Deformation rate estimation on changing landscapes using Temporarily Coherent Point InSAR

Lei Zhang(1), Xiaoli Ding(1) and Zhong Lu(2)

(1)The Hong Kong Polytechnic University, Kowloon, Hong Kong

(2)U.S. Geological Survey, Vancouver, Washington, USA

FRINGE 2011 WORKSHOP

esa

Deformation rate estimation on changing landscapes using Temporarily Coherent Point InSAR

Lei Zhang[1], Xiaoli Ding[1] and Zhong Lu[2]

(1)The Hong Kong Polytechnic University, Kowloon, Hong Kong

(2)U.S. Geological Survey, Vancouver, Washington, USA

The Hong Kong Polytechnic University 香港理工大學

USGS science for a changing world

Background

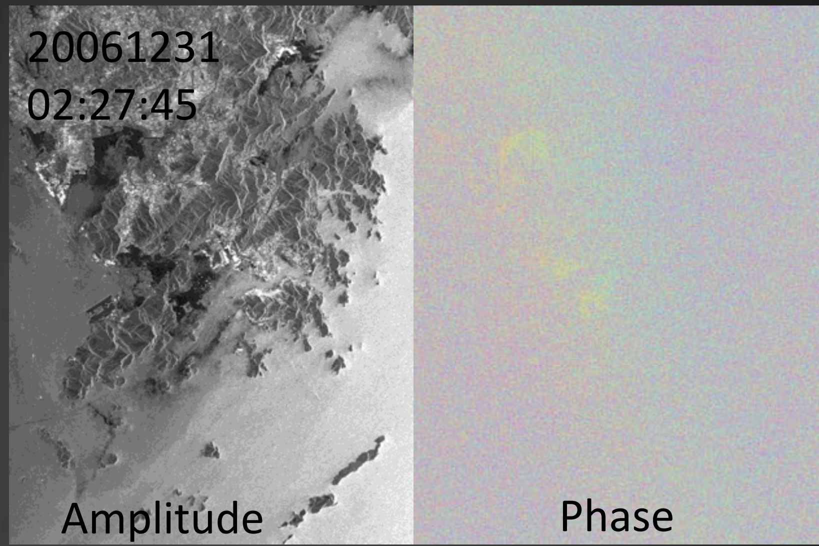
SAR data: single look complex (SLC)

Amplitude Phase

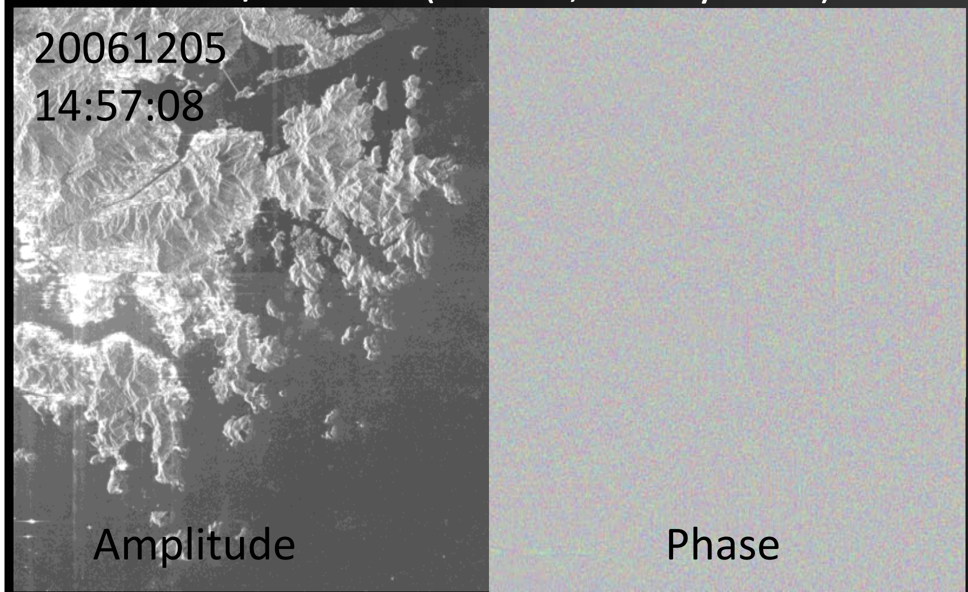
All-weather day/night imagery

For a single SLC image, phase is useless…

Envisat/ASAR (C-band, 5m-by-25m)



ALOS/PALSAR (L-band, 3m-by-10m)



COSMO-SkyMed (X-band, 1m-by-1m)

Background

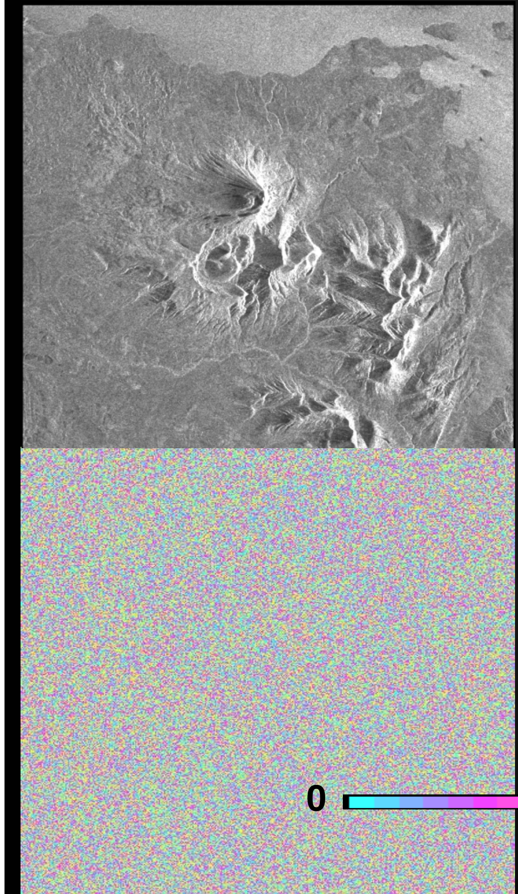
SAR data: application

>> Monitoring sea ice zones and the arctic environment
>> Surveillance of marine environment (e.g. oil spill monitoring)
>> Maritime security (e.g. ship detection)
>> Wind, wave, current monitoring
>> Monitoring of land surface motion (subsidence, landslide, tectonics, volcanoes, etc.)
>> Support to emergency/risk management (e.g. flooding etc.)
>> Mapping of land surface: forest, water and soil, agriculture, etc.

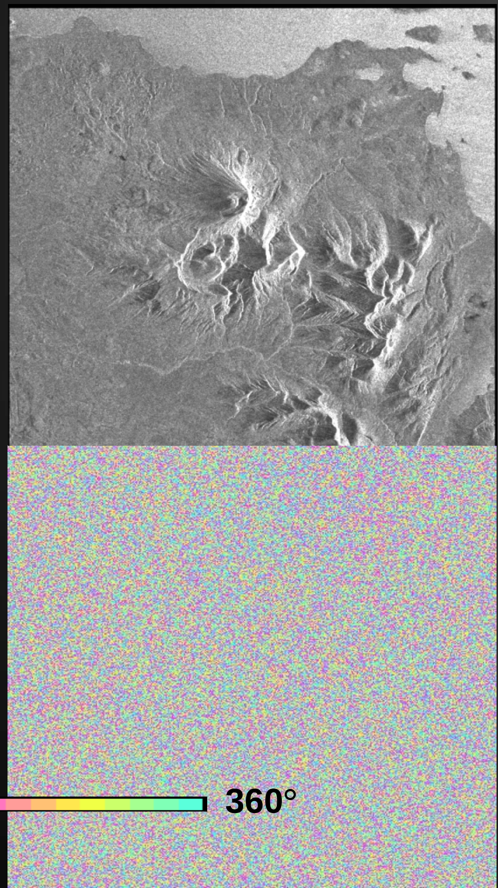
(source: ESA's GMES program)

Background

InSAR : phase analysis technique



$$\phi_1 = -\frac{4\pi}{\lambda} r_1 + \boxed{a_1}$$

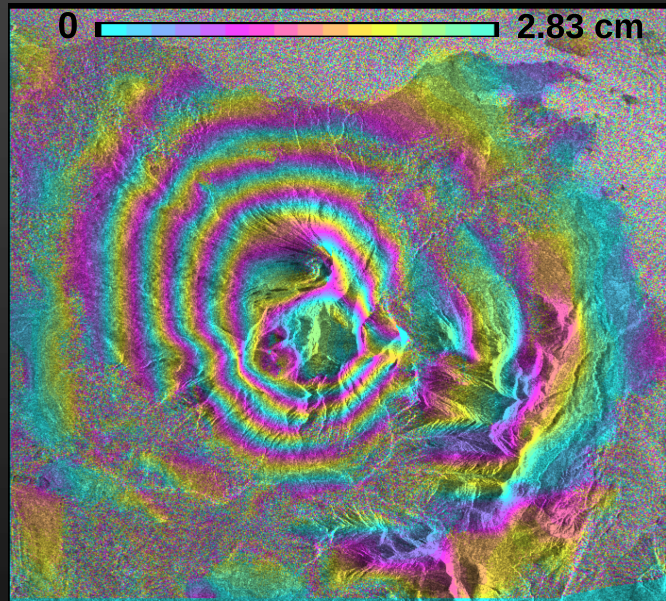


$$\phi_2 = -\frac{4\pi}{\lambda} r_2 + \boxed{a_2}$$

$$\phi = \phi_1 - \phi_2 = -\frac{4\pi(r_1 - r_2)}{\lambda} + (a_1 - a_2)$$

If $a_1 = a_2$ ...

$$\phi = \phi_1 - \phi_2 = -\frac{4\pi(r_1 - r_2)}{\lambda}$$



Interferometric phase is useful!!

Background

InSAR : phase analysis technique

$$\phi = \phi_1 - \phi_2 = -\frac{4\pi(r_1 - r_2)}{\lambda} \Longleftrightarrow \text{Target height and target motion}$$

$$\phi^i_{l,m} = \phi^i_{topo,l,m} + \phi^i_{defo,l,m} + \phi^i_{atmo,l,m} + \phi^i_{orbit,l,m} + \phi^i_{noise,l,m}$$

InSAR : precision (deformation) 1cm~ several cm

Advanced InSAR : multi-temporal InSAR technique

-Analysis of a large set of SAR images

-Focus on persistently coherent points

-Product: deformation rate & deformation time series

-Precision: 1mm~several mm

Background

Advanced InSAR : limitations of current techniques

-- phase unwrapping: low efficiency and/or unreliable

It has been solved by TCPInSAR that can avoid phase unwrapping!!

-- dependence on persistently coherent points

Current advanced InSAR techniques work well on stable landscapes

How about on changing landscapes?

Background

Stable vs. Changing Landscapes

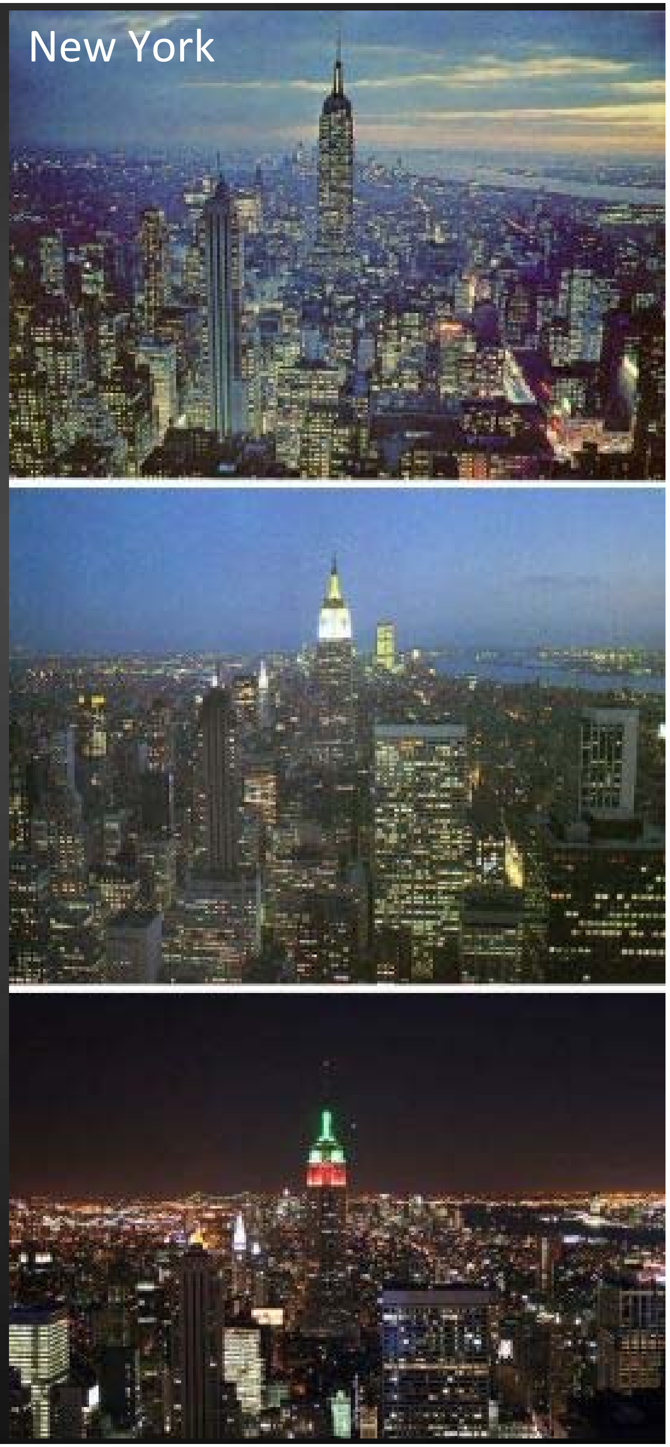
on stable landscapes there are abundant scatterers that can keep visible during a long observation time span

In well-developed urban areas, dense persistent scatterers can be identified

1954

1985

2009



Background

Stable vs. Changing Landscapes

However on changing landscapes there are abundant scatterers that cannot keep visible during a long observation time span

In developing urban areas, persistent scatterers cannot be densely identified

1990

2003

2007

Background

Urban renewal and sprawl…

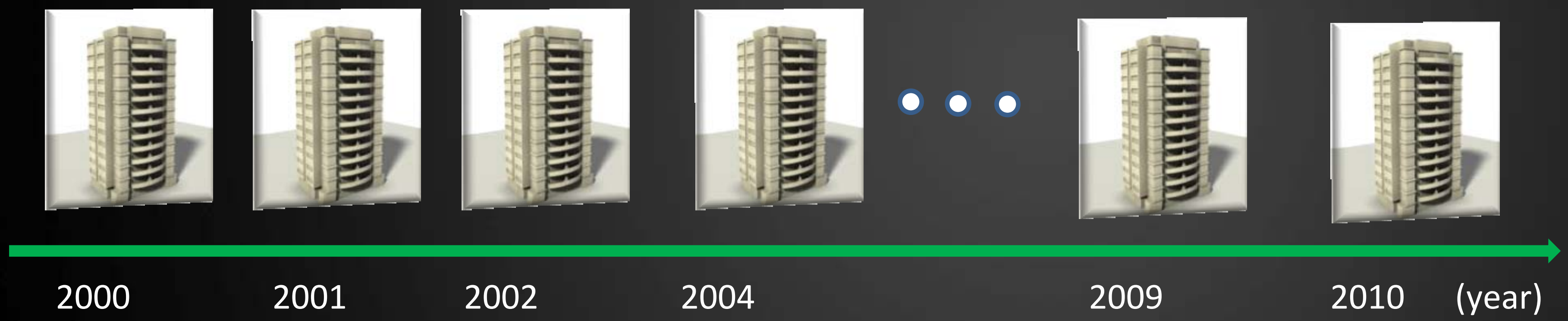
Most developing countries are undergoing surprisingly fast urbanization…

Townscapes have changed significantly, raising difficulties for current MT-InSAR techniques to get detailed defo. maps…

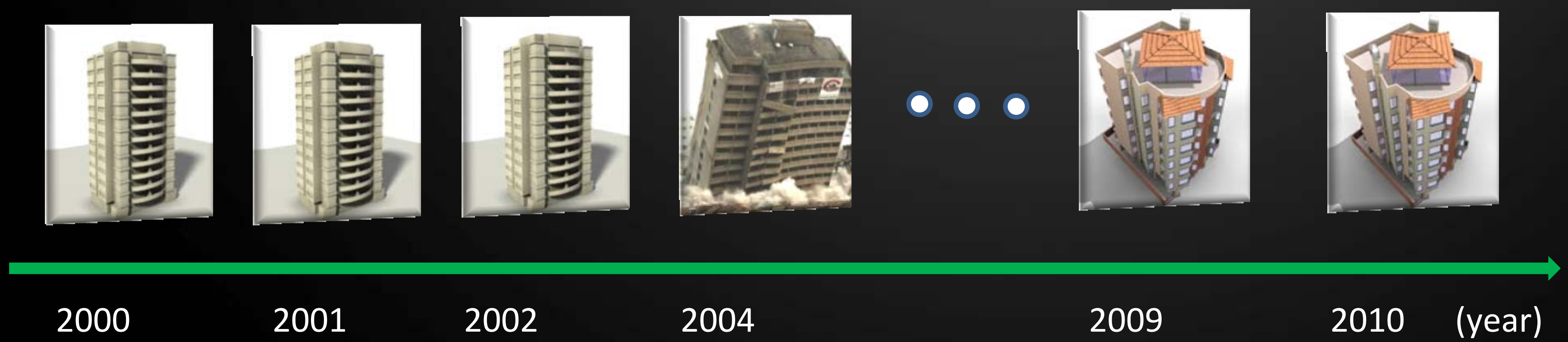
Background

Persistently Coherent Point vs. Partially Coherent Point

Persistently Coherent Point– Visible over the whole observation time span



Partially Coherent Point – Visible over a part of observation time span



Background

Can we identify both persistently coherent points and partially coherent points simultaneously and retrieve deformation from these points?

Temporarily Coherent Pont

InSARTemporarily Coherent Point

– not necessary to keep coherent during the whole time span

– including persistently coherent point and partially coherent point

TCPInSAR

TCP Identification

>> image pair based method (offset deviation#)

>> image based method (amplitude mad median ratio (AMMR))

Deformation estimation

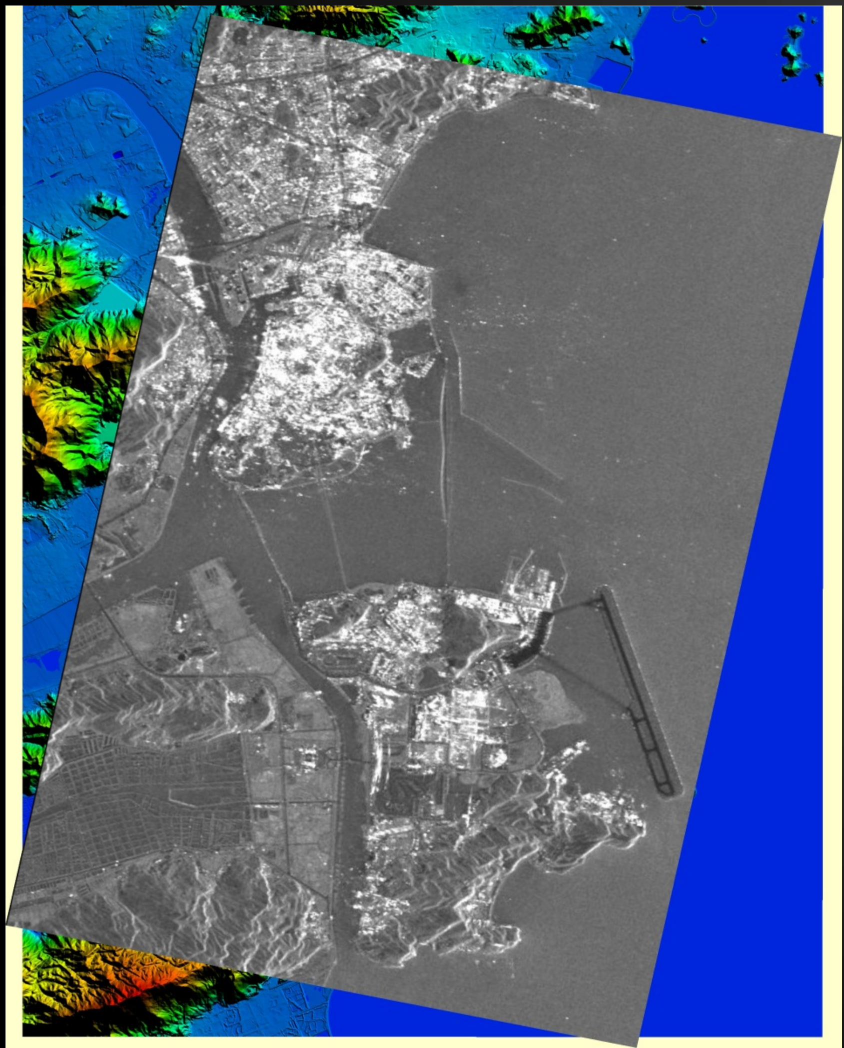
>> L2 norm (least squares) estimator with phase ambiguity detector*

>> L1 norm estimator

#: Zhang, L., Ding, X.L., & Lu, Z. (2011a). *ISPRS Journal of Photogrammetry and Remote Sensing, 66*, 146-152

*: Zhang, L., Ding, X.L., & Lu, Z. (2011b). IEEE Transactions on Geoscience and Remote Sensing, 49, 547-556

Case studies: 1. Macau with C-band data

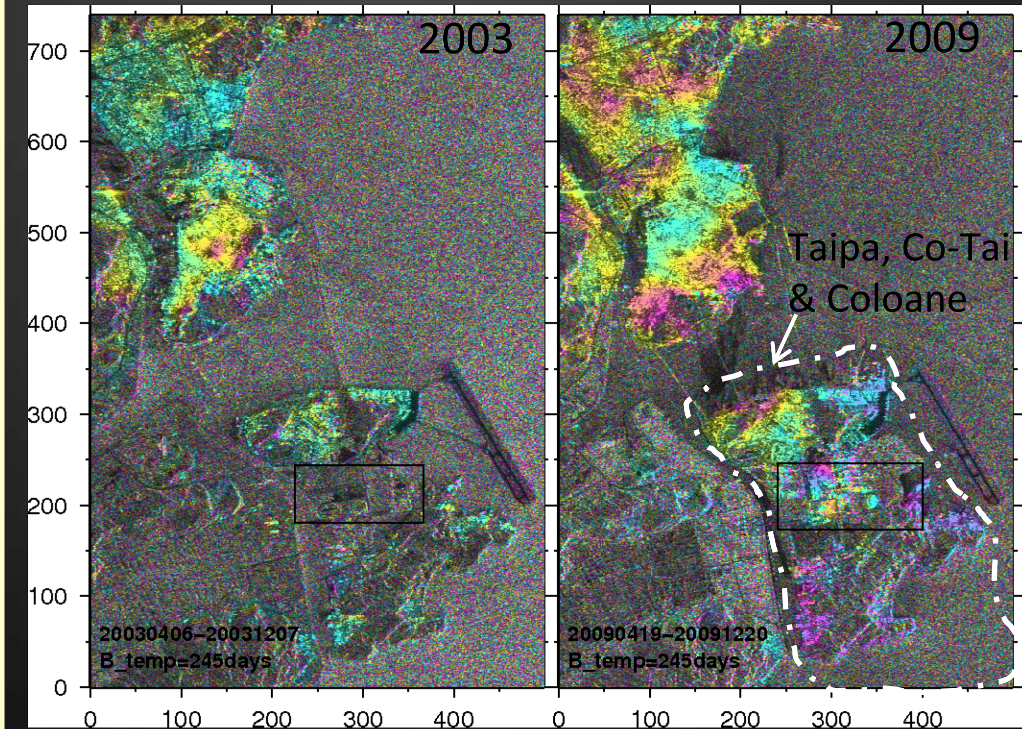


(Macau)A

Data:

38 Envisat/ASAR images acquired from 2003 to 2010

81 interf. selected with baseline thresholds: 250day,150m and 300Hz



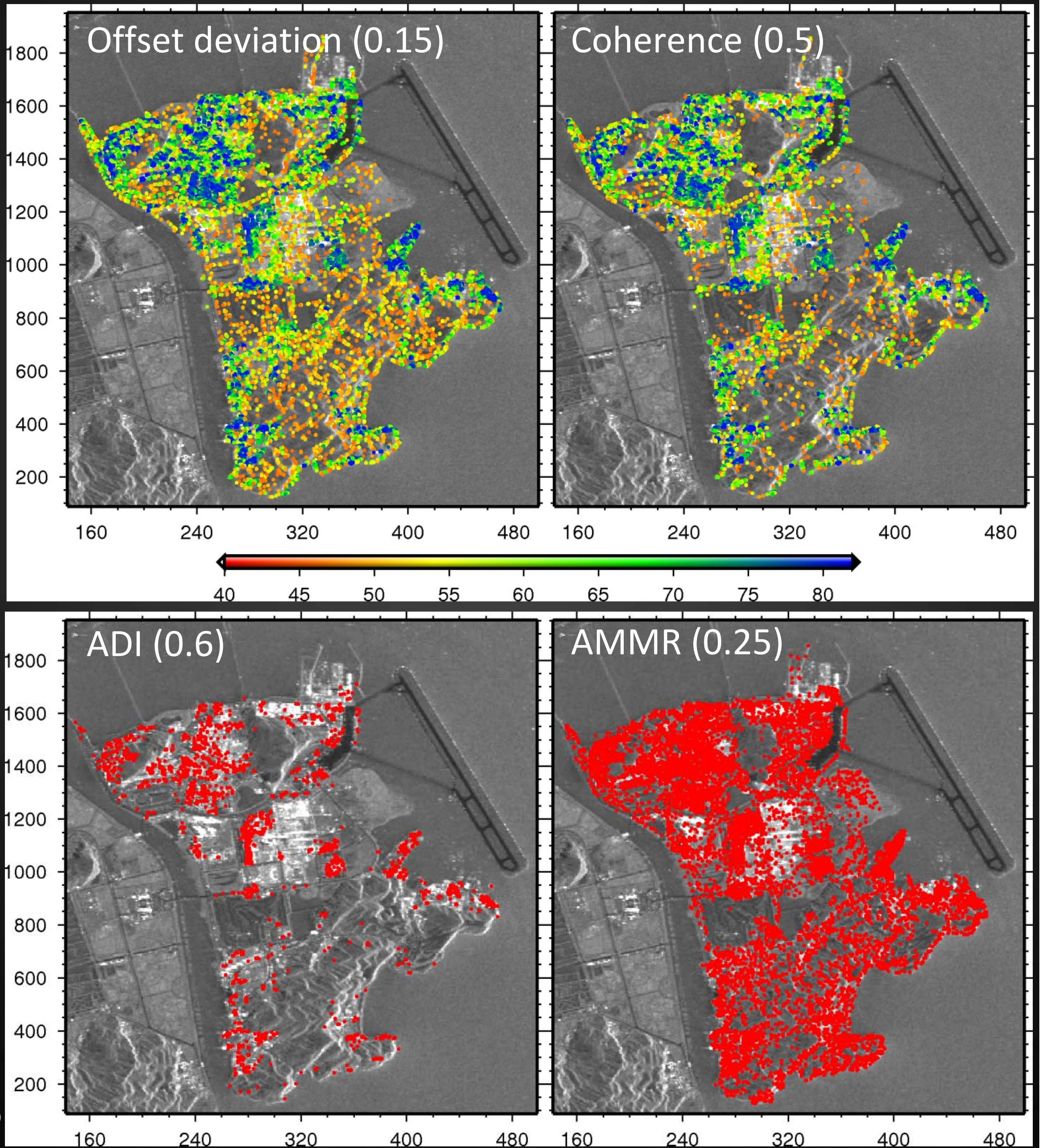
(Many buildings have been put up…)

Case studies

Image pair based methods:

TCP selection

Image based methods:



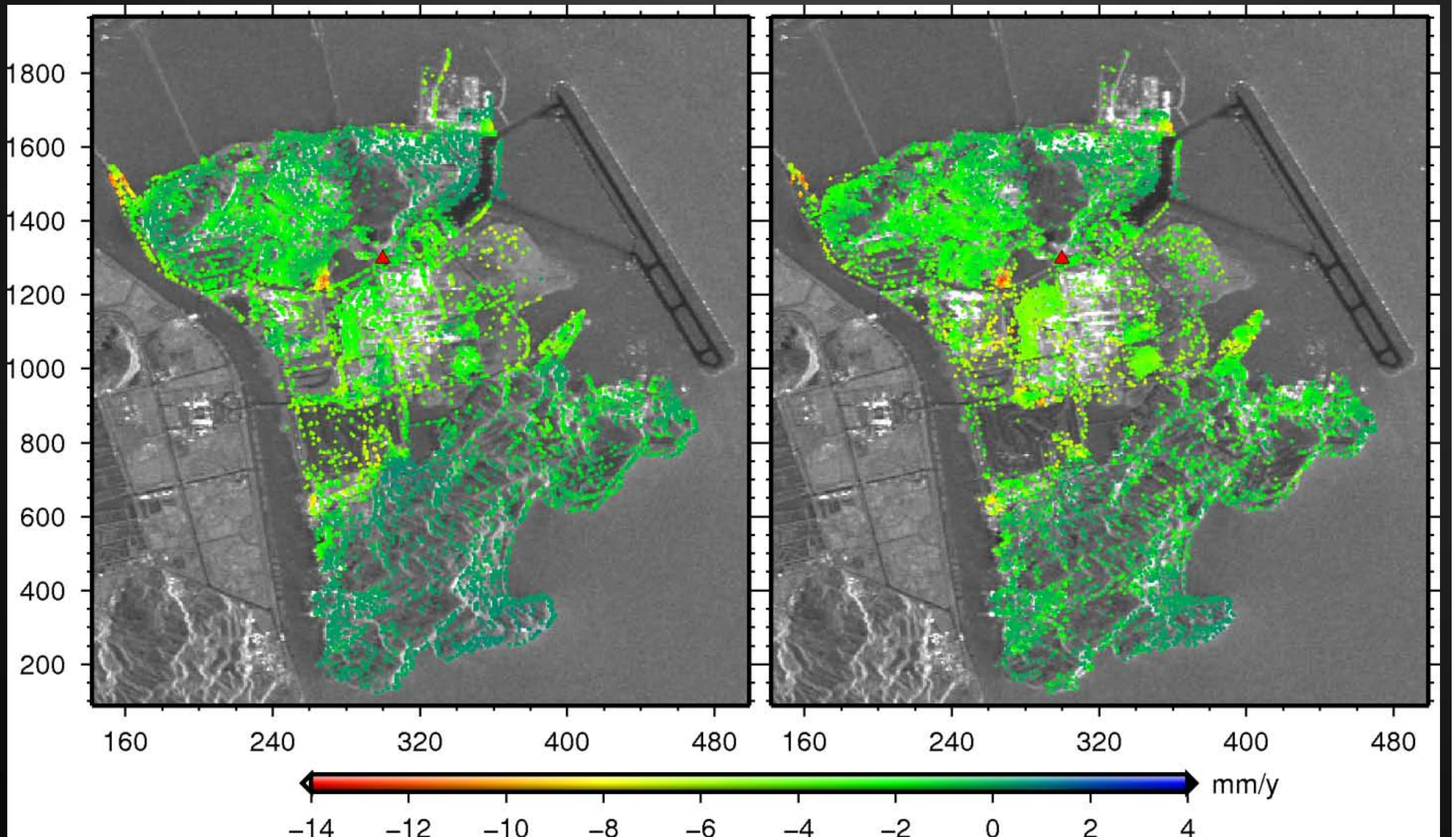
ADI: Amplitude Dispersion Index
AMMR: Amplitude Mad Median Ratio

Case studies

Result
s

LS estimator on TCPs selected by offset deviation

L-1 norm estimator on TCPs selected by AMMR

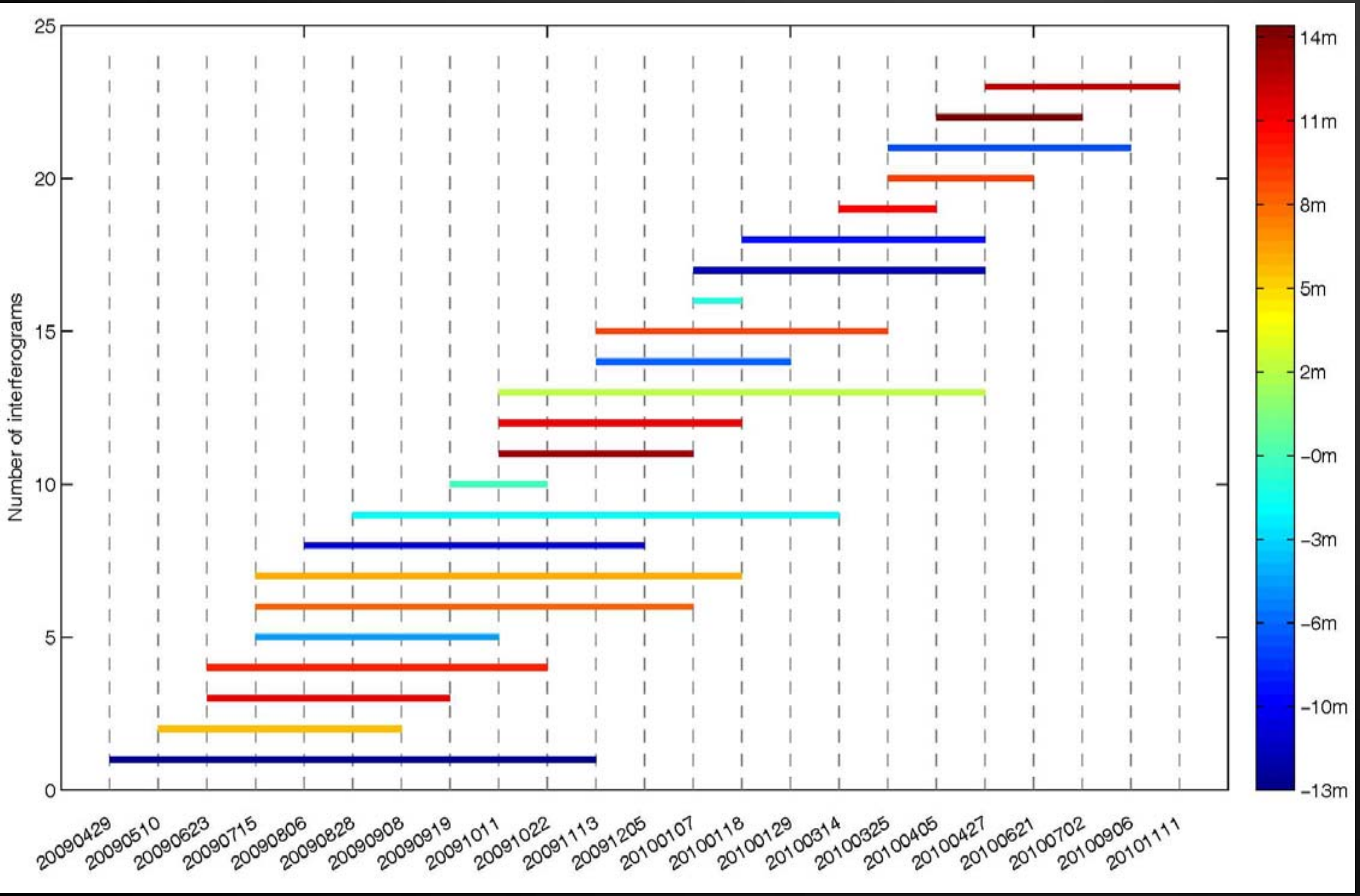


Consistent with ground measurements provided by DSCC of Macau

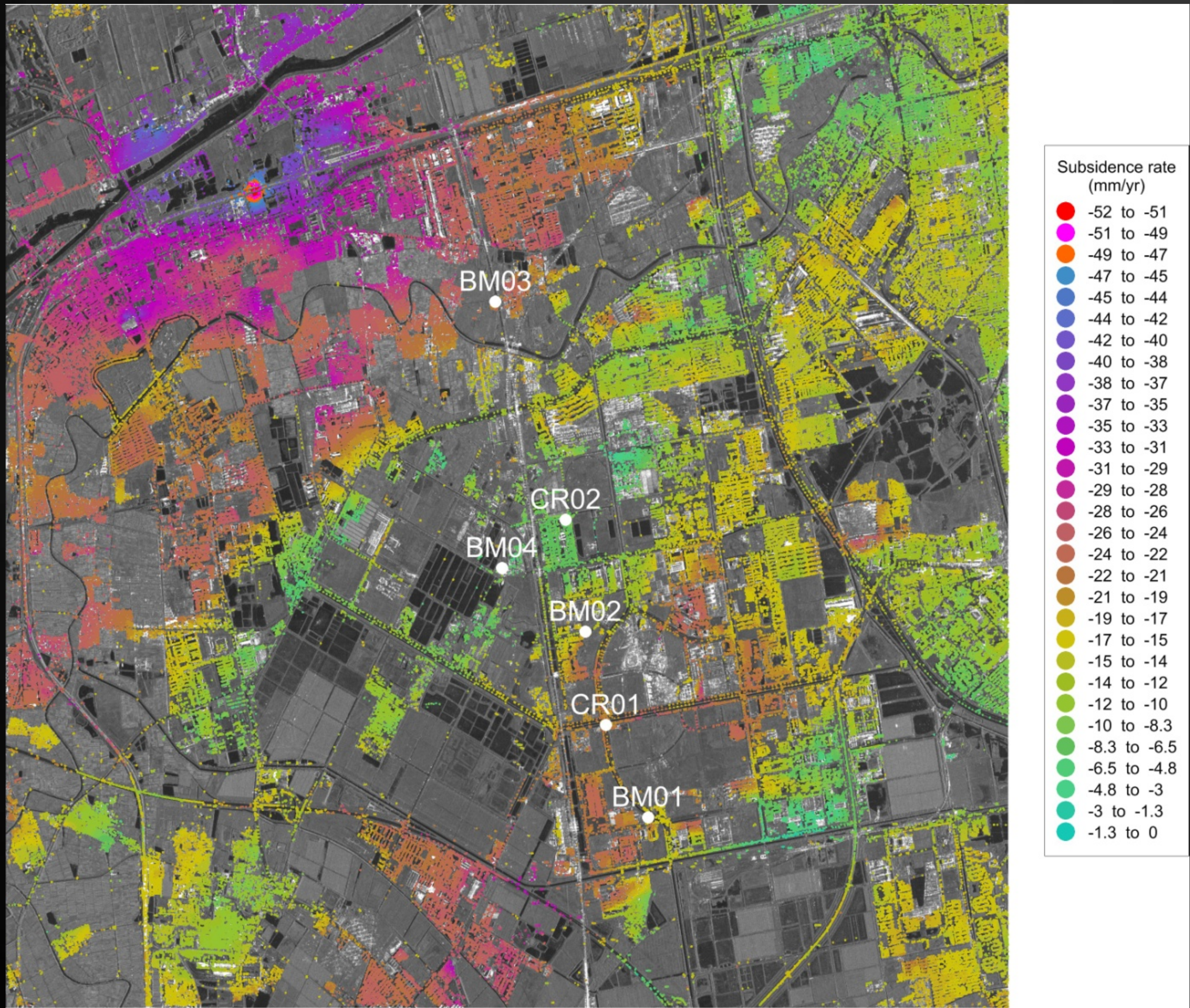
Case studies: 2. Tianjin with X-band data

TerraSAR-X: High resolution (3m-by-3m)
External DEM: Low resolution (90m)

Ultra short baselines!!

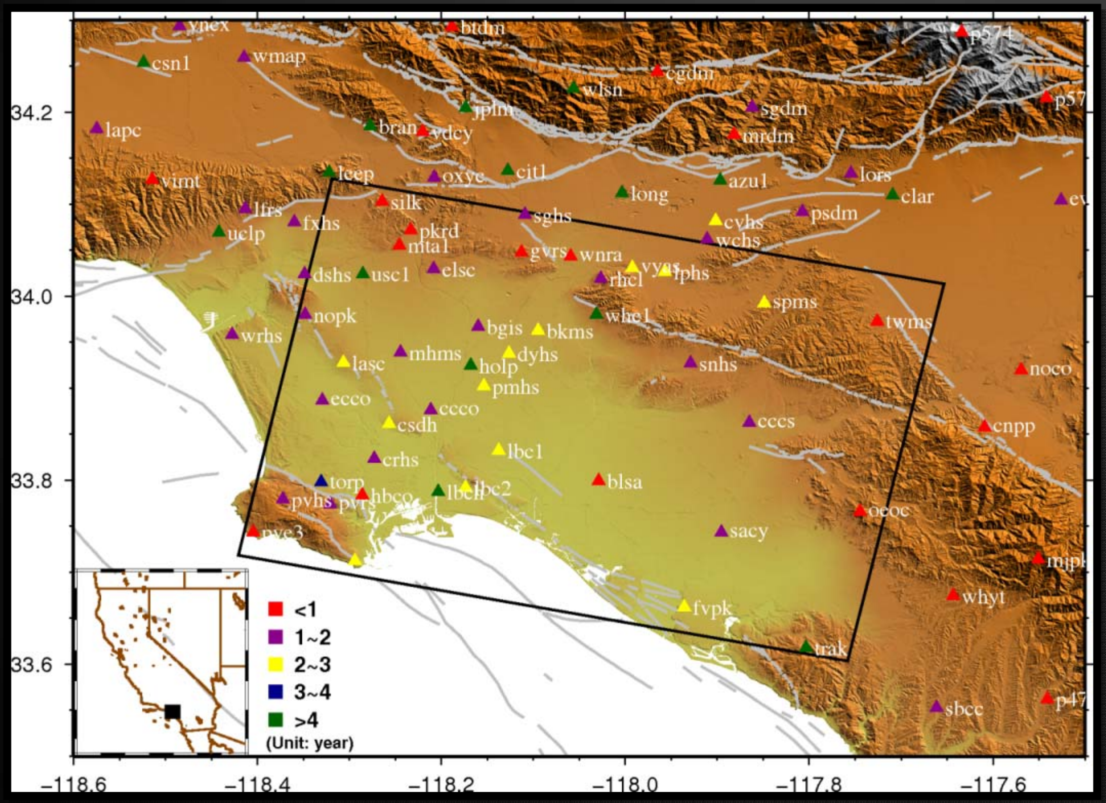


Case studies: 2. Tianjin with X-band data



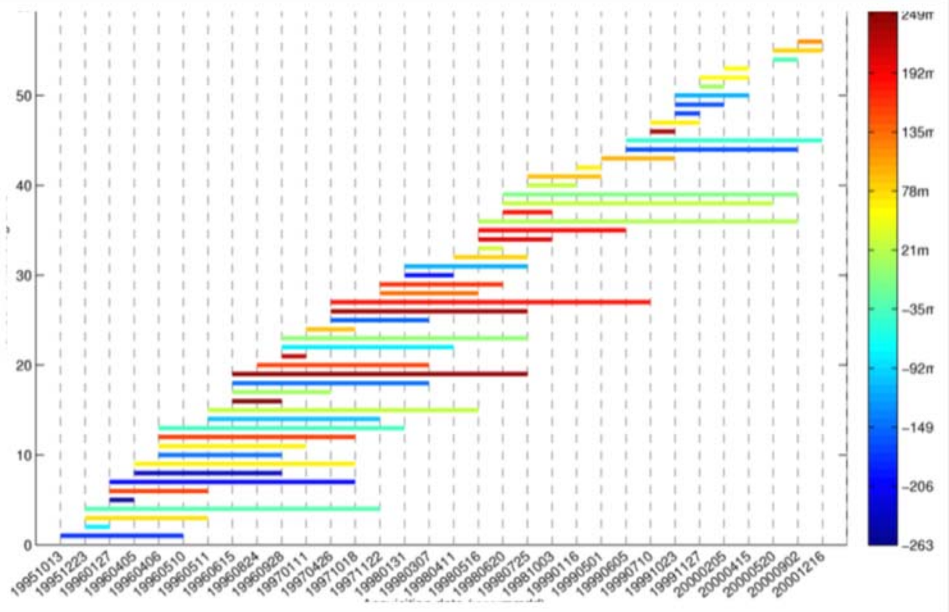
Mean defo. rate over Tianjin from 2009 to 2010

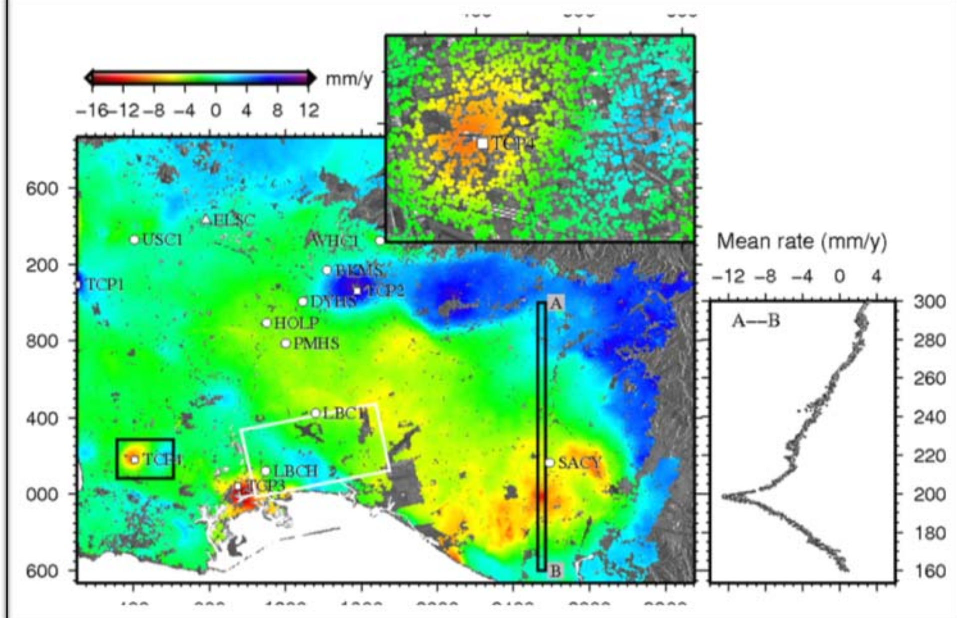
Case studies: 3. LA basin with C-band data

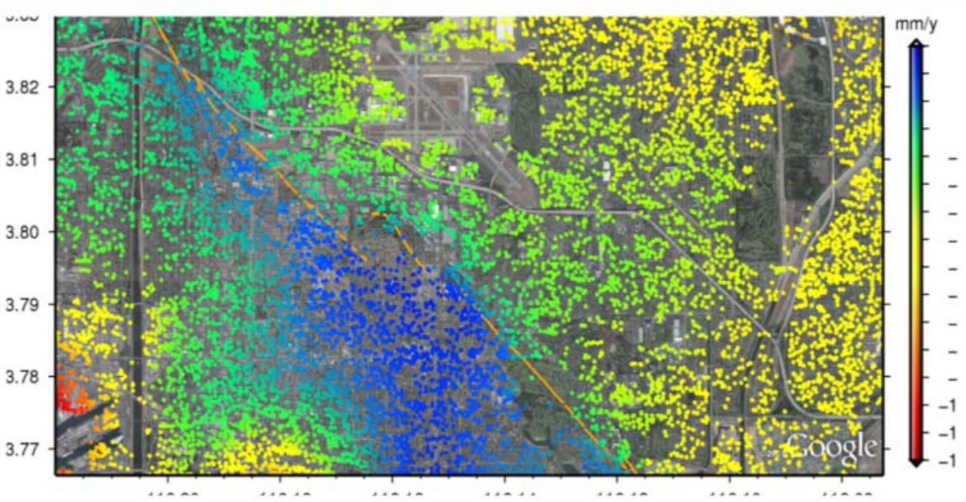


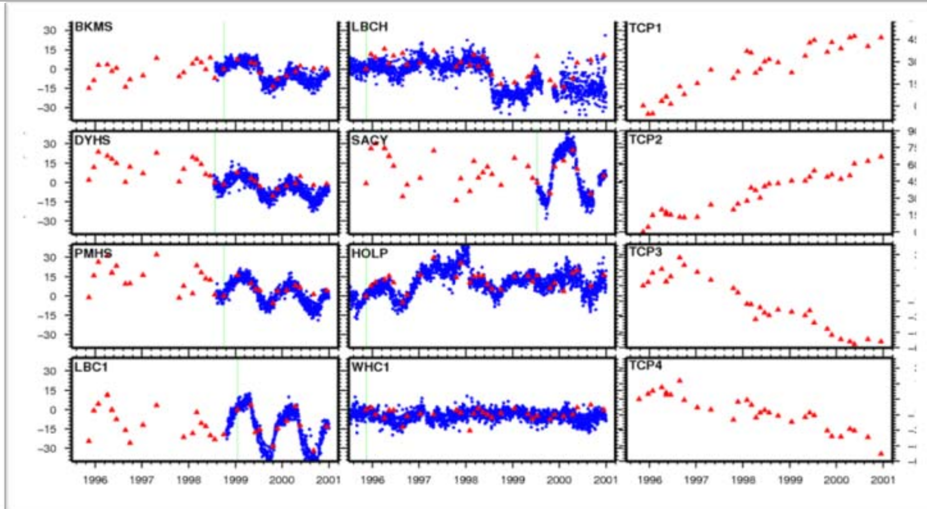
55 interferograms from 32
ERS-1/2 images
Baseline threshold:
300m;2.5yr;300Hz

Case studies: 3. LA basin with C-band data





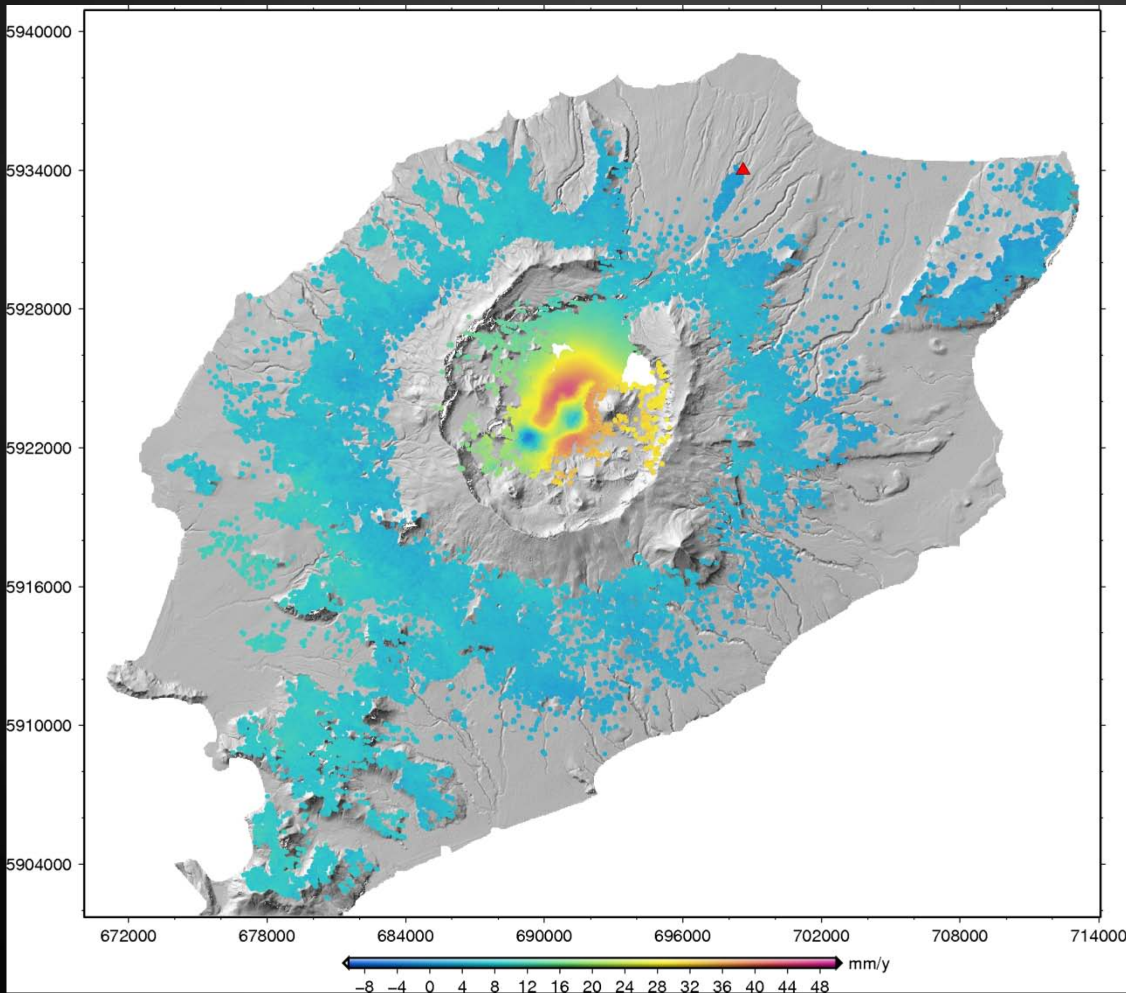




Case studies: 3.Okmok volcano with C-band data

24 interferograms with spatial baseline less than 300m and temporal baseline less than 700d constructed from **19 Envisat/ASAR images**

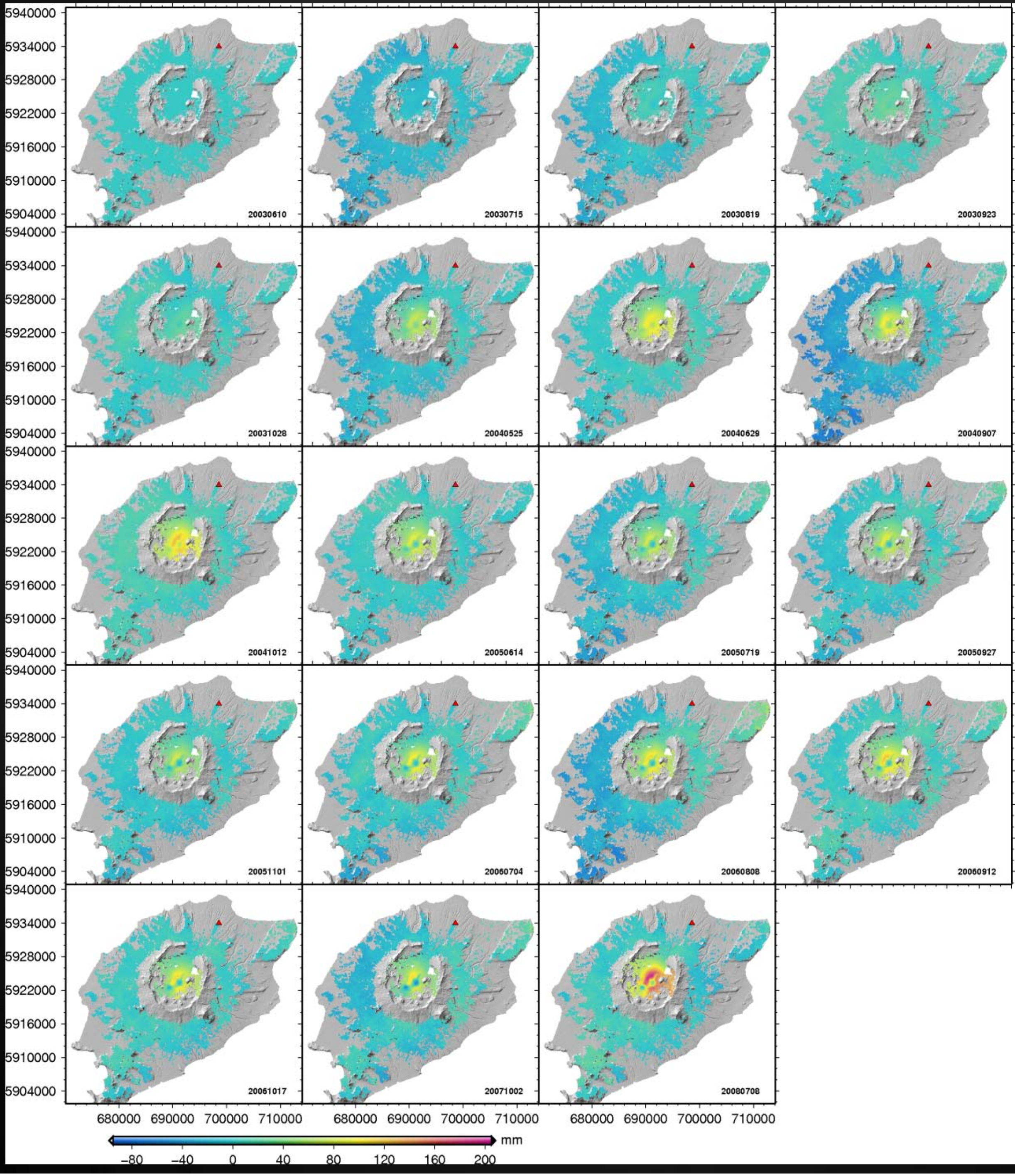
Mean defo. rate
20030610-20080708



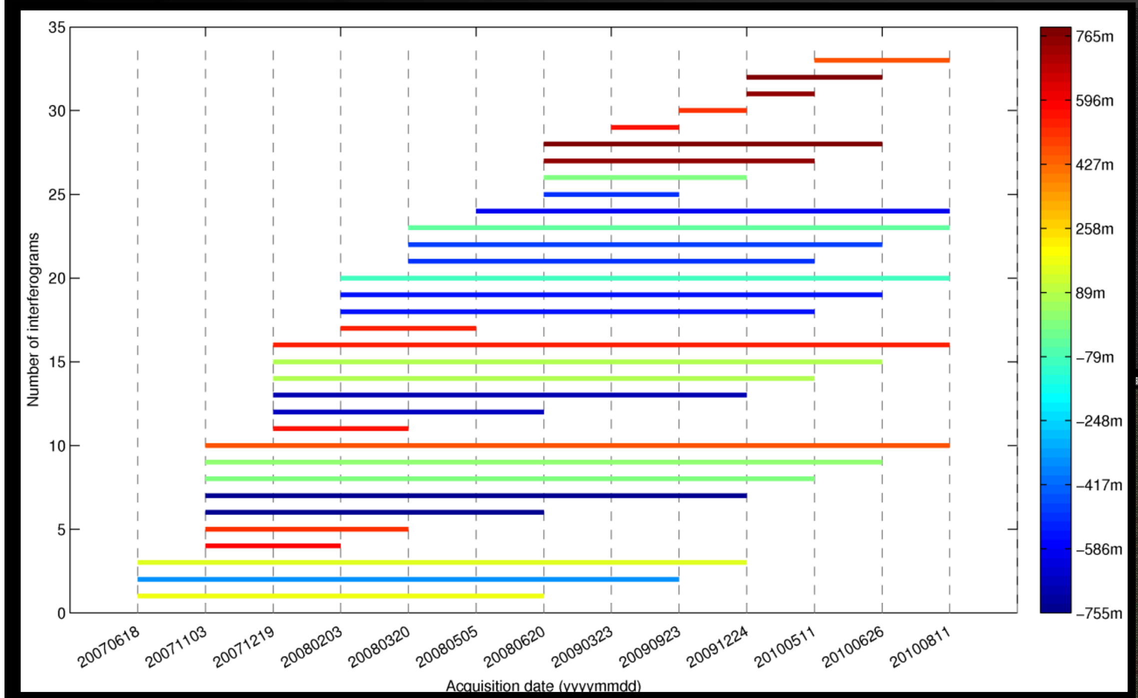
Okmok: deformation time series

20030610
⇩
20080708

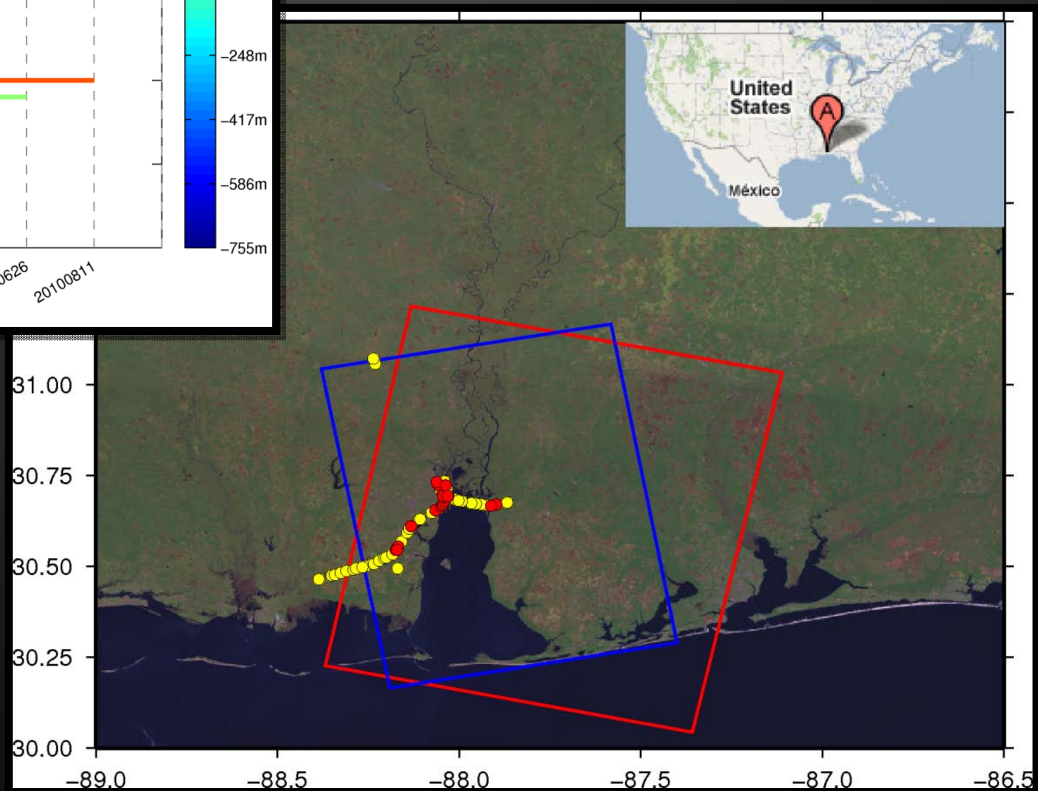
Eruption: 20080712



Case studies: 4. Mobile city with L-band data



ALOS/PALSAR data



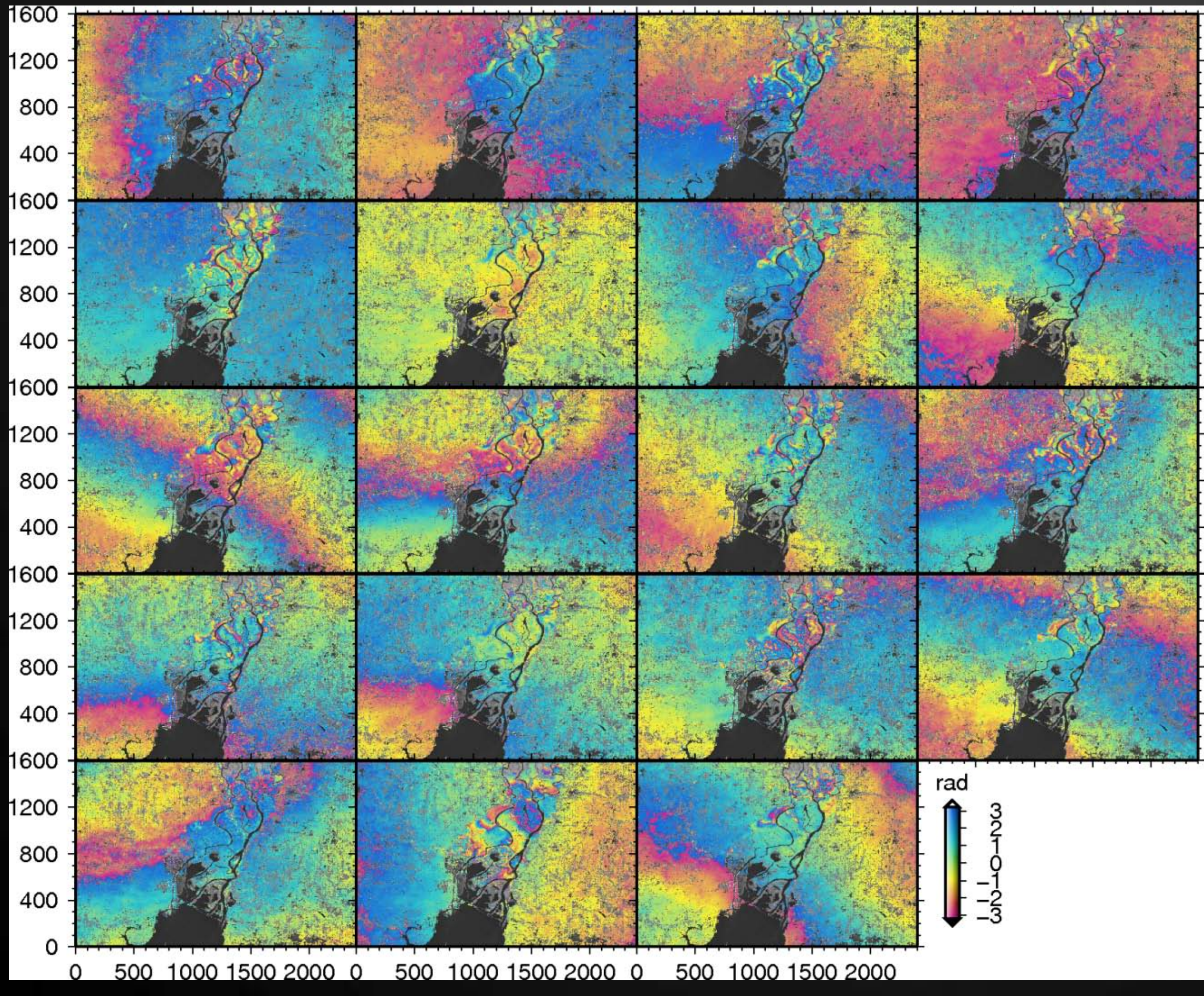
19 interferograms generated from 12 SAR images.

422,440 TCPs and 1,444,800 arcs

Case studies: 5. Mobile city with L-band data

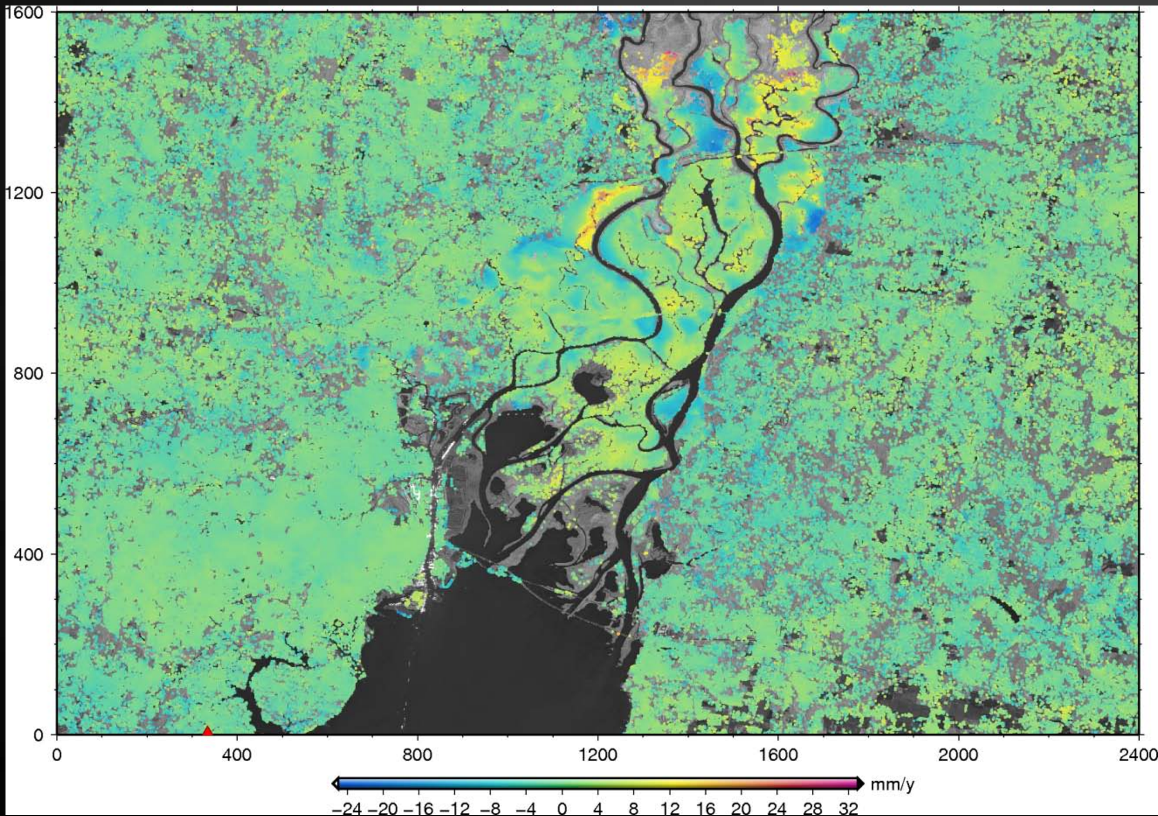
Solution: TCPInSAR (v2.0)

---Resolving the deformation parameters together with orbital errors!



Case studies: 5. Mobile city with L-band data

Solution: TCPInSAR (v2.0)
---Resolving the deformation parameters together with orbital errors!

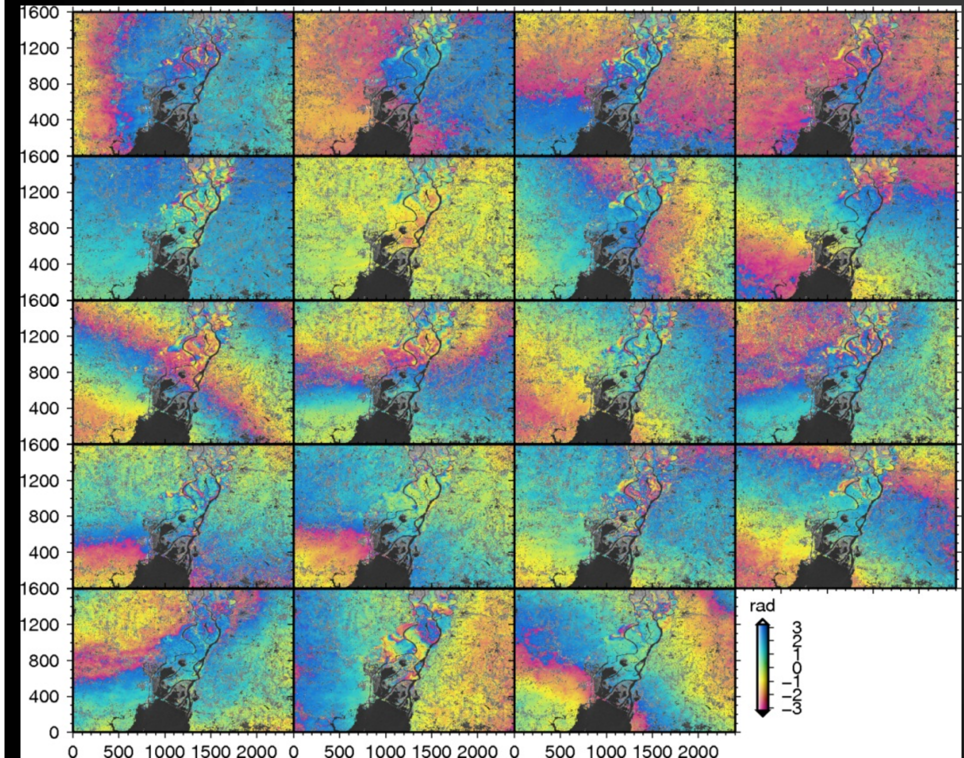


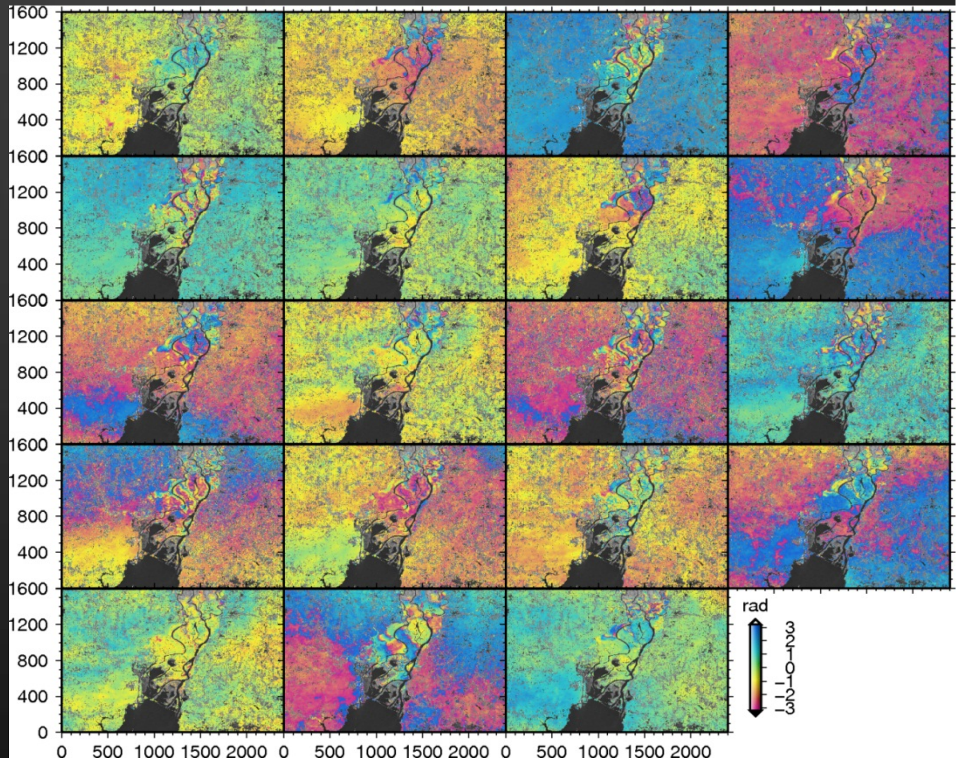
Mean defo. rate (2007-2010)

Case studies: 5. Mobile city with L-band data

Solution: TCPInSAR (v2.0)

---Resolving the deformation parameters together with orbital errors!





Conclusion

TCPInSAR is a promising tool for deformation monitoring on changing landscapes with multi-temporal SAR images.

- TCPInSAR can identify both persistently and partially coherent points
- TCPInSAR can estimate linear deformation rate (for partially coherent points) and deformation time series (for persistently coherent points) with no need of phase unwrapping
- TCPInSAR (v2.0) can estimate deformation rate and orbital errors simultaneously
- TCPInSAR(v2.0) can estimate ground deformation without external DEM
- Deformation time series over Hong Kong?
  Reclaimed areas, infrastructures ...
  Lack of funding for ordering SAR data…

Thanks!
Questions?

Contact:
lsxlding@polyu.edu.hk
lslzhang@polyu.edu.hk
lu@usgs.gov

Temporarily Coherent Point InSAR

TCP identification: Image based method

- Amplitude Mad-Median Ratio (AMMR)

Median absolute deviation
Mad(X)=median(abs(X-median(X))

$$\sigma_v \cong \frac{\sigma_A}{m_A} \Rightarrow \sigma_v \cong \frac{Mad_A}{Median_A}$$

A point with scaled intensity time series (25): PS? No; TCP? Yes!

[0.1, 0.2, 0.2, 0.3, 0.2, 0.2, 0.3, 0.8, 0.85, 0.9, 0.9, 0.92, 0.92, 0.91, 0.94, 0.93, 0.95, 0.95, 0.92, 0.94, 0.92, 0.91, 0.91, 0.92, 0.93];

$$\sigma_v \cong \frac{\sigma_A}{m_A} = 0.45 \quad \sigma_v \cong \frac{Mad_A}{Median_A} = 0.03$$

We do not know in which interferogram the selected TCPs are coherent.

Temporarily Coherent Point InSAR

TCP Parameter Estimator

- To resolve DEM error and linear deformation rate without the need of phase unwrapping

- Observations are **differential phases at the arcs** (point pairs) in multi-master interferograms with short baselines

- Core algorithms:

  L-2 norm (least squares) estimator with ambiguity detector[5]
  L-1 norm estimator

[5] Zhang, L., Ding, X.L., & Lu, Z. (2011b). *IEEE Transactions on Geoscience and Remote Sensing, 49*, 547-556

Temporarily Coherent Point InSAR

The system of observations

$$\phi^i_{l,m} = \phi^i_{topo,l,m} + \phi^i_{defo,l,m} + \phi^i_{atmo,l,m} + \phi^i_{orbit,l,m} + \phi^i_{noise,l,m}$$

$$\phi^i_{defo,l,m} = -\frac{4\pi}{\lambda}\Delta r^i_{l,m} = -\frac{4\pi}{\lambda}\sum_{j=S_{i+1}}^{M_i}(t_j - t_{j-1})v_j$$

$$= \beta_i V$$

$$\phi^i_{topo,l,m} = -\frac{4\pi}{\lambda}\frac{B^i_{\perp,l,m}}{r^i_{l,m}\sin\theta^i_{l,m}}\Delta h_{l,m}$$

$$= \alpha^i_{l,m}\Delta h_{l,m}$$

Wrapped phases!!

For each arc, we have

$$\Delta\Phi = A\begin{bmatrix}\Delta h_{l,m,l',m'} \\ \Delta V\end{bmatrix} + W$$

$$\Delta\Phi = \begin{bmatrix}\Delta\phi^1_{l,m,l',m'} & \Delta\phi^2_{l,m,l',m'} & \cdots & \Delta\phi^I_{l,m,l',m'}\end{bmatrix}$$

$$A = \begin{bmatrix}\alpha & \beta\end{bmatrix}$$

$$\alpha = \begin{bmatrix}\alpha^1_{l,m} & \alpha^2_{l,m} & \cdots & \alpha^I_{l,m}\end{bmatrix}^T$$

$$\beta = \begin{bmatrix}\beta_1 & \beta_2 & \cdots & \beta_I\end{bmatrix}^T$$

$$W = \begin{bmatrix}w^1_{l,m,l',m'} & w^2_{l,m,l',m'} & \cdots & w^I_{l,m,l',m'}\end{bmatrix}$$

$$\Delta\phi^i_{l,m,l',m'} = \alpha^i_{l,m}\Delta h_{l,m,l',m'} + \beta_i\Delta V + w^i_{l,m,l',m'}$$

$$w^i_{l,m,l',m'} = \Delta\phi^i_{atmo,l,m,l',m'} + \Delta\phi^i_{orbit,l,m,l',m'} + \Delta\phi^i_{noise,l,m,l'm'}$$

How to resolve the parameters?

Temporarily Coherent Point InSAR

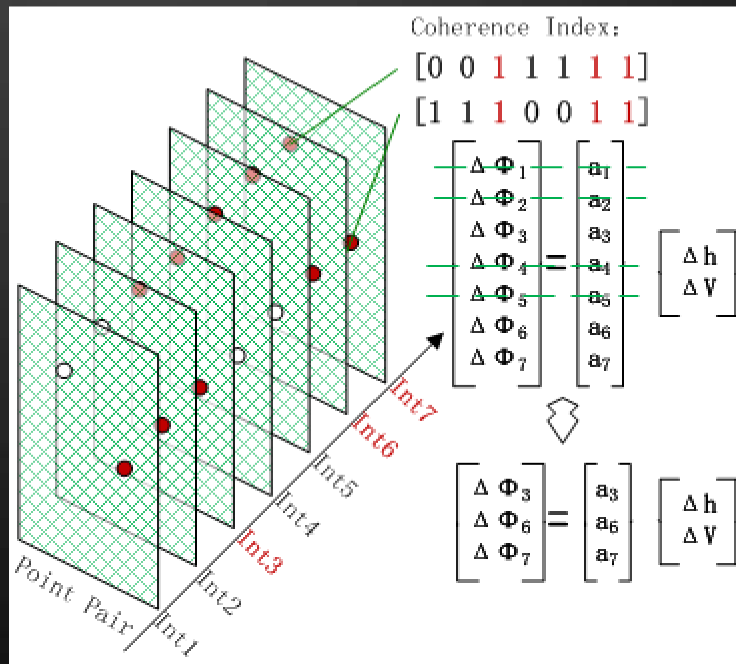
L-2 norm (least squares) estimator with ambiguity detector

- This algorithm is suitable for TCPs identified by image-pair based methods
- Since we exactly know in which interferograms the selected TCPs keep high coherence, we can get a coherence index for each TCP
- For each arc, only interferograms in which both points keep coherent are selected.

$$\begin{bmatrix}\Delta\hat{h}_{l,m,l',m'} \\ \Delta\hat{V}\end{bmatrix} = \left(A^T P^{dd} A\right)^{-1} A^T P^{dd} \Delta\Phi$$

$$\Delta\hat{\Phi} = A\left(A^T P^{dd} A\right)^{-1} A^T P^{dd} \Delta\Phi$$

$$r = \Delta\Phi - A\left(A^T P^{dd} A\right)^{-1} A^T P^{dd} \Delta\Phi$$



$\Delta\Phi$ might have phase ambiguities!!

Temporarily Coherent Point InSAR

L-2 norm (least squares) estimator with ambiguity detector

- Ambiguity detector

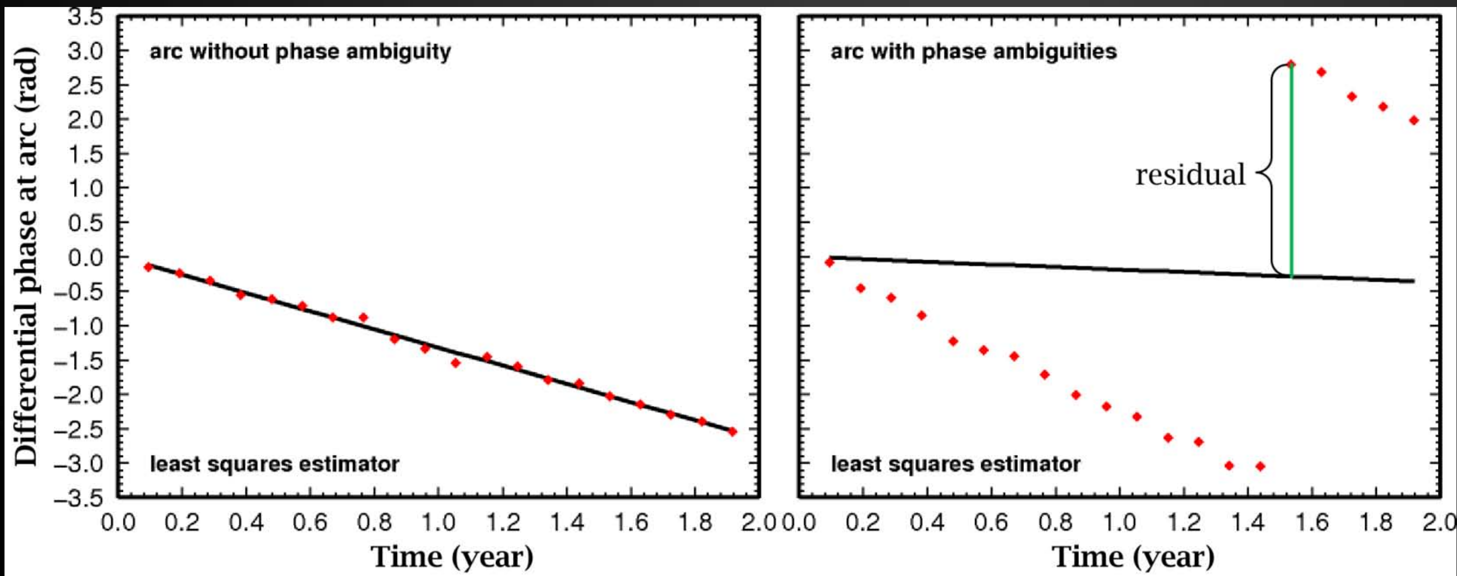
$$Q_{\Delta\hat{\Phi}\Delta\hat{\Phi}} = A(A^T P^{dd} A)^{-1} A^T$$

$$Max(|r_i|) > c\sqrt{Max((Q^{dd})_{ii})} + 2\sqrt{Max((Q_{\Delta\hat{\Phi}\Delta\hat{\Phi}})_{ii})}$$

- TCP parameters

After removing modulo-2pi arcs, perform Arc-Point integration

LS residuals can tell us whether the arc has ambiguity or not!



Temporarily Coherent Point InSAR

L-1 norm estimator

- For TCPs selected by image based approach, we do not exactly know in which interferograms the TCPs are coherent
- When taking all interferograms as observations, we need to design a robust estimator to suppress the effect of "outliers" (i.e., decorrelated phases and phase ambiguities at arcs)
- L-1 norm estimator is a good choice since it is less sensitive to outliers than LS

With L-1 norm estimator, we do not need to remove arcs having decorrelated phases and phase ambiguities!!

Temporarily Coherent Point InSAR

L-1 norm estimator

- How to perform L-1 norm estimation?

  L-1 norm estimator is to find $\hat{x}$ as follows:

$$\hat{x} = \arg\min_x \left\| b - Ax \right\|_1$$

$$\Delta\Phi = A\begin{bmatrix} \Delta h_{l,m,l',m'} \\ \Delta V \end{bmatrix} + W \quad \Rightarrow \quad \text{minimize} \sum_i \left| \Delta\phi^i_{l,m,l',m'} - \sum_j A_{ij} \begin{bmatrix} \Delta h_{l,m,l',m'} \\ \Delta V \end{bmatrix} \right|$$

- Solution by iteratively reweighted least squares used in [6] for robust SBAS

- Solution by linear programming

[6] Lauknes, T. R., Zebker, H.A. and Larsen Y. (2011). IEEE Transactions on Geoscience and Remote Sensing, 49, 536-546

Temporarily Coherent Point InSAR

L-1 norm estimator: Solution by linear programming

$$\text{minimize } \sum_i \left| \Delta\phi^i_{l,m,l',m'} - \sum_j A_{ij} \begin{bmatrix} \Delta h_{l,m,l',m'} \\ \Delta V \end{bmatrix} \right|$$

$$\Downarrow$$

$$\text{minimize } \sum_i f_i$$

$$\text{subject to } \quad f_i - \left| \Delta\phi^i_{l,m,l',m'} - \sum_j A_{ij} \begin{bmatrix} \Delta h_{l,m,l',m'} \\ \Delta V \end{bmatrix} \right| = 0$$

$$\Downarrow$$

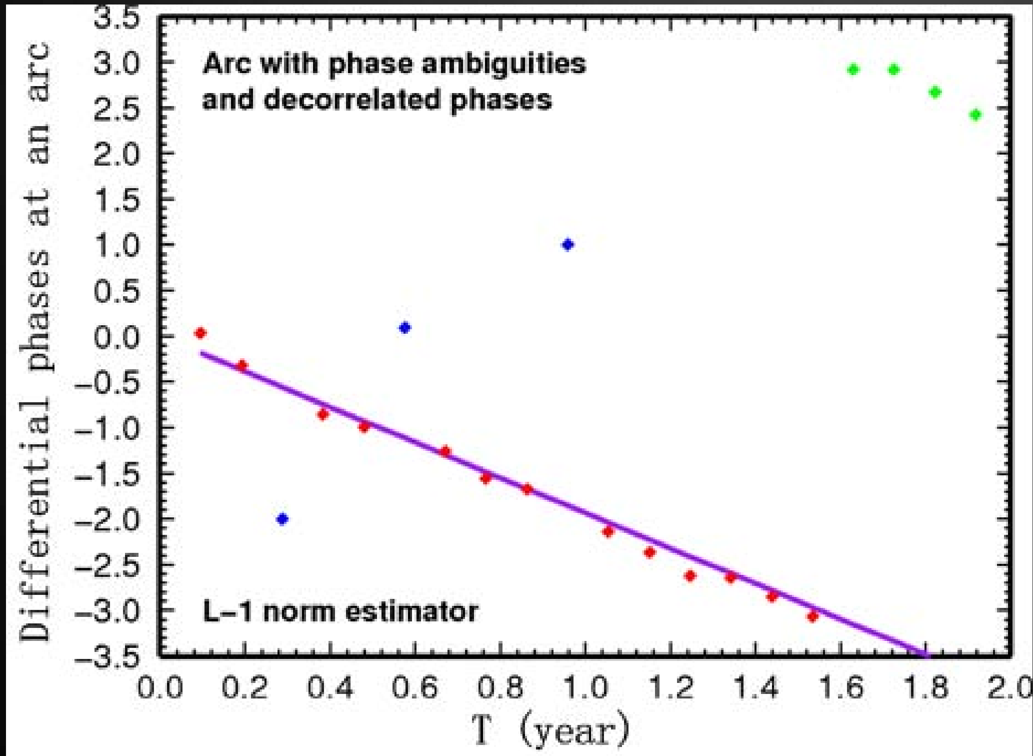
$$\text{minimize } \sum_i f_i$$

$$\text{subject to } \quad -f_i \le \Delta\phi^i_{l,m,l',m'} - \sum_j A_{ij} \begin{bmatrix} \Delta h_{l,m,l',m'} \\ \Delta V \end{bmatrix} \le f_i$$

With any linear programming software package, it can be solved easily.

Temporarily Coherent Point InSAR

The performance of the L-1 norm estimator?



Even though the arc contains decorrelated phases as well as phase ambiguities, the L-1 norm estimator can precisely resolve the defo. rate!