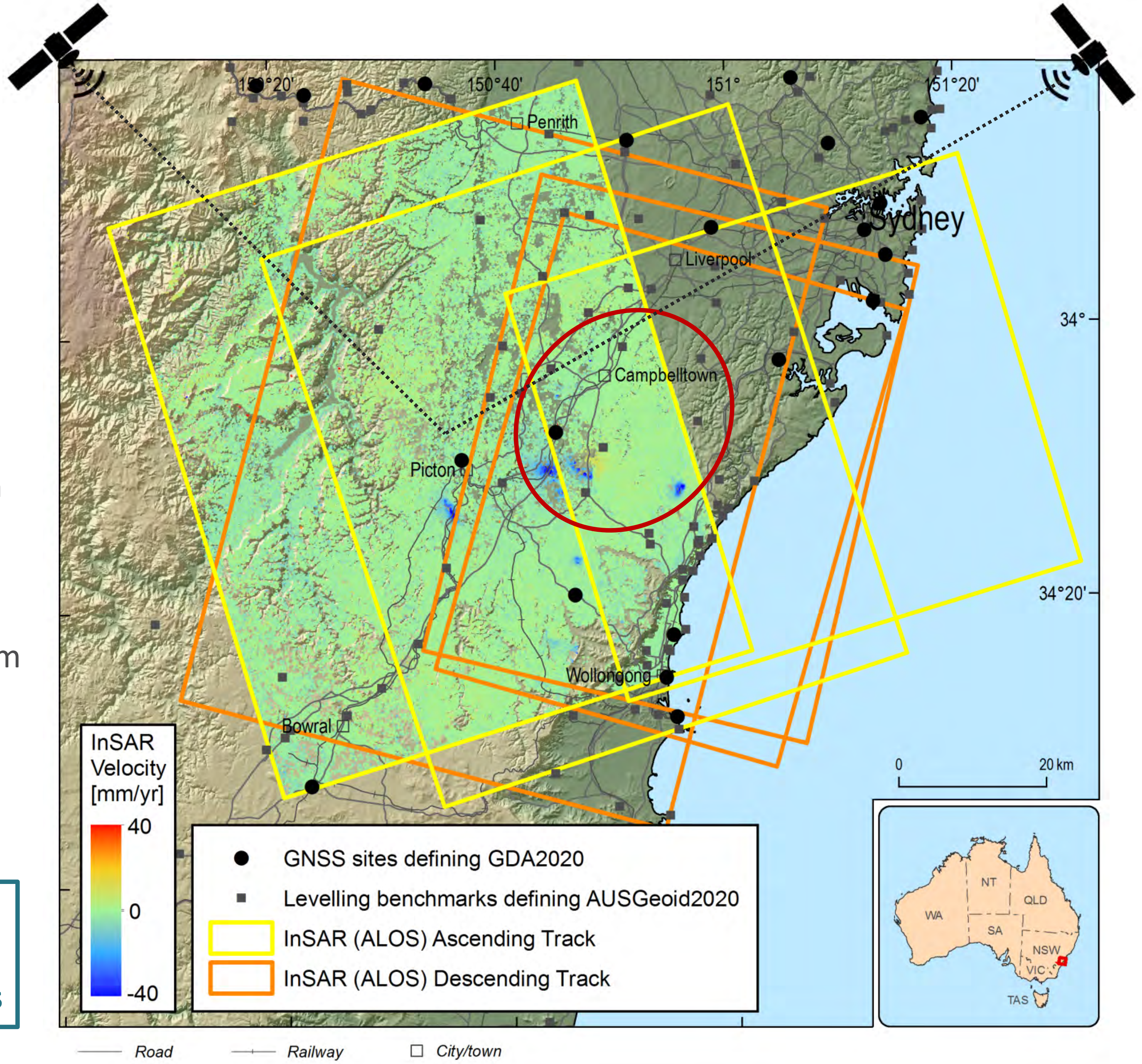


Motivation

InSAR …

- is an active remote sensing technique
- works best in urban or non-vegetated areas (sensor-dependent)
- can resolve spatial patterns of deformation at ground pixels of several metres in size
- can detect surface displacements at the mm to cm scale
- only measures displacement along a slanted, 1D LOS, but …

Multi-track combination to solve for vertical and East-West displacements



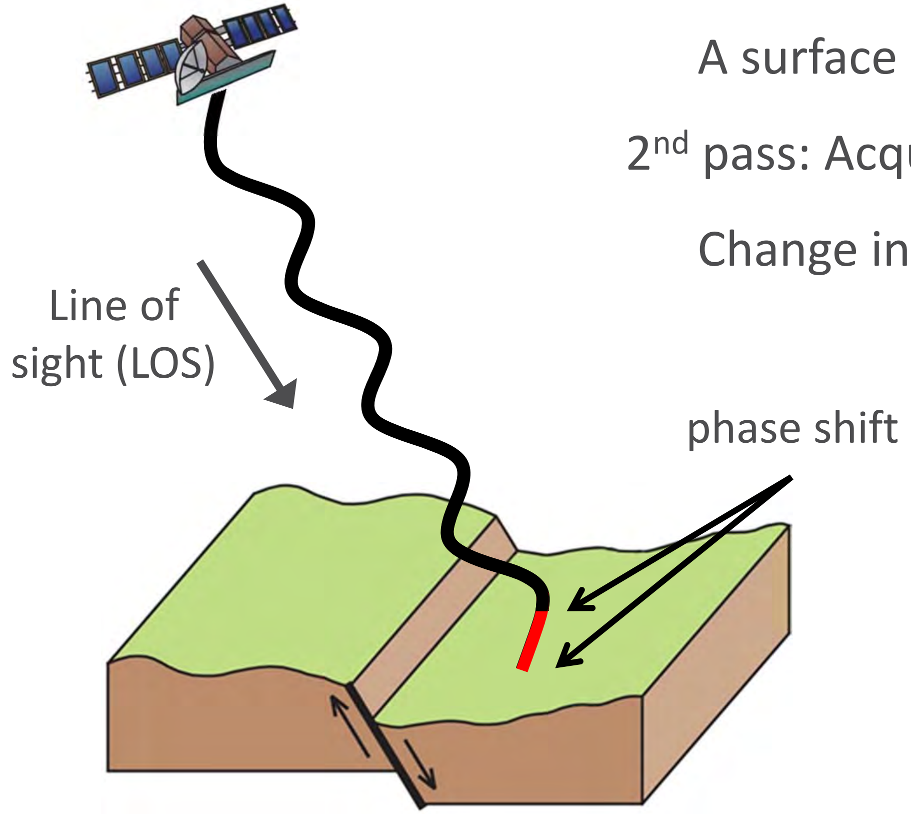
How InSAR works…

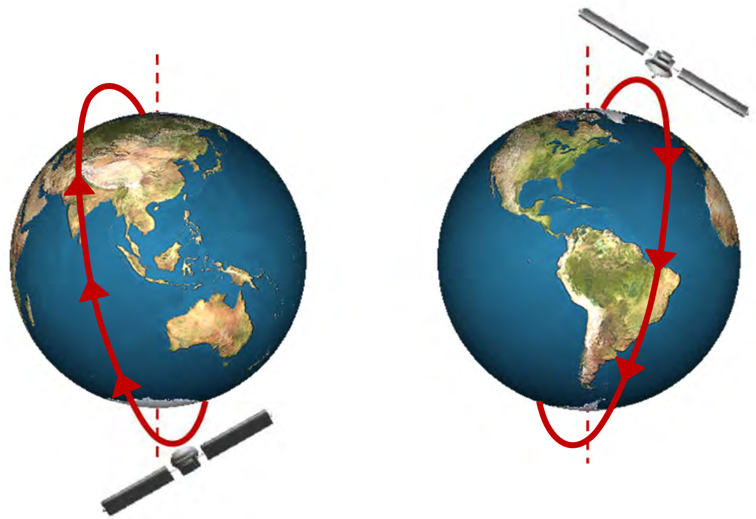
1st pass: Acquire imagery over an area

A surface motion occurs

2nd pass: Acquire imagery over same area

Change in phase occurs between images





Ascending orbit

Descending orbit

InSAR data used in the Sydney Region

ALOS (Advanced Land Observing Satellite)

L-band,
Period: 2006-2011,
Revisit: 46 days

Envisat (Environmental Satellite)

C-band,
Period: 2002-2010,
Revisit: 35 days

RADARSAT-2

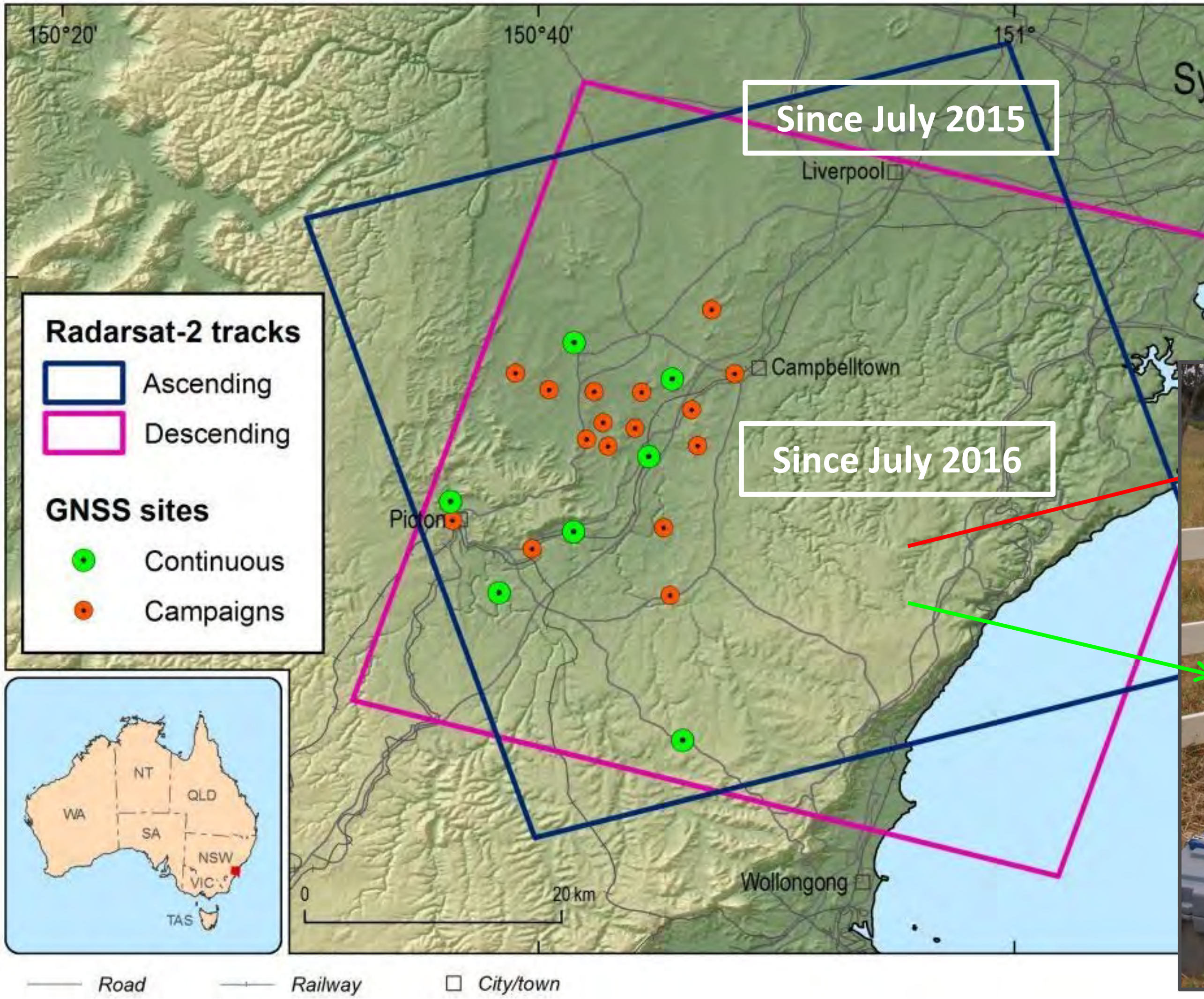
C-band,
Period: 2007 – now,
Revisit: 24 days

Other SAR sensors

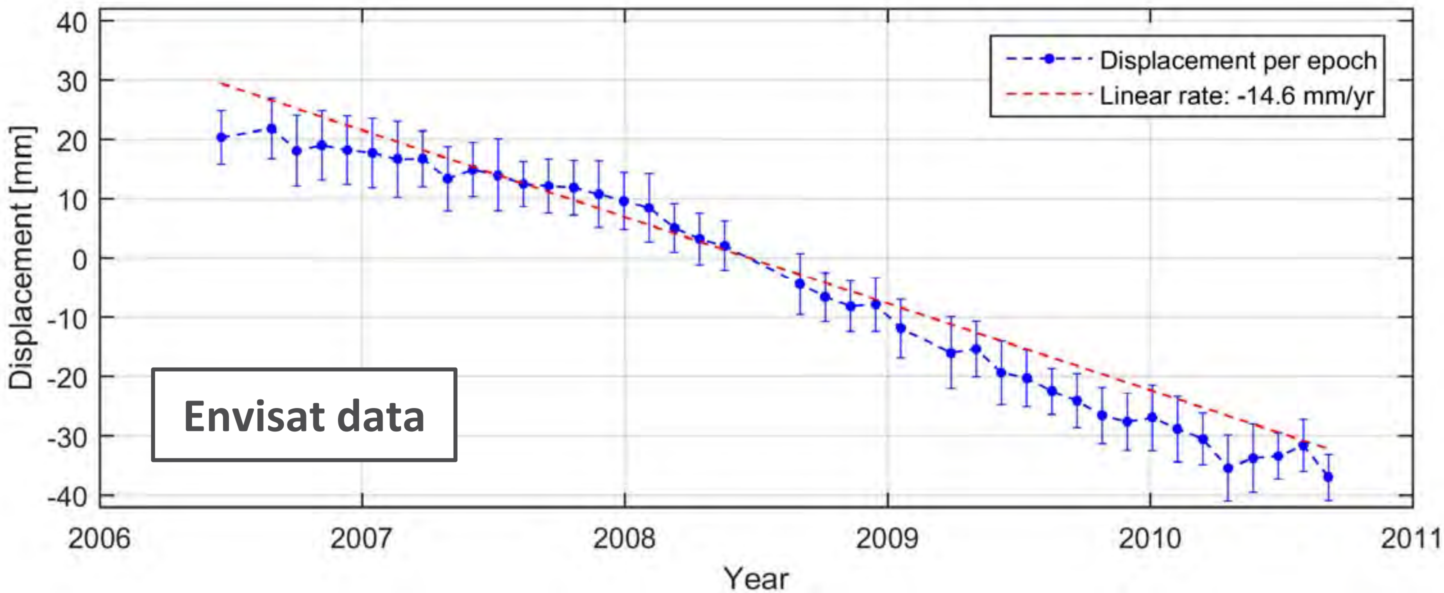
- **ALOS-2**
- **Sentinel-1**
- **TerraSAR-X**
- **COSMO-Skymed**
- **…**

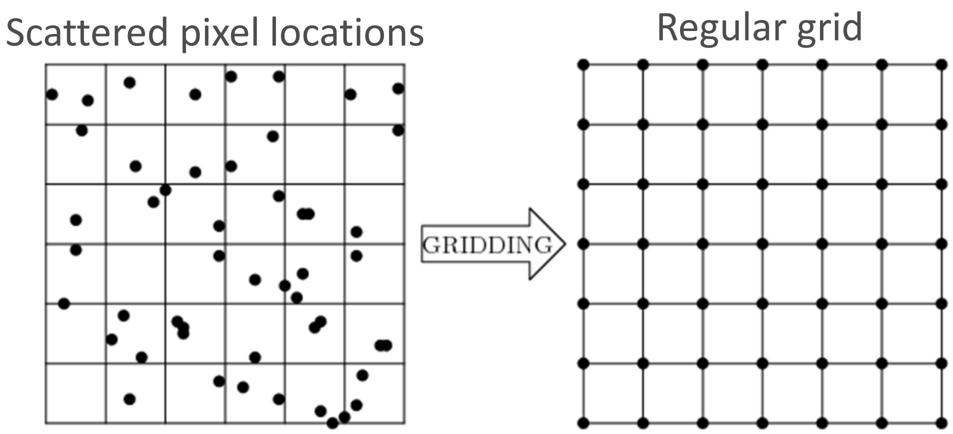
Overview of InSAR and GNSS data

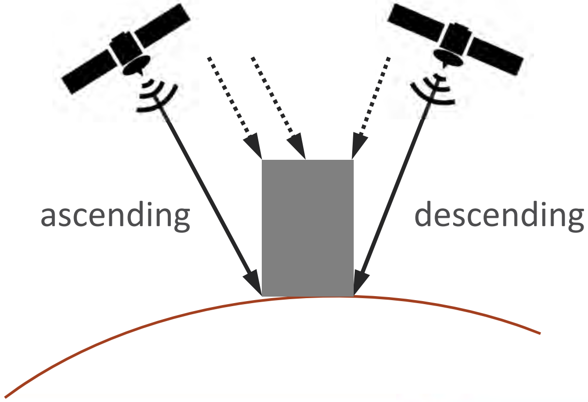
asc./desc. radar corner reflectors co-located with GNSS site



InSAR result: time series of LOS displacements







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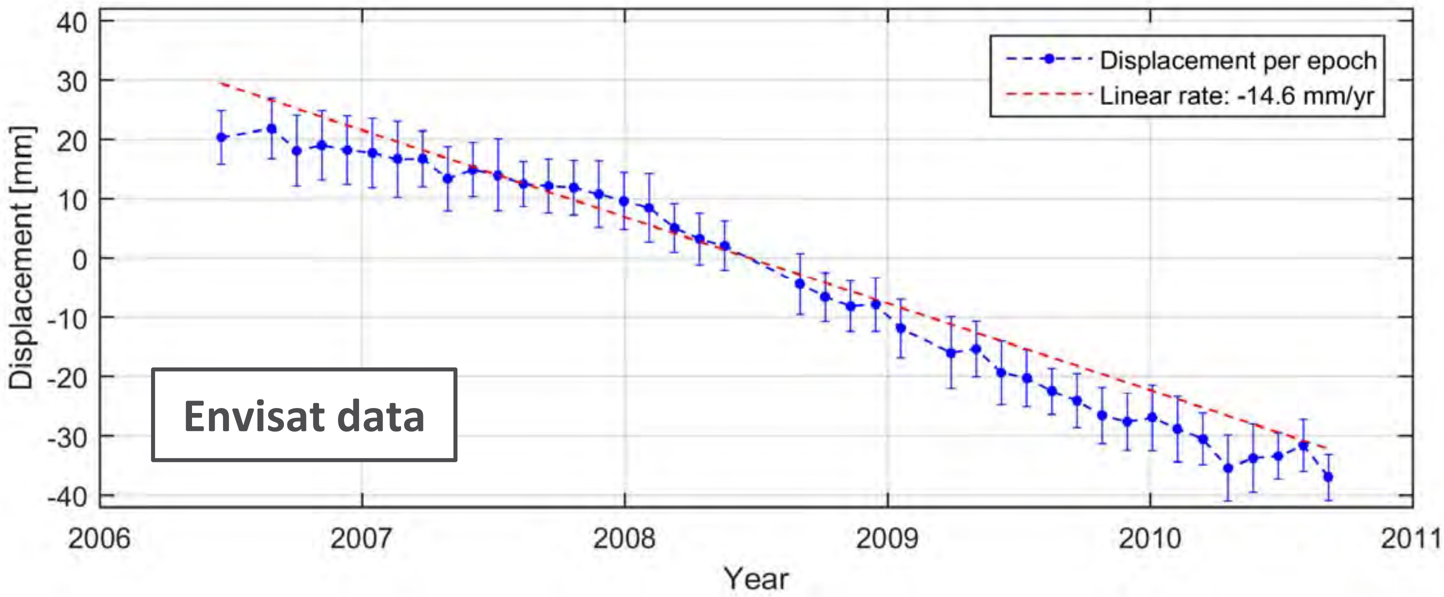
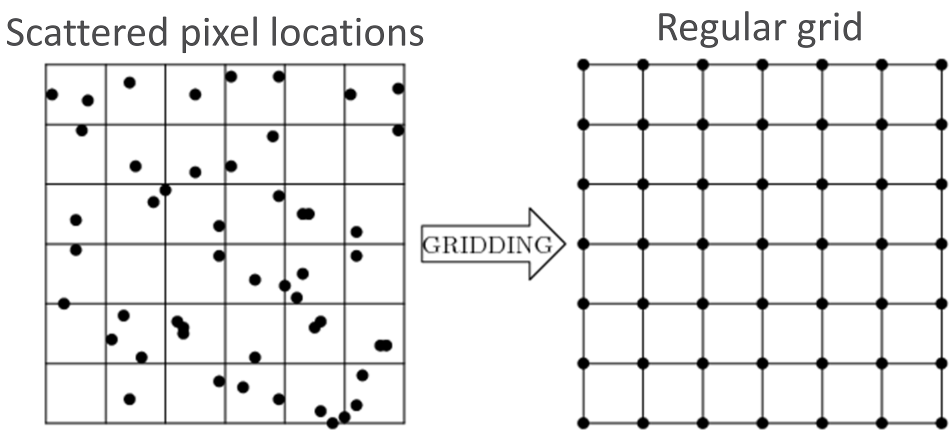
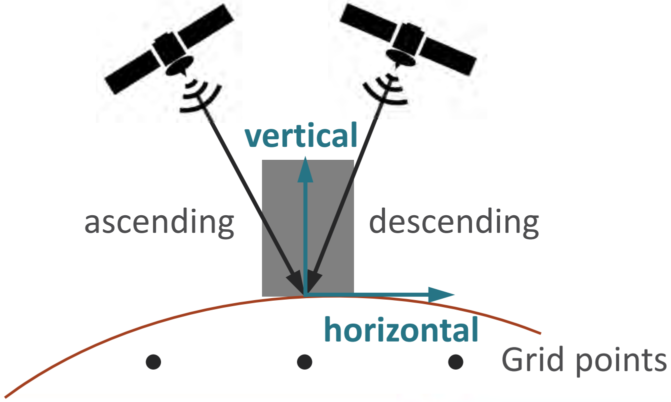
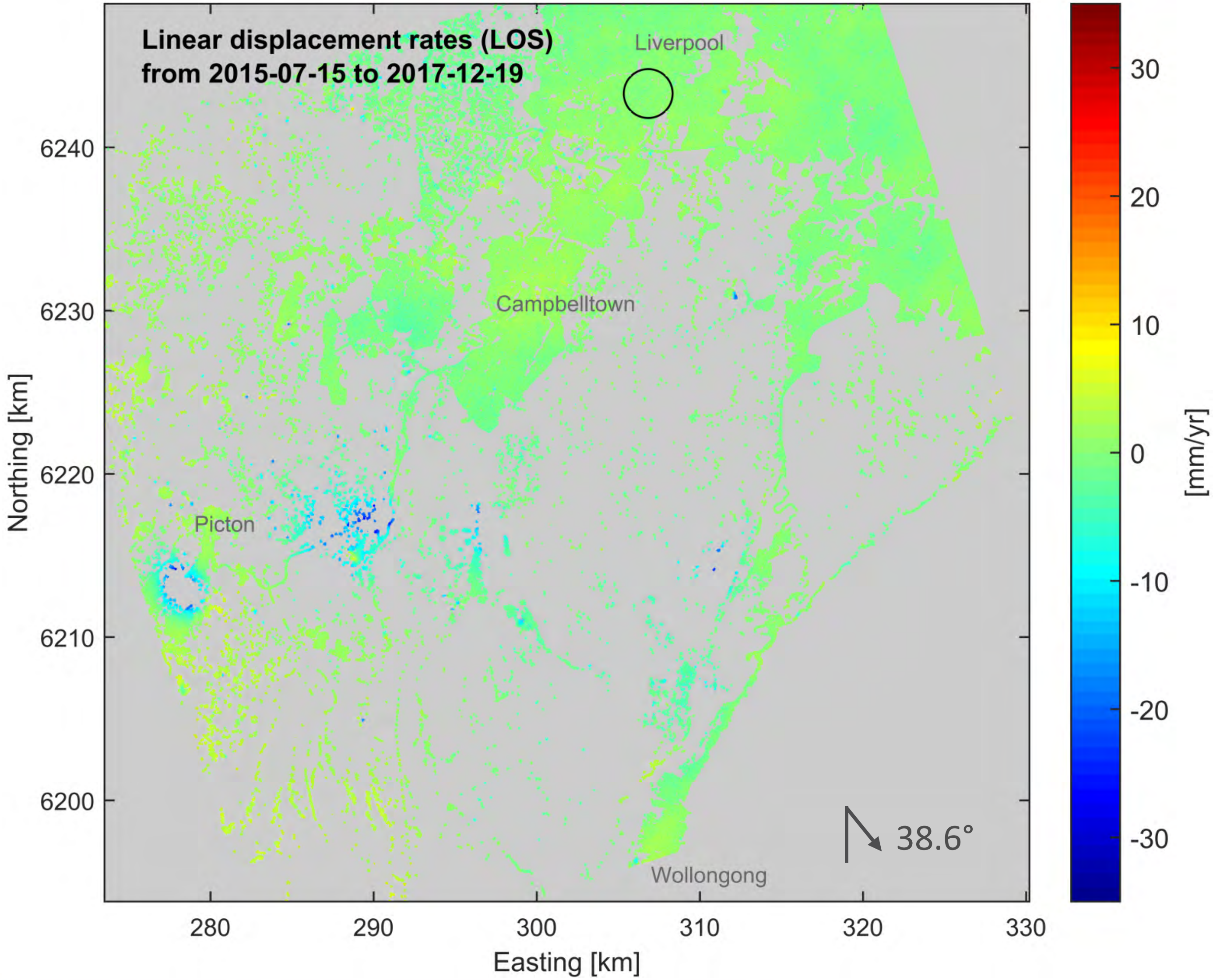






Results: linear rates (since July 2015)

RADARSAT-2 data



Ascending line-of sight (LOS)

Interpolated to 50 m grid

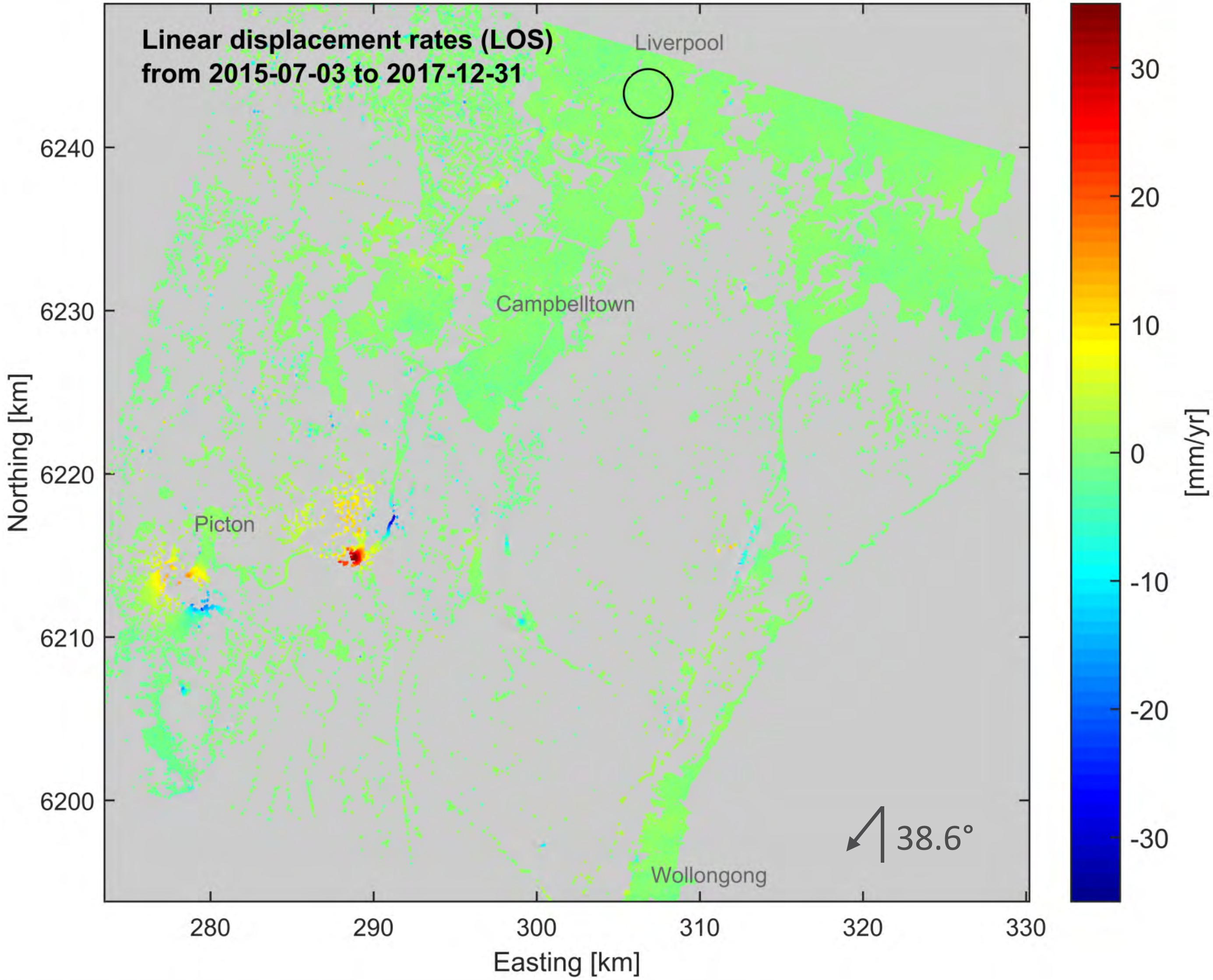
C-band data:
sparser pixel coverage compared to L-band (ALOS data), but higher accuracy (~ factor of 4)

Mean 2σ STD of epoch displacements: 3.2 mm

Mean 2σ STD of LOS velocities: 0.8 mm/yr

Results: linear rates (since July 2015)

RADARSAT-2 data



Descending line-of sight (LOS)

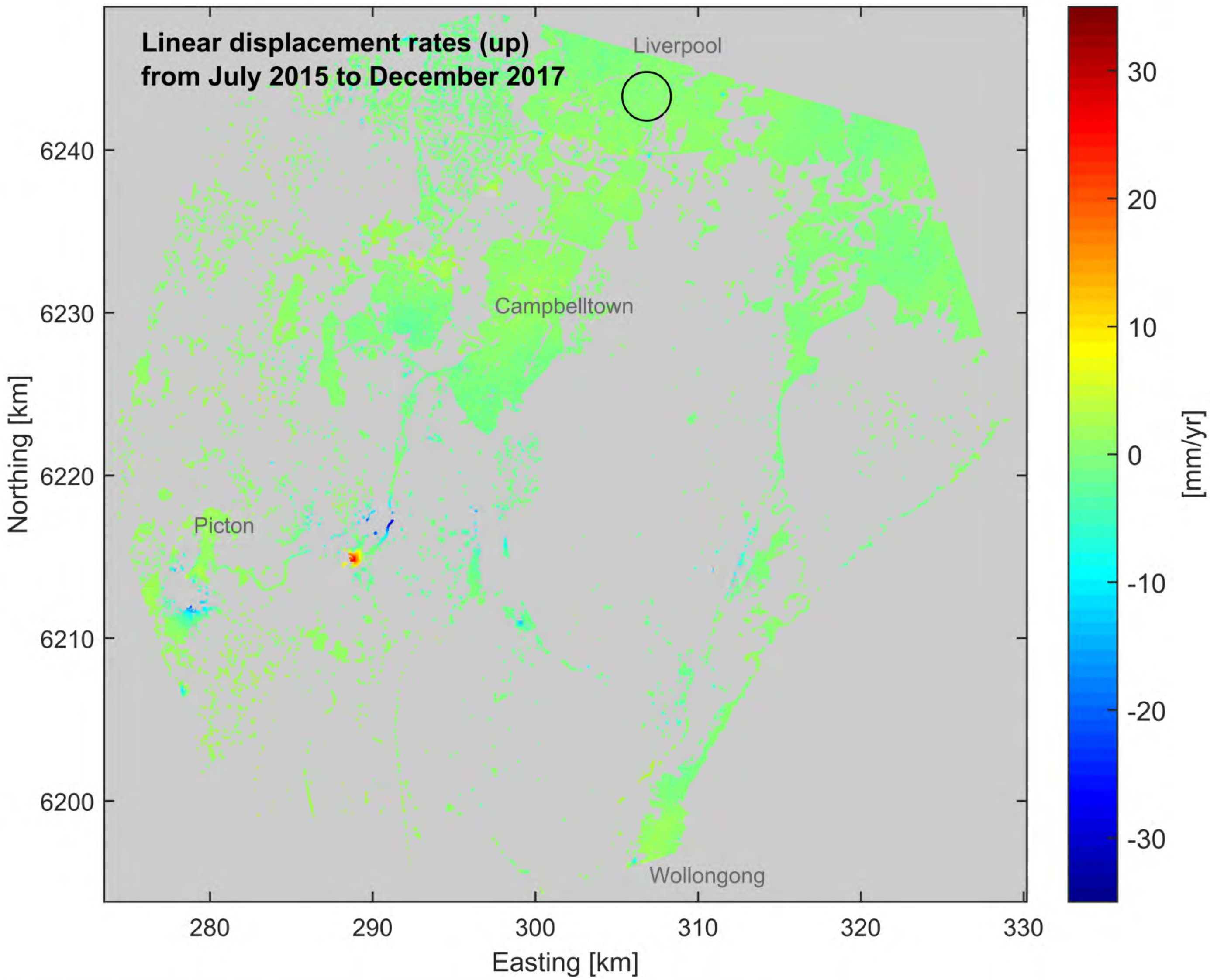
Interpolated to 50 m grid

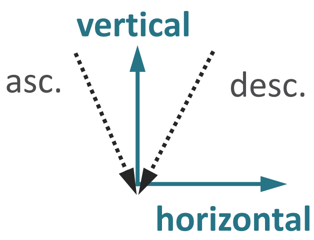
C-band data:
sparser pixel coverage compared to L-band (ALOS data), but higher accuracy (~ factor of 4)

Mean 2σ STD of epoch displacements: 3.0 mm

Mean 2σ STD of LOS velocities: 0.7 mm/yr

Combined linear velocities

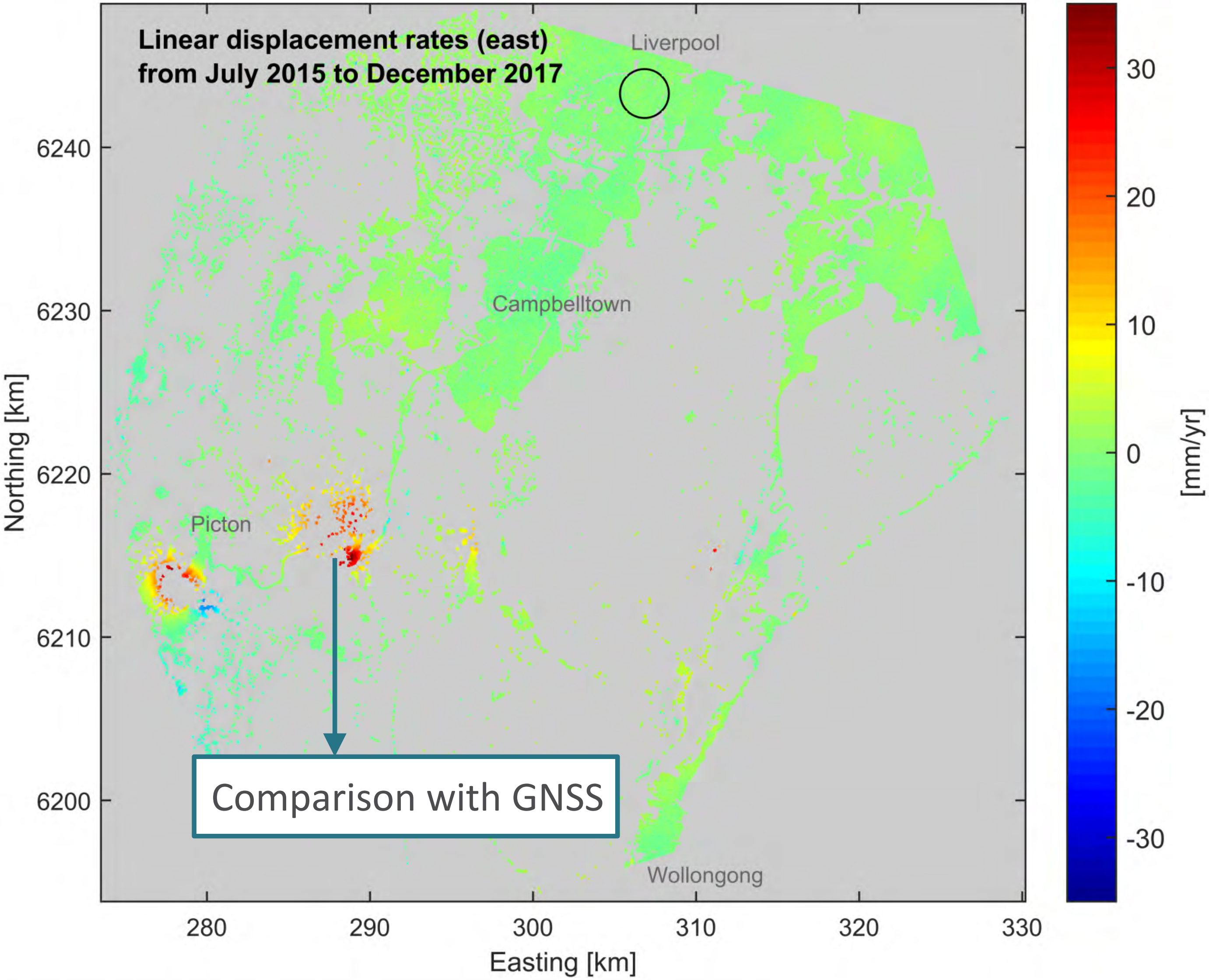


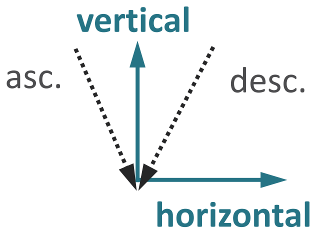


Up-Down component

50 m grid

Combined linear velocities





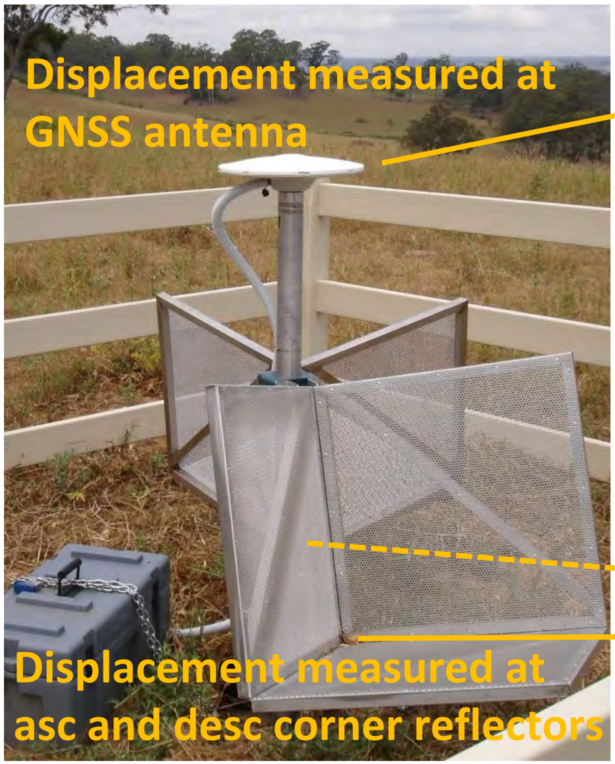
East-West component

50 m grid

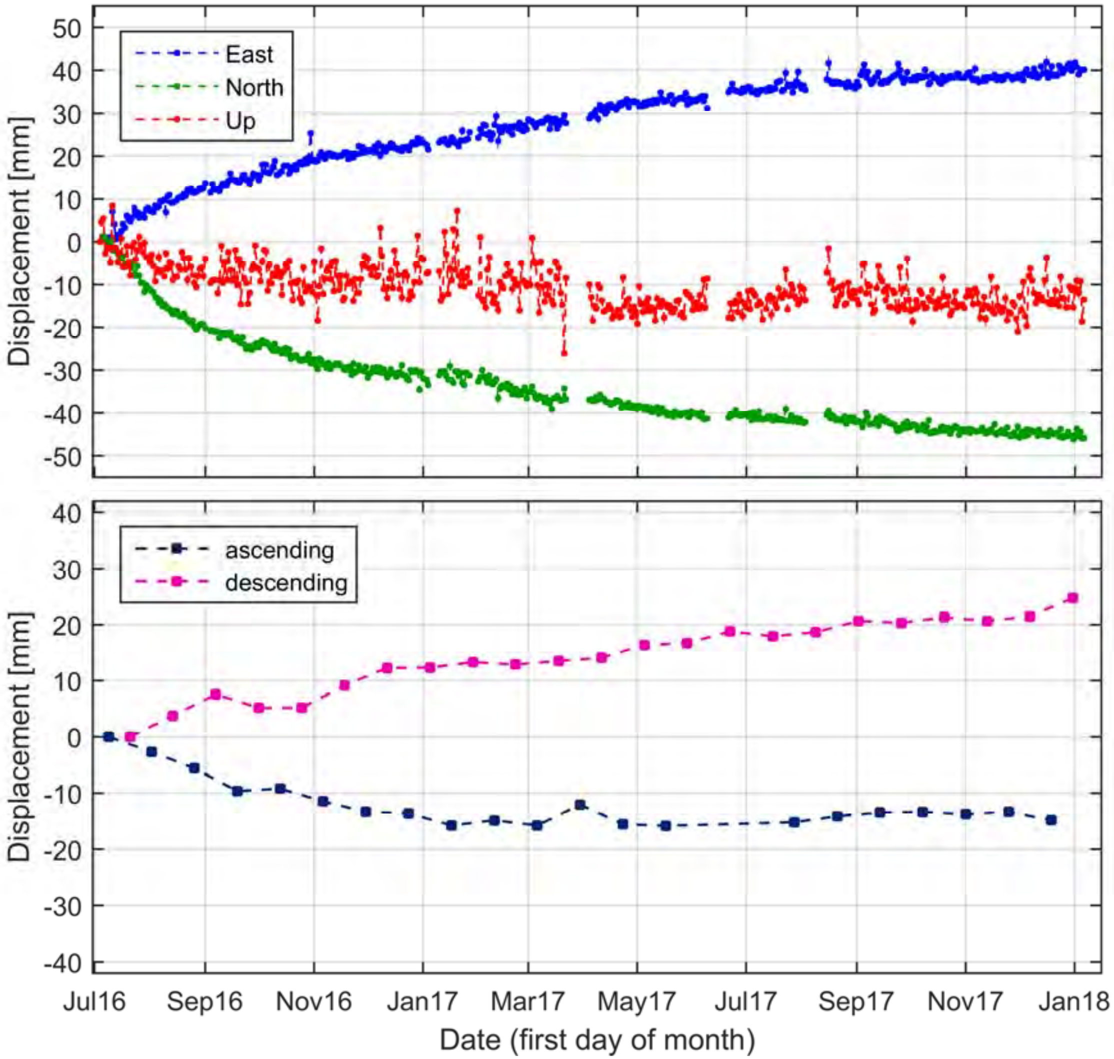
Validation of InSAR and GPS results

Differential Processing of GPS observations using a network incl. surrounding IGS/APREF reference sites

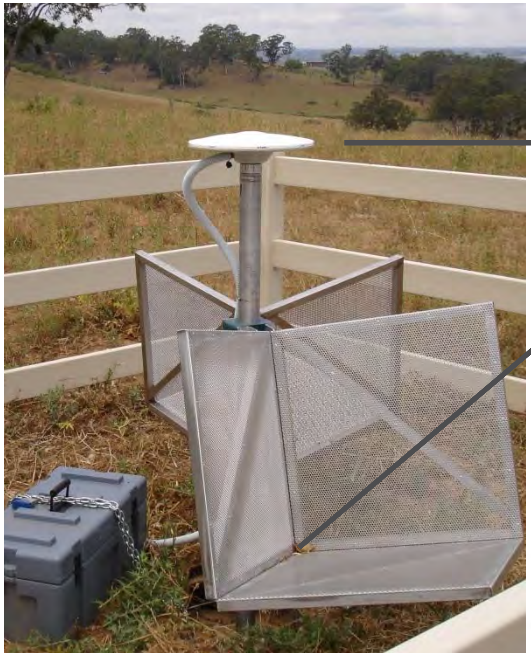
Site CA19



RADARSAT-2 data

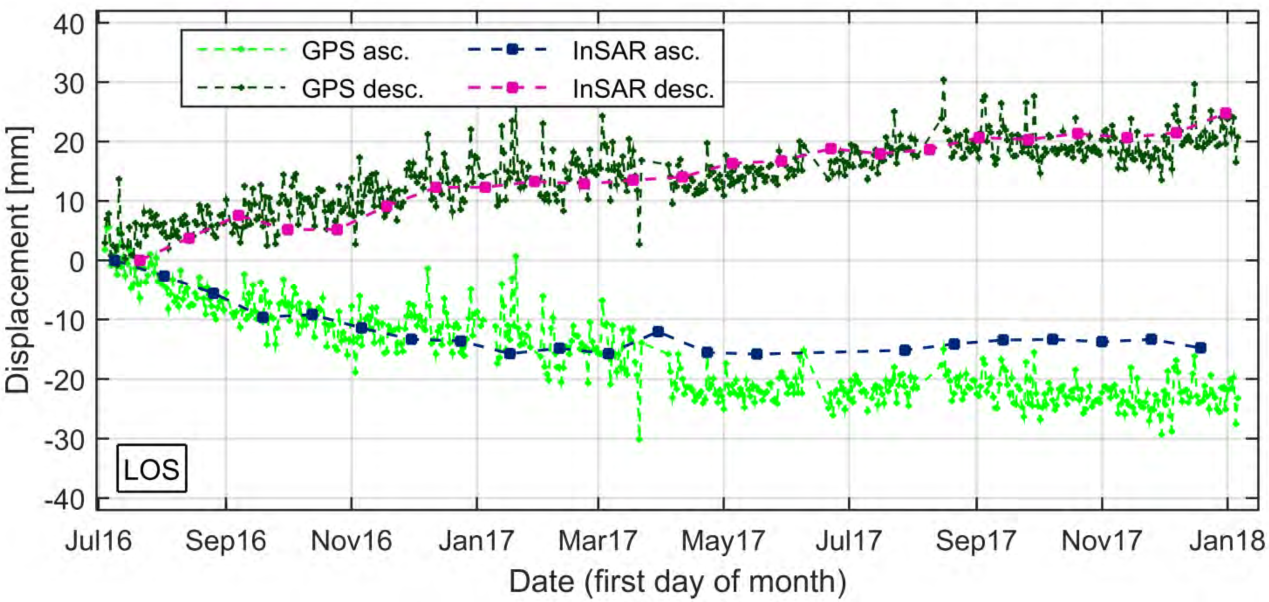


Validation of InSAR and GPS results



GPS East, North and Up components transformed to asc and desc LOS

InSAR results at asc and desc CRs



Average difference between GPS and InSAR displacements at 21 sites: 4.8 mm / 4.2 mm (ascending / descending)

Summary and Outlook

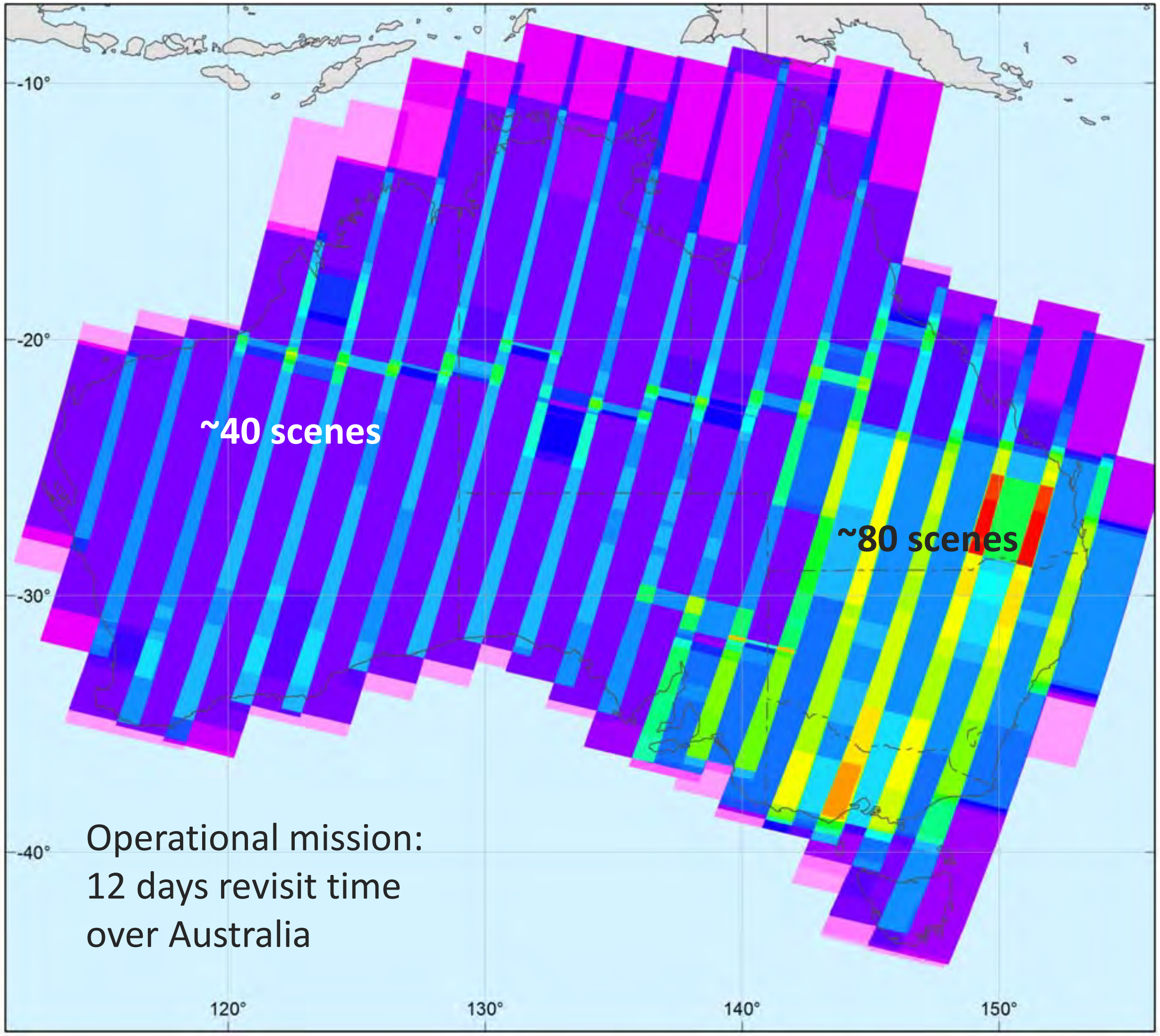
- InSAR can provide a greater understanding of the **temporal and spatial evolution of local deformation.**
- Information on surface displacements from InSAR can be provided **frequently** (revisit time of the sensor) and within **short latency** (days).
- **InSAR and GNSS are complimentary** with respect to spatial and temporal resolution as well as the sensitivity to different displacement components.
- Validation at geodetic sites **reveals good agreement** between displacements measured by InSAR and GNSS (mm to cm scale)

→ **combined usage for future Datums**

Outlook: Sentinel-1 mission

- Data is acquired **routinely** and provided **free of charge** by ESA.
- **Nationwide coverage** of Sentinel-1 enables radar remote sensing of the entire Australian continent in the future.
- **Validation and combination** with national GNSS network possible.

Sentinel-1 coverage over Australia

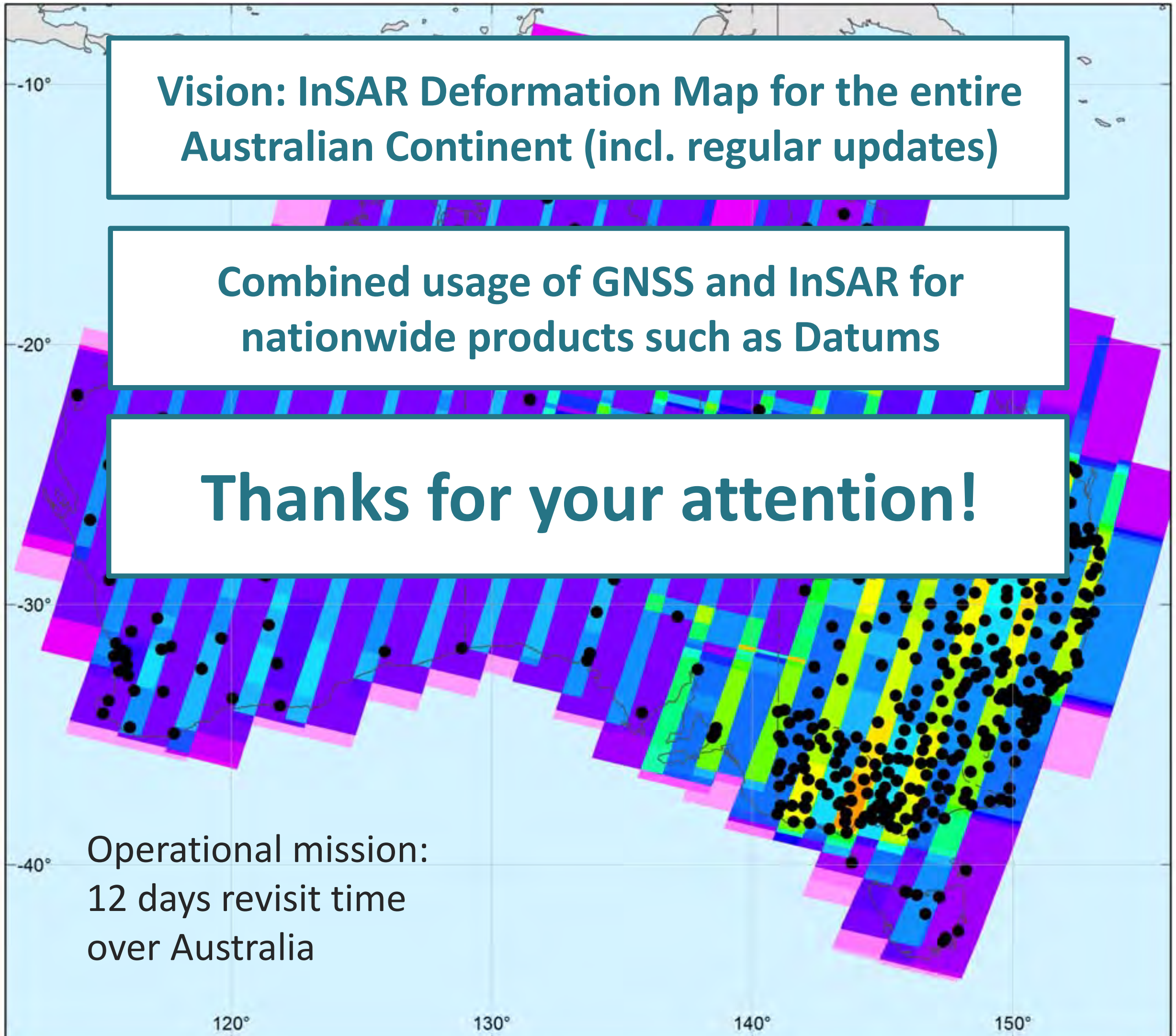


Number of SAR scenes:

1 - 5	66 - 70	131 - 135
6 - 10	71 - 75	136 - 140
11 - 15	76 - 80	141 - 145
16 - 20	81 - 85	146 - 150
21 - 25	86 - 90	151 - 155
26 - 30	91 - 95	156 - 160
31 - 35	96 - 100	161 - 165
36 - 40	101 - 105	166 - 170
41 - 45	106 - 110	171 - 175
46 - 50	111 - 115	176 - 180
51 - 55	116 - 120	181 - 185
56 - 60	121 - 125	186 - 188
61 - 65	126 - 130	

Status: December 2017

Sentinel-1 coverage over Australia



Vision: InSAR Deformation Map for the entire Australian Continent (incl. regular updates)

Combined usage of GNSS and InSAR for nationwide products such as Datums

Thanks for your attention!

Operational mission:
12 days revisit time
over Australia

Number of SAR scenes:

1 - 5	66 - 70	131 - 135
6 - 10	71 - 75	136 - 140
11 - 15	76 - 80	141 - 145
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● **permanent GNSS sites**

Status: December 2017

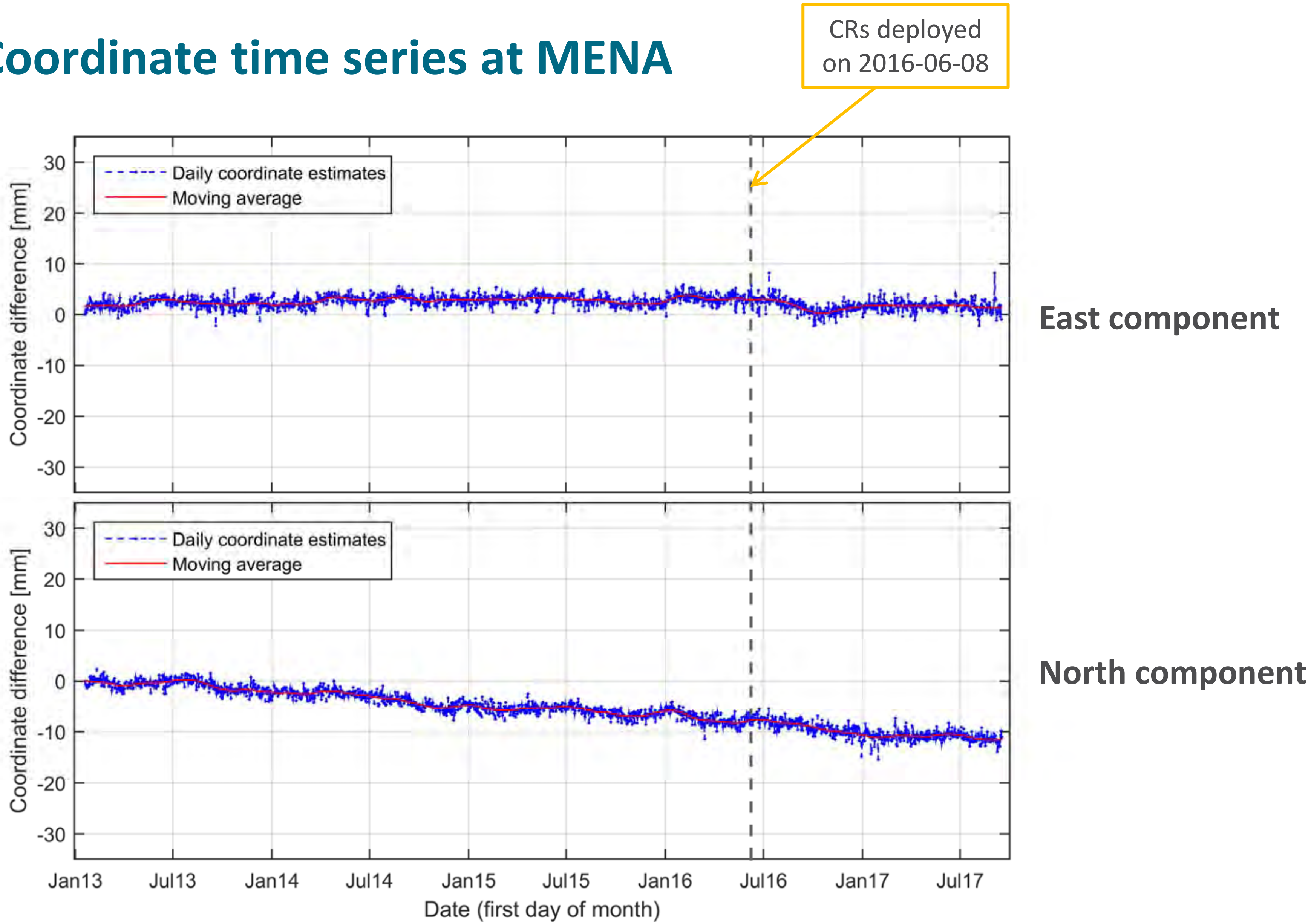
Appendix

Corner Reflector test at site MENA

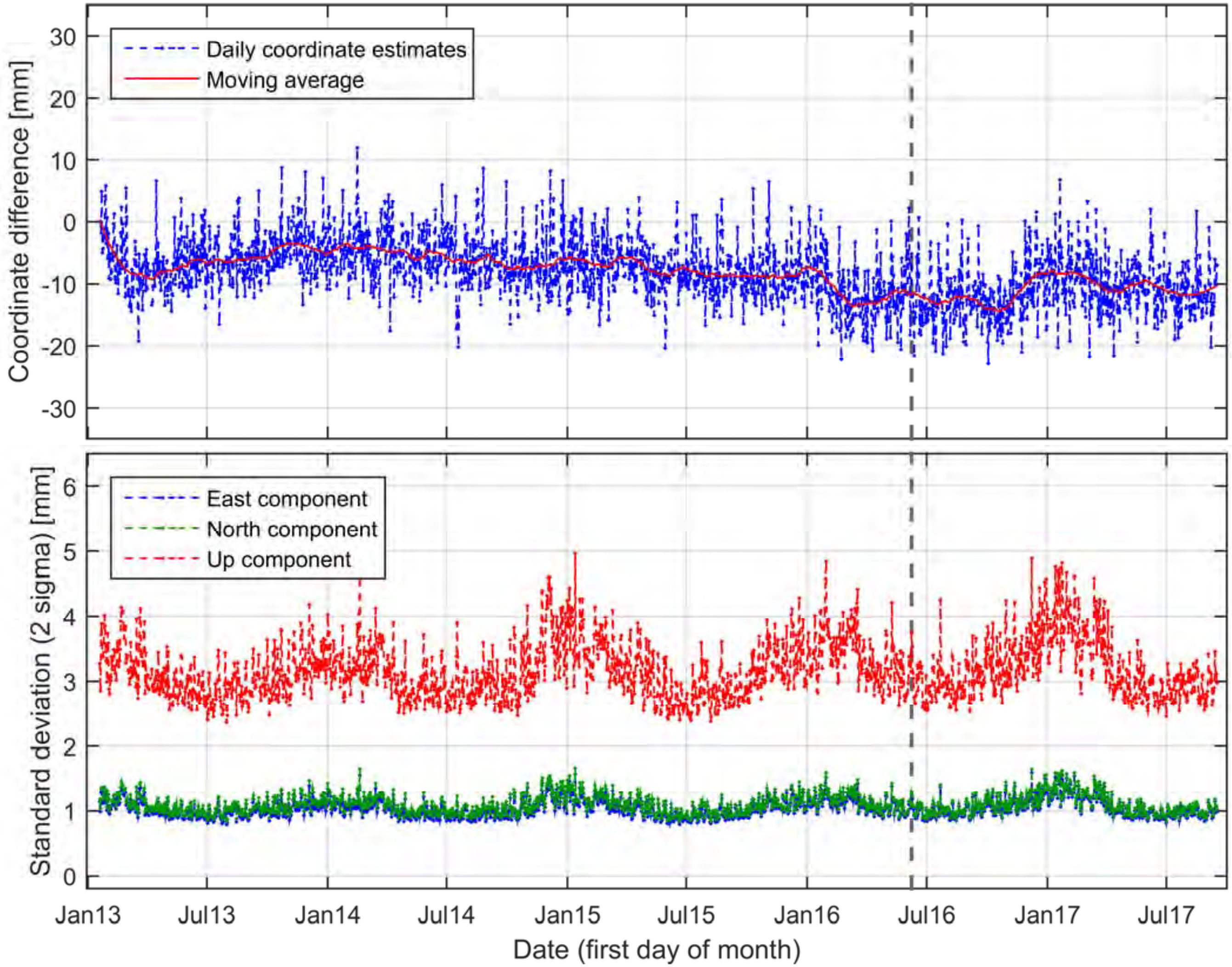
- Objective: Check influence of attached Corner Reflectors (CRs) on GPS position estimates at site MENA.
- Background: reflections of GPS signals at the attached CRs may cause multi-path effects for the signals received at the GPS antenna.

Site MENA before and after CRs have been attached

Coordinate time series at MENA



Coordinate time series at MENA



Up component

Standard deviation of coordinate estimates

Corner Reflector test at site MENA

- Statistical assessment of the period **before** (2013-01-09 to 2016-06-07) and **after** (2016-06-09 to 2017-09-16) the CRs have been attached to the pole.
- GPS processing accuracy is the mean 2-sigma standard deviation resulting from the processing of 24 h of GPS observations.
- Coordinate variability is the mean absolute difference of daily coordinates w.r.t. a moving average (red line on the slides before).

Period	Analysed days	GPS processing accuracy [mm]			Coordinate variability [mm]		
		East	North	Up	East	North	Up
Before	1236	1.04	1.09	3.15	0.71	0.63	3.21
After	464	1.06	1.10	3.22	0.78	0.68	3.31

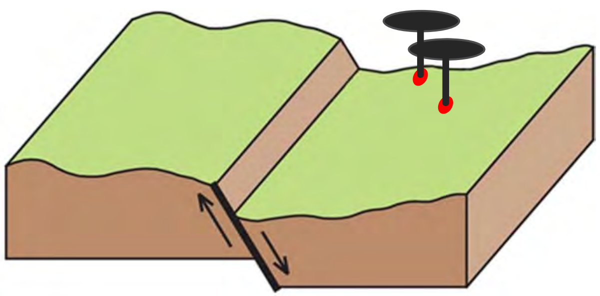
Conclusions:

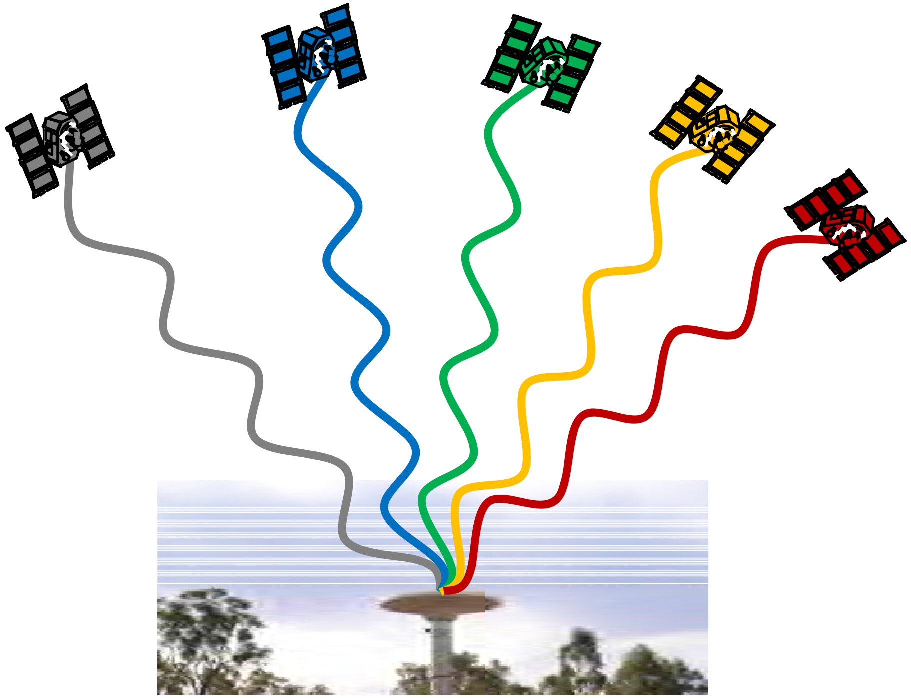
- Slight decrease in accuracy of the resulting coordinates (below 0.1 mm).
- Negligible effect for long-term monitoring of surface displacements

GNSS methodology

- Positioning with mm accuracy using GNSS phase measurements at geodetic antennas along with post-processing strategies
- 24 hours of GNSS observations
  ⟶ one 3D coordinate estimate
- Displacement at a GNSS site
  ⟶ coordinate change

GPS only used within this project





Coordinate time series analysis

- GPS processing result: geocentric coordinates (XYZ) for each measured day at each site w.r.t. ITRF2008
- Calculation of velocity at each site from Australian plate model and subtraction of linear trend from XYZ time series
- Calculation of latitude, longitude and height from de-trended XYZ coordinates
- Calculation of coordinate differences for each measurement epoch w.r.t. the first epoch (reference measurement)
- Transformation of latitude and longitude differences to metric measure using local radii of curvature
- Visualisation of resulting coordinate differences and accuracies
- In addition to the CEMP sites, the NSW CORSnet sites Cordeaux (CRDX), Menangle (MENA) and Picton (PCTN) are considered

GNSS data analysis

Differential processing of GPS data using a network of surrounding reference sites

7 IGS cores sites:
ALIC, CEDU, HOB2, MOB2, STR1, TIDB, TOW2

GNSS data analysis

Differential processing of GPS data using a network of surrounding reference sites

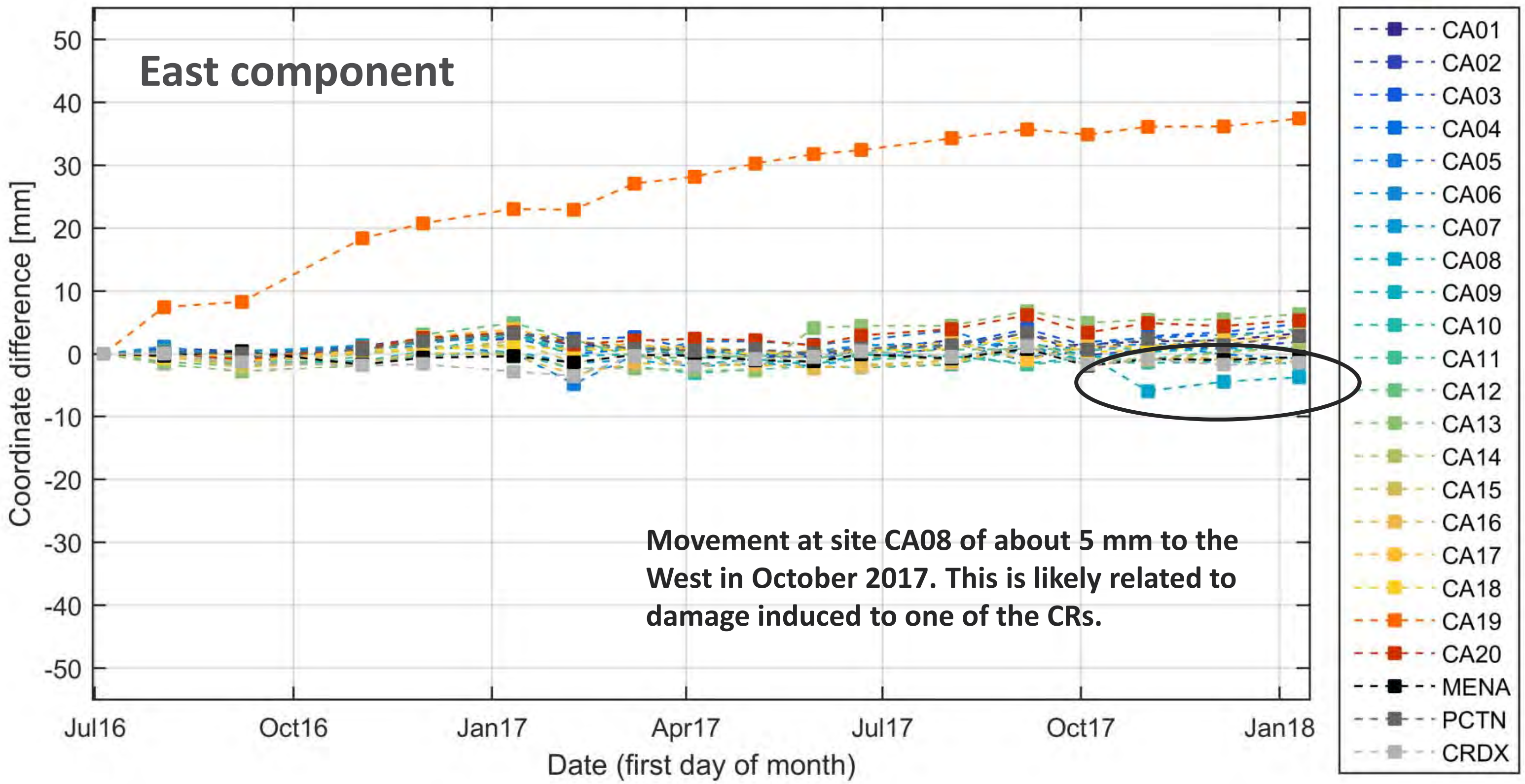
7 IGS cores sites:
ALIC, CEDU, HOB2, MOB2, STR1, TIDB, TOW2

10 APREF sites
BING, BROC, CNBN, GABO, IHOE, NBRK, NSTA, PTKL, SYDN, TURO

Selected based on
- Distance to the area of interest
- Data quality
- Long term coordinate stability

Result of GPS processing – campaigns

- Coordinate time series at each site, East, North and Up component
- Coordinate displacements w.r.t. first measurement (= reference epoch)



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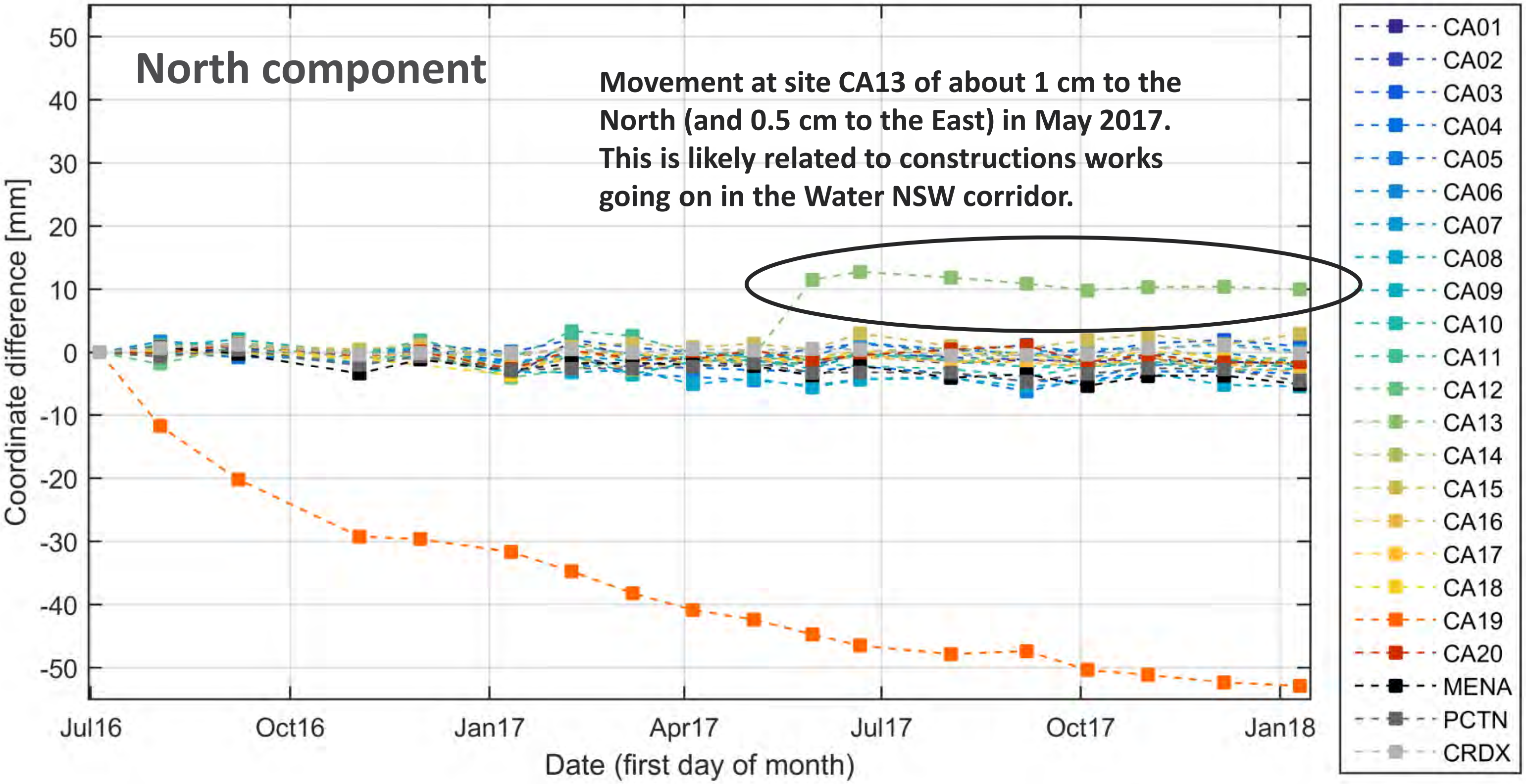

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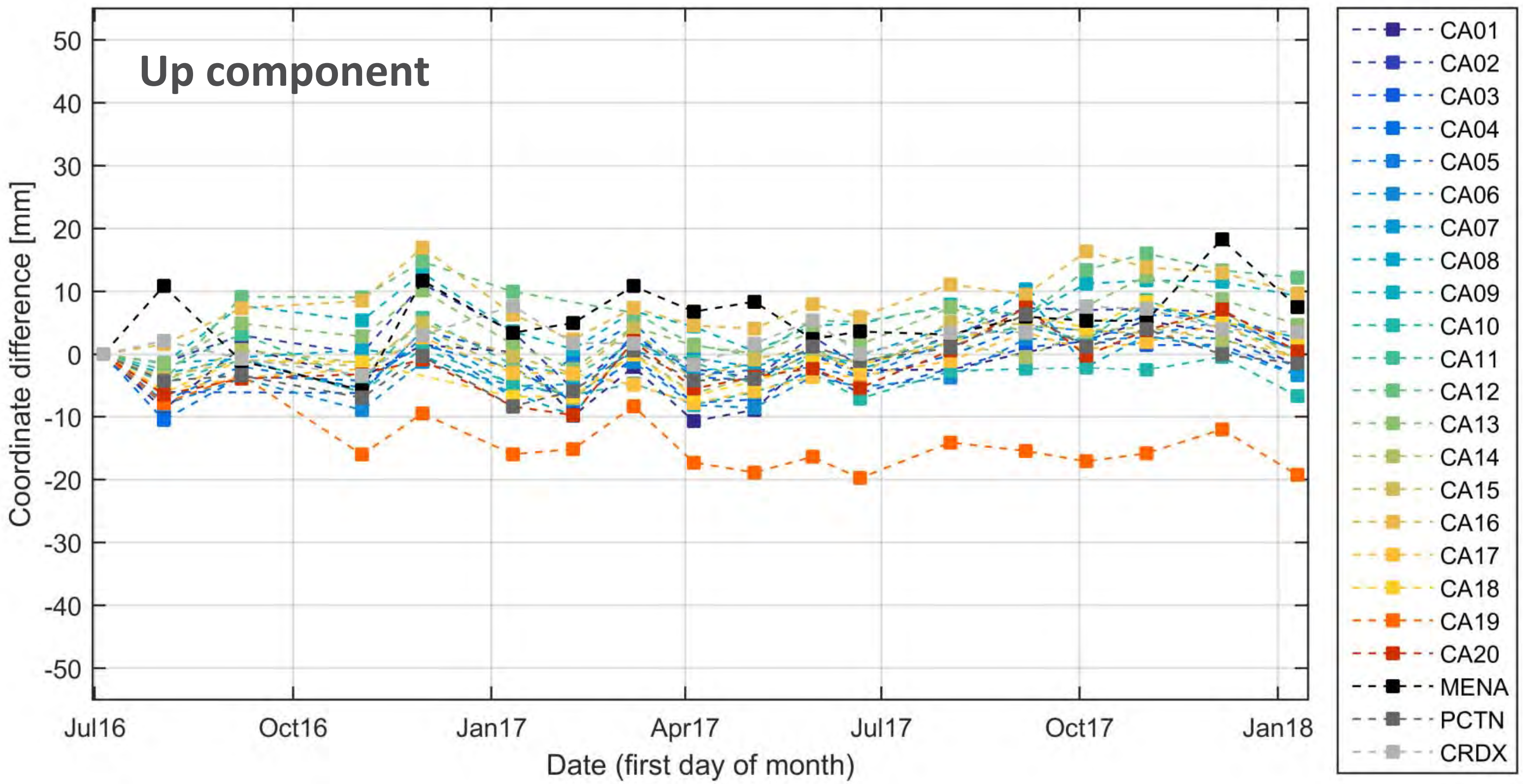
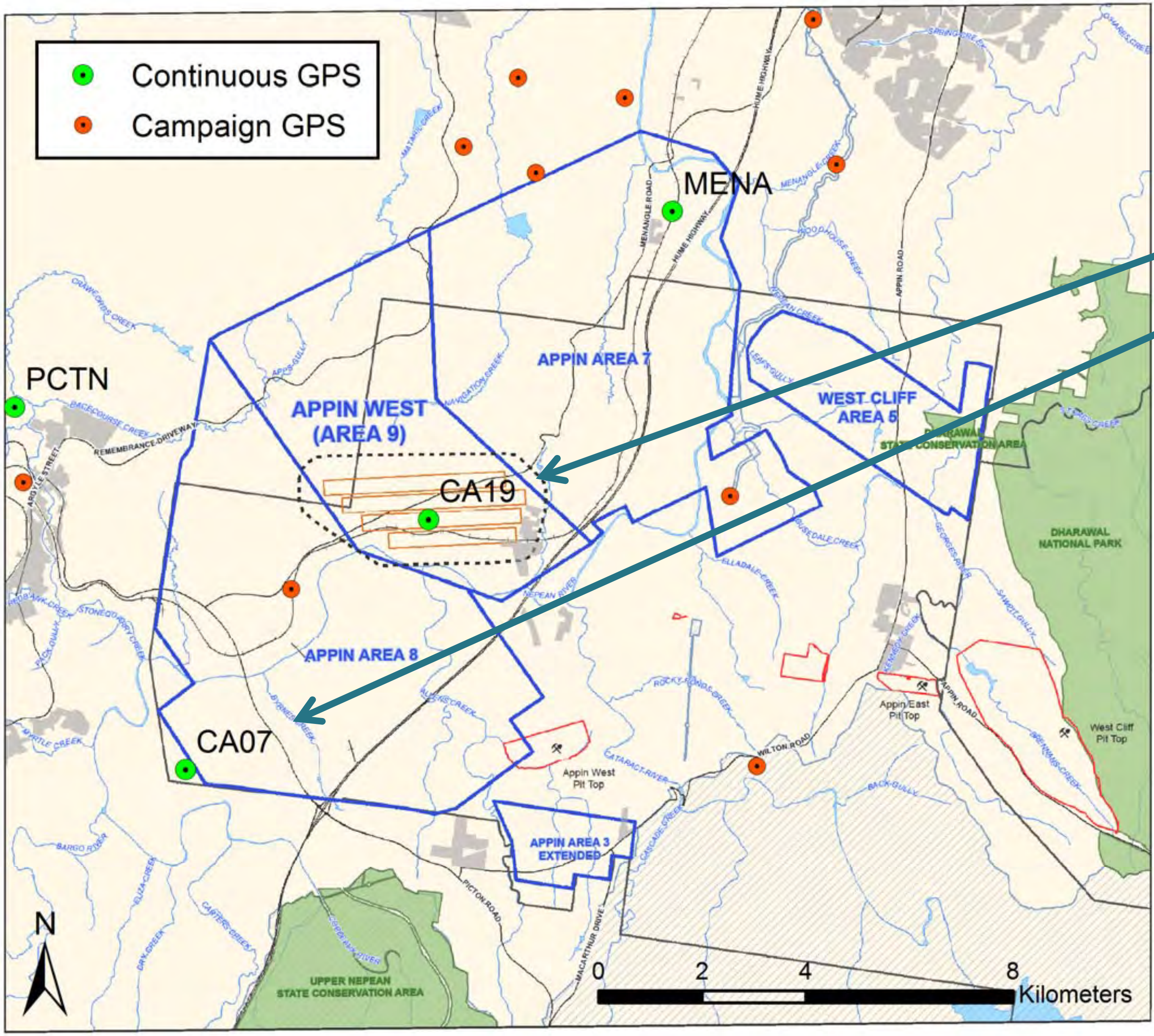
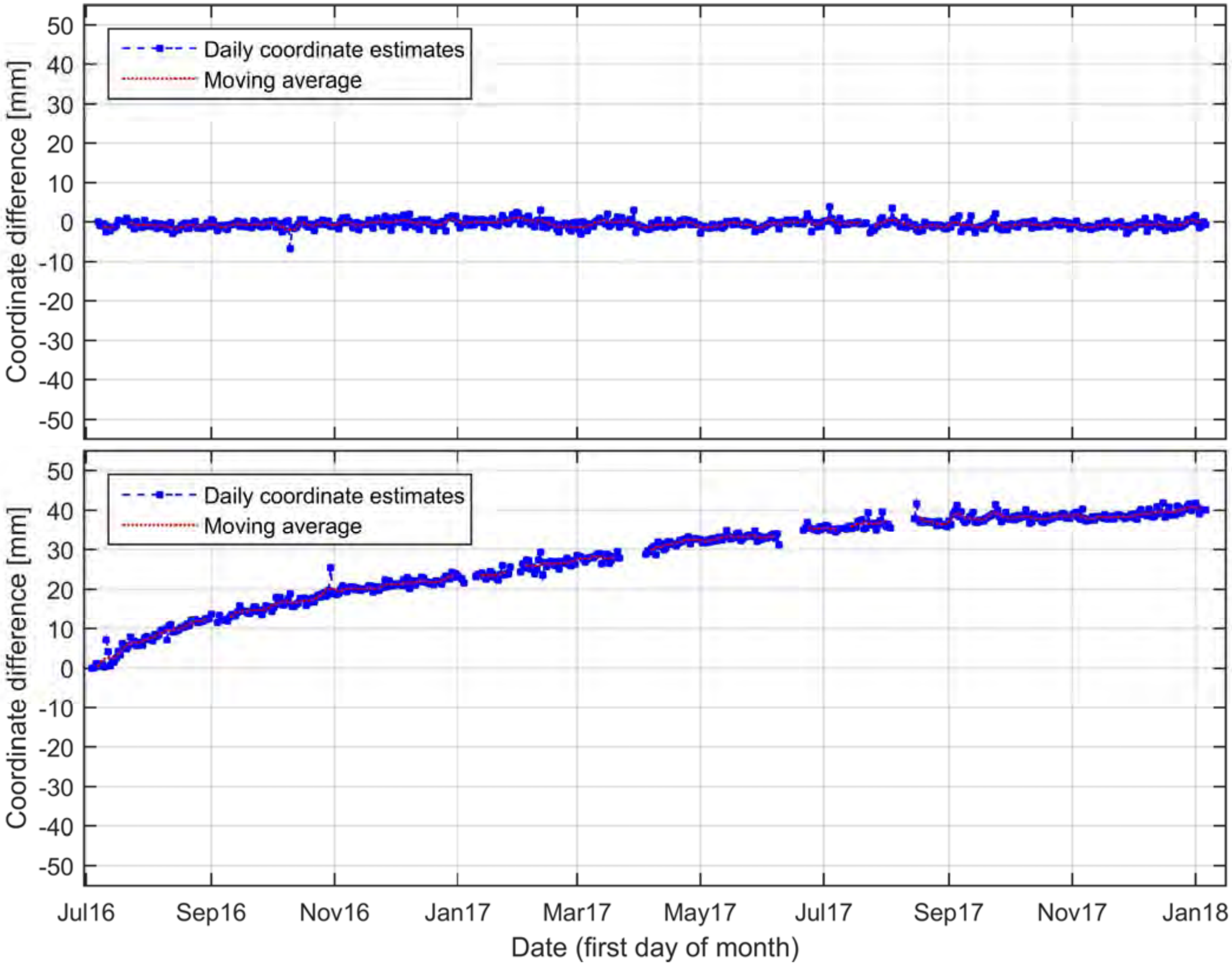




Results: displacement time series at CA19 and CA07

Background Image:
BHP Billiton Illawarra Coal,
Extraction Plan Appin Area 9
2 September 2014, page 6

Result of GPS processing – continuously operating sites

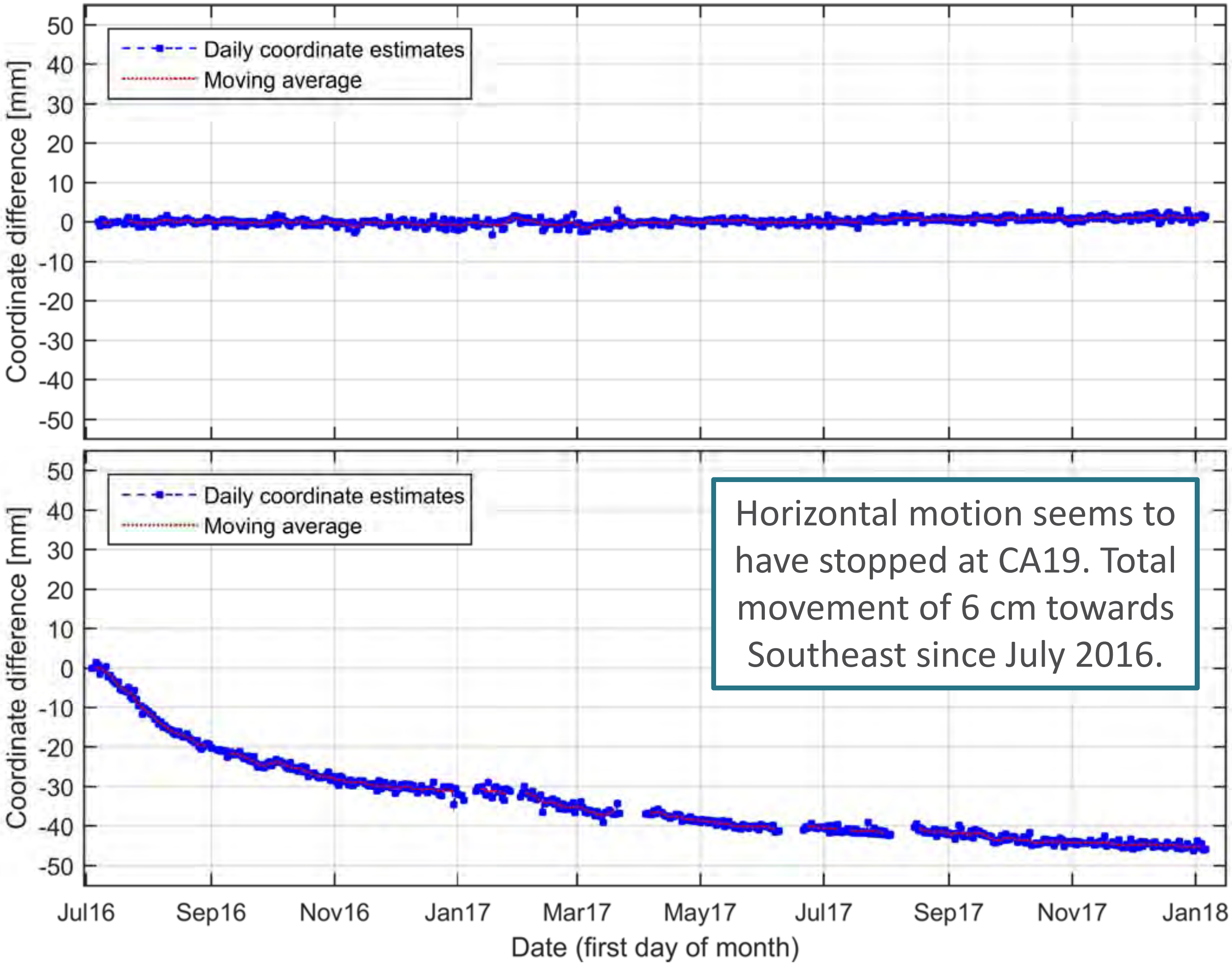


CA07
Wilton Park Road

East component

CA19
Menangle Road

Result of GPS processing – continuously operating sites

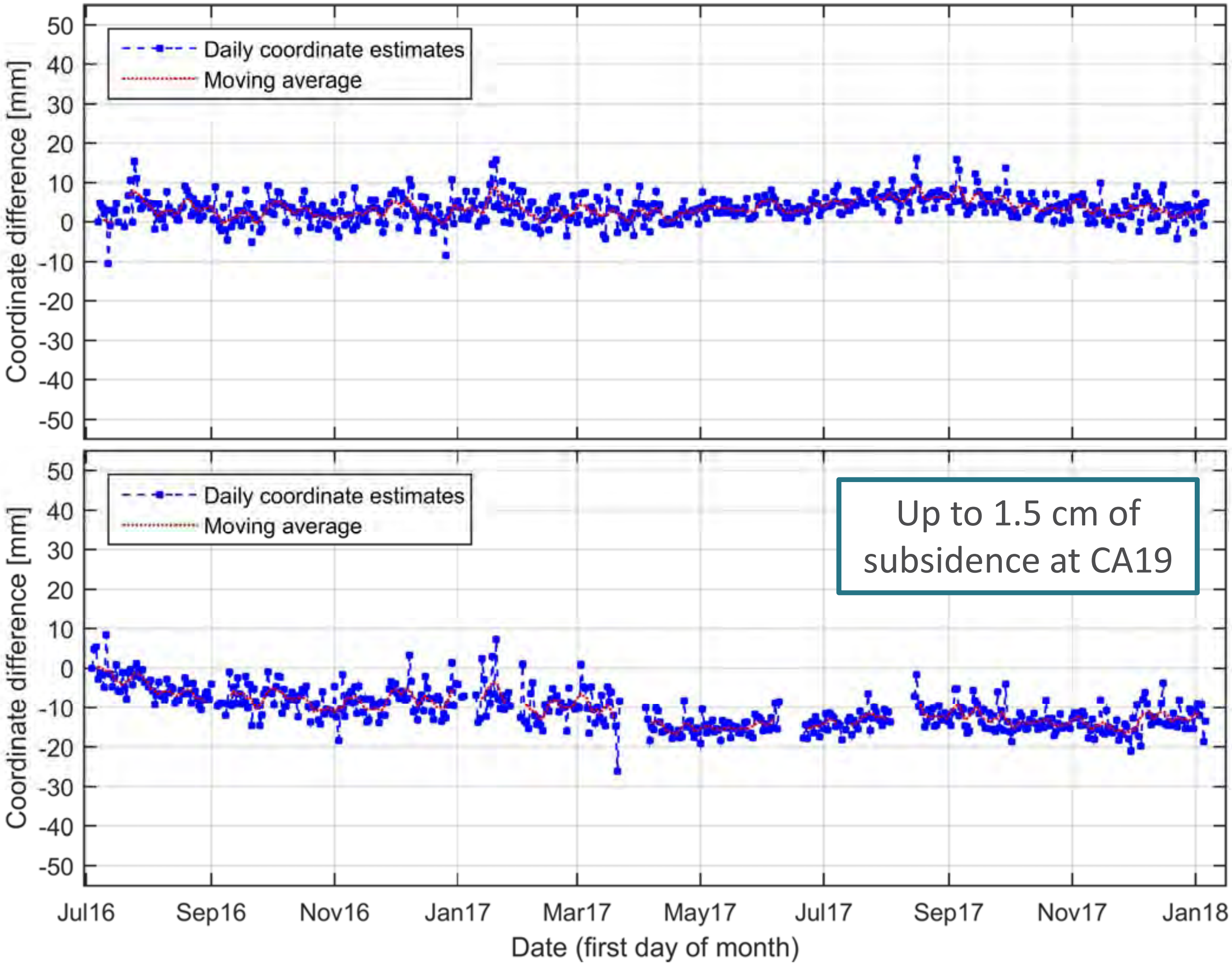


CA07
Wilton Park Road

North component

CA19
Menangle Road

Result of GPS processing – continuously operating sites

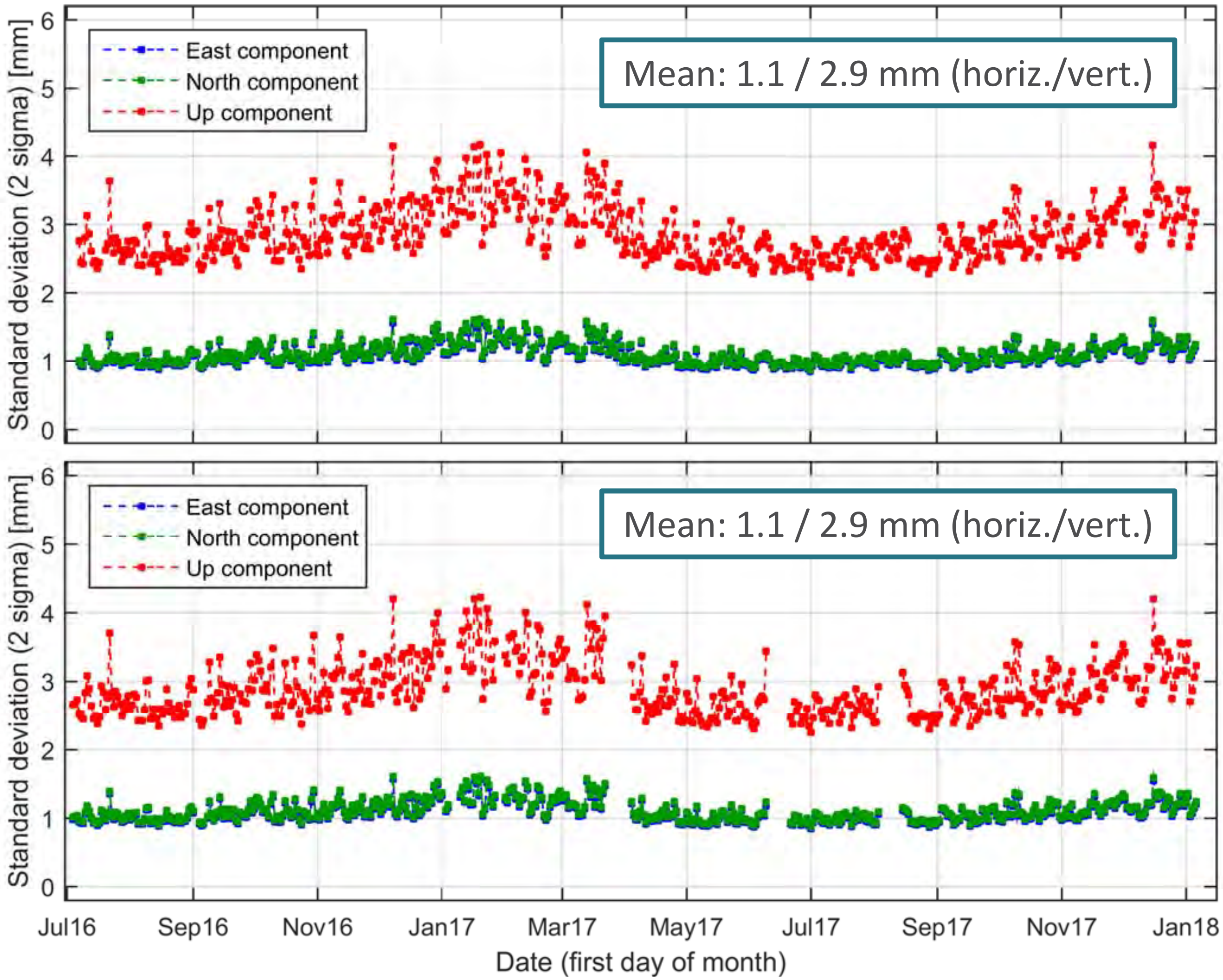


CA07
Wilton Park Road

Up component

CA19
Menangle Road

Result of GPS processing – continuously operating sites



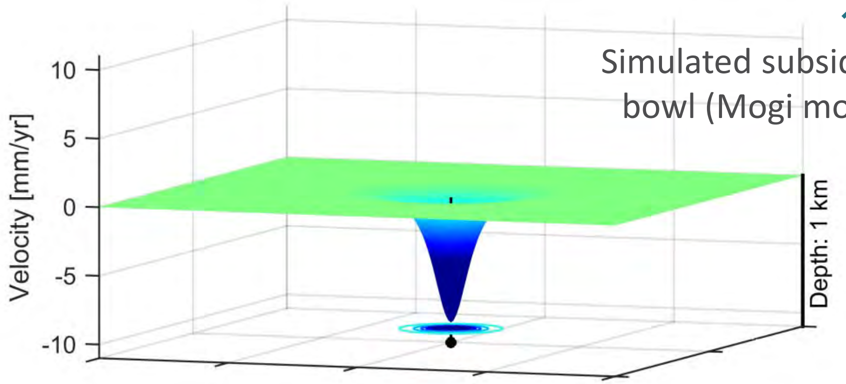
CA07
Wilton Park Road

Standard deviations

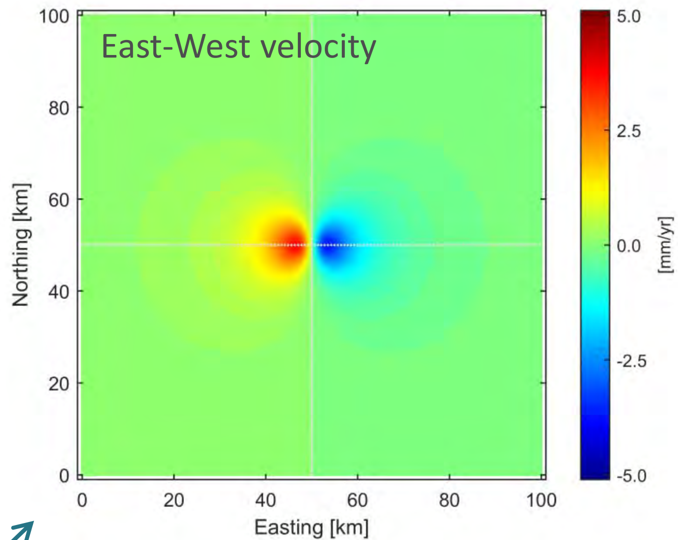
CA19
Menangle Road

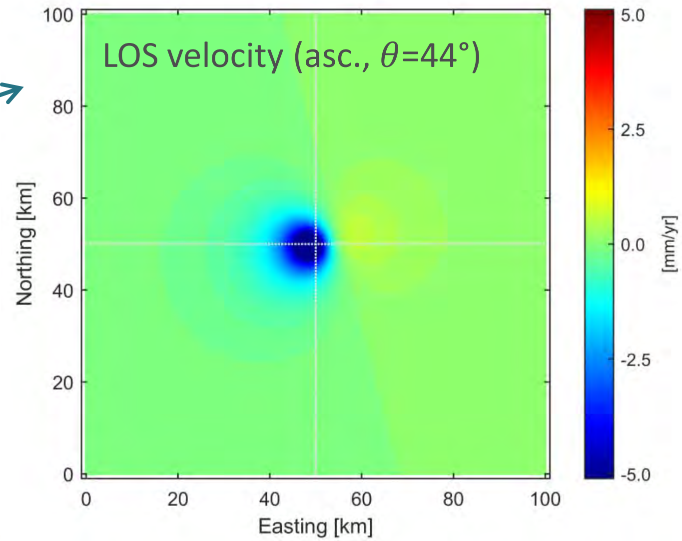
Combination of displacements

- Every displacement happens in three dimensions, e.g. in a coordinate system defined by North, East and Up (E, N, U). With InSAR we can only detect displacements in the 1D Line of Sight (LOS) towards the sensor.
- Often a vertical displacement component is derived from LOS measurements by assuming no horizontal movement. This is wrong and leads to errors in the resulting vertical displacements, particularly for image geometries with large incidence angles ($\theta > 25°$). The maximum absolute error in the vertical displacement can reach 47% of the horizontal displacement component for $\theta = 25°$, see Samieie-Esfahany et al. (2009).

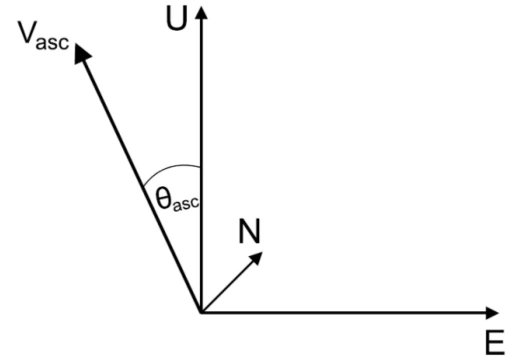


Simulated subsidence bowl (Mogi model)





Mathematical data combination



V: velocity or displacement
α: satellite heading
θ: incidence angle

- Least-squares adjustment of displacements/velocities:

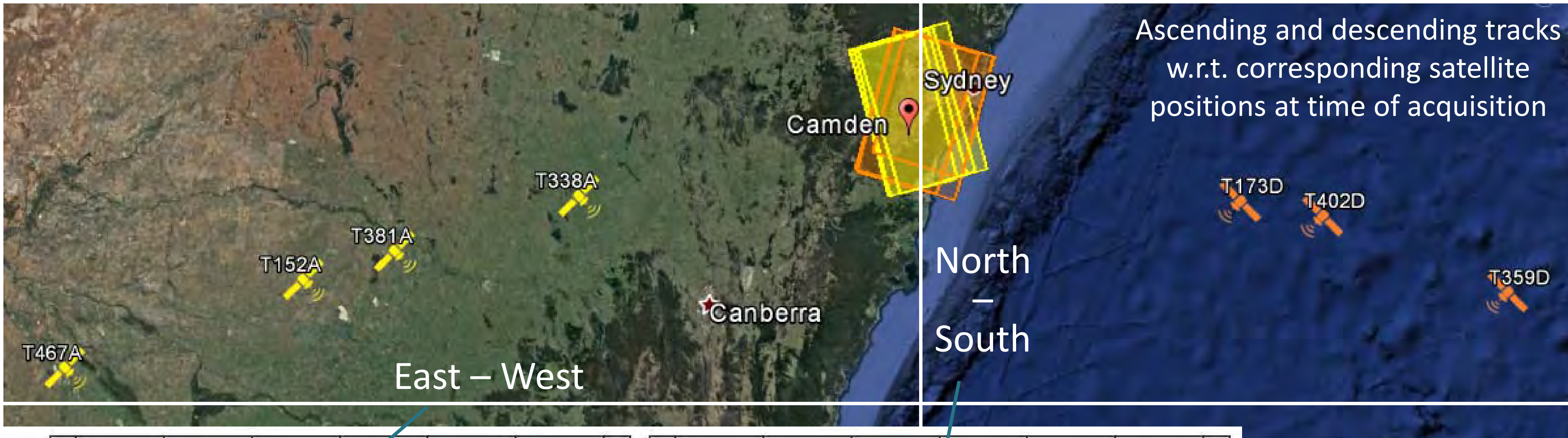
Observations — Estimated parameters

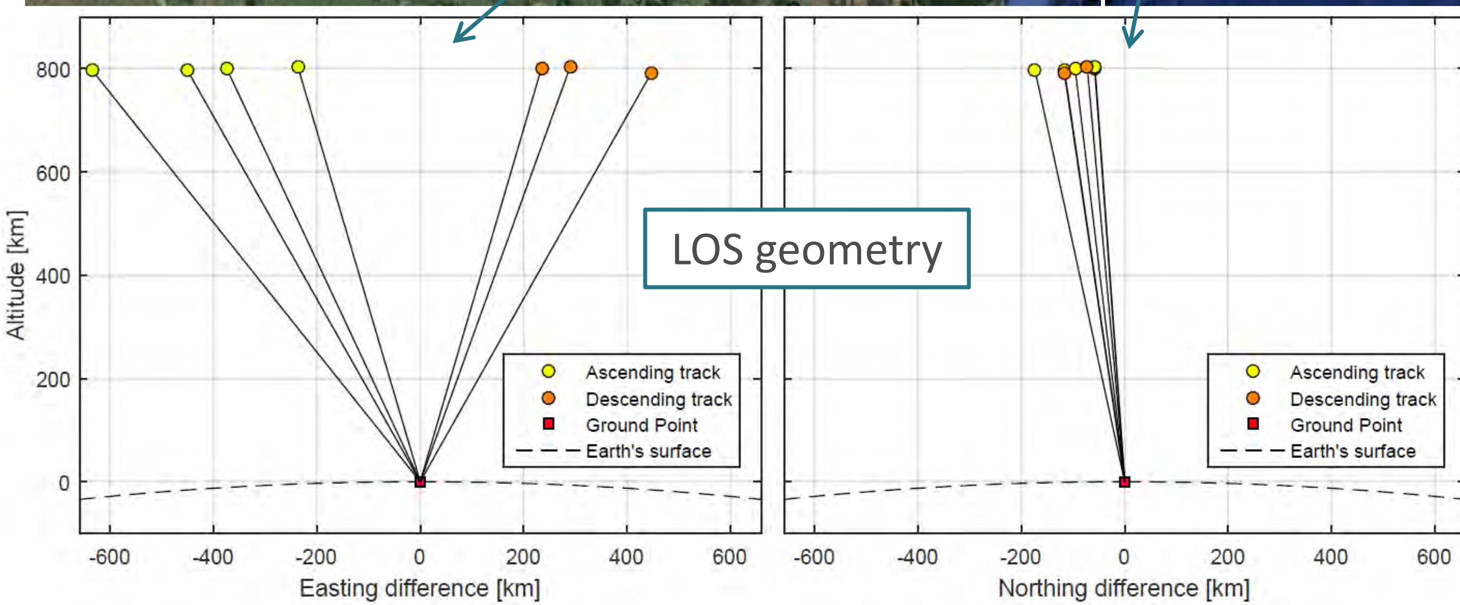
$$y = A \cdot x + e$$

$$\begin{pmatrix} V_{asc1} \\ V_{asc2} \\ \vdots \\ V_{desc1} \\ V_{desc2} \\ \vdots \end{pmatrix} = \begin{pmatrix} -\sin\theta_{asc1}\cos\alpha_{asc1} & \sin\theta_{asc1}\sin\alpha_{asc1} & \cos\theta_{asc1} \\ -\sin\theta_{asc2}\cos\alpha_{asc2} & \sin\theta_{asc2}\sin\alpha_{asc2} & \cos\theta_{asc2} \\ \vdots & \vdots & \vdots \\ -\sin\theta_{desc1}\cos\alpha_{desc1} & \sin\theta_{desc1}\sin\alpha_{desc1} & \cos\theta_{desc1} \\ -\sin\theta_{desc2}\cos\alpha_{desc2} & \sin\theta_{desc2}\sin\alpha_{desc2} & \cos\theta_{desc2} \\ \vdots & \vdots & \vdots \end{pmatrix} \begin{pmatrix} V_E \\ V_N \\ V_U \end{pmatrix} + e$$

- Displacements in East, North and Up can (theoretically) be estimated from ascending and descending LOS velocities at every grid pixel with at least three observations.
- Note that the number of lines in the observation vector y and the design matrix A is adapted according to the number of observations in each grid pixel.

Geometric considerations – satellite positions





The InSAR geometry is **good** to solve **for East and Up components** of a displacement, but **poor for the North component** as all satellites are observing the area of interest from a similar position in north direction.