1-6

PALSAR データを用いた微小地殻変動検出

Detection of small crustal deformation using PALSAR data

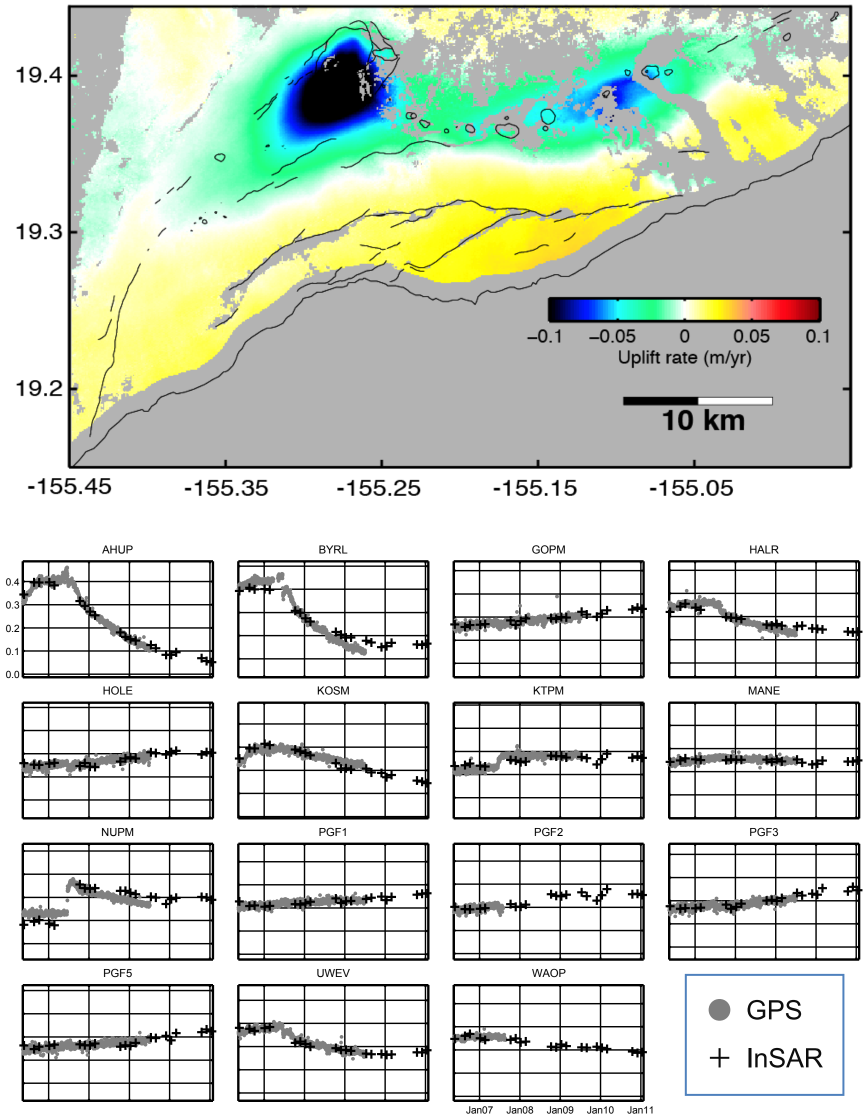
福島　洋（京都大学防災研究所）

Yo Fukushima (DPRI, Kyoto University)

地震・火山噴火・地すべりのメカニズムを探り、それらの発生・推移を予測するためには、微小な変形を時空間的に詳細に捉えることが重要である。合成開口レーダ干渉法（InSAR）を用いると、違う時期に撮像された二枚の SAR 画像から期間内に生じた地表面の変形を面的に捉えることができるが、定期的に撮像された多数の SAR 画像を用いることにより、さらに変形を時間的に追跡することができる。

発表者は、2006～2011 年の間に活躍した ALOS 衛星の PALSAR データを主に用い、この InSAR 時系列解析に関連する手法開発および地震火山プロセスの解明のための実データへの適用を行ってきた。InSAR 時系列解析には、1）高品質データの安定的供給、2）ロバストな自動干渉処理システム、3）変動時系列について解くための解析処理が必要である。さらに、その精度向上のためには、4）ノイズ軽減処理も重要である。PALSAR は比較的低頻度な撮像回数（年5回程度）と軌道制御方針が InSAR 時系列解析にとって理想的ではなかったが、高品質なデータを安定的に供給した。自動干渉処理は、シーンの広範囲を海が占める等の場合にも自動処理が可能となるよう条件分岐等を工夫し実現した。変動時系列を解くための解析処理については、主要なノイズ源となる大気遅延や軌道決定誤差の影響も同時に推定することにより時系列解析の精度向上を図った。

InSAR 時系列解析におけるシグナル検出能力のボトルネックは、解析対象シグナルの場所や空間的広がりによって異なるが、運用側（ハード対応）とユーザ側（ソフト対応）および両者の協働（意見交換を通じた観測方針決定等）が大切だろうと思う。この観点から、PALSAR 時代は、関係者の尽力により、一定の成功を収めたと考えられる。

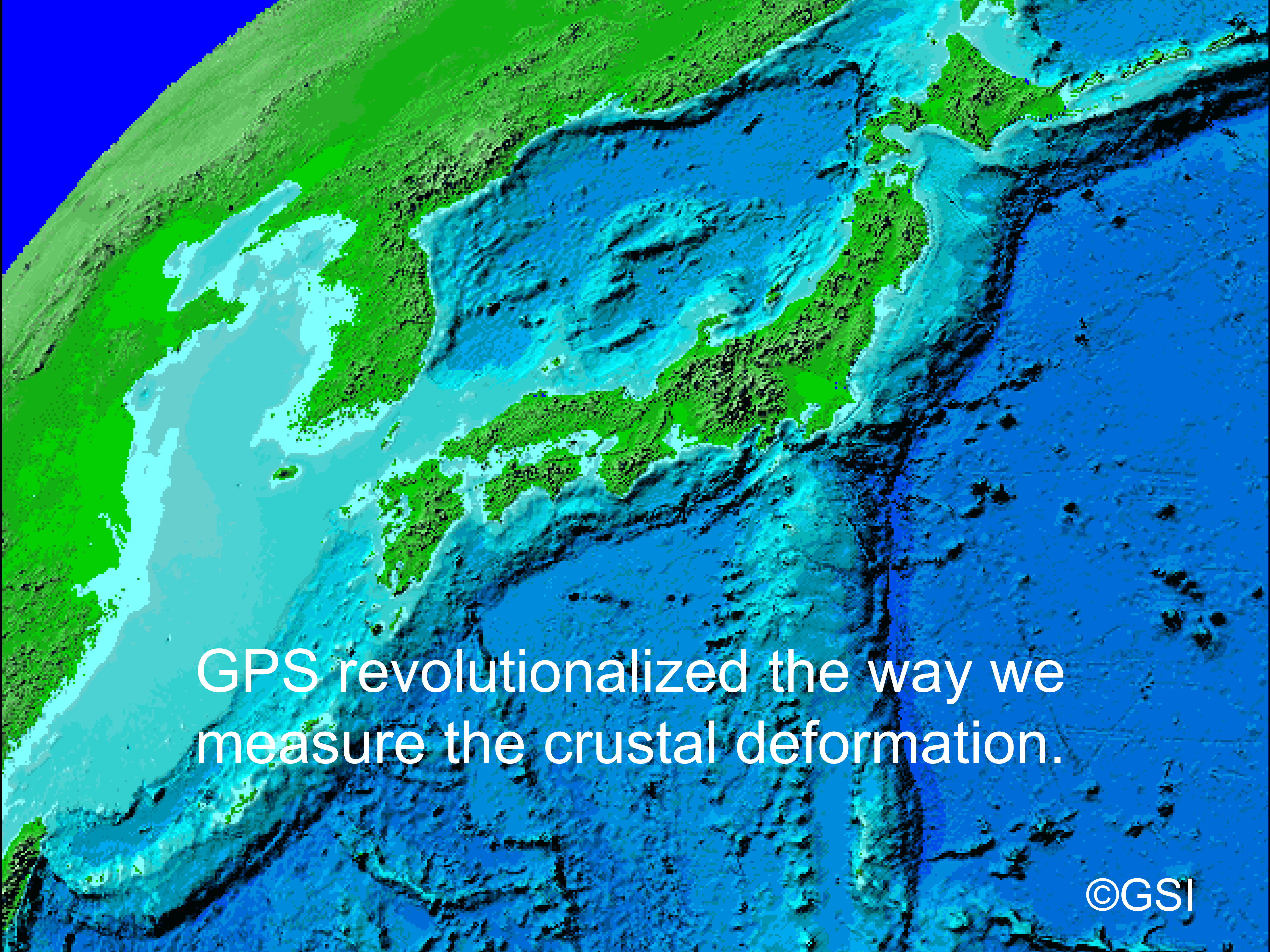


（上）InSAR 時系列解析によって得られたハワイ島キラウエア火山における 2007/10/9-2009/8/29 の平均上下速度。（下）GPS と InSAR の変位時系列の比較。

PALSARを用いた微小地殻変動検出
Measurement of small crustal deformation using PALSAR data

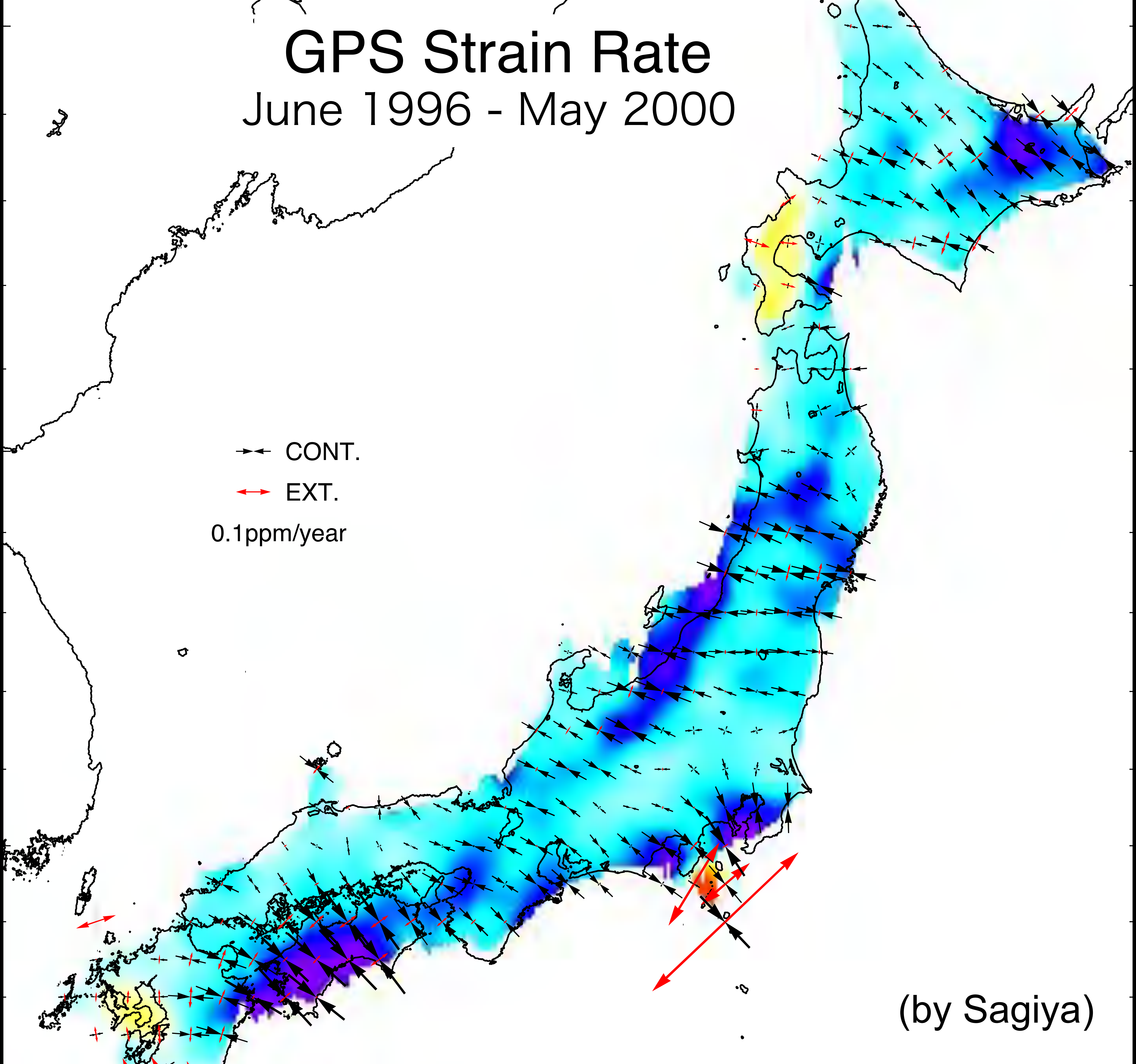
- My “activity report” for the past 6 years on InSAR TS studies -

福島　洋（京都大学防災研究所）
Yo Fukushima (DPRI, Kyoto University)

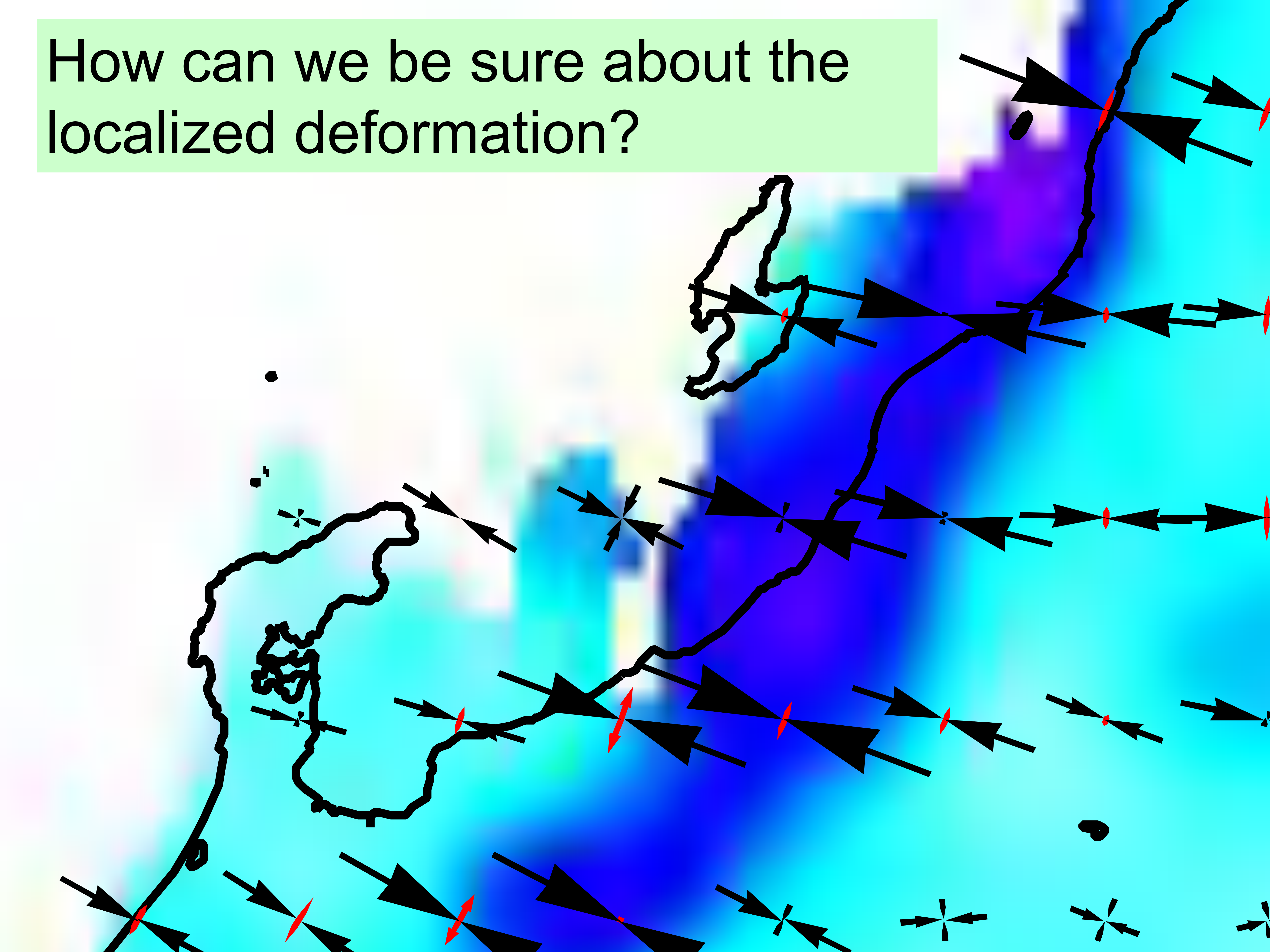

GPS revolutionalized the way we
measure the crustal deformation.
©GSI

GPS Strain Rate

June 1996 - May 2000

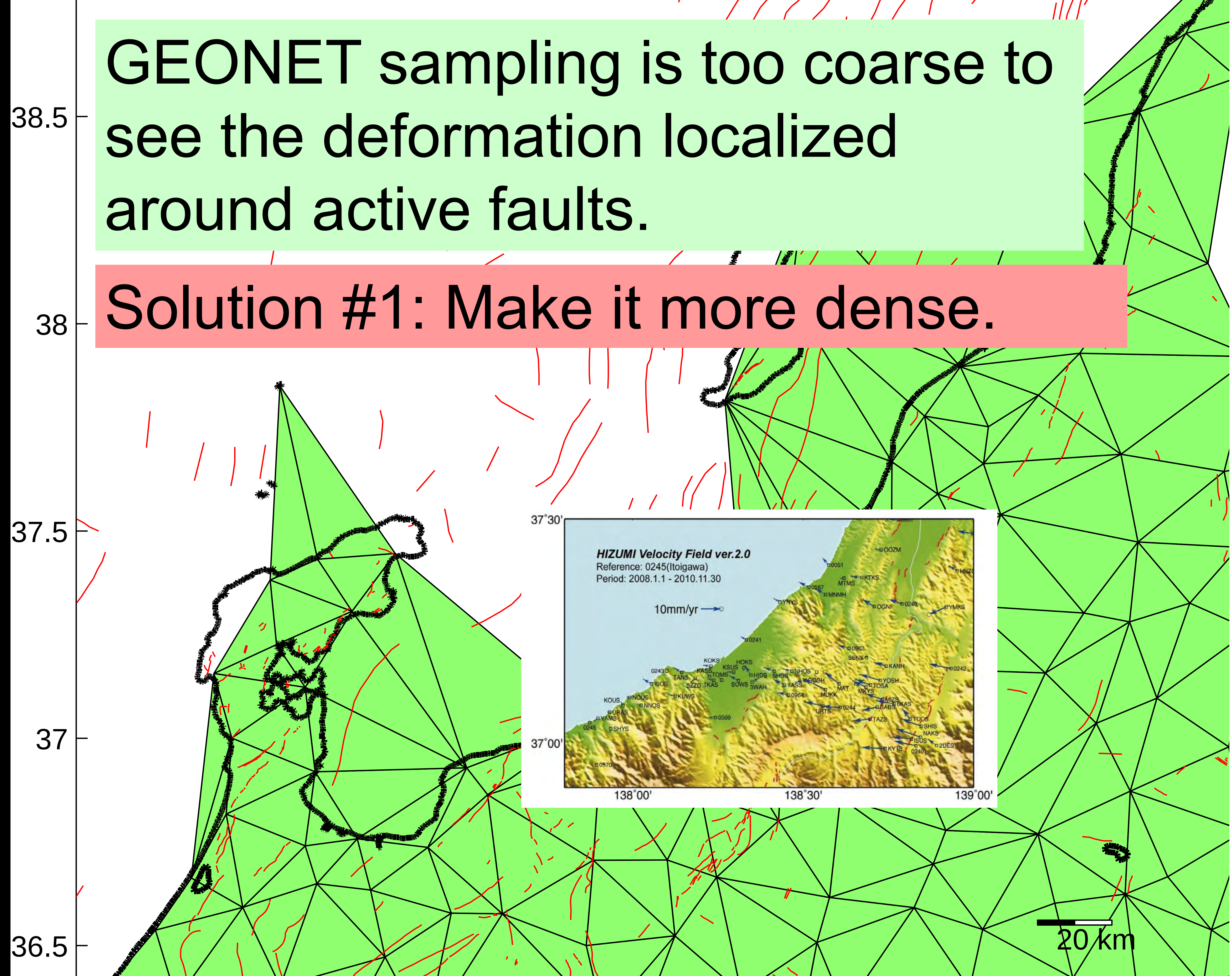


How can we be sure about the localized deformation?

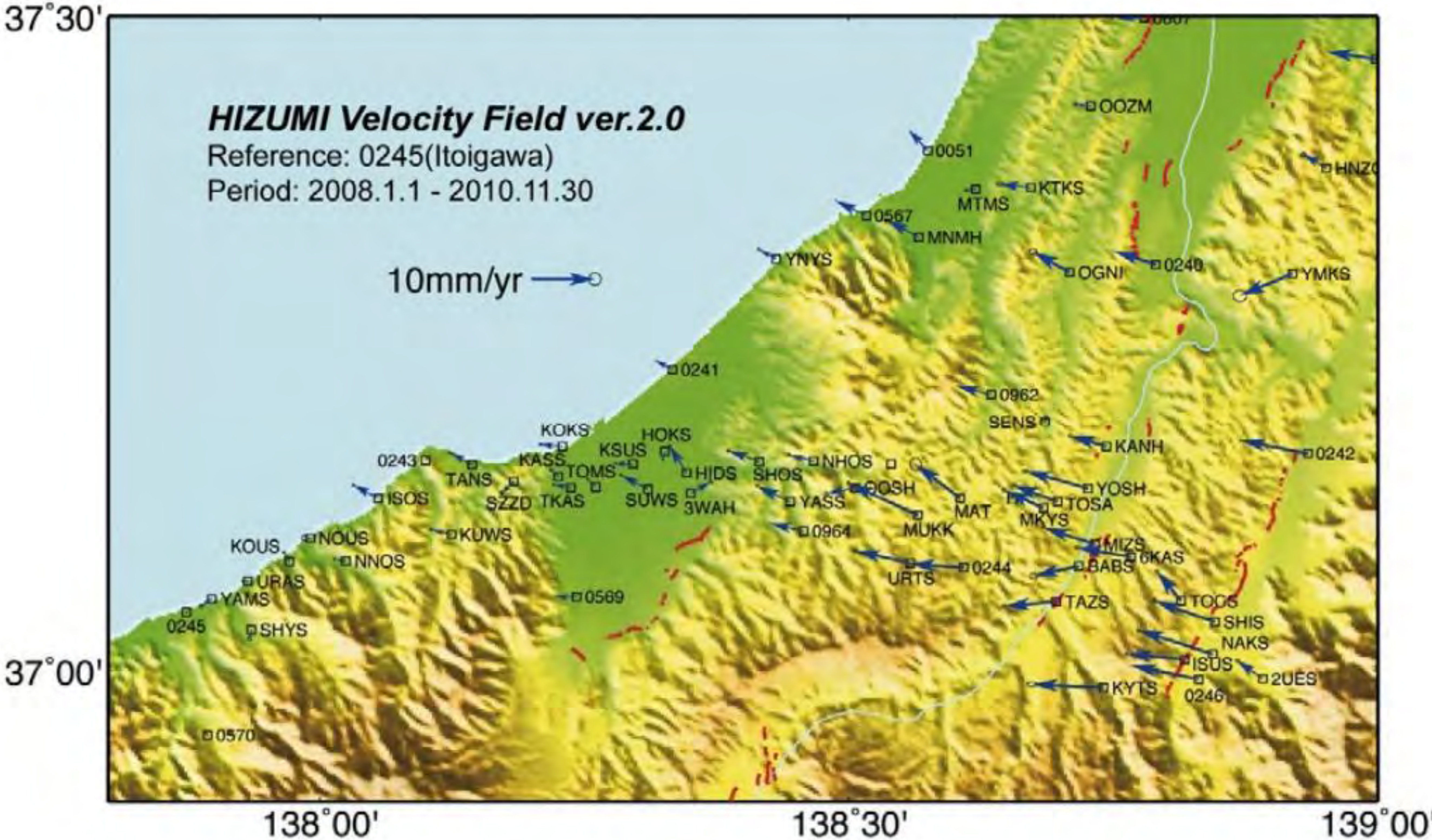


GEONET sampling is too coarse to see the deformation localized around active faults.

Solution #1: Make it more dense.

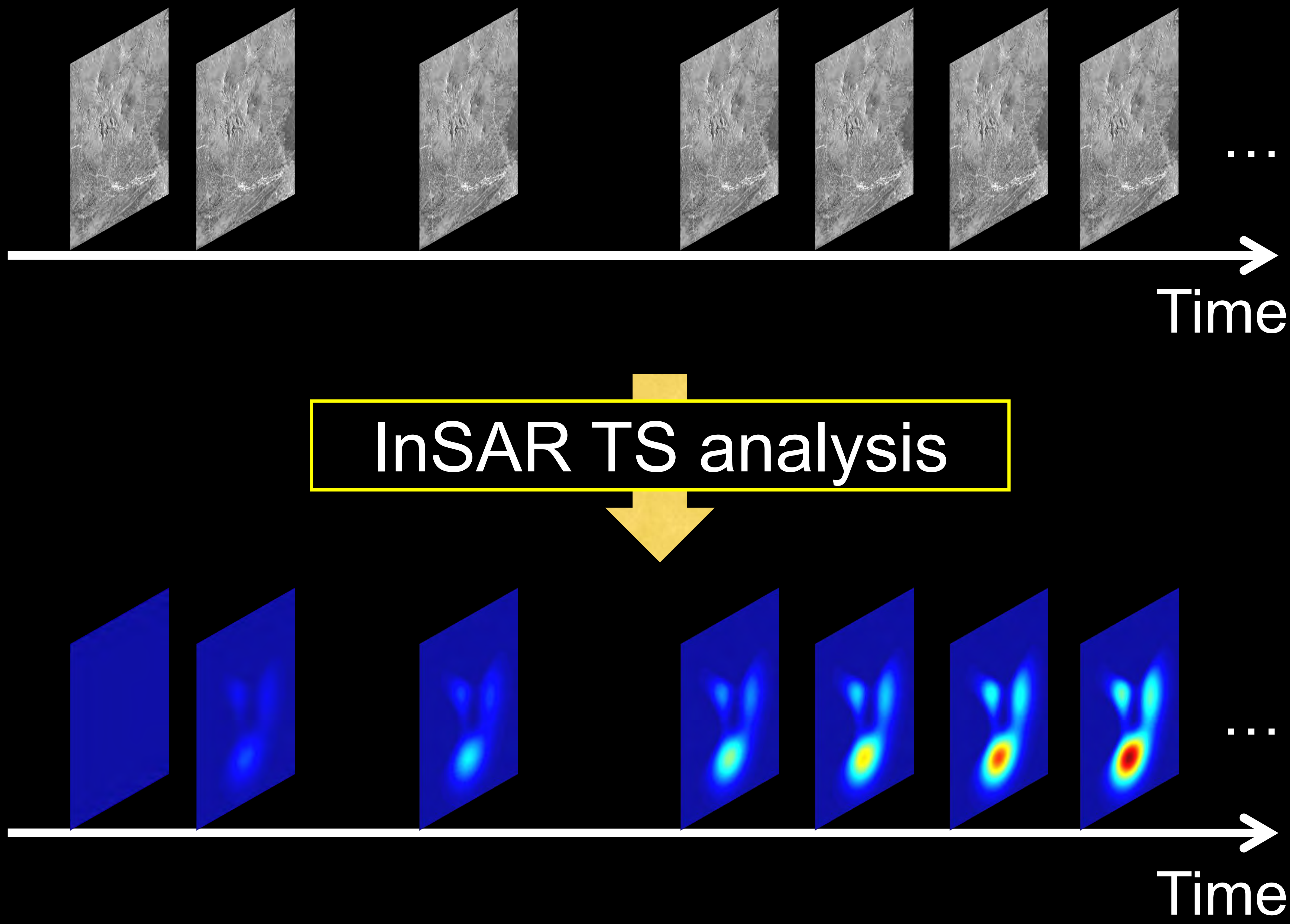


Spatial sampling at a few km



http://www.hizumi.bosai.go.jp/pdf/report/H23/H23_3.3.pdf

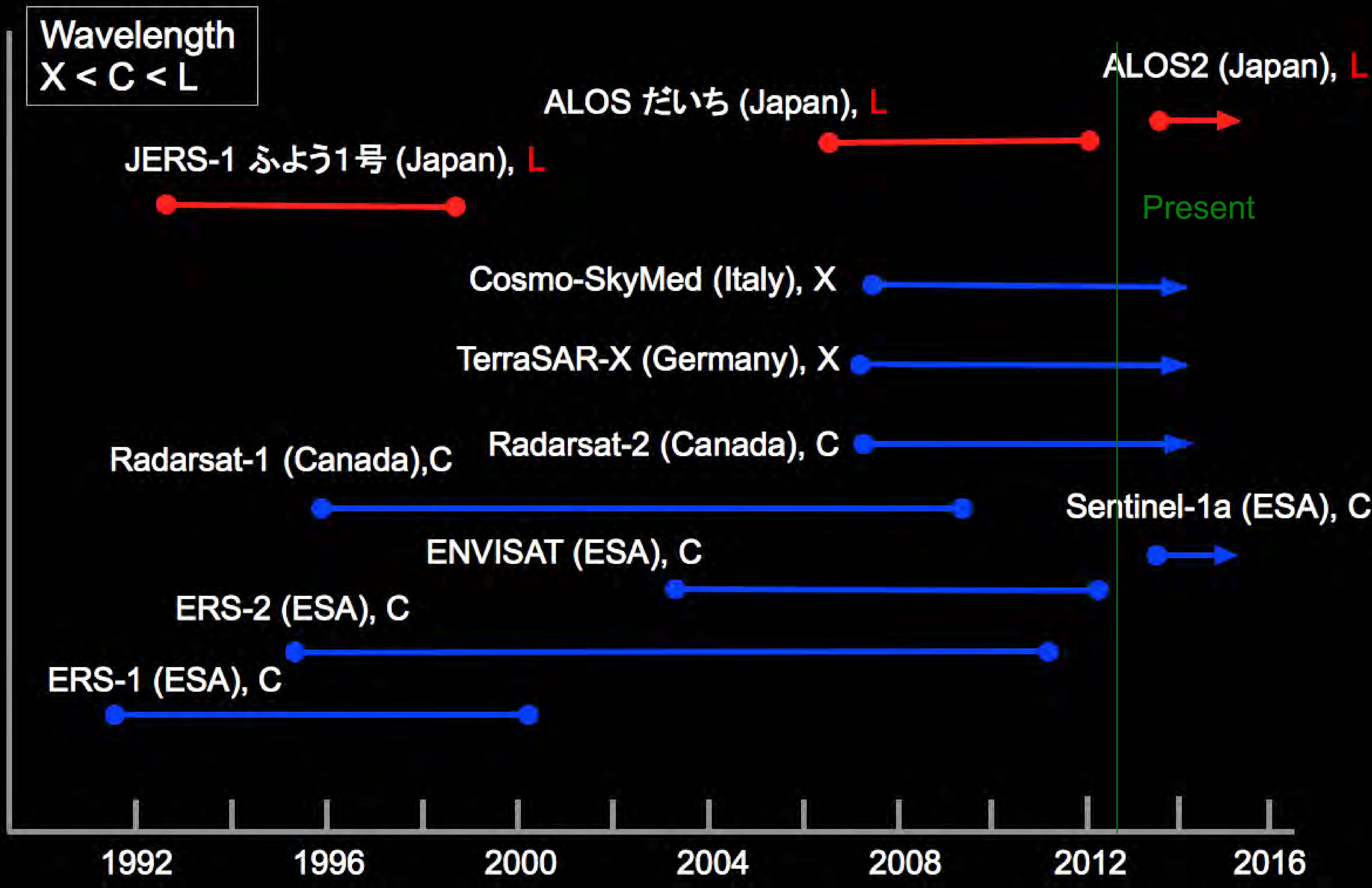
Solution #2: InSAR TS analysis!



Necessary conditions for the detection of small displacements using InSAR time-series analysis

- Continuity of the satellite missions
- Regular and frequent acquisitions
- Data quality and acquisition stability
- Bulk InSAR processing with a robust, automated and reliable system
- Method to solve for the time-series
- Reduction of noise in each interferogram

Principal EO satellite missions



How have I/we done (with ALOS data)?

- Continuity of the satellite missions

OK (5 yrs). More long-term missions like ERS-1 to 2 would be ideal.

- Regular and frequent acquisitions

  OK. More frequent acquisitions is favorable but prioritizing the background mission was nice.

- Data quality and acquisition stability

  Excellent!

- Bulk InSAR processing with a robust, automated and reliable system

  This became possible thanks to the quality of the products.

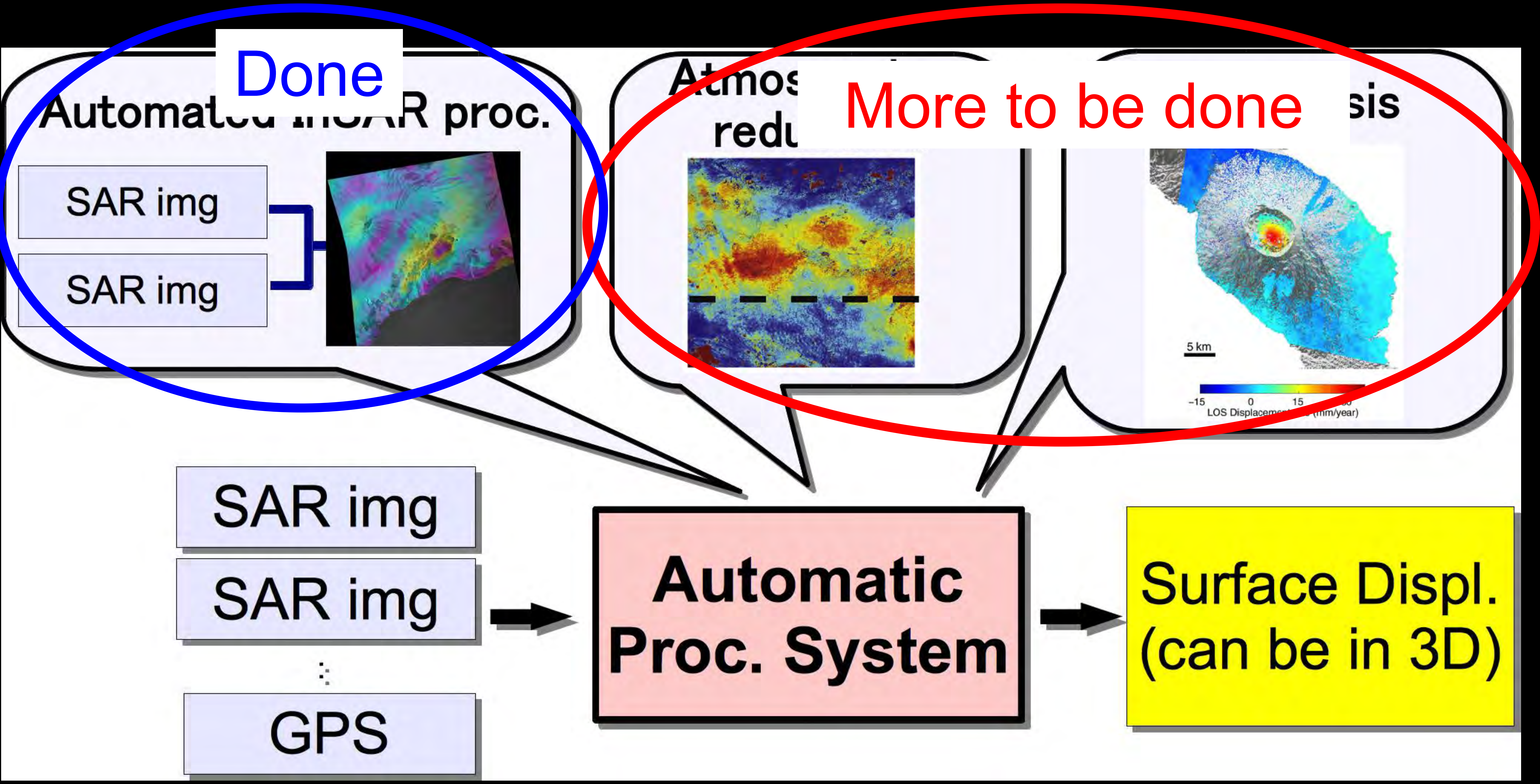
- Method to solve for the time-series

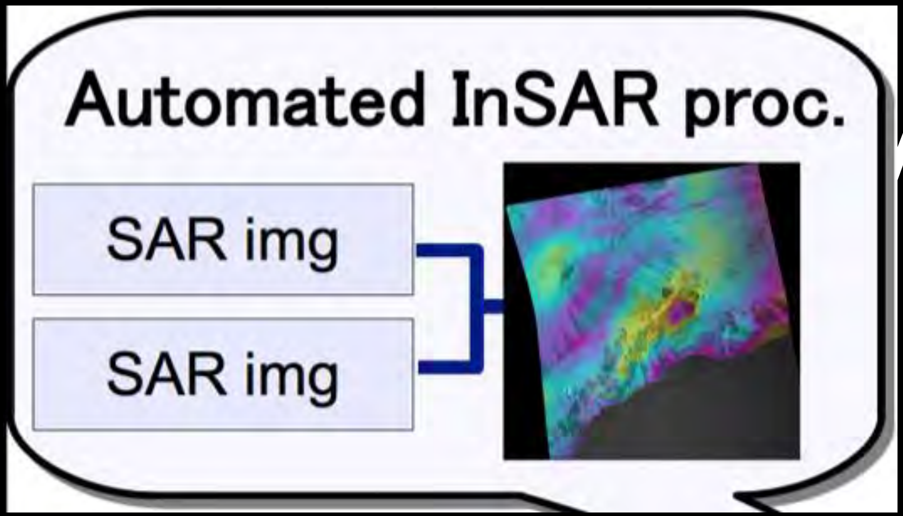
  Basic part of the algorithms are now mature. Improvements being developed.

- Reduction of noise in each interferogram

  There is room for improvements.

Automated processing chain





Automated InSAR processing (w/Gamma)

- No need to worry about different sensors
- Automatic DL of raw data for PALSAR
- Automatic preparation of DEM (DL, mosaic, crop)
- Robustness was emphasized especially in focusing and coregistration (trials w/different params and patches -> the best one is chosen)
- Bulk ifg processing for PALSAR (just specify the path, frames, dates, the threshold baselines -> stack of ifgs will be obtained)

A study on the atmos. noise reduction

(Fukushima, FRINGE, 2011)

General Observation Equation:

$$\mathbf{d} = \mathbf{A}\mathbf{x}$$

where $\mathbf{x}^{\mathbf{T}} = [a_1, a_2, ..., a_N, u_1, u_2, ..., u_{N-1}]$

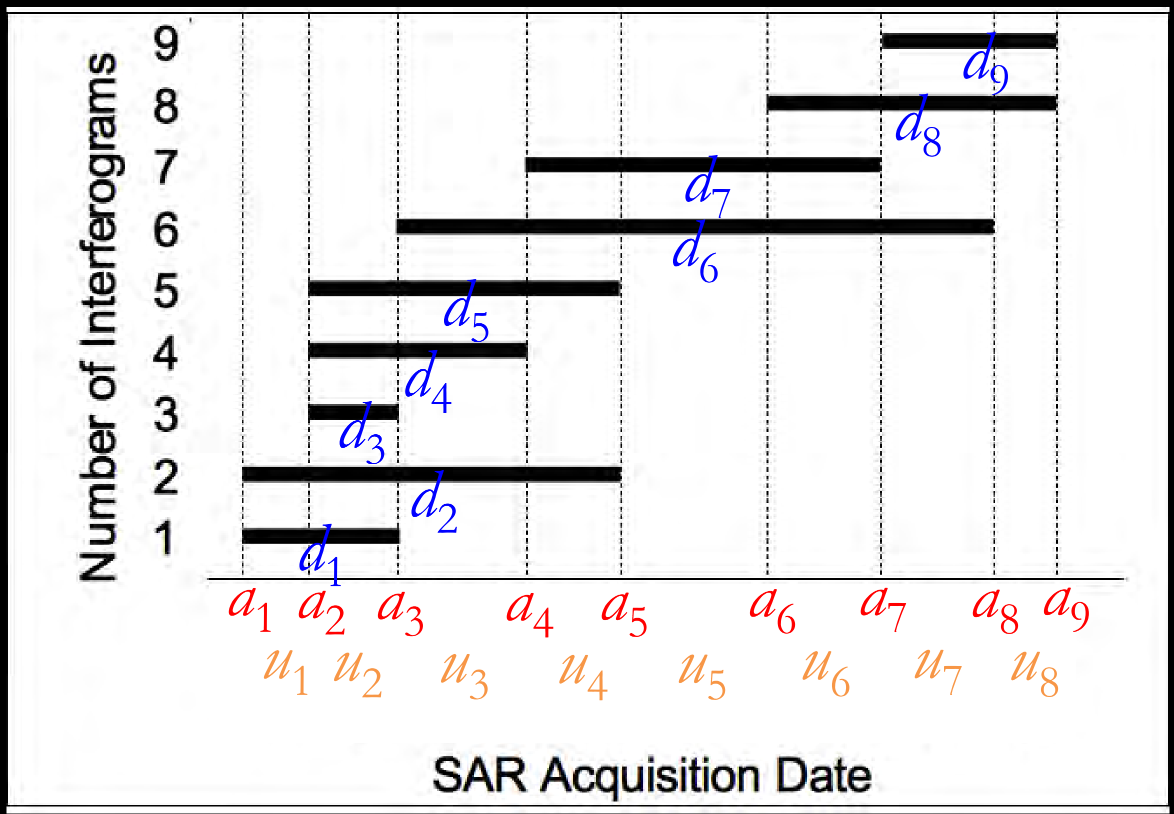
$\mathbf{d}^{\mathbf{T}} = [d_1, d_2, ...]$: Unwrapped InSAR

$a_n (n = 1, 2, ..., N)$: Atmospheric and orbital noise in n-th SAR image

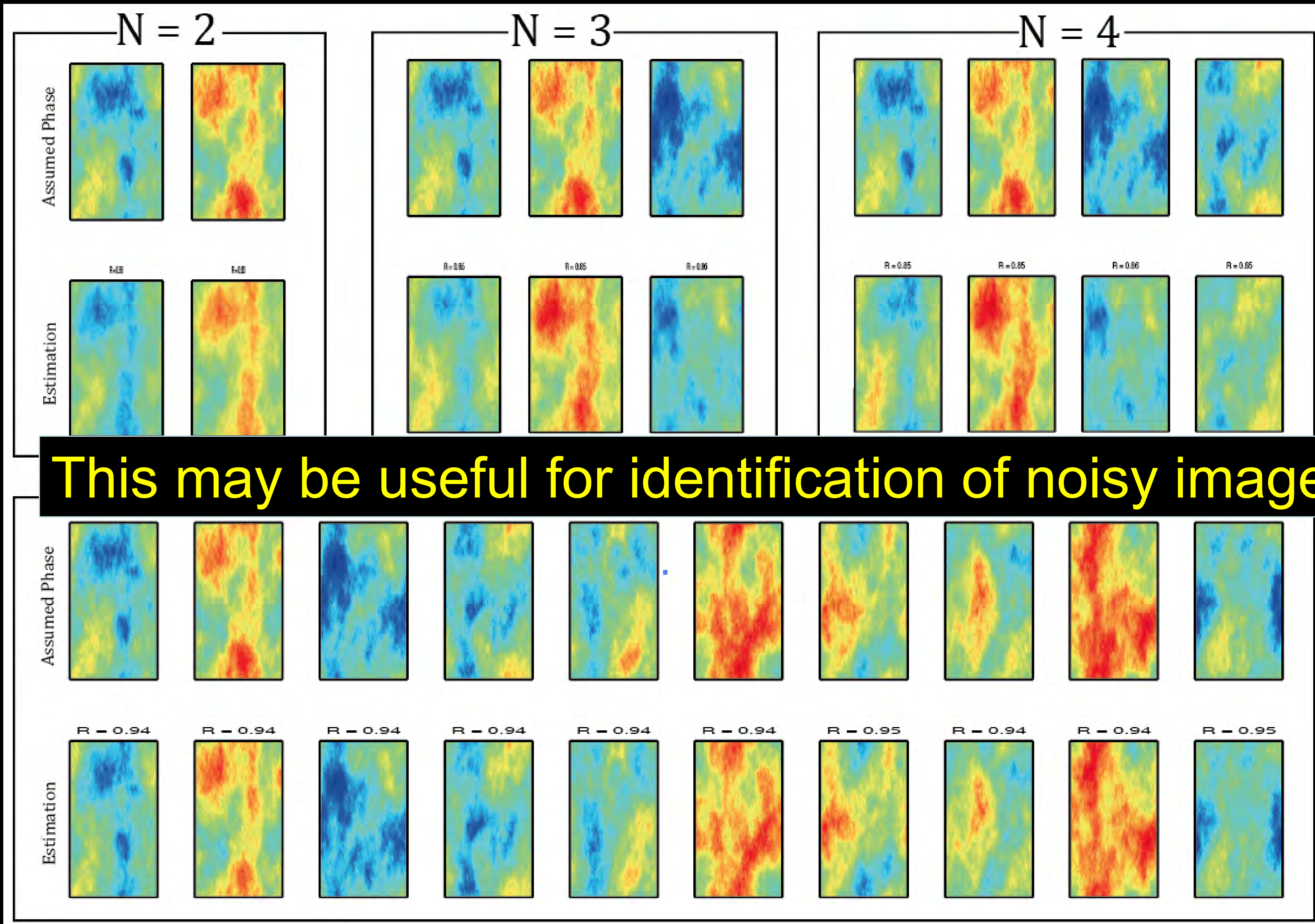
$u_n (n = 1, 2, ..., N-1)$: Incremental LOS displ. in n-th time interval

2N-1 unknowns
(↔ rank(A) = N-1)

→ for the time being, solve by assuming no deformation
→ N unknowns: solve with a minimum norm condition



Synth. tests on atmos. noise reduction



←True

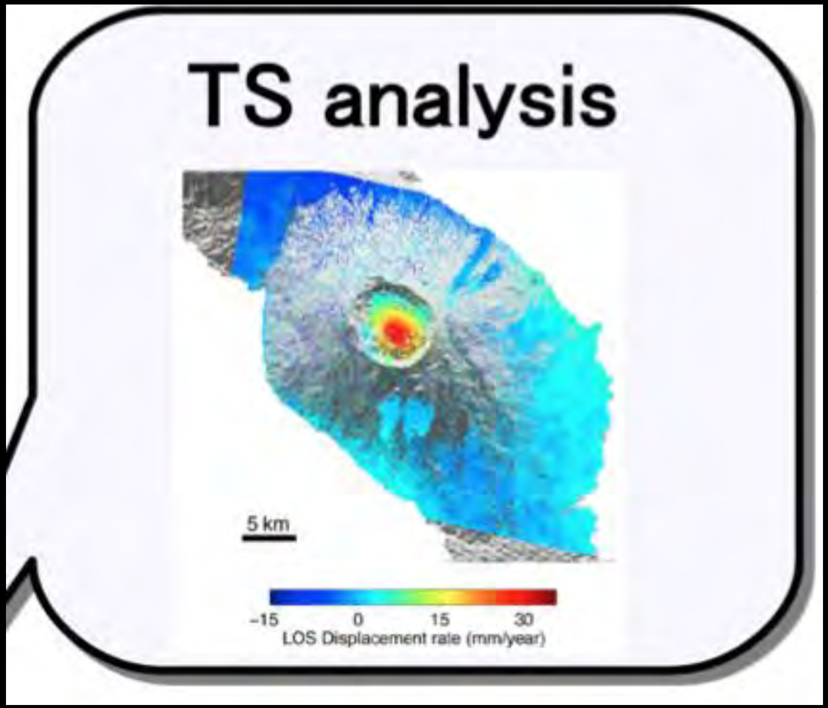
← Estimation

This may be useful for identification of noisy images.

←True

← Estimation

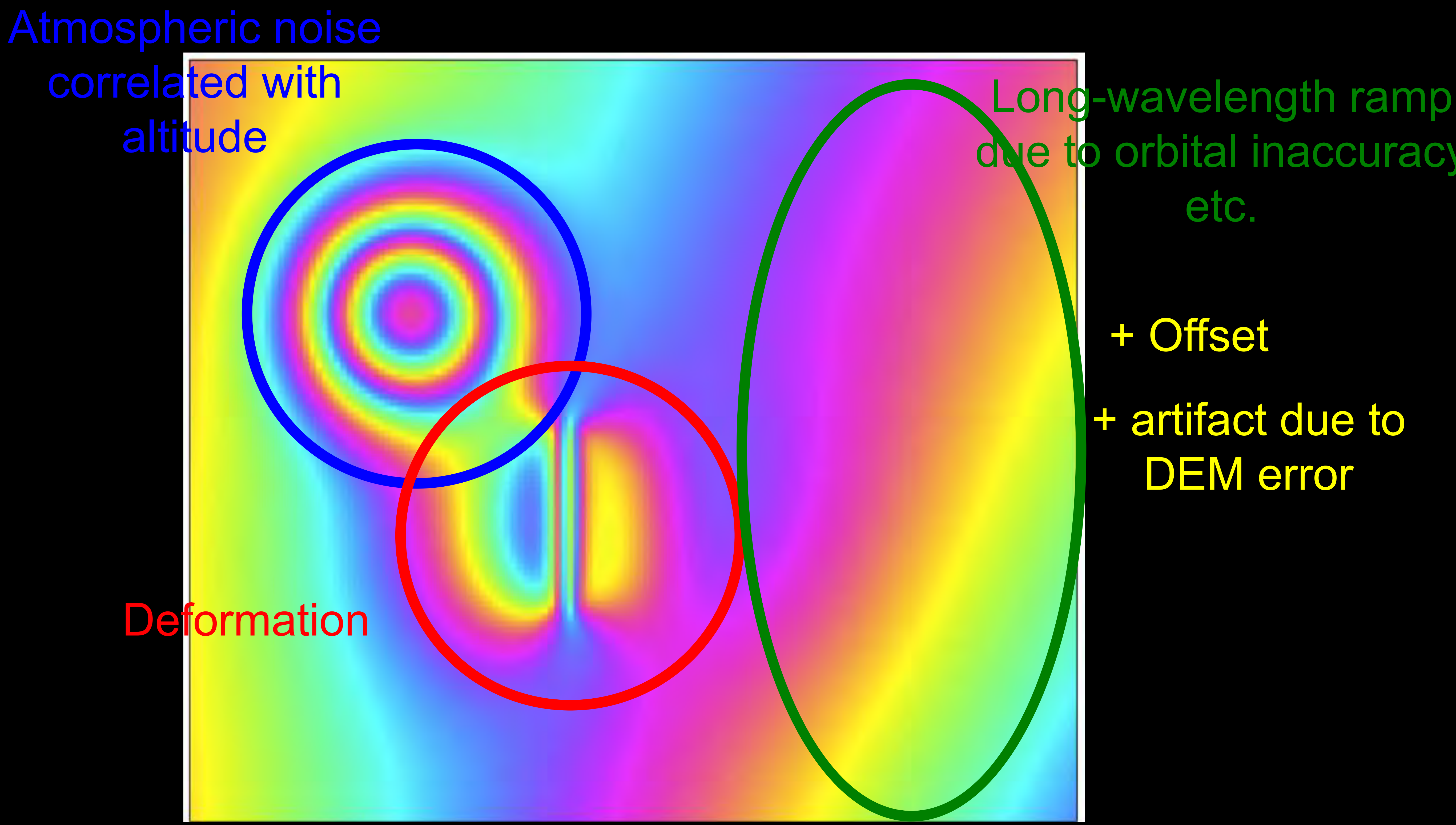
Time-series analysis



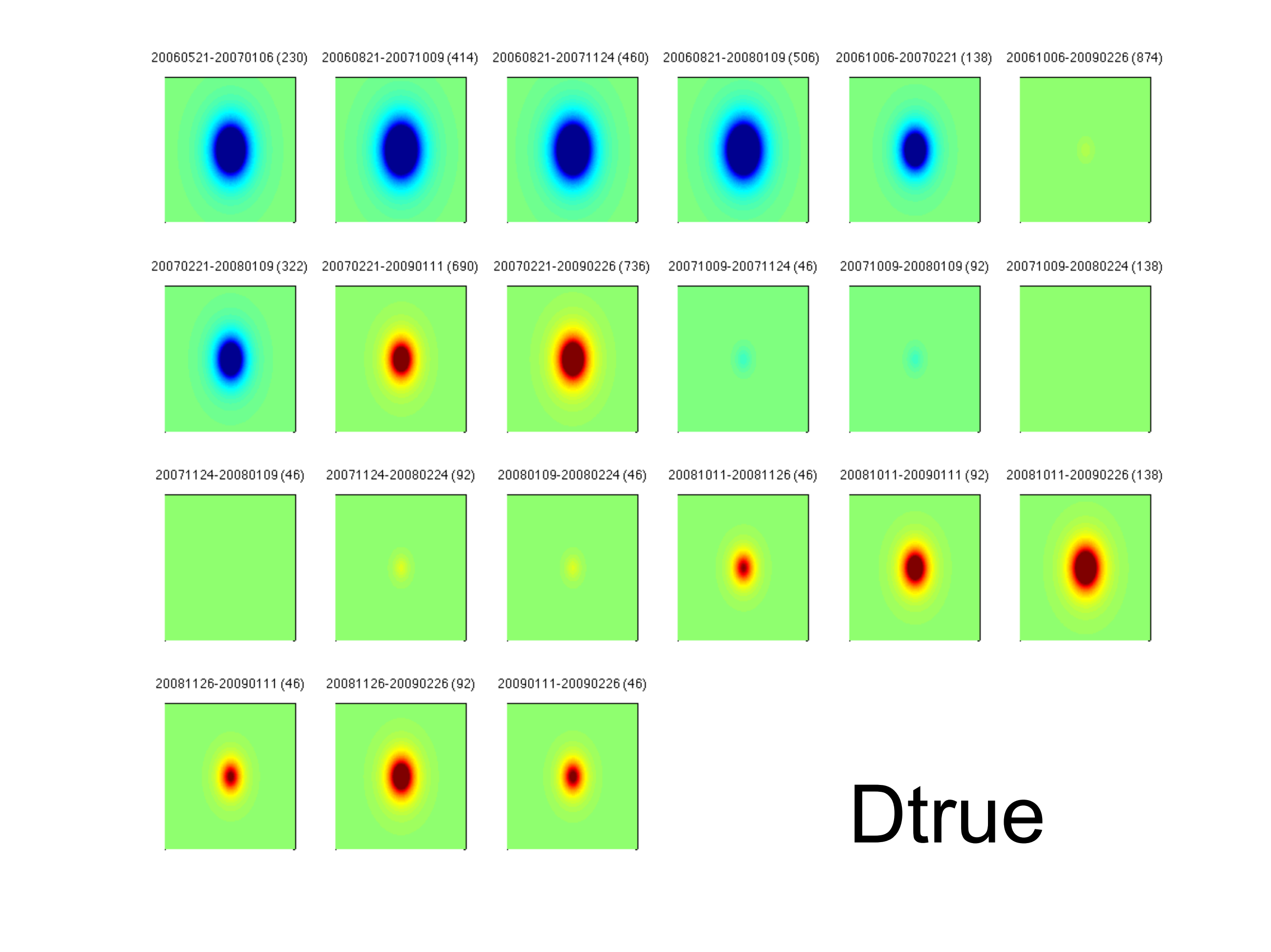
- Small-baseline approach: coded with matlab, simultaneous estimation of the phase ramps & altitude-dependent phase

- StaMPS/MTI + post-processing: Combination with GPS to obtain spatiotemporal displacement field reliable also in broad signals

My version of SB approach



Solve for all of these simultaneously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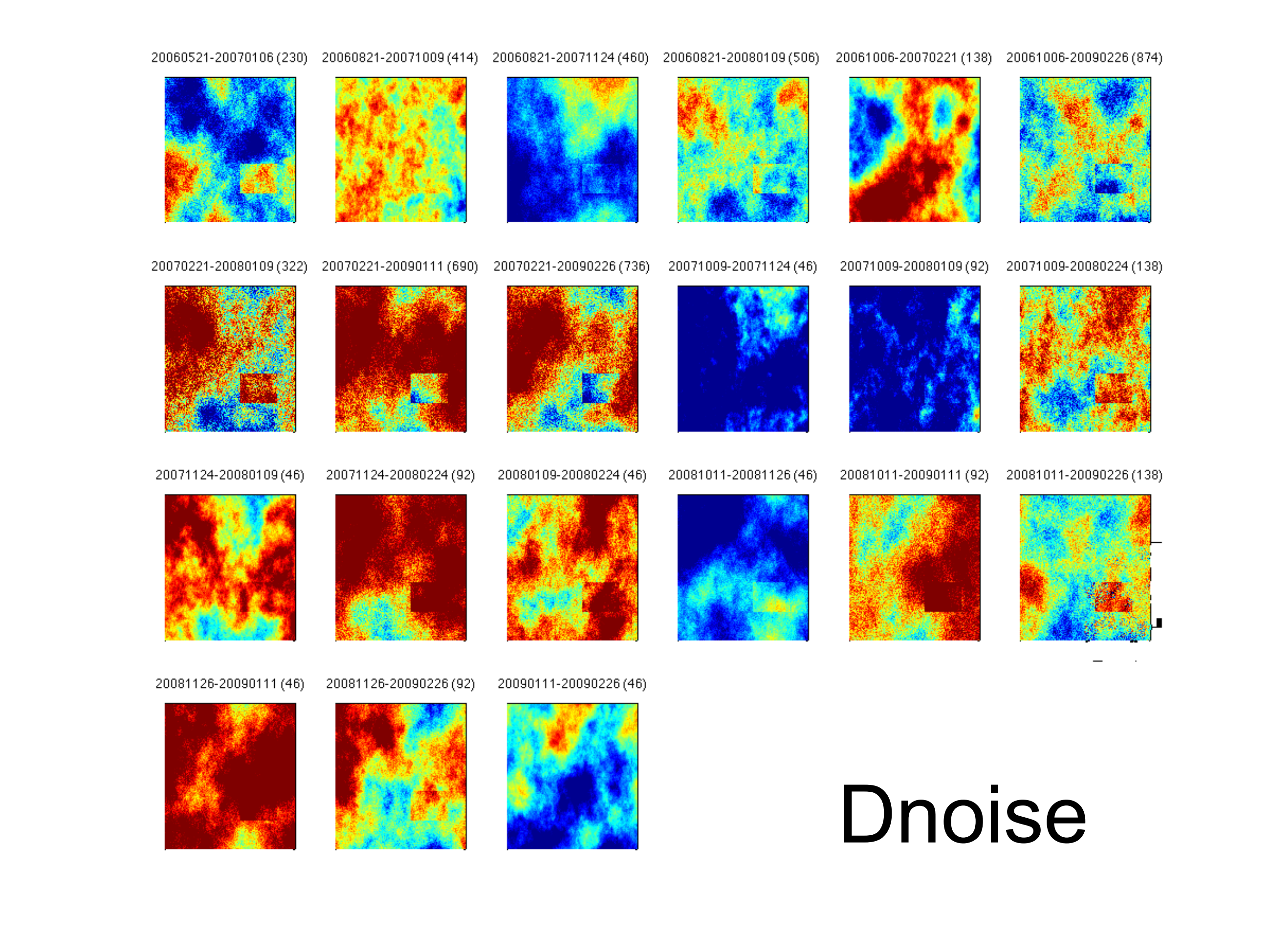
Dtrue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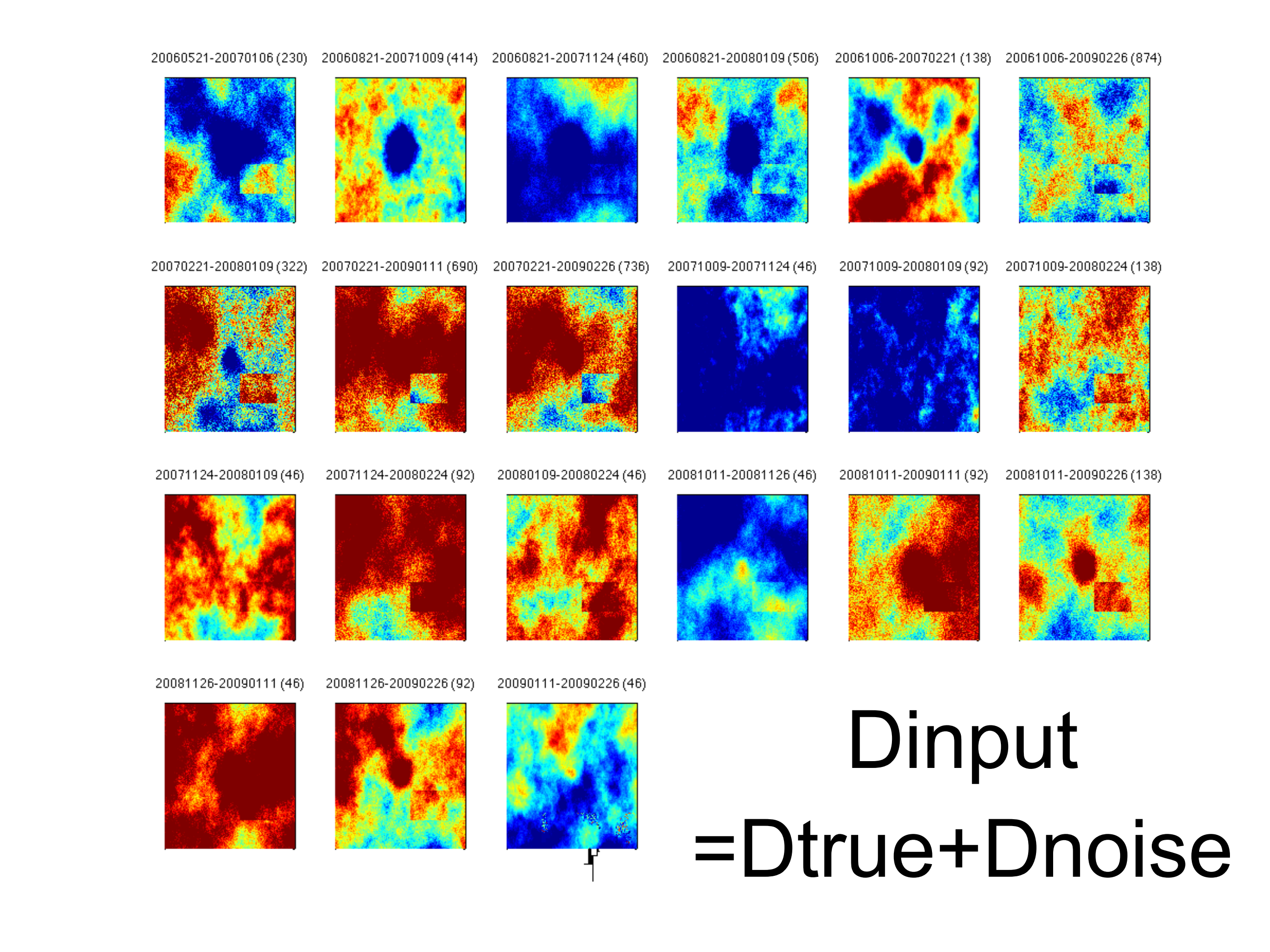
Dnoise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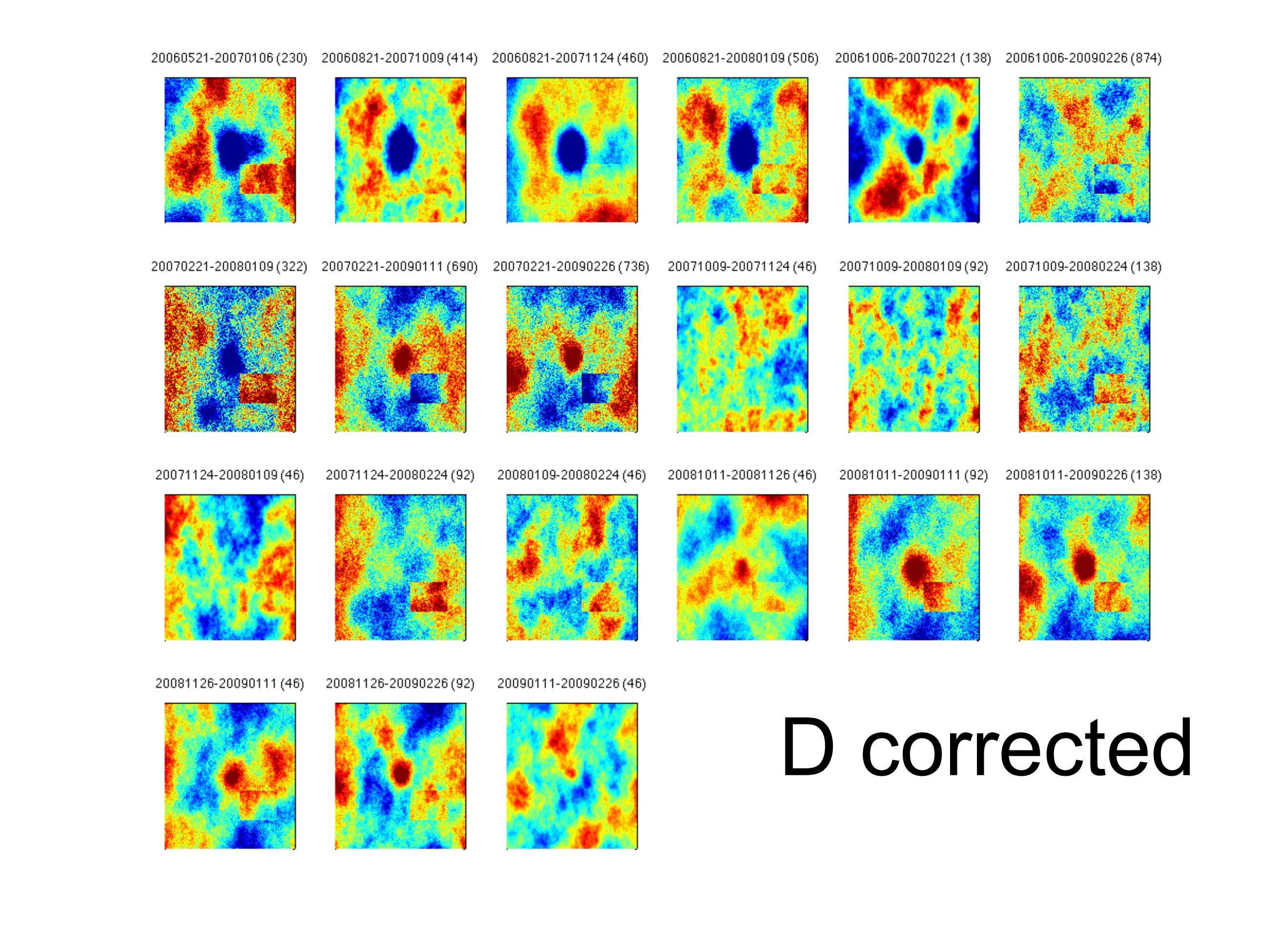
Dinput
=Dtrue+Dnoise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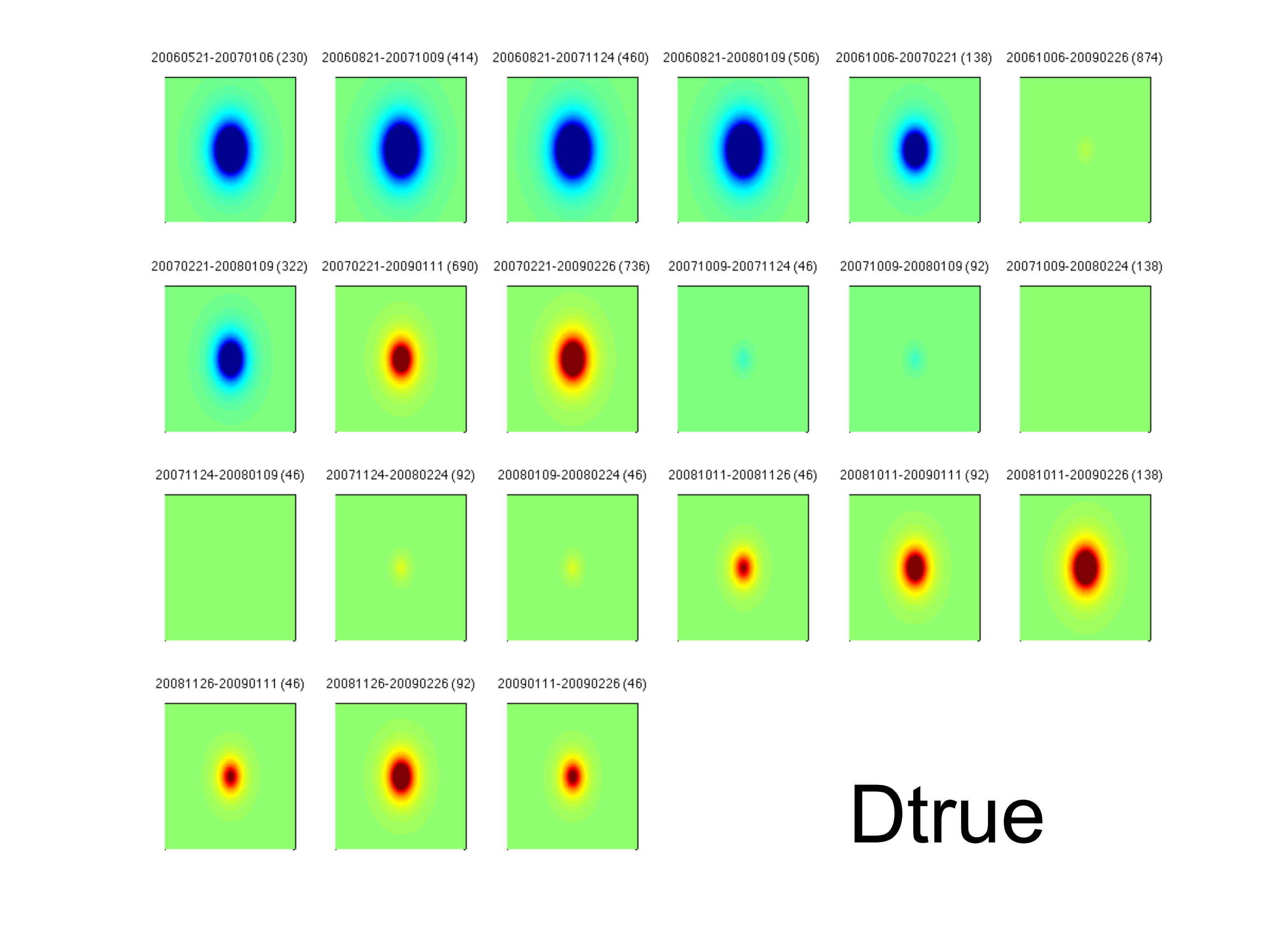
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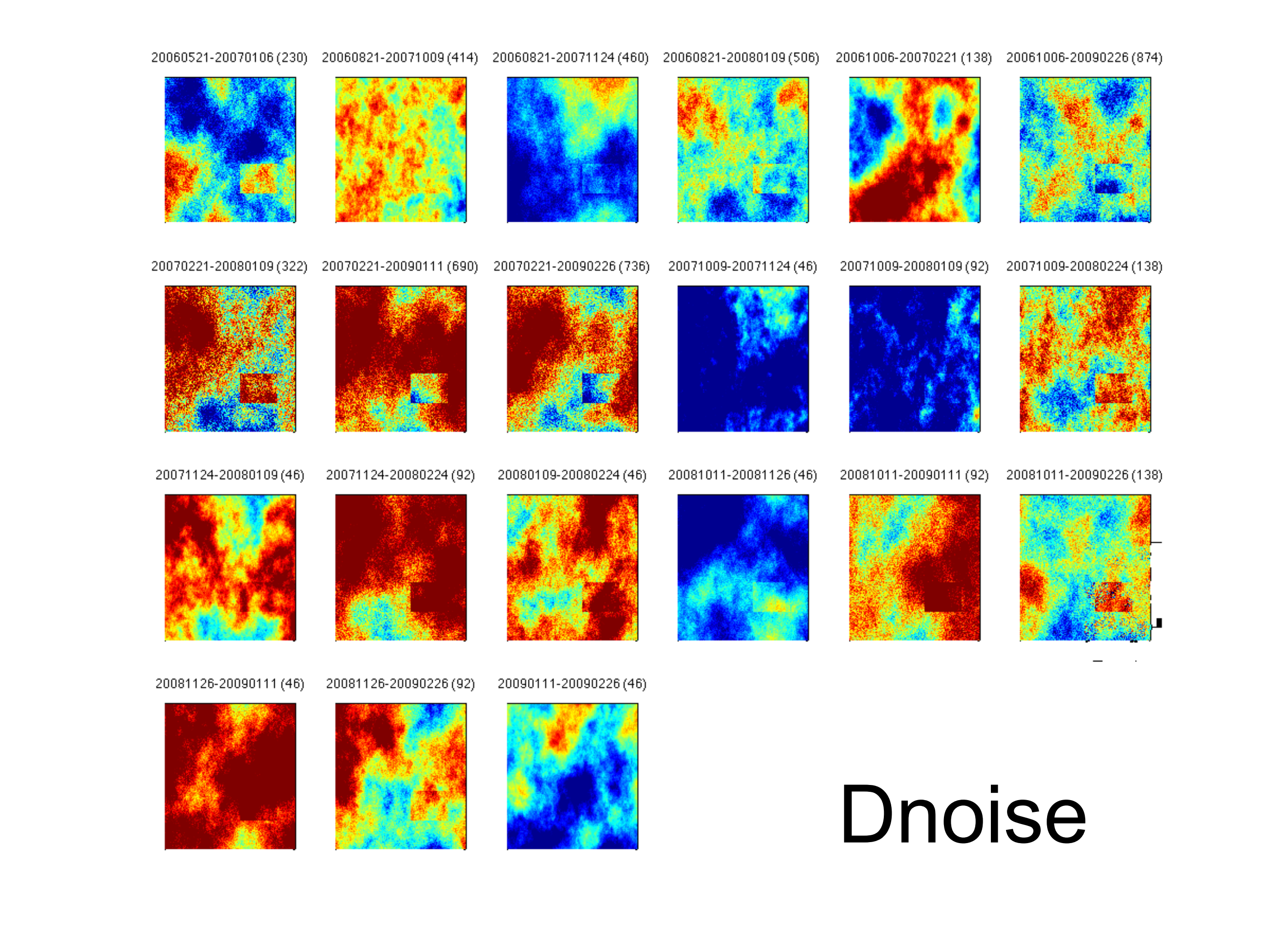
Dtrue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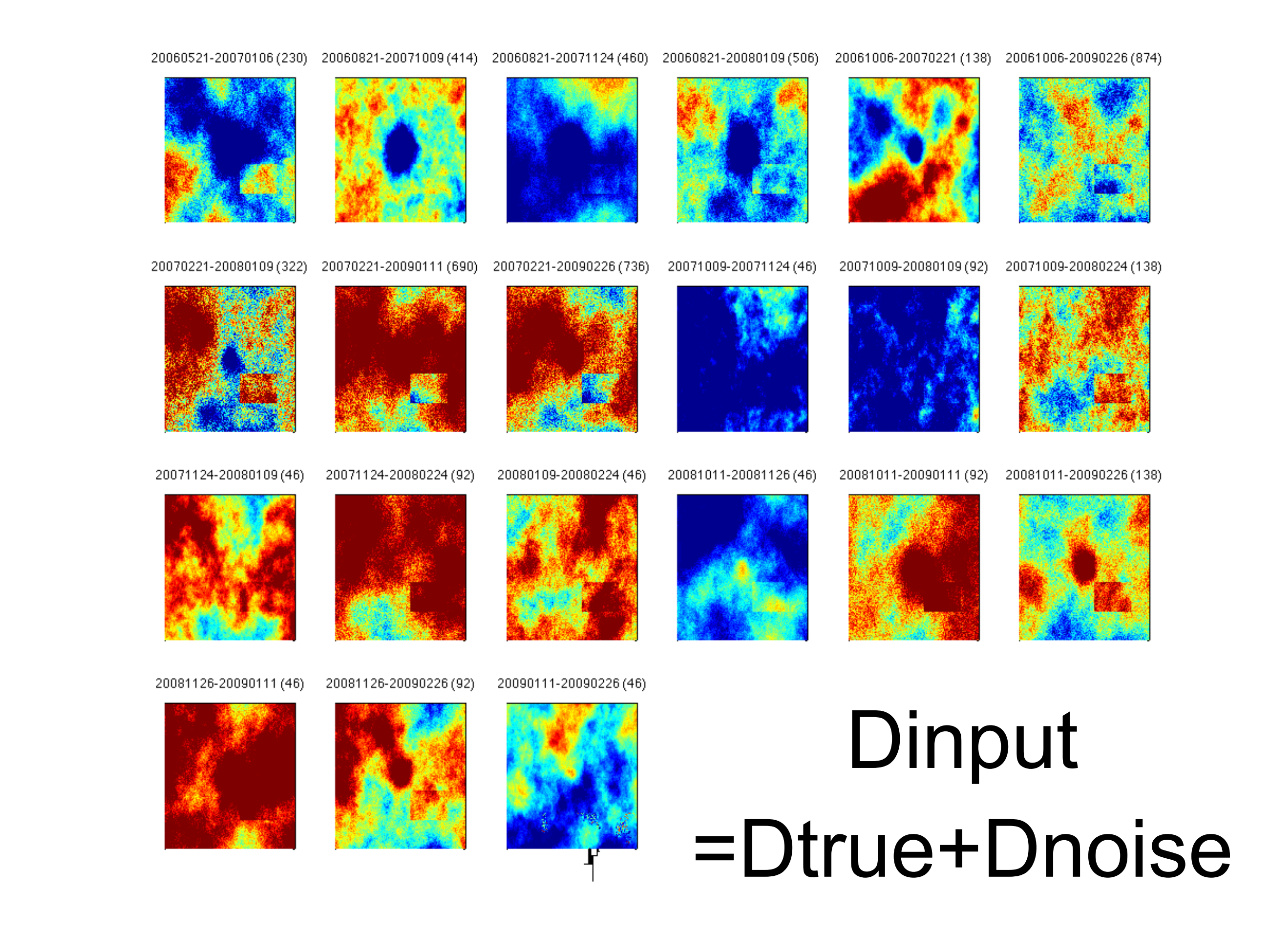
Dnoise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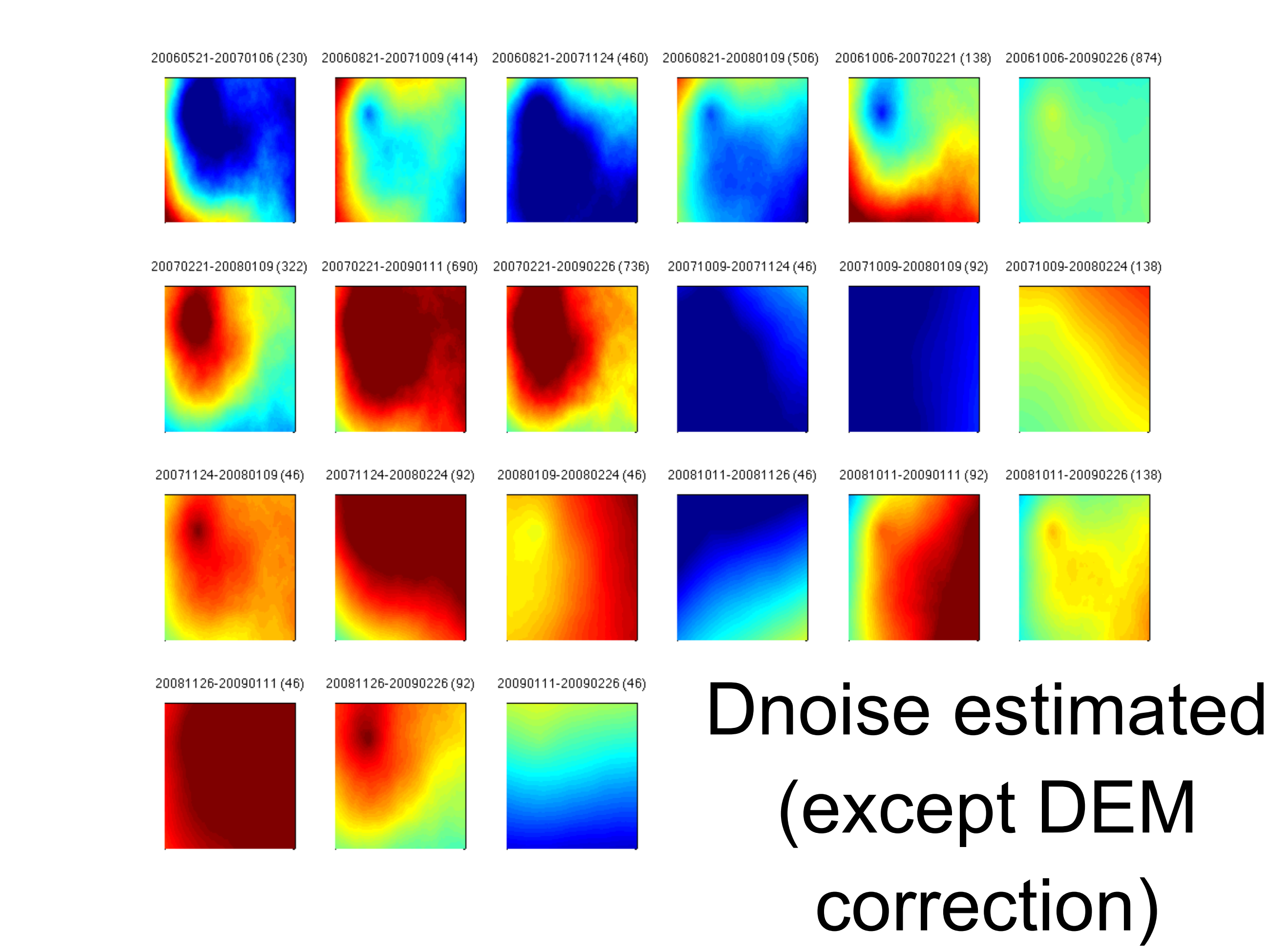
Dinput
=Dtrue+Dnoise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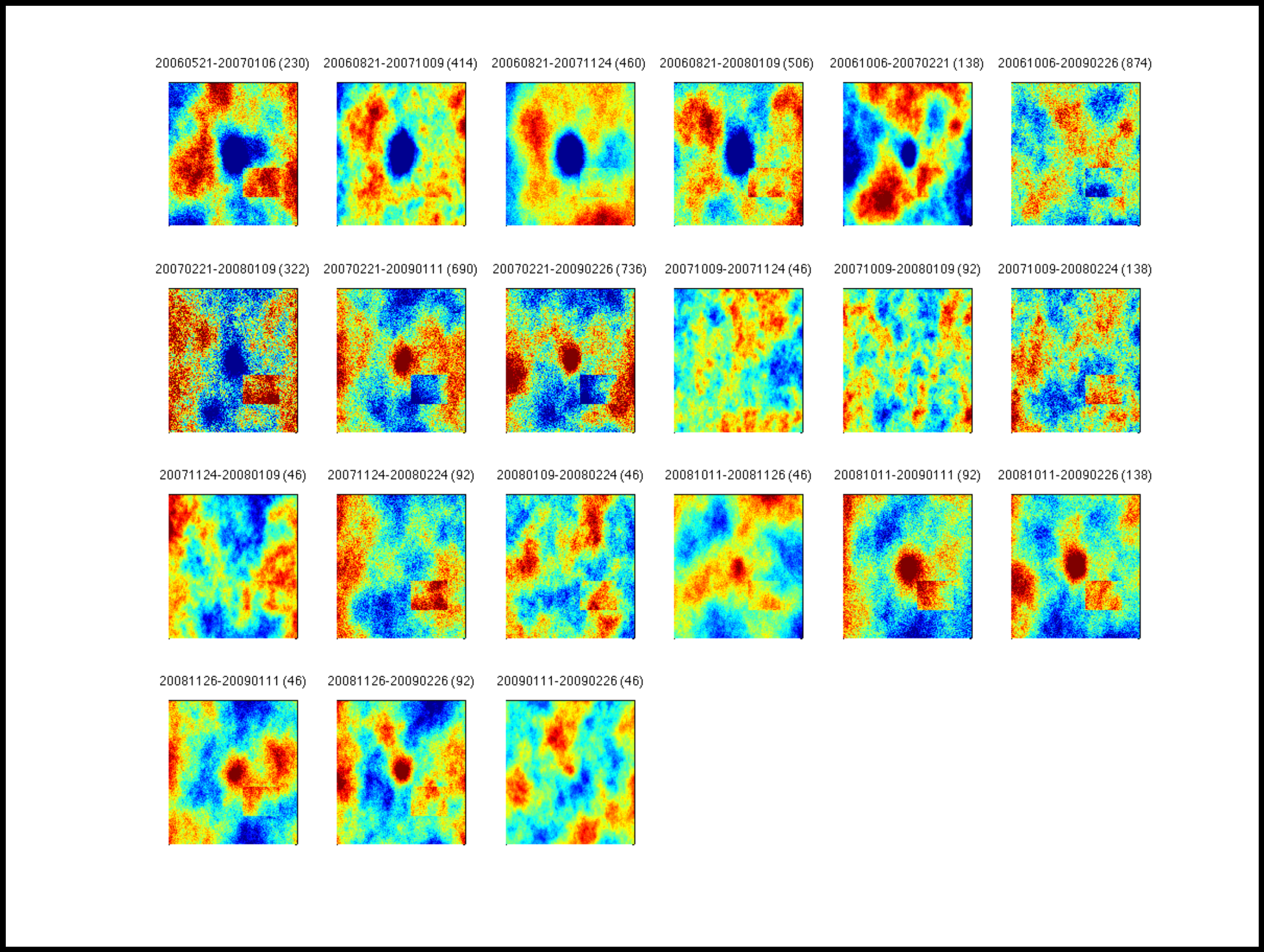
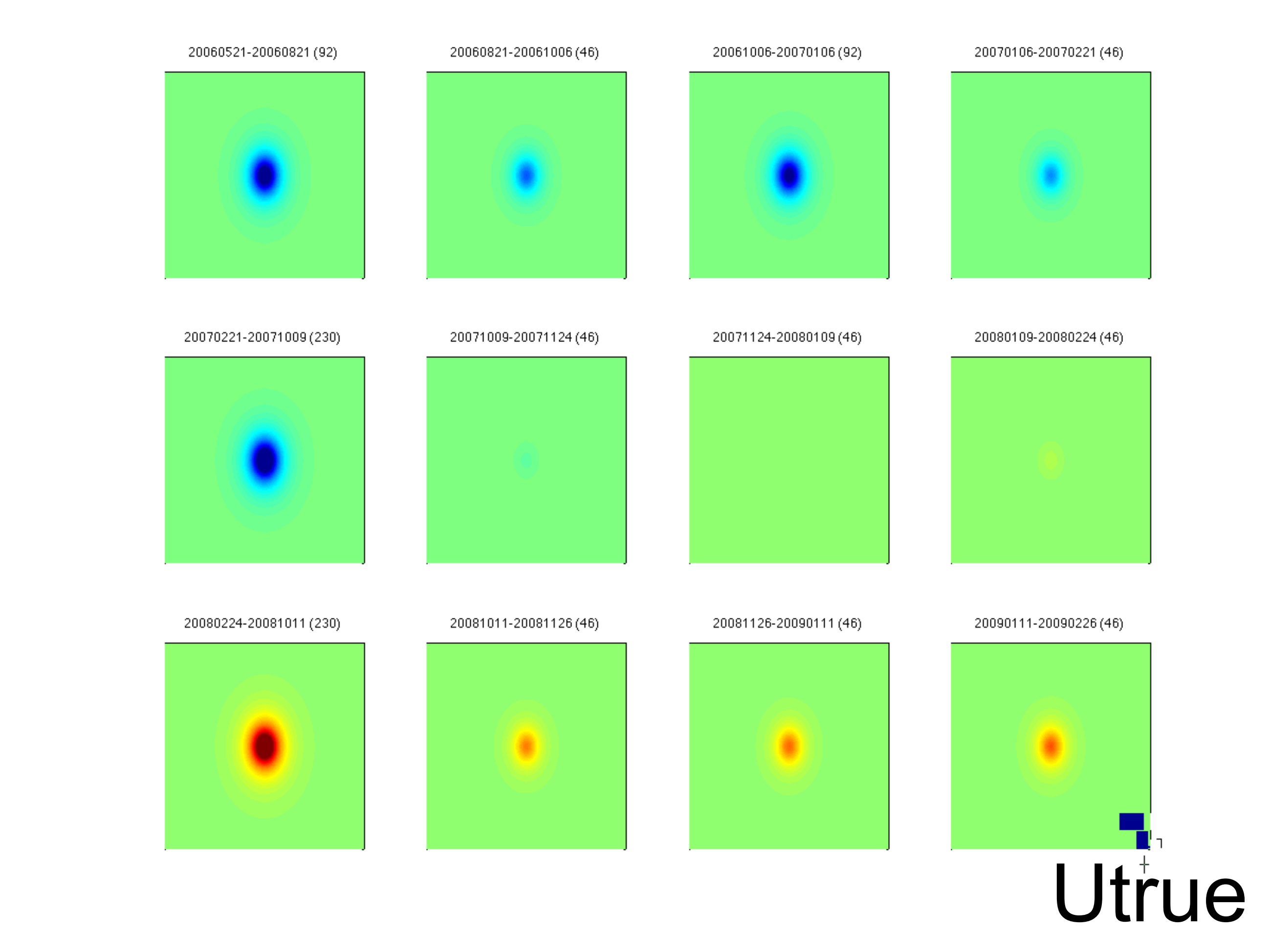
Dnoise estimated
(except DEM
correction)

2nd step: invert the corrected ifgs pixel-by-pixel



$$\phi_k^c \equiv \begin{bmatrix} \phi_{1,k}^c \\ \phi_{2,k}^c \\ \vdots \\ \phi_{N,k}^c \end{bmatrix} = \begin{bmatrix} \frac{4\pi}{\lambda}\mathbf{g}_1 & q_{1,k} \\ \frac{4\pi}{\lambda}\mathbf{g}_2 & q_{2,k} \\ \vdots & \vdots \\ \frac{4\pi}{\lambda}\mathbf{g}_N & q_{N,k} \end{bmatrix} \begin{bmatrix} \mathbf{v}_k \\ \delta h_k \end{bmatrix} + \epsilon_k$$

$$= \mathbf{G}_k \mathbf{m}_k + \epsilon_k,$$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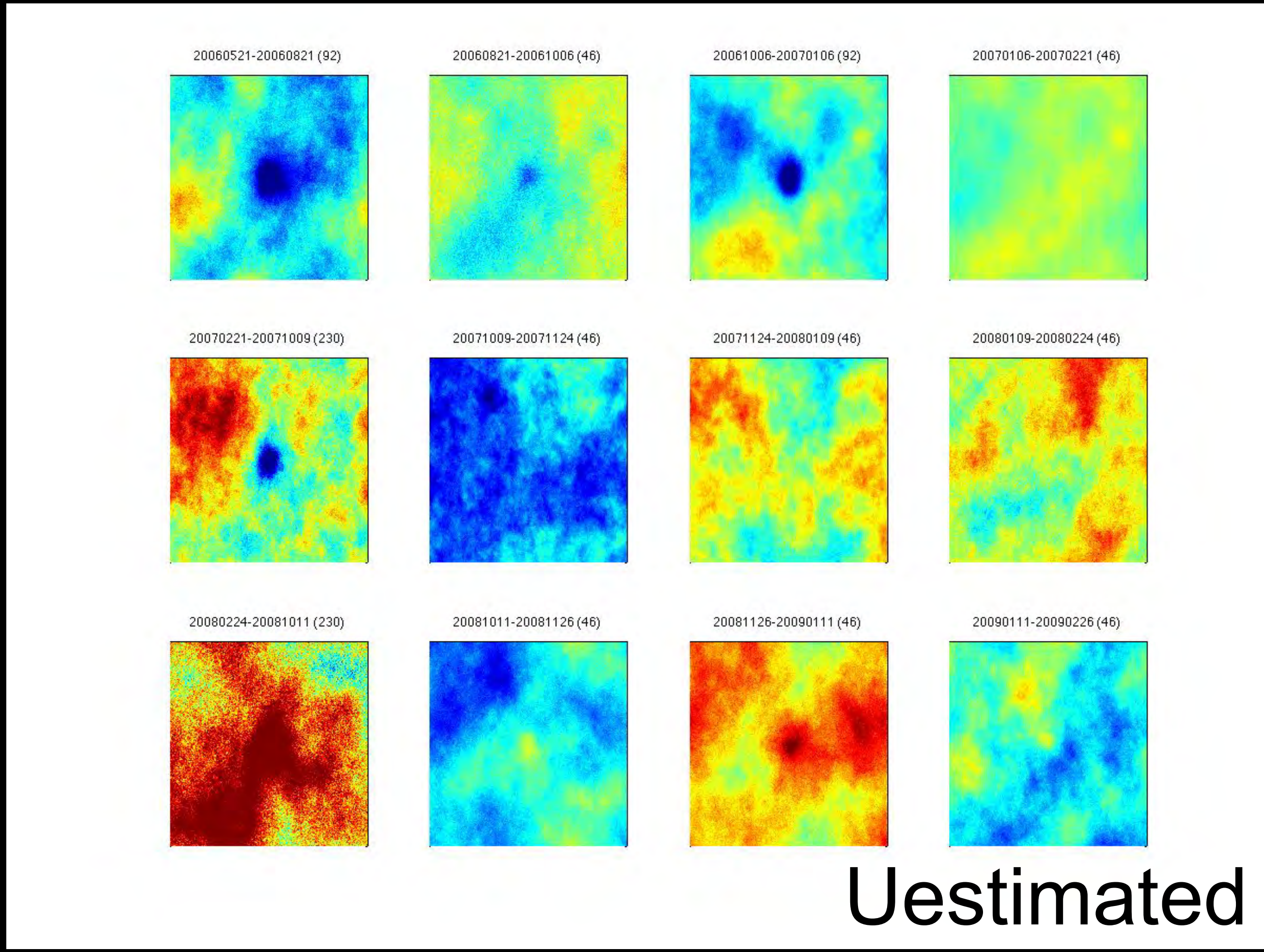
Utrue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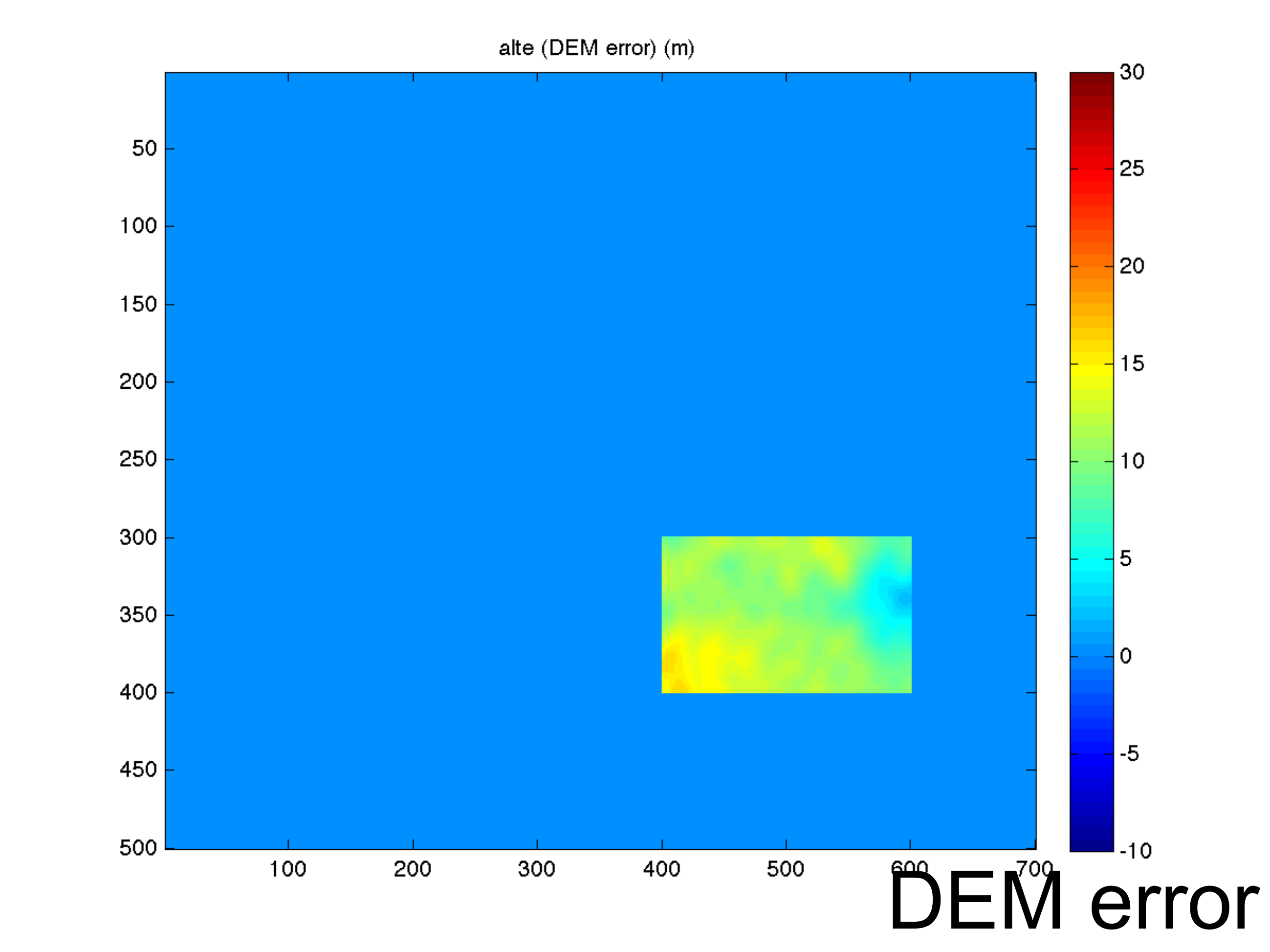
Uestimated


alte (DEM error) (m)
50
100
150
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25
20
15
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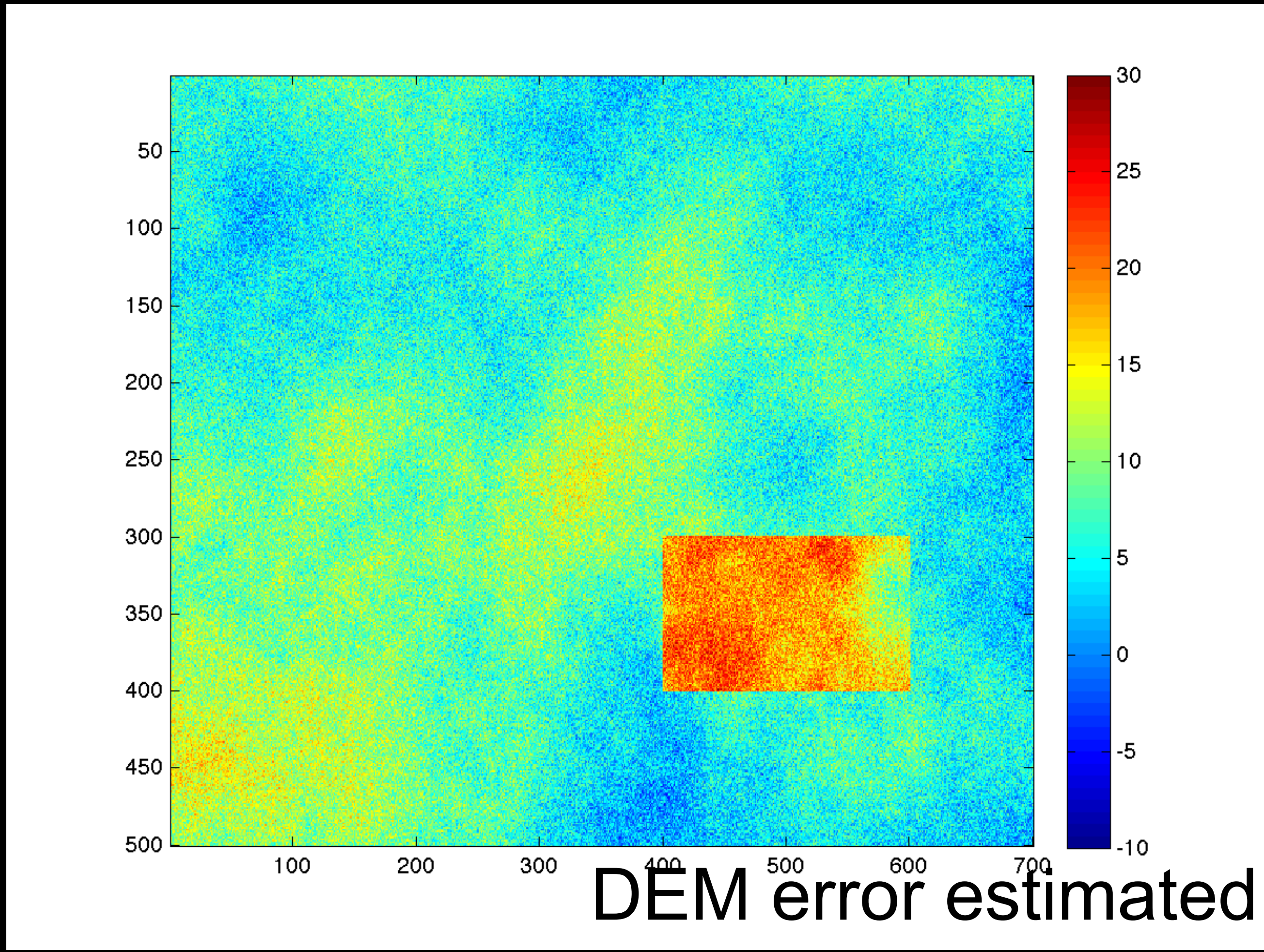
0
-5
-10
DEM error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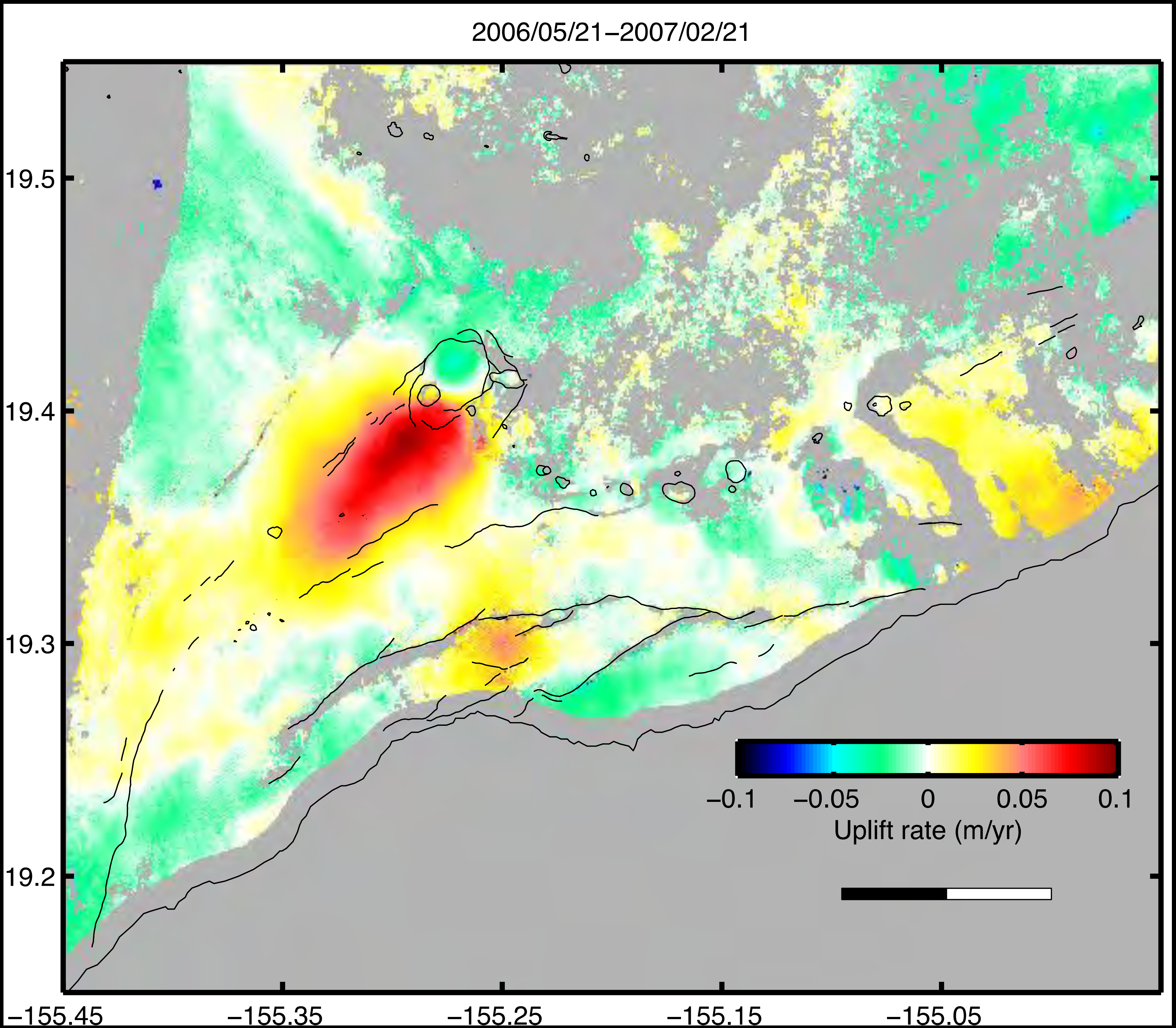
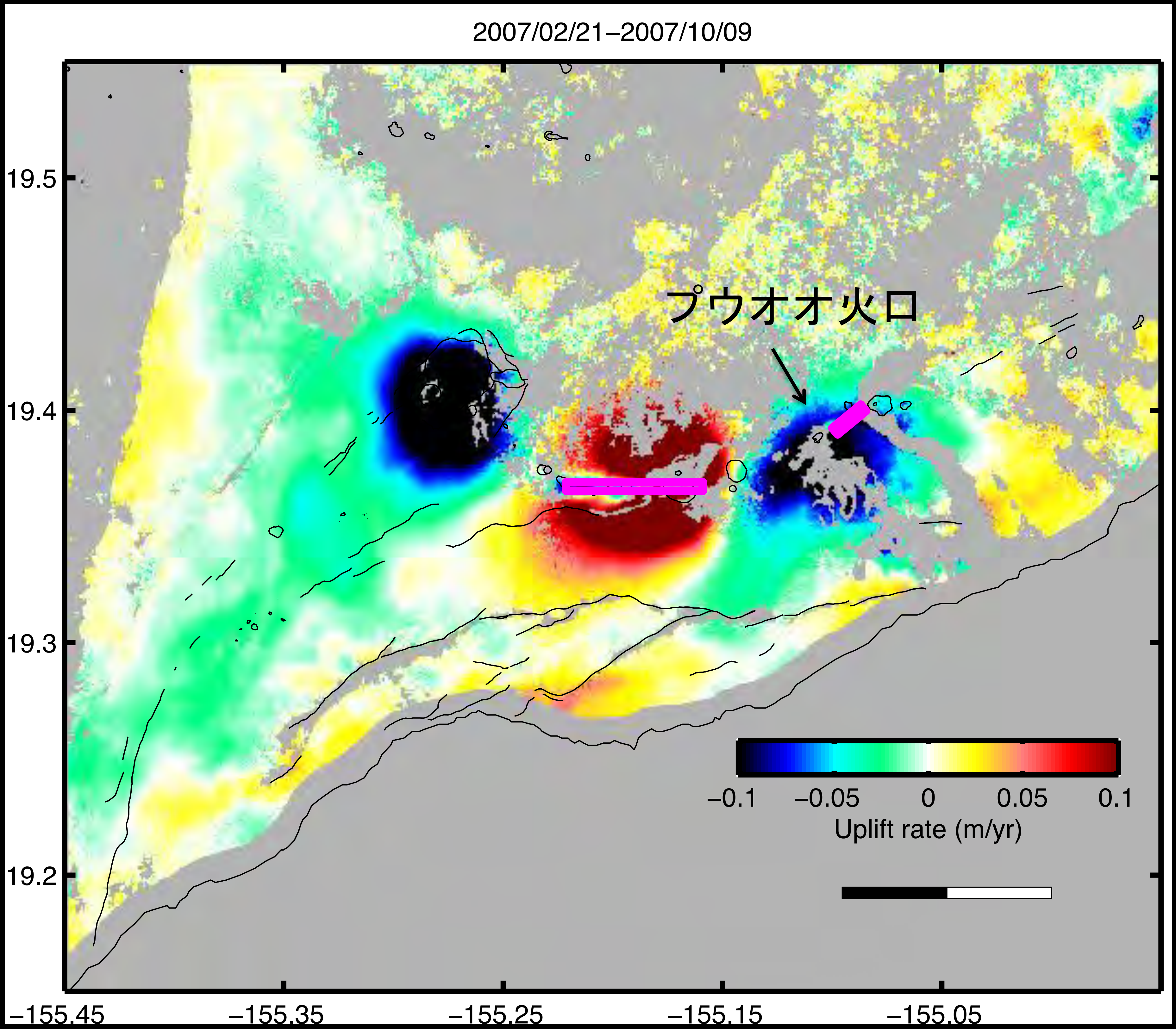
-5
-10
DEM error estimated

Applications

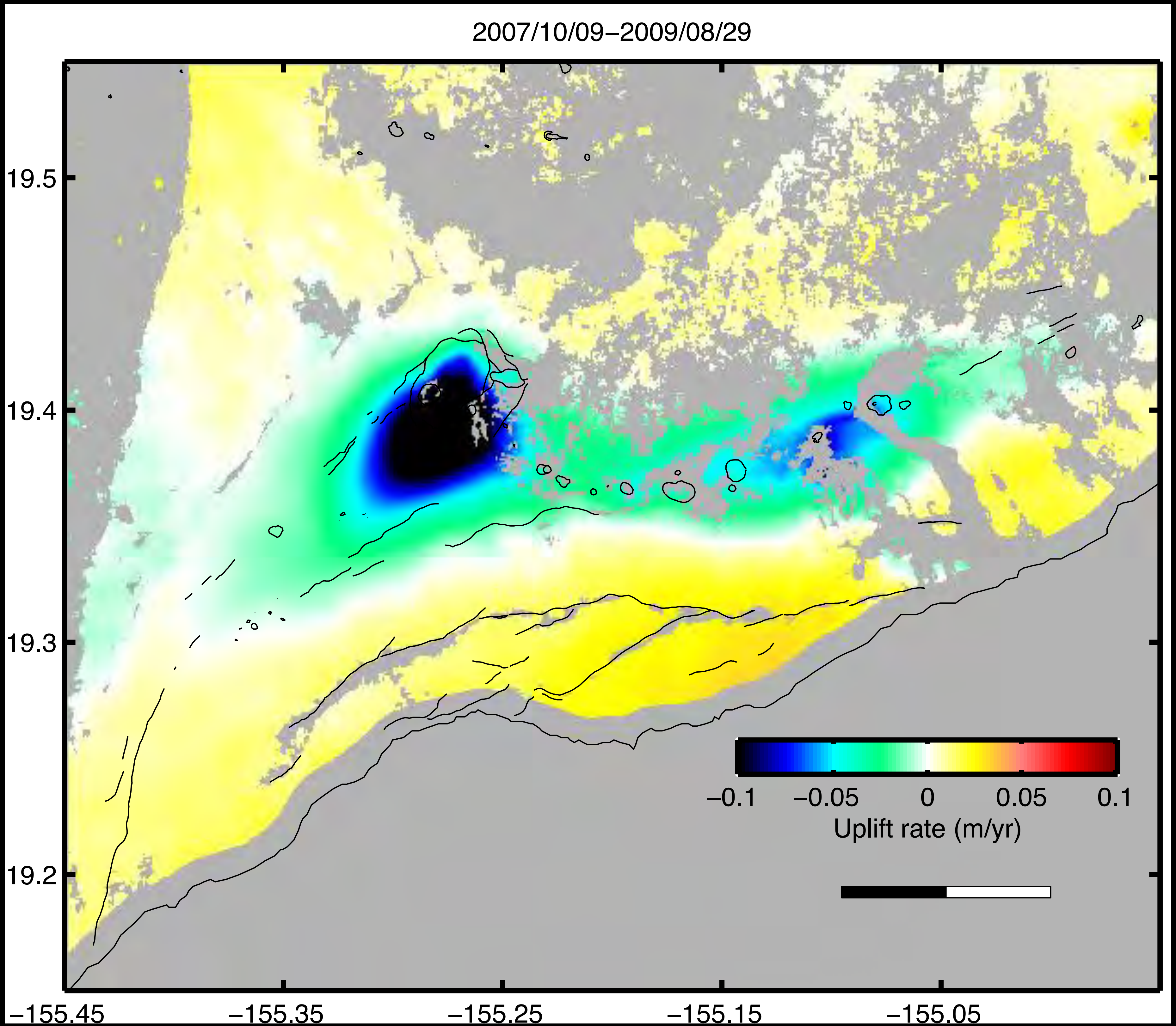
Kilauea, Hawaii



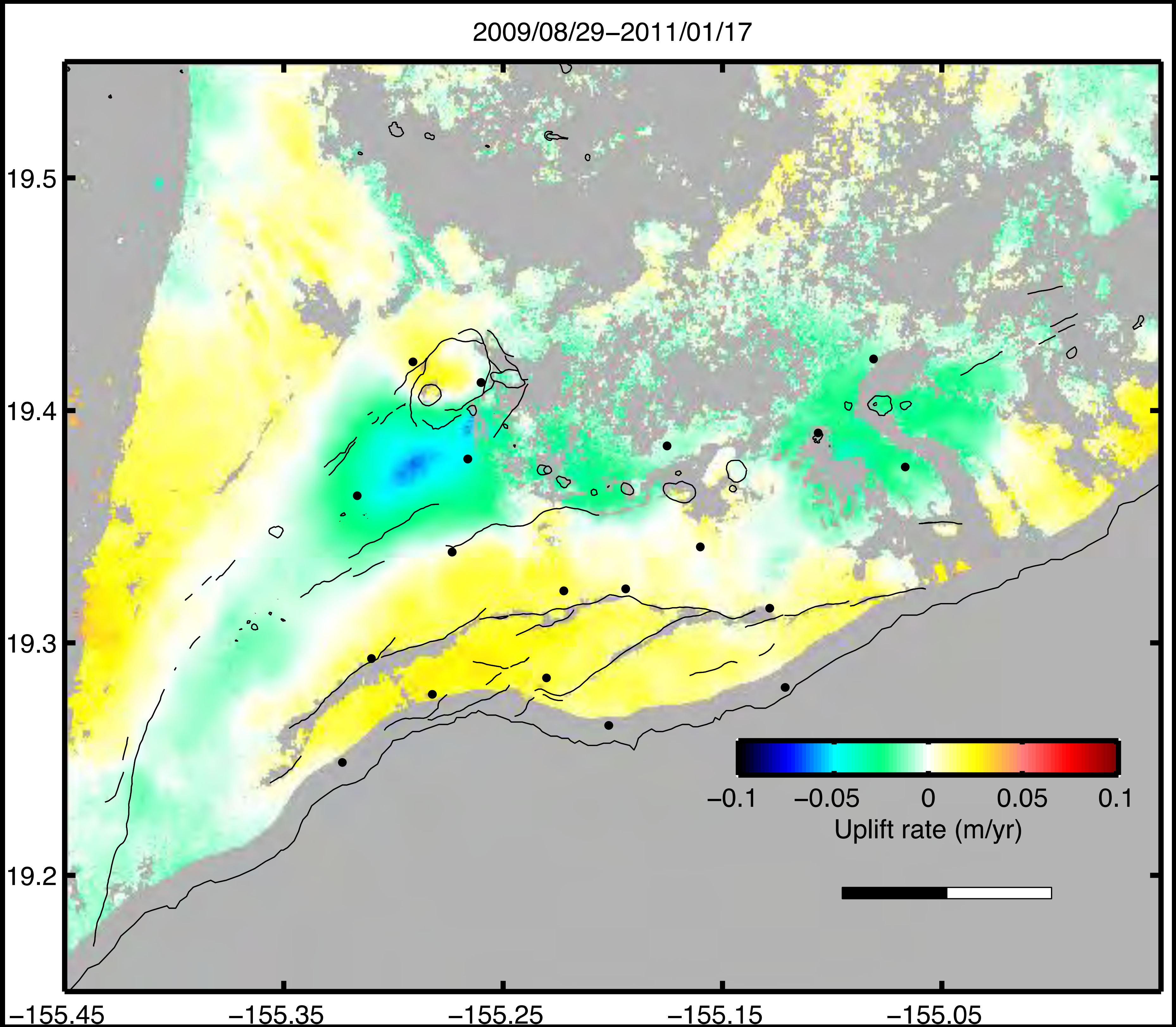
Kilauea, Hawaii



Kilauea, Hawaii

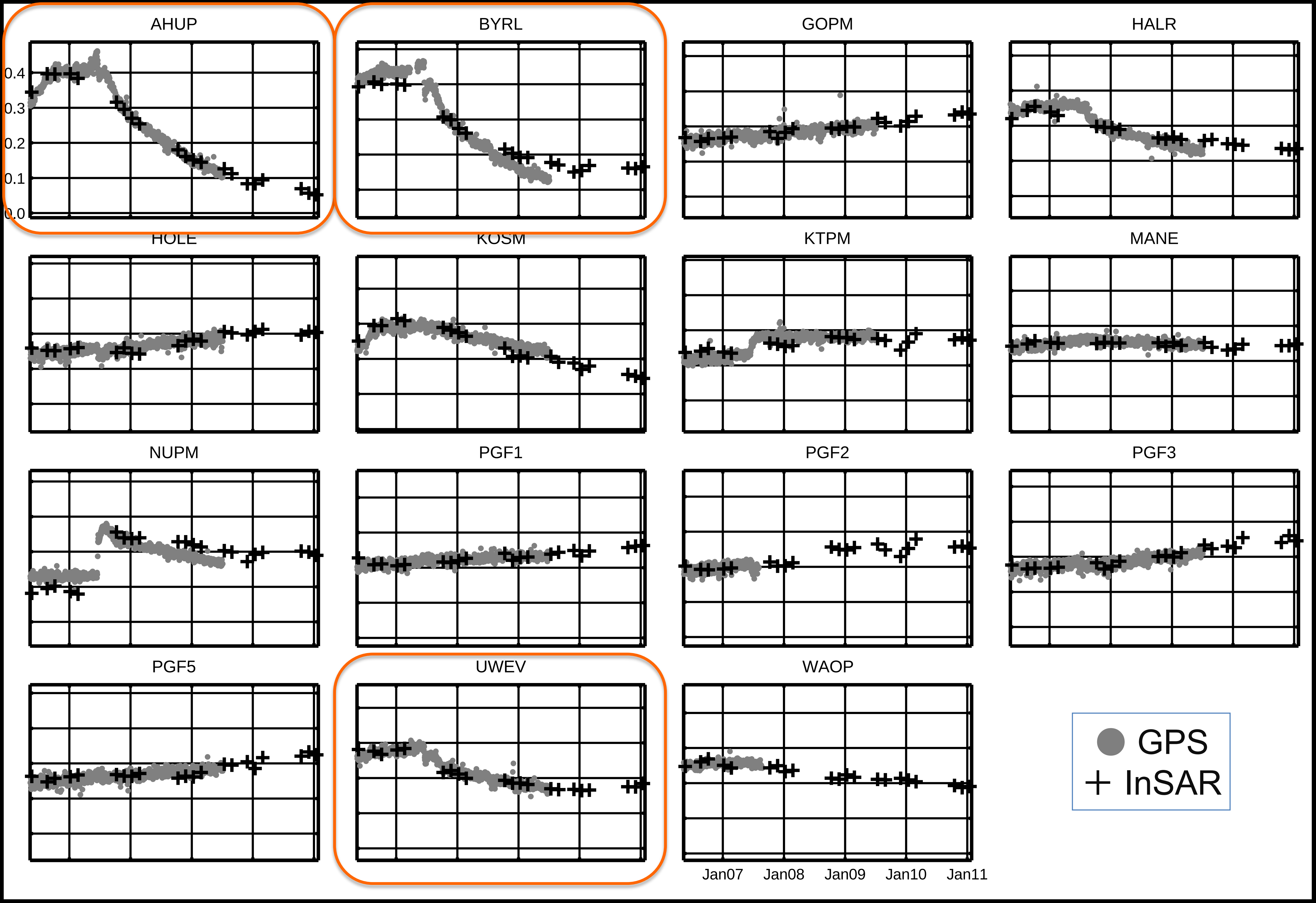


Kilauea, Hawaii

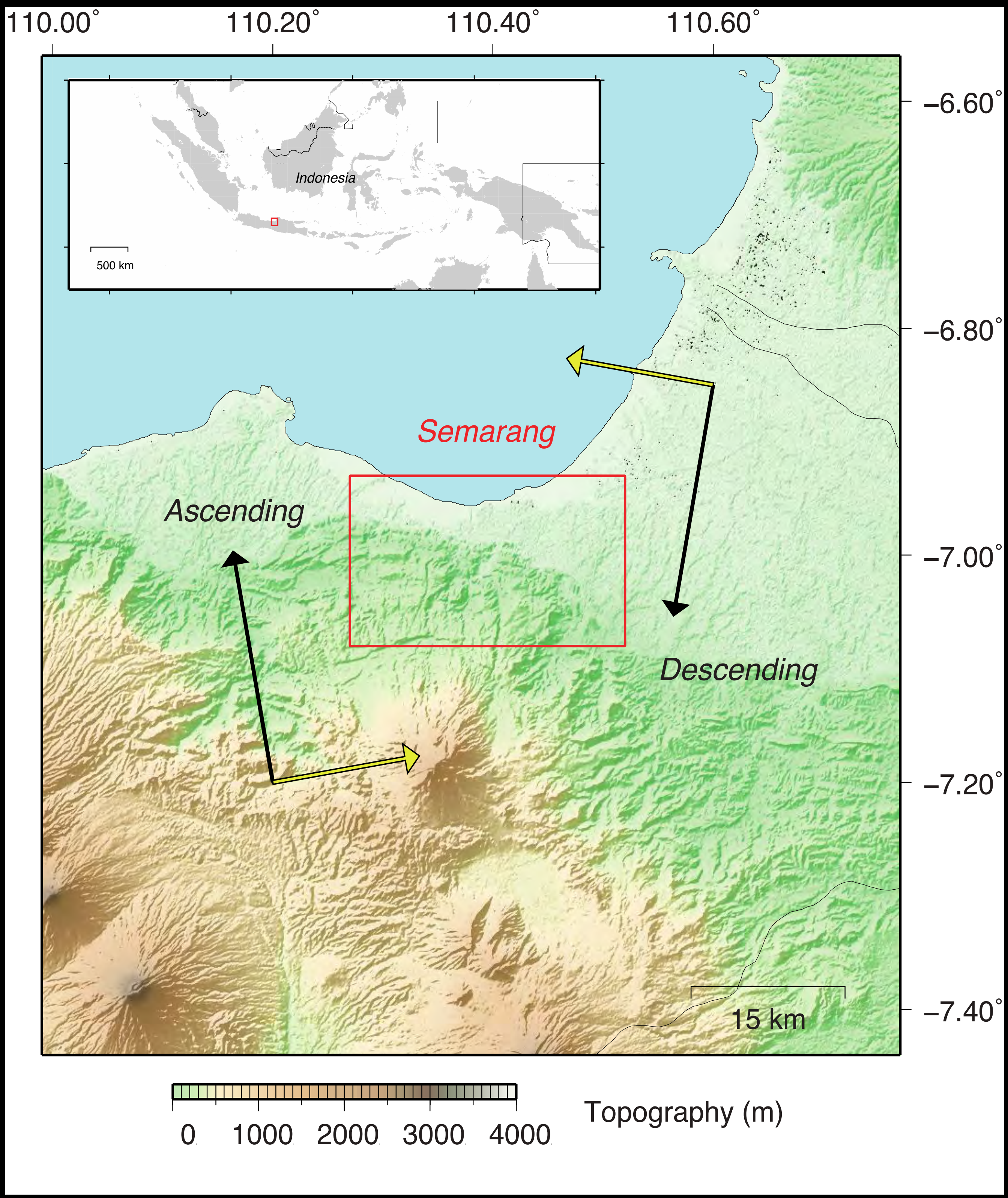


Fairly consistent with GPS vertical
（RMS 1.6 cm）

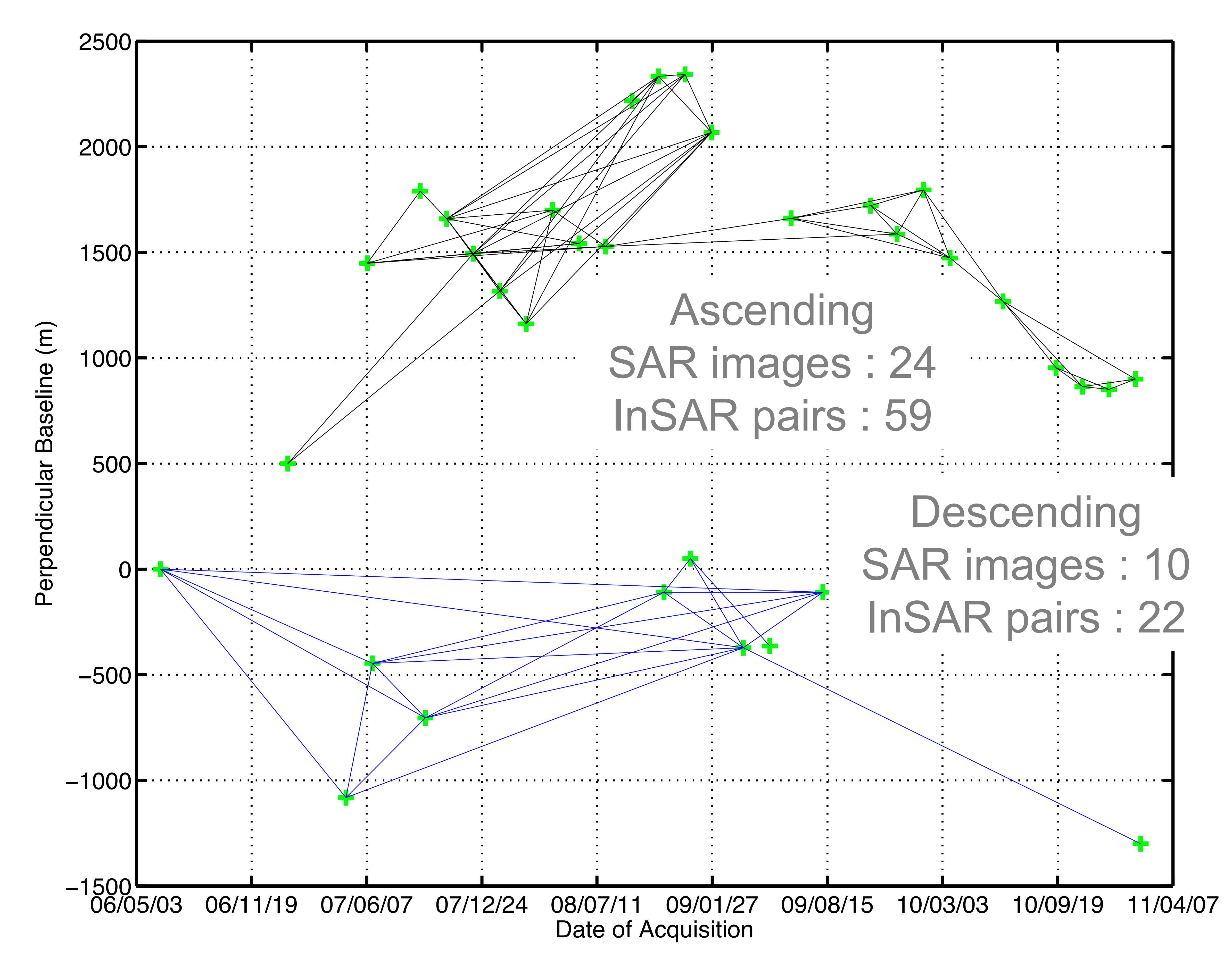
山頂付近



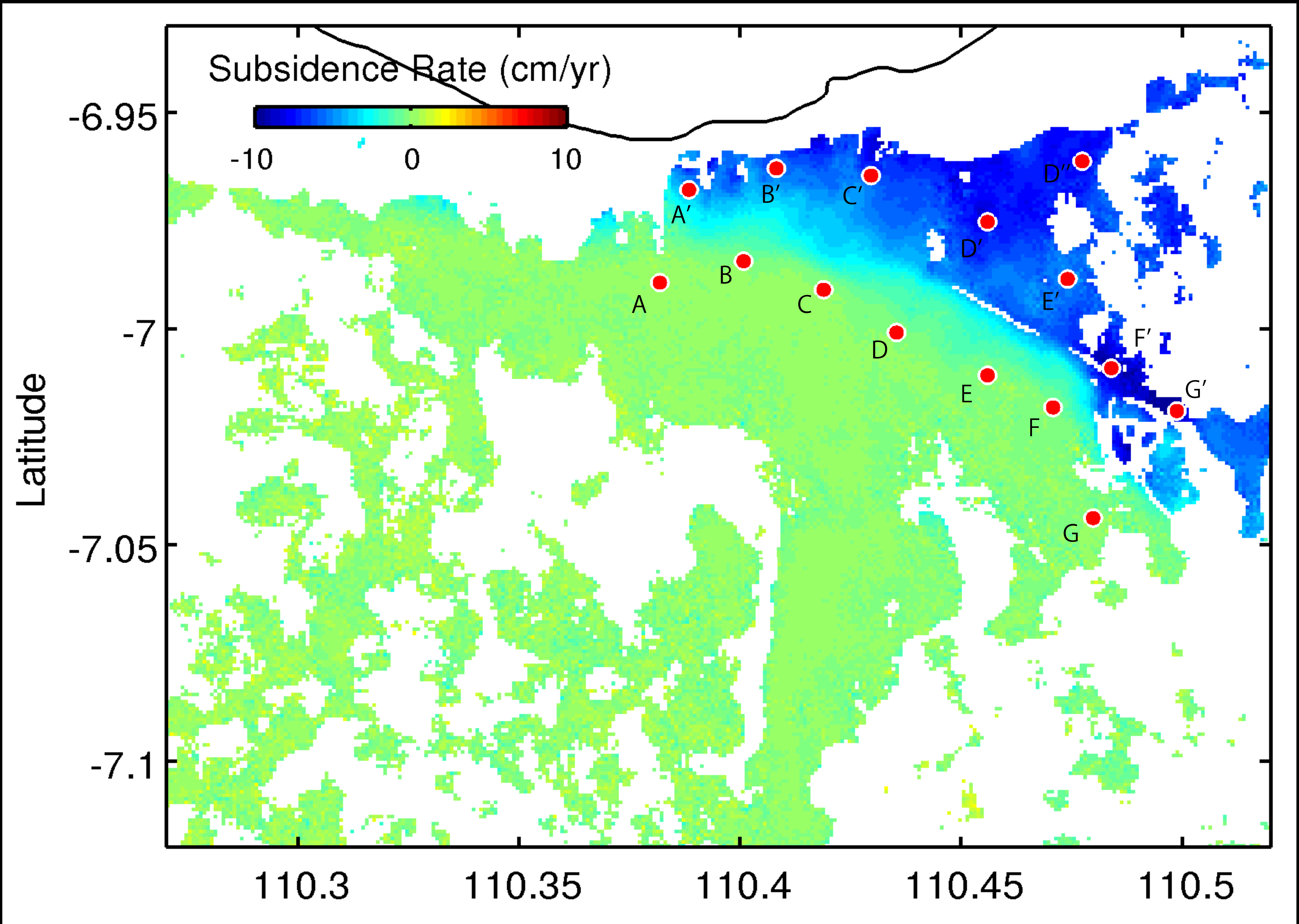
Land subsidence in Semarang, Indonesia (analyzed by M. Arimoto)



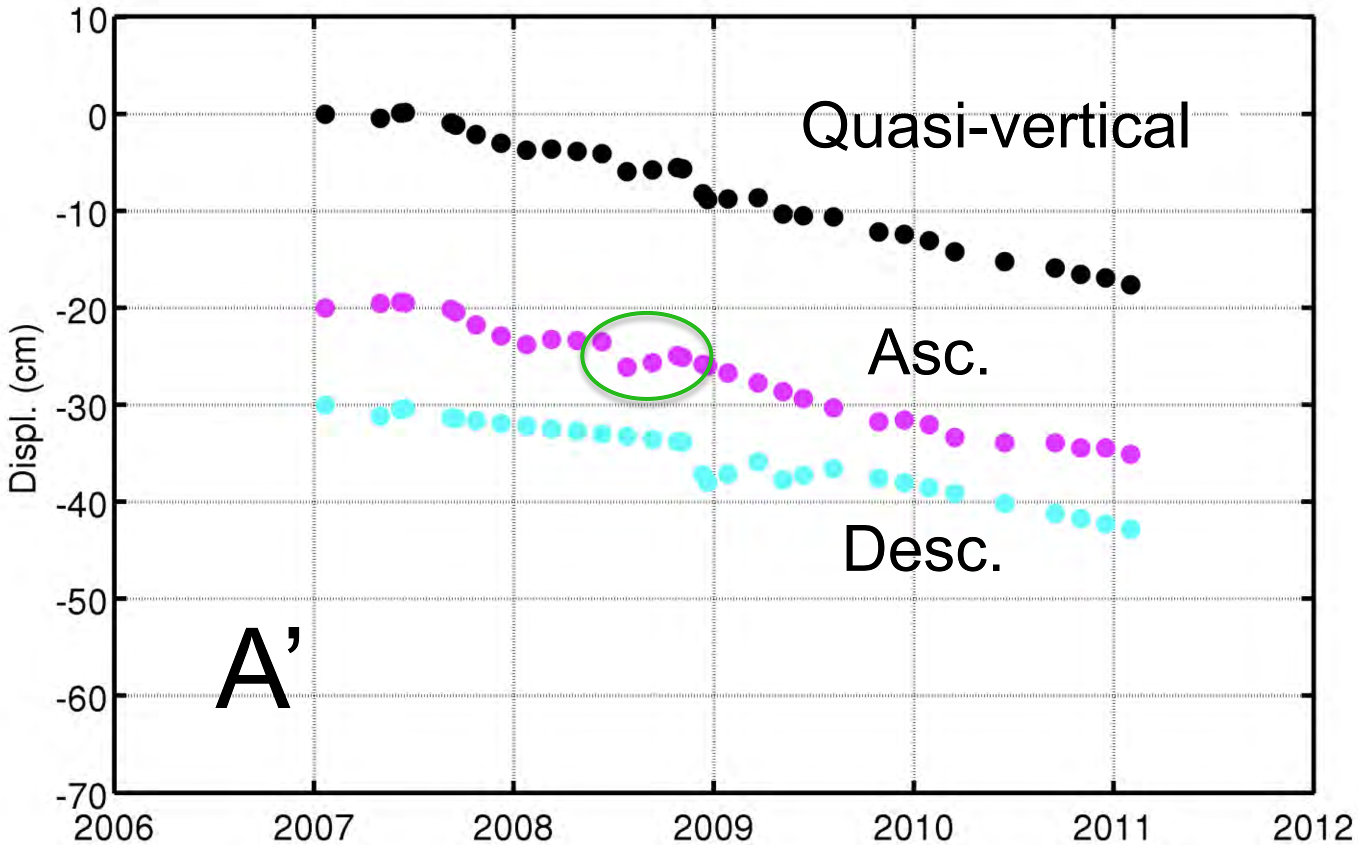
Baselines: Ascending and Descending

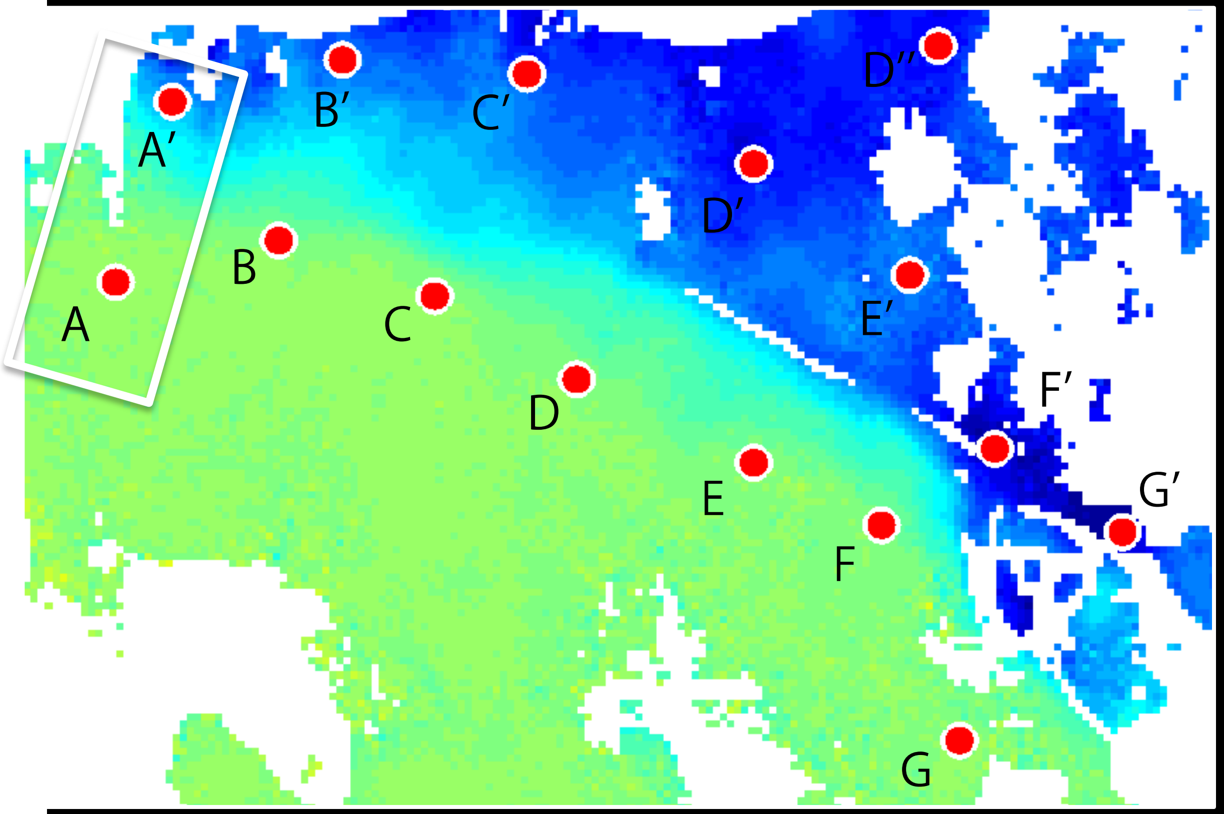


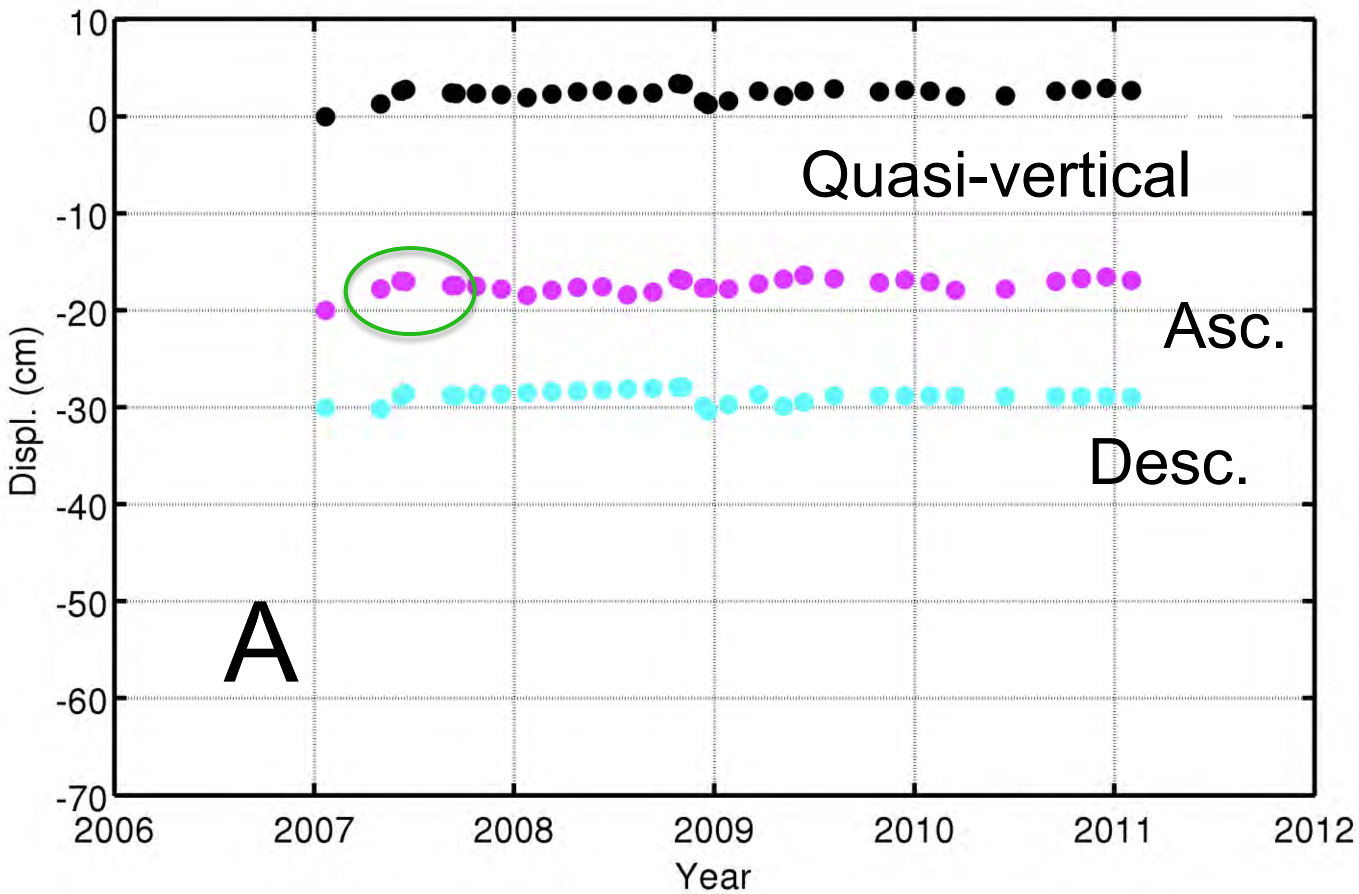
Velocity of quasi-vertical component

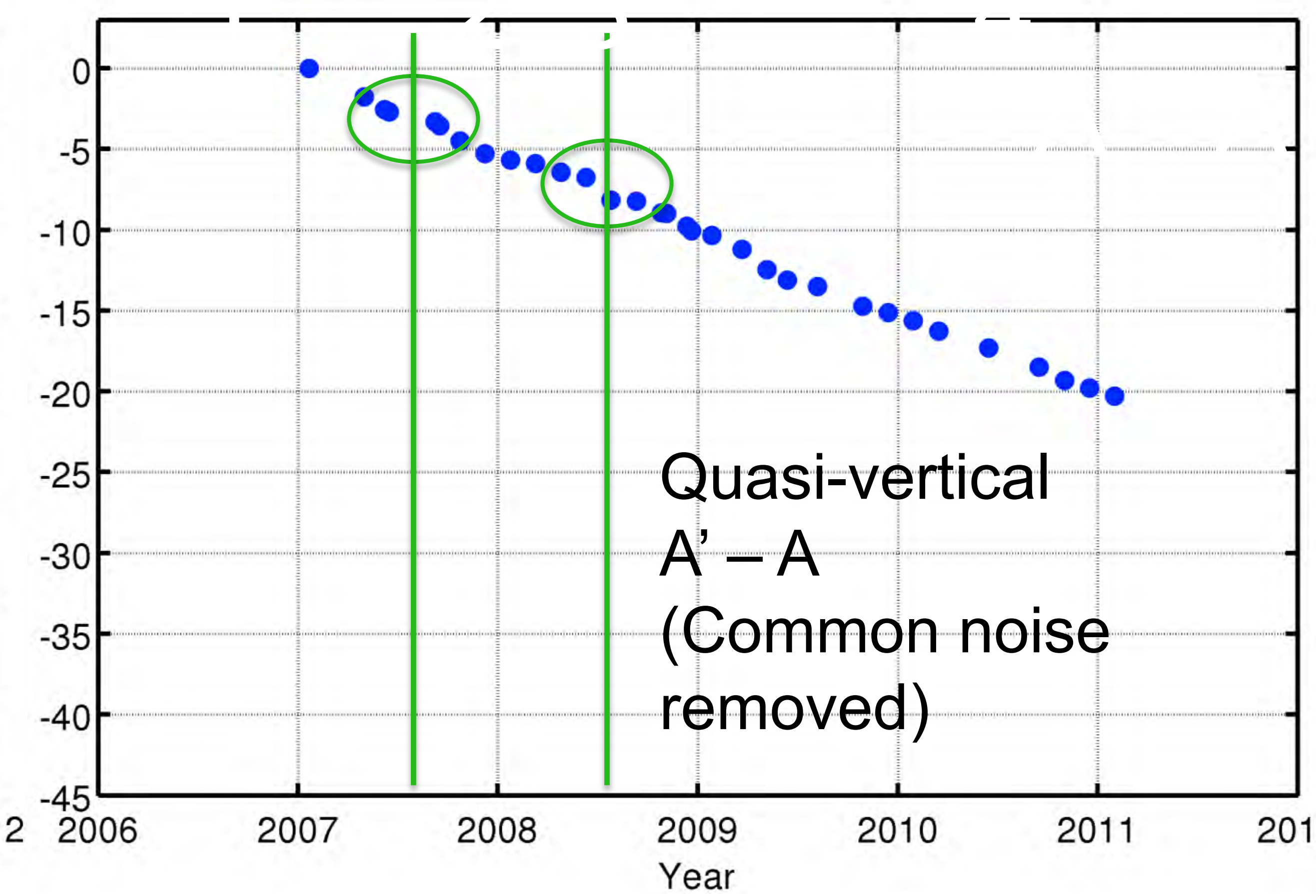


Profiles at Selected Points

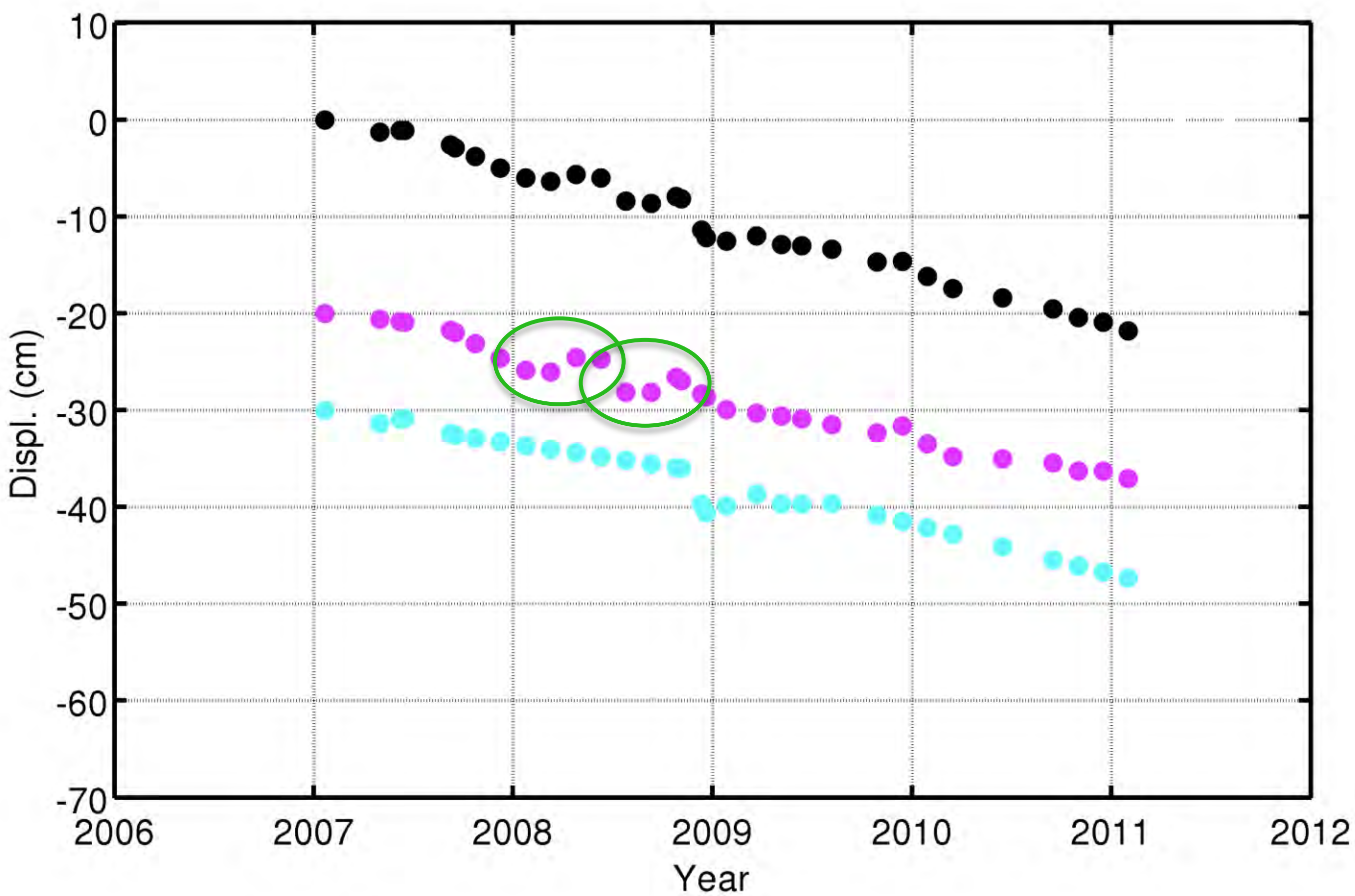


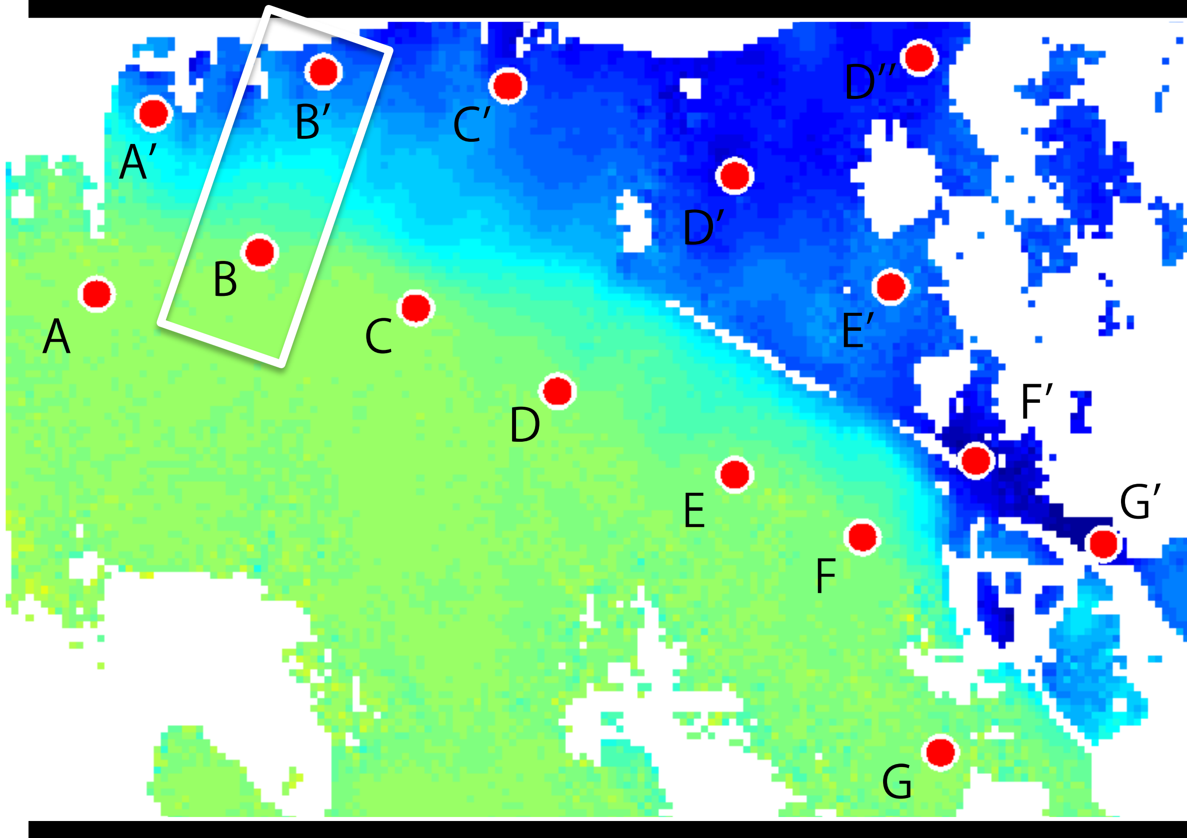


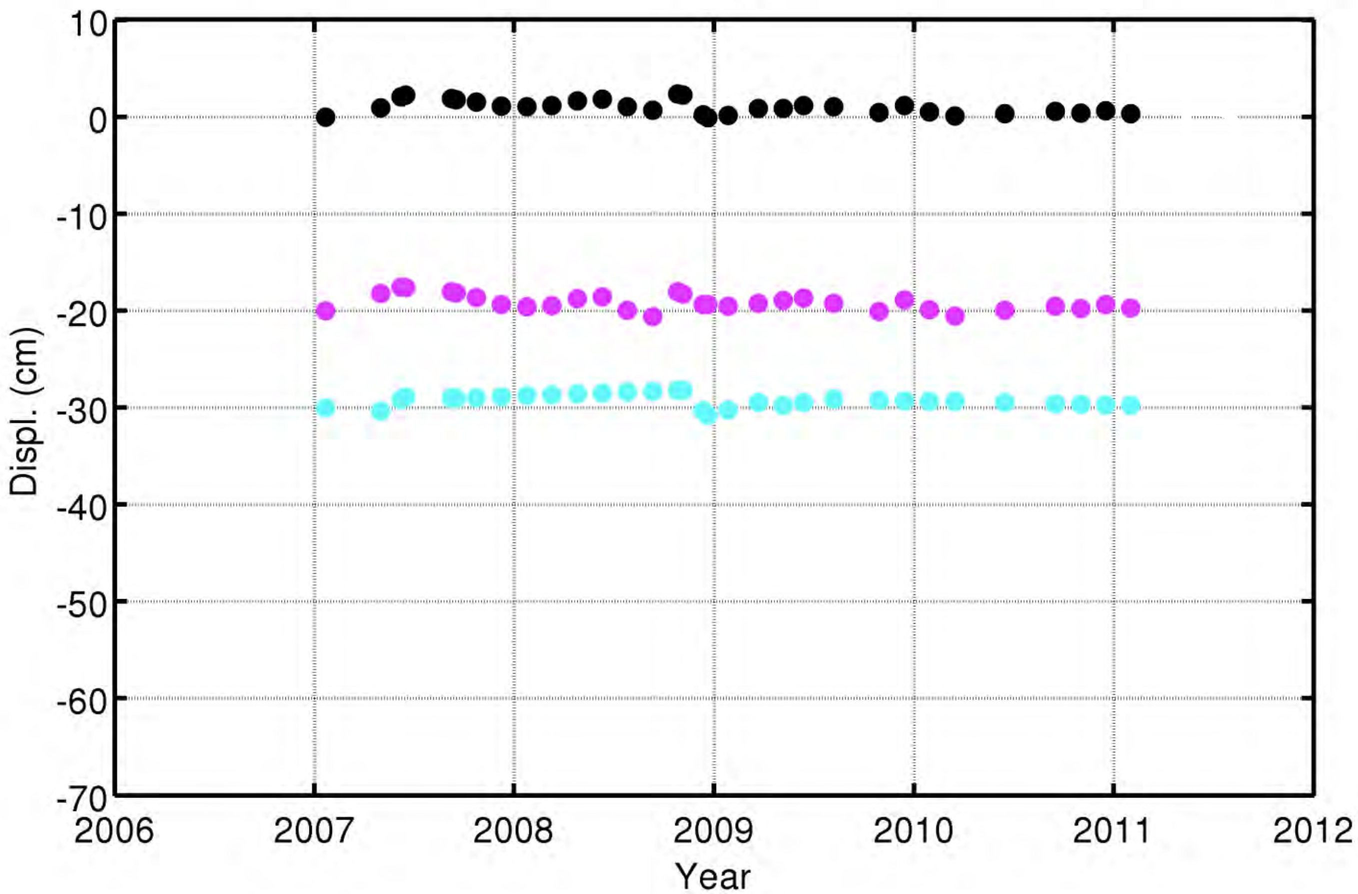


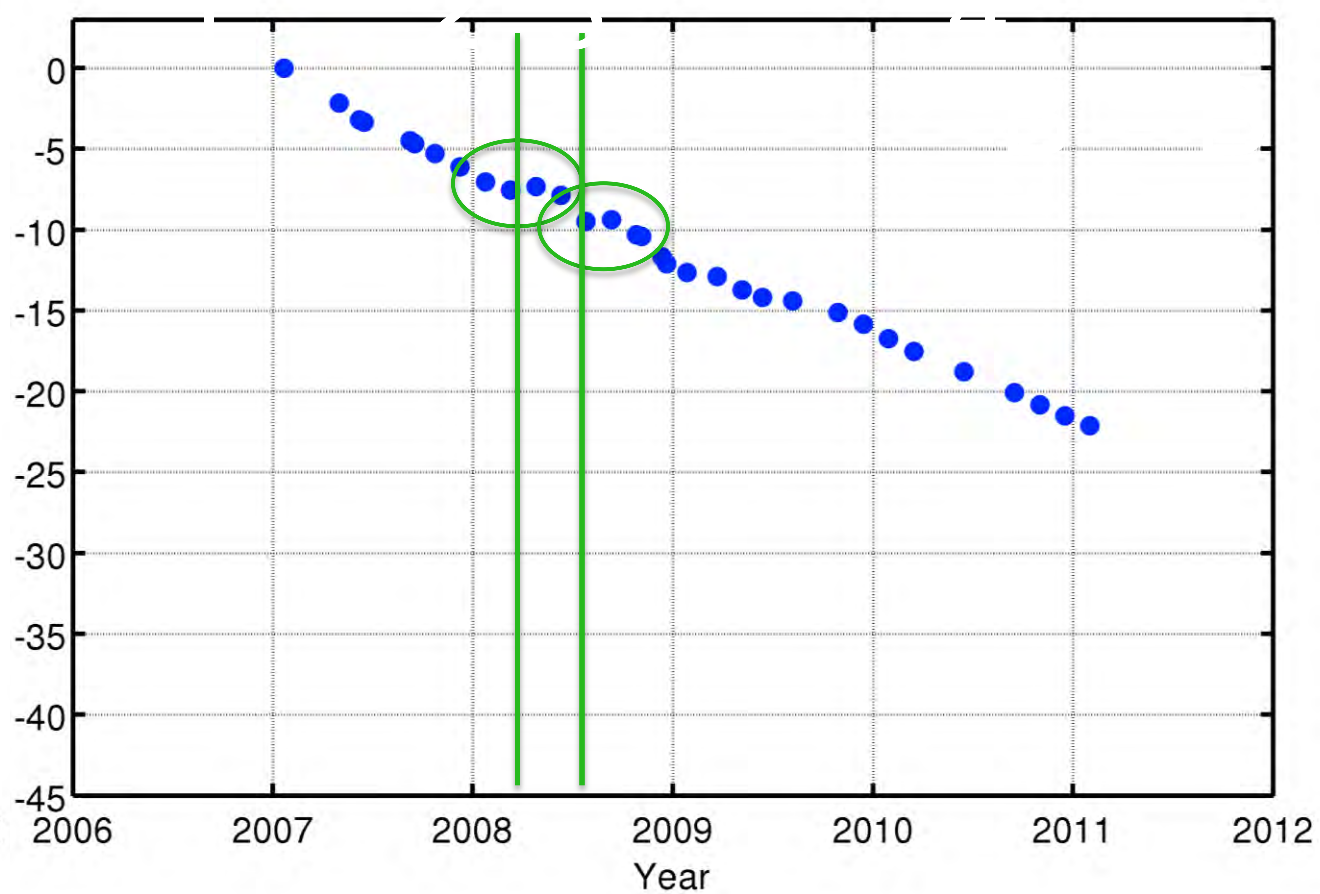


Profiles at Selected Points









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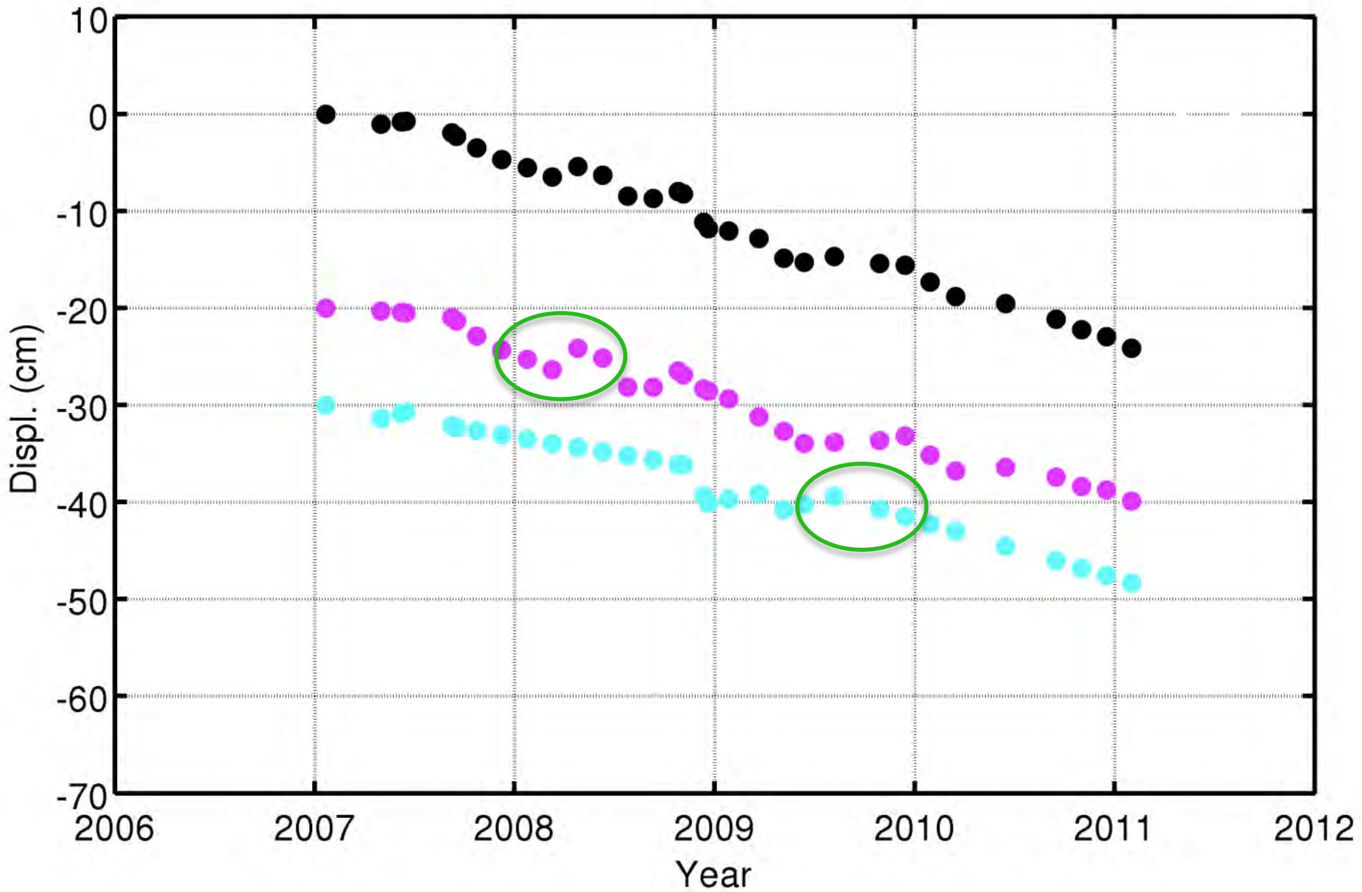
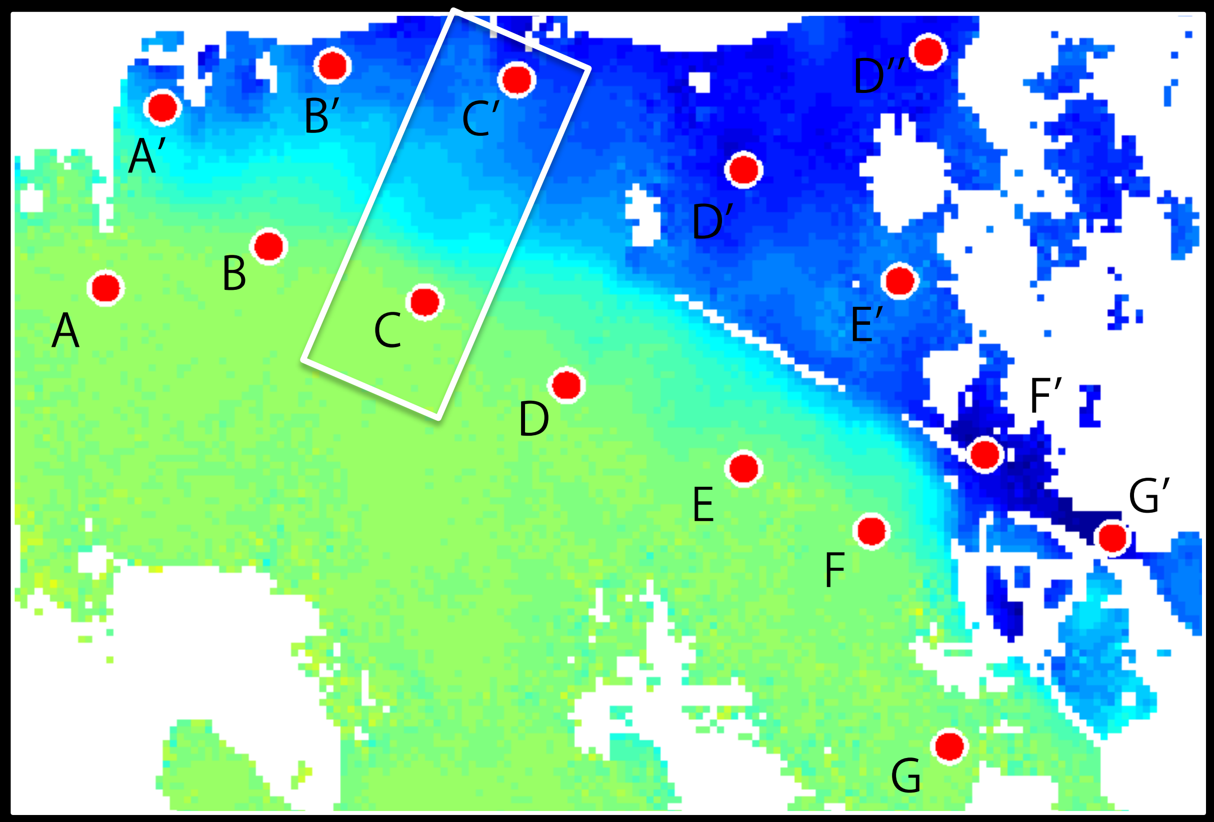
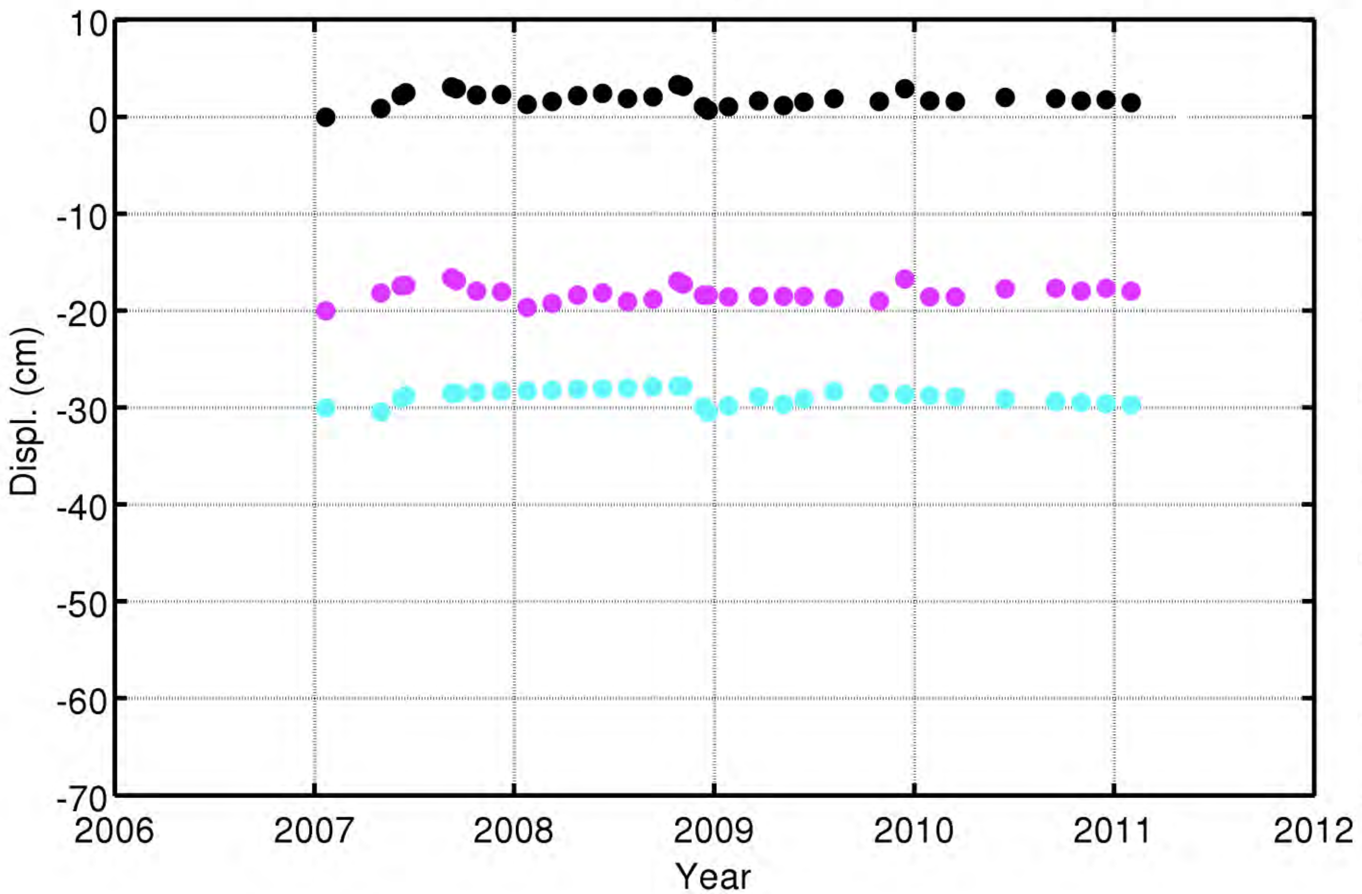
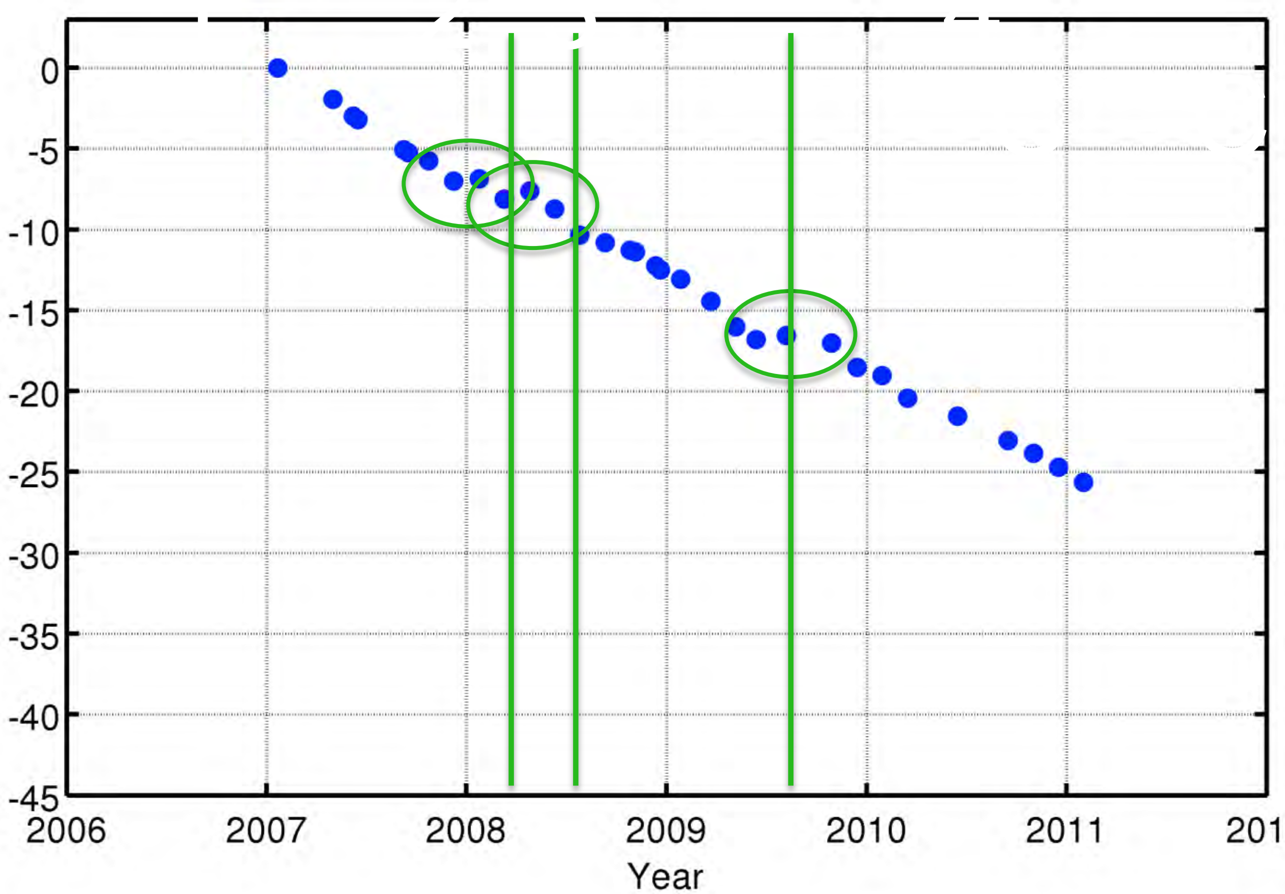
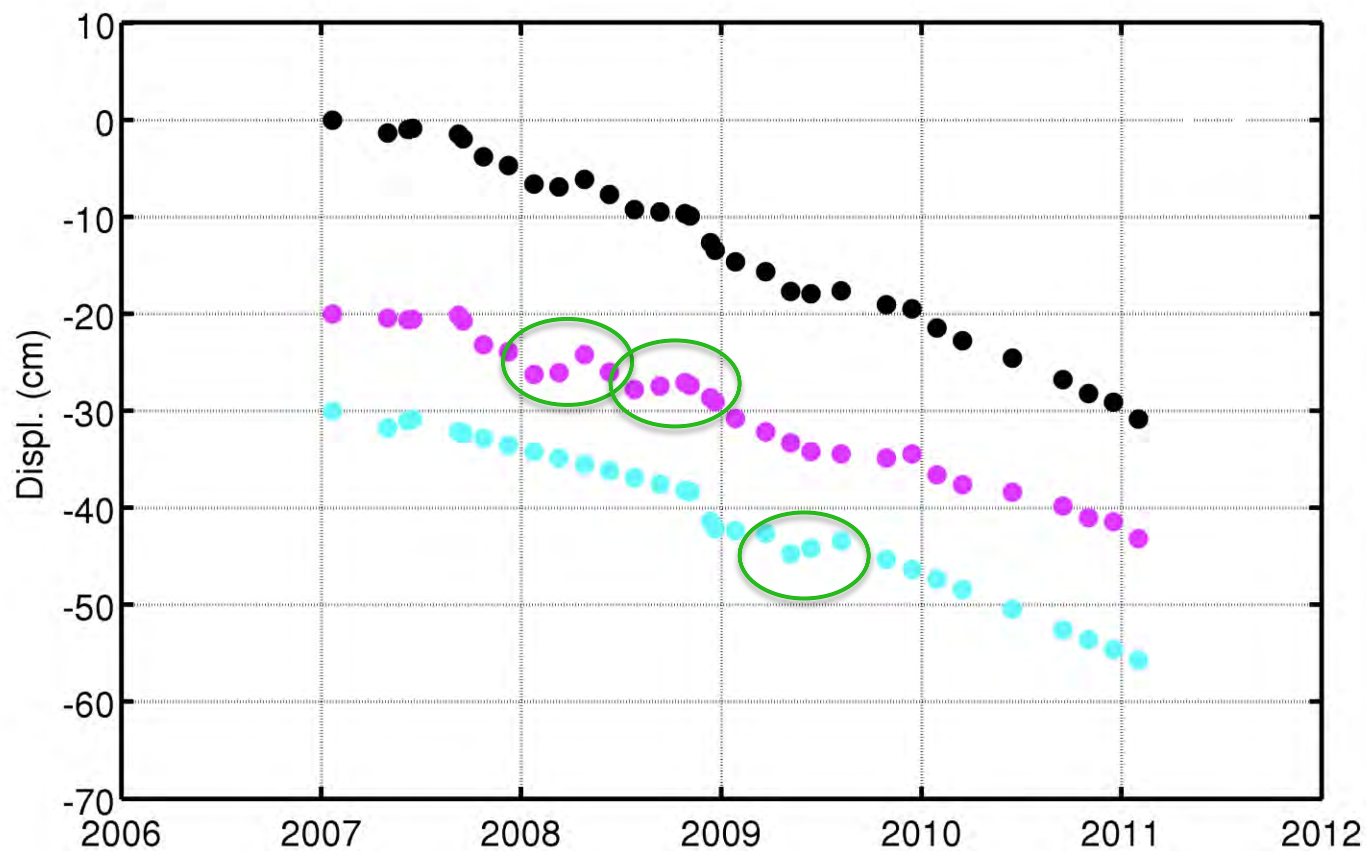


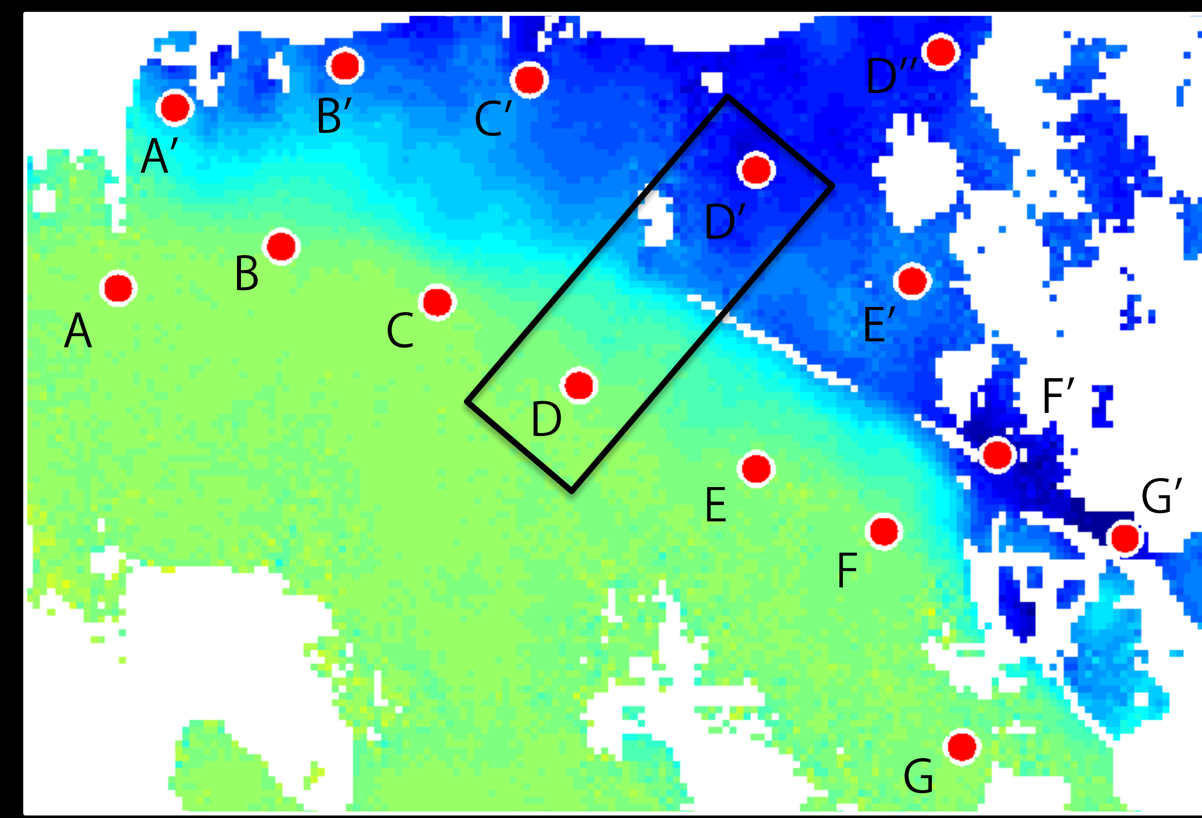


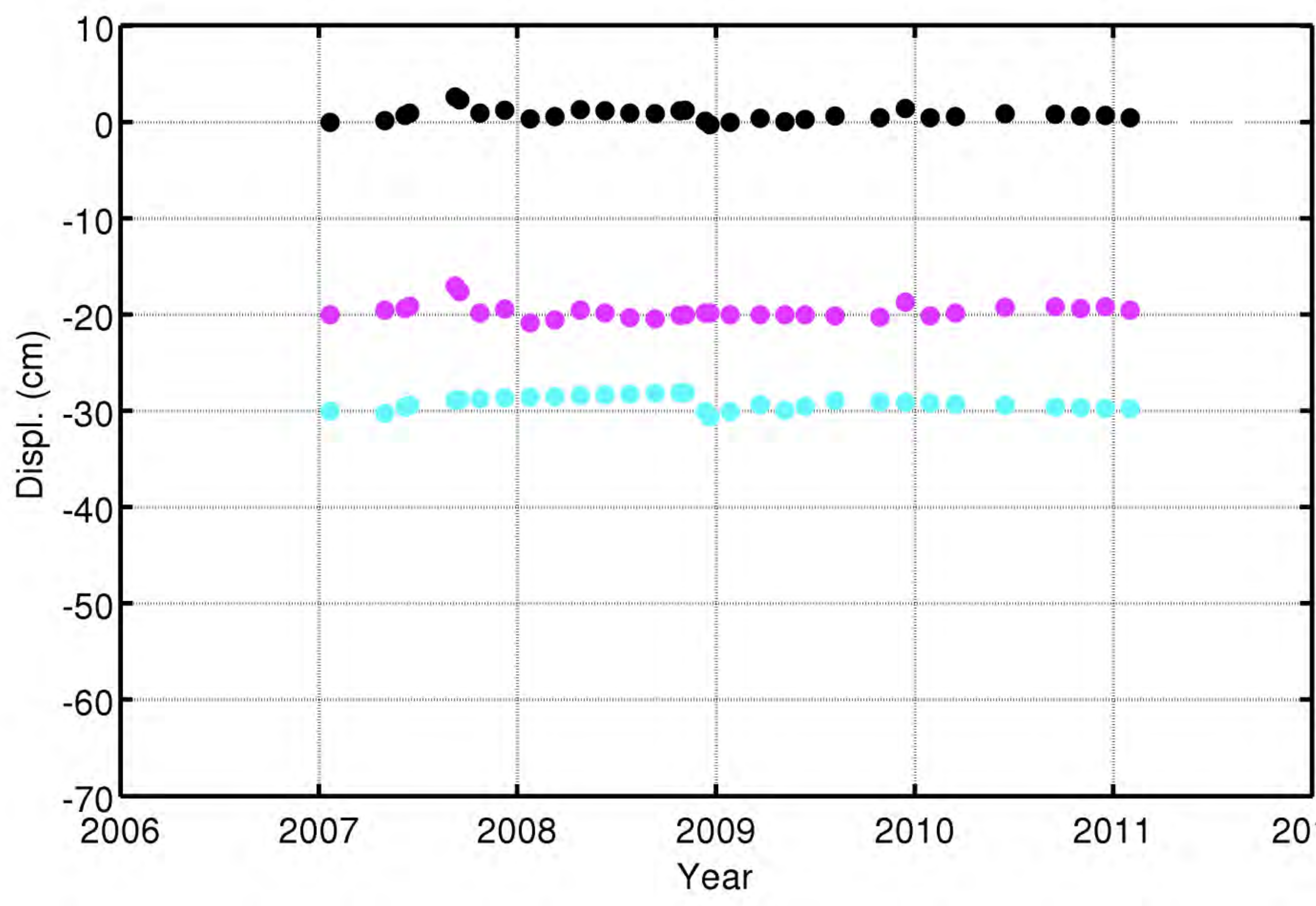


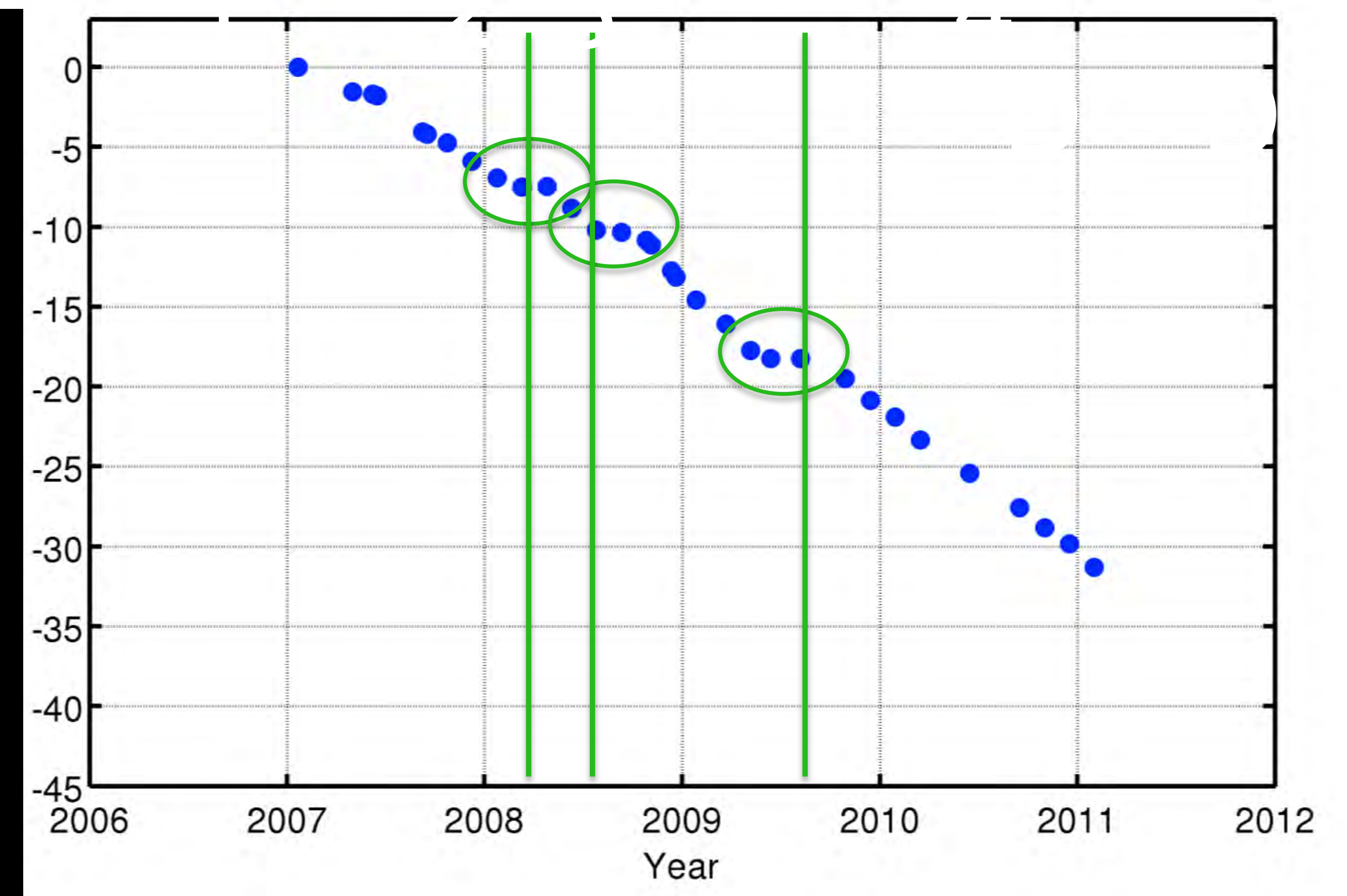


Profiles at Selected Points









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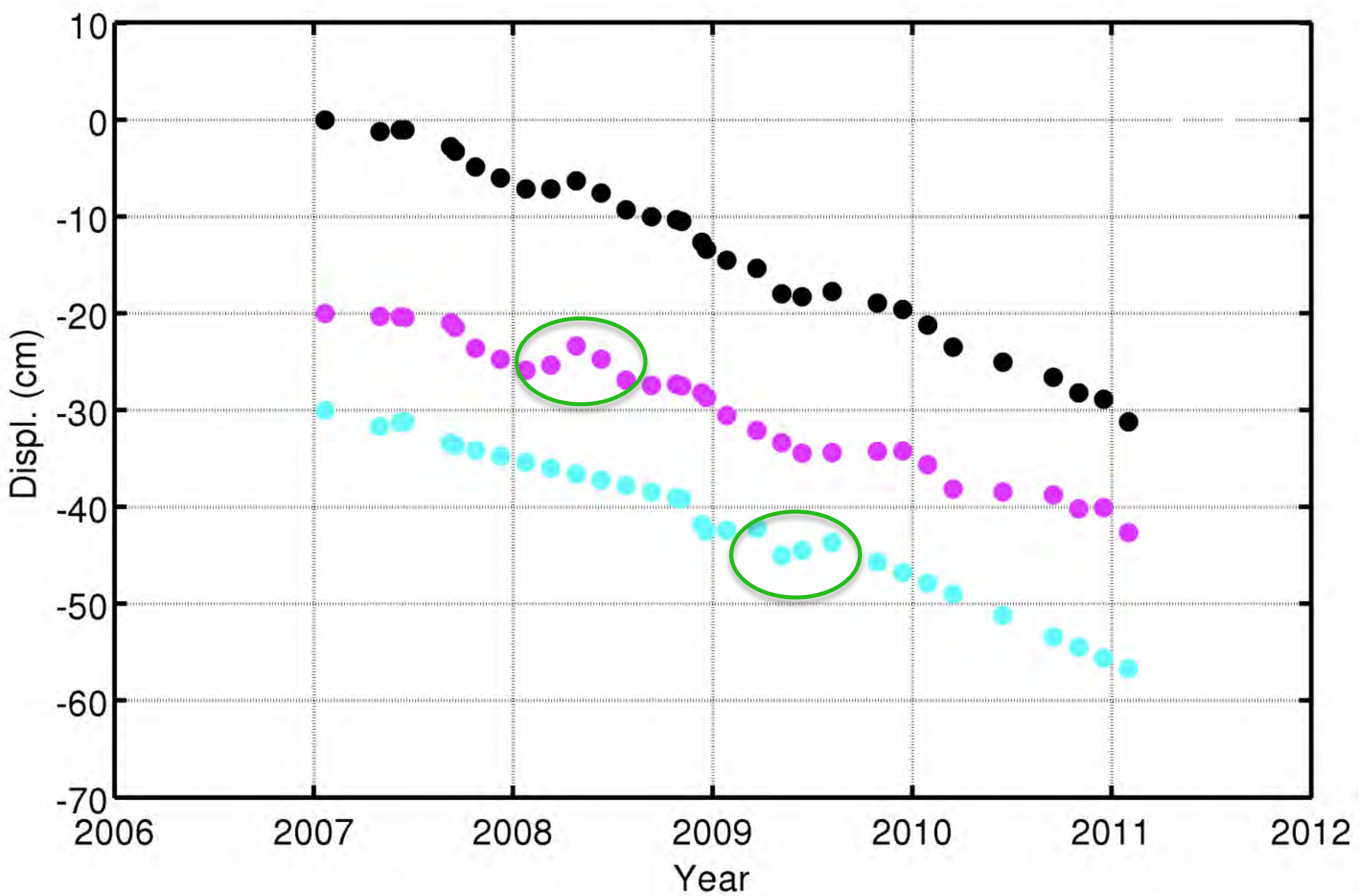

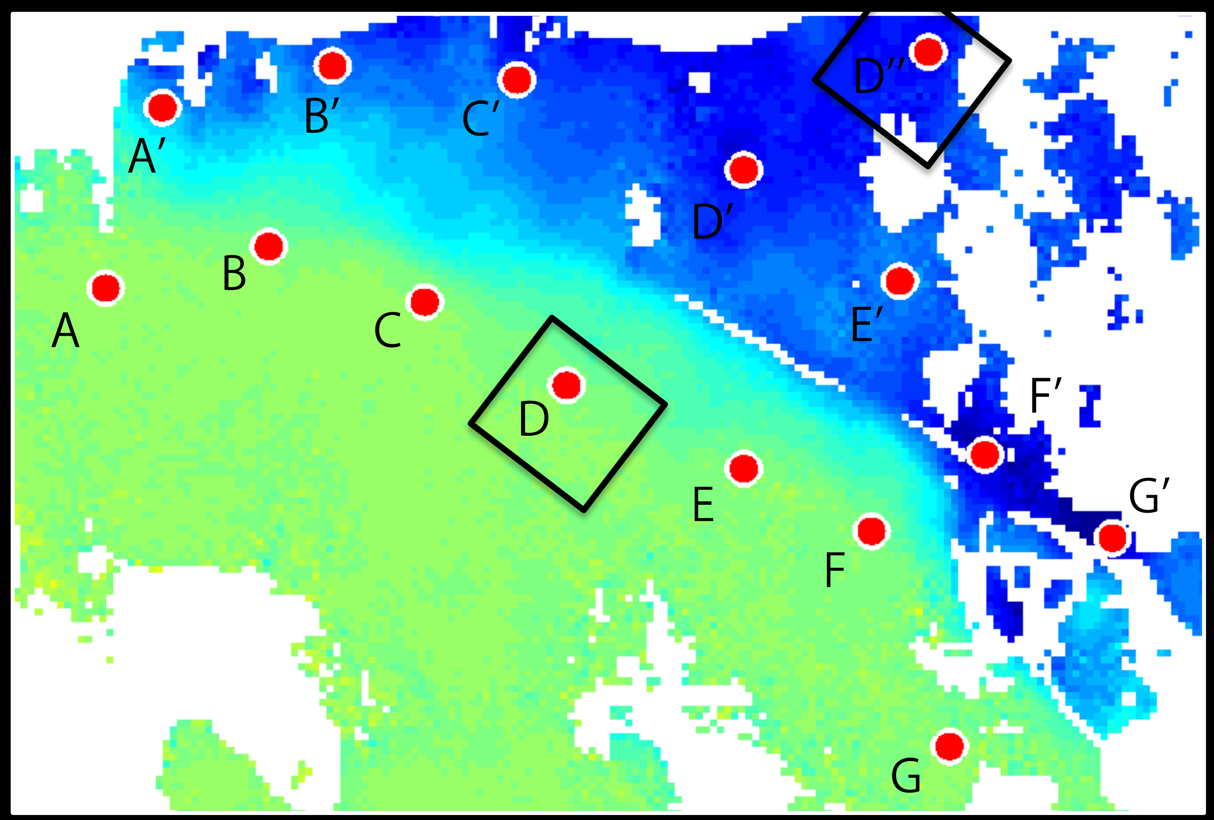

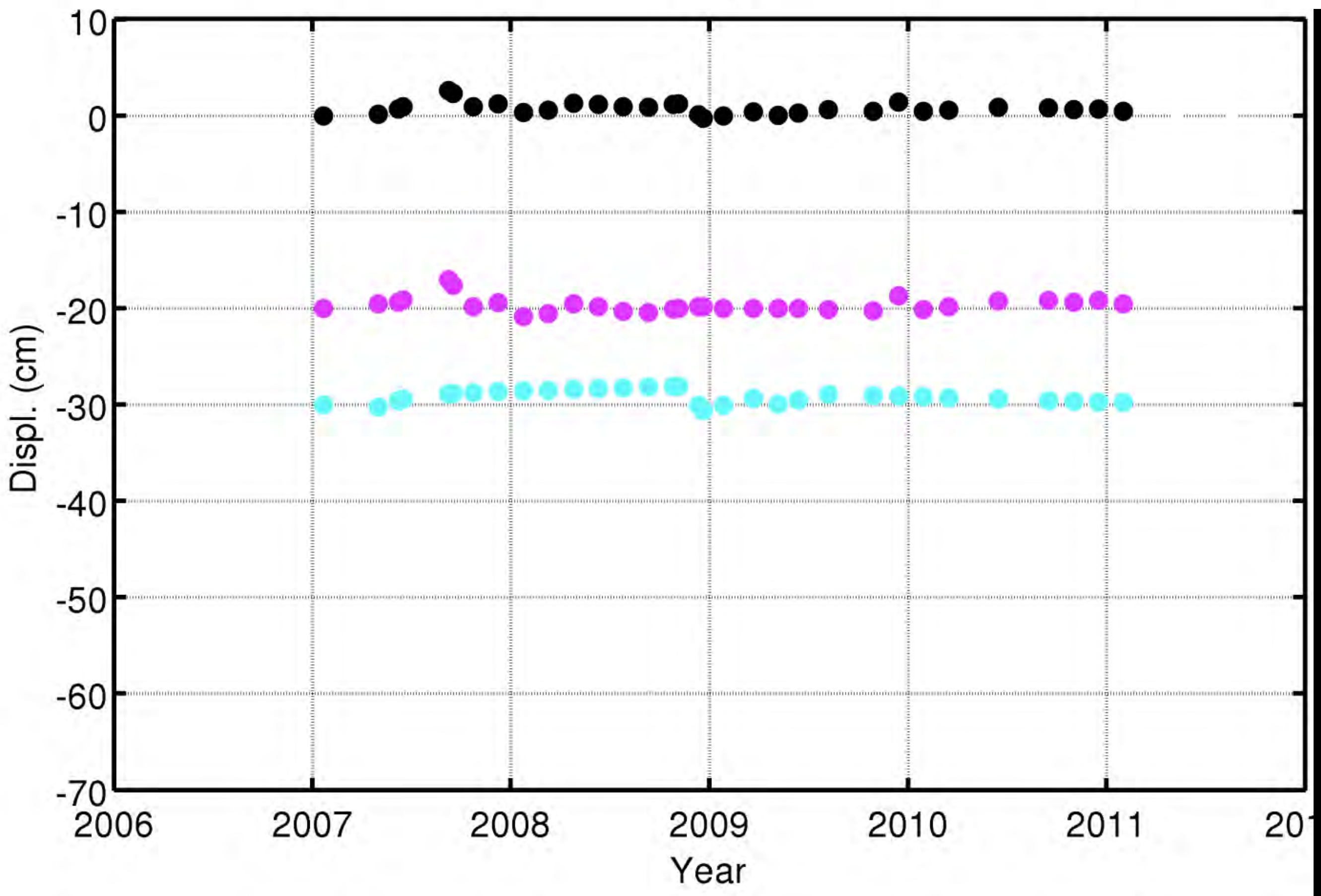

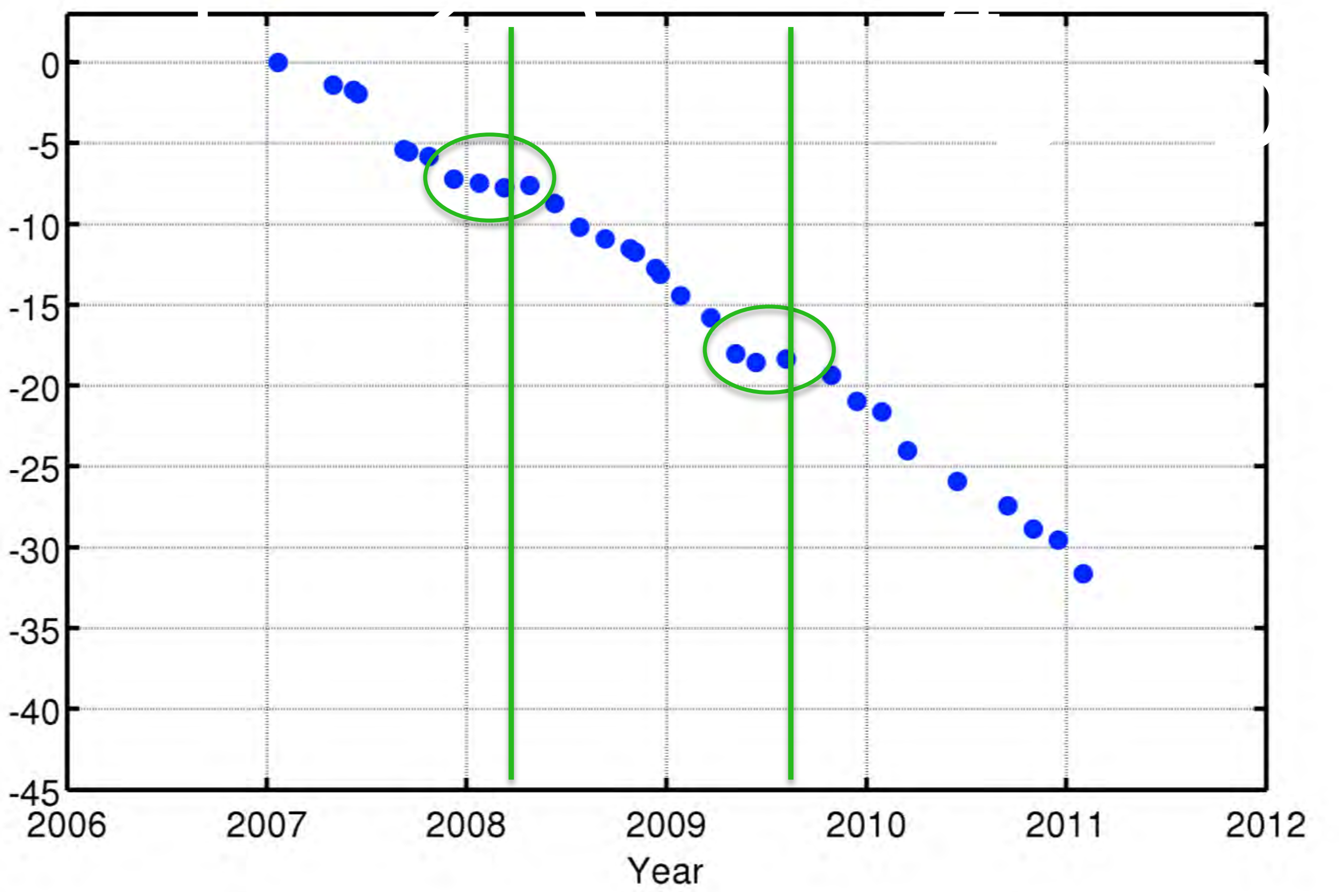

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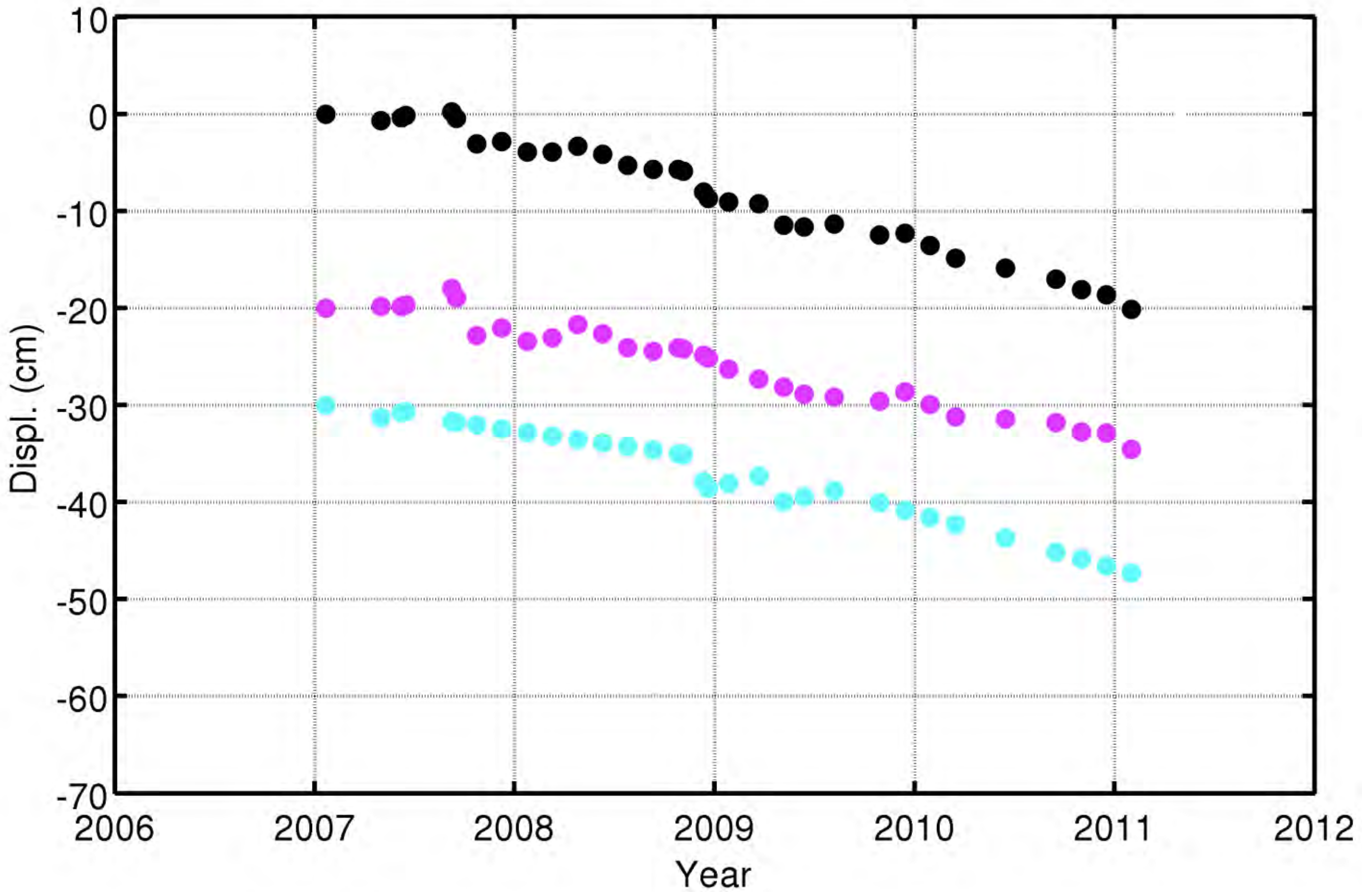
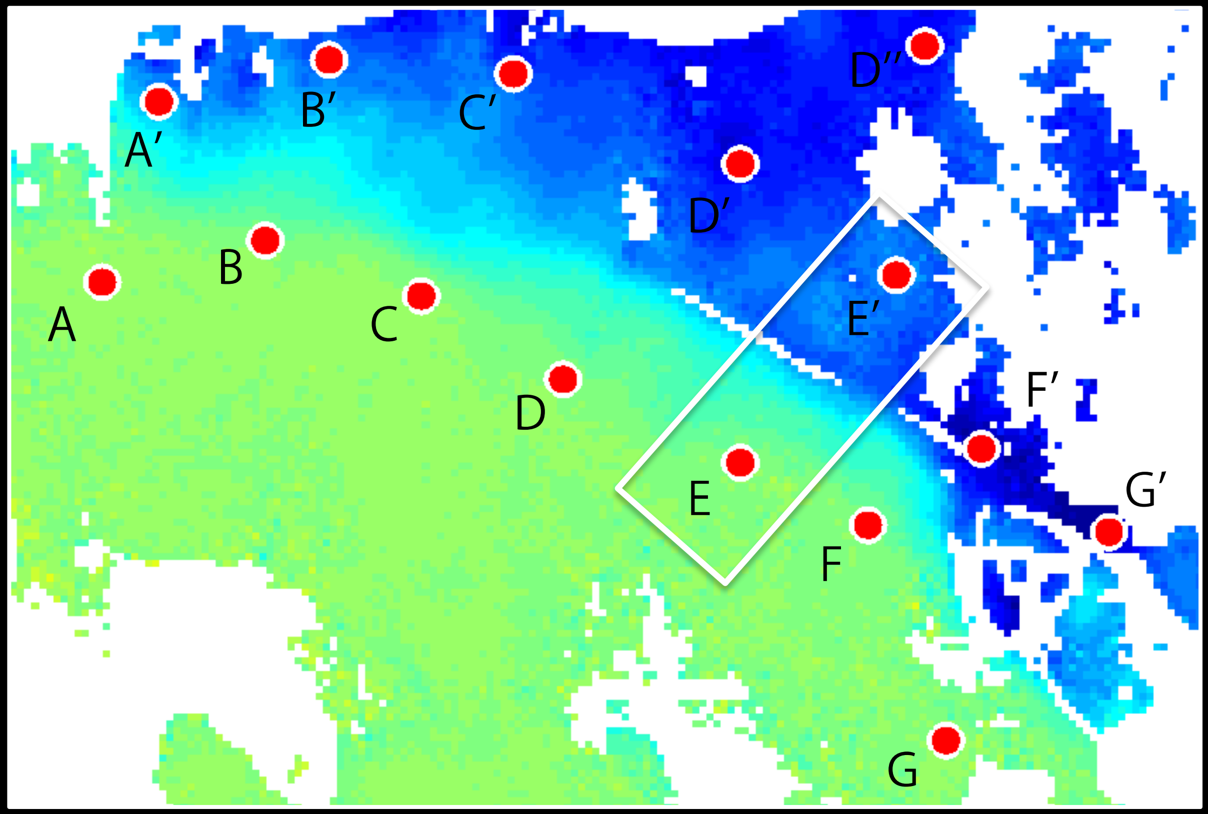
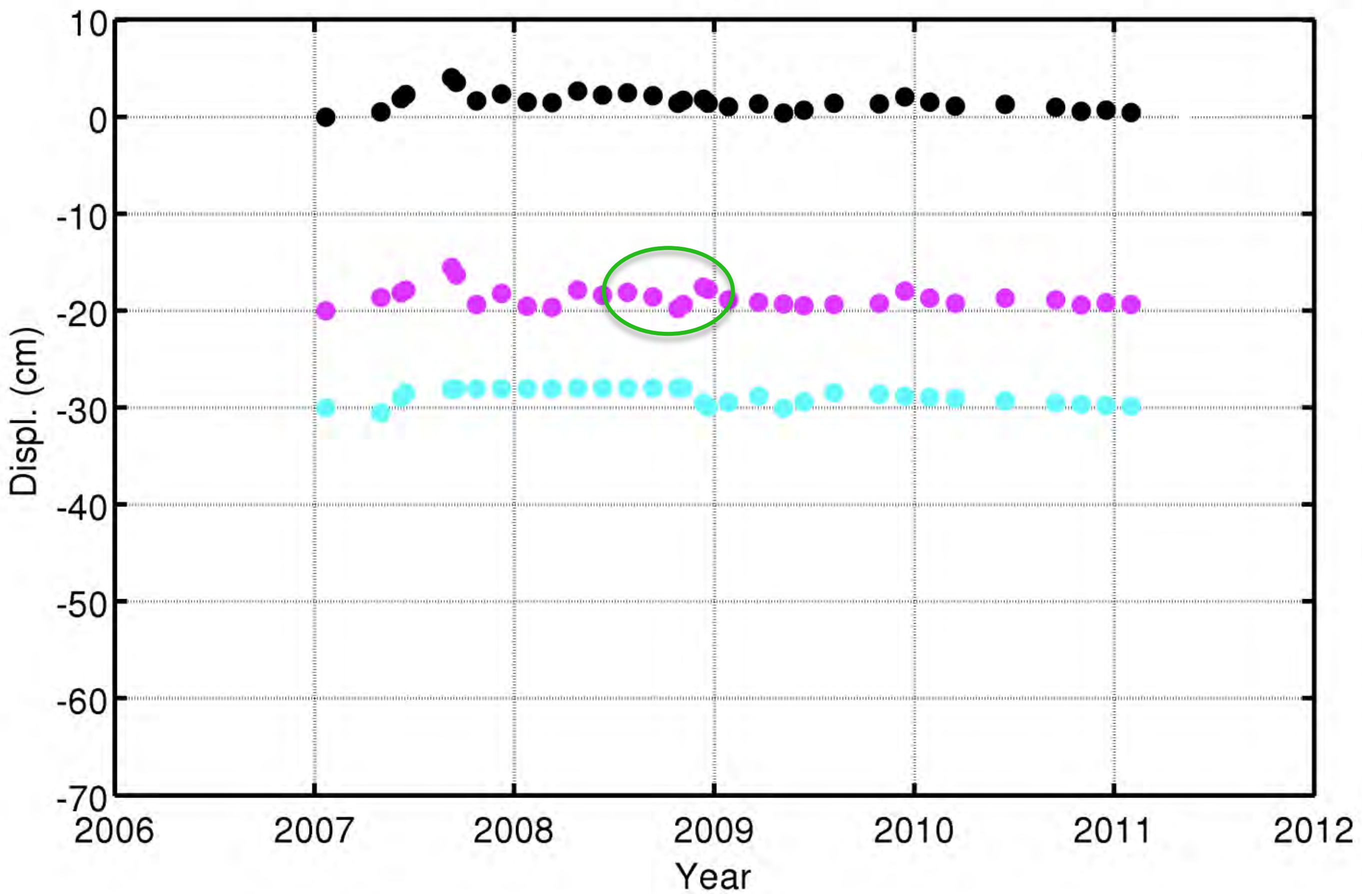
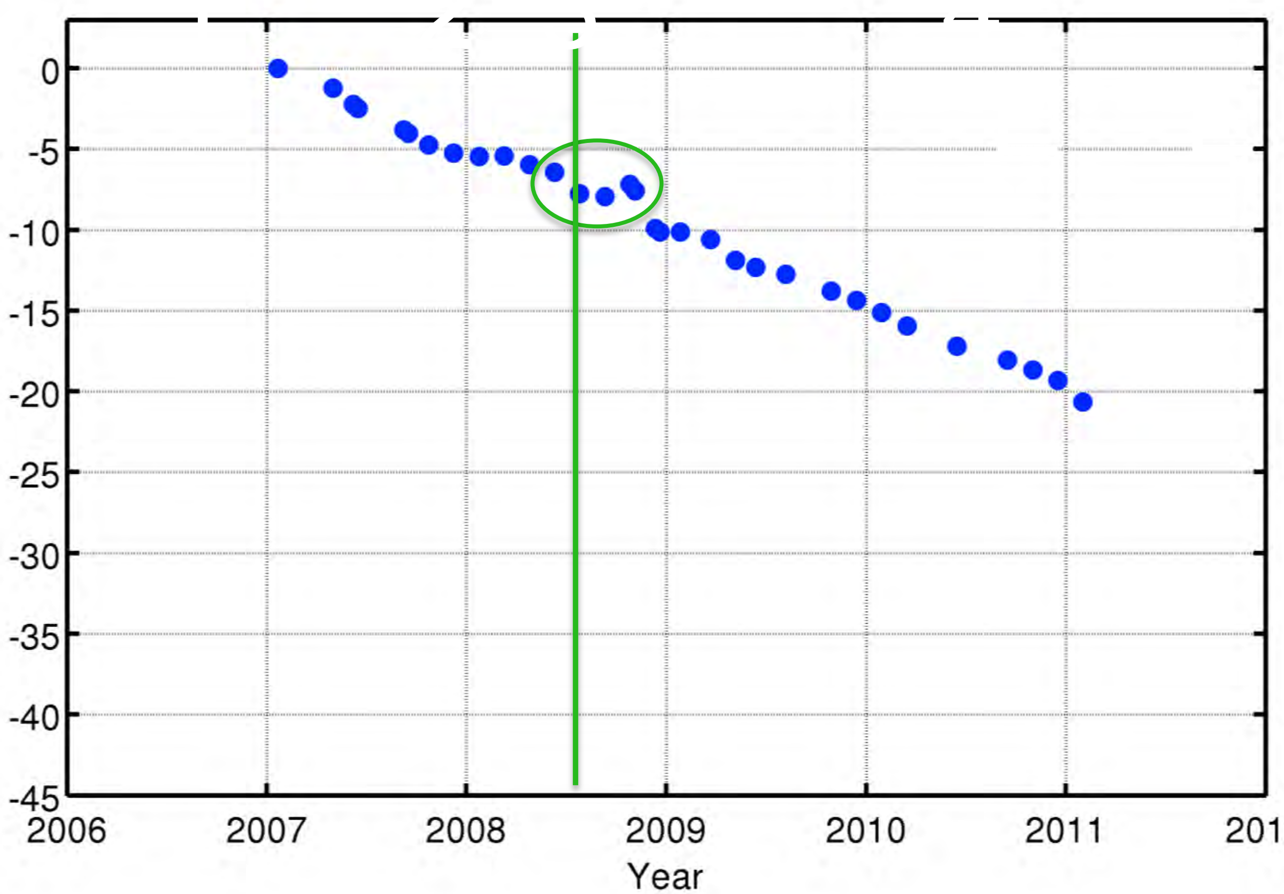
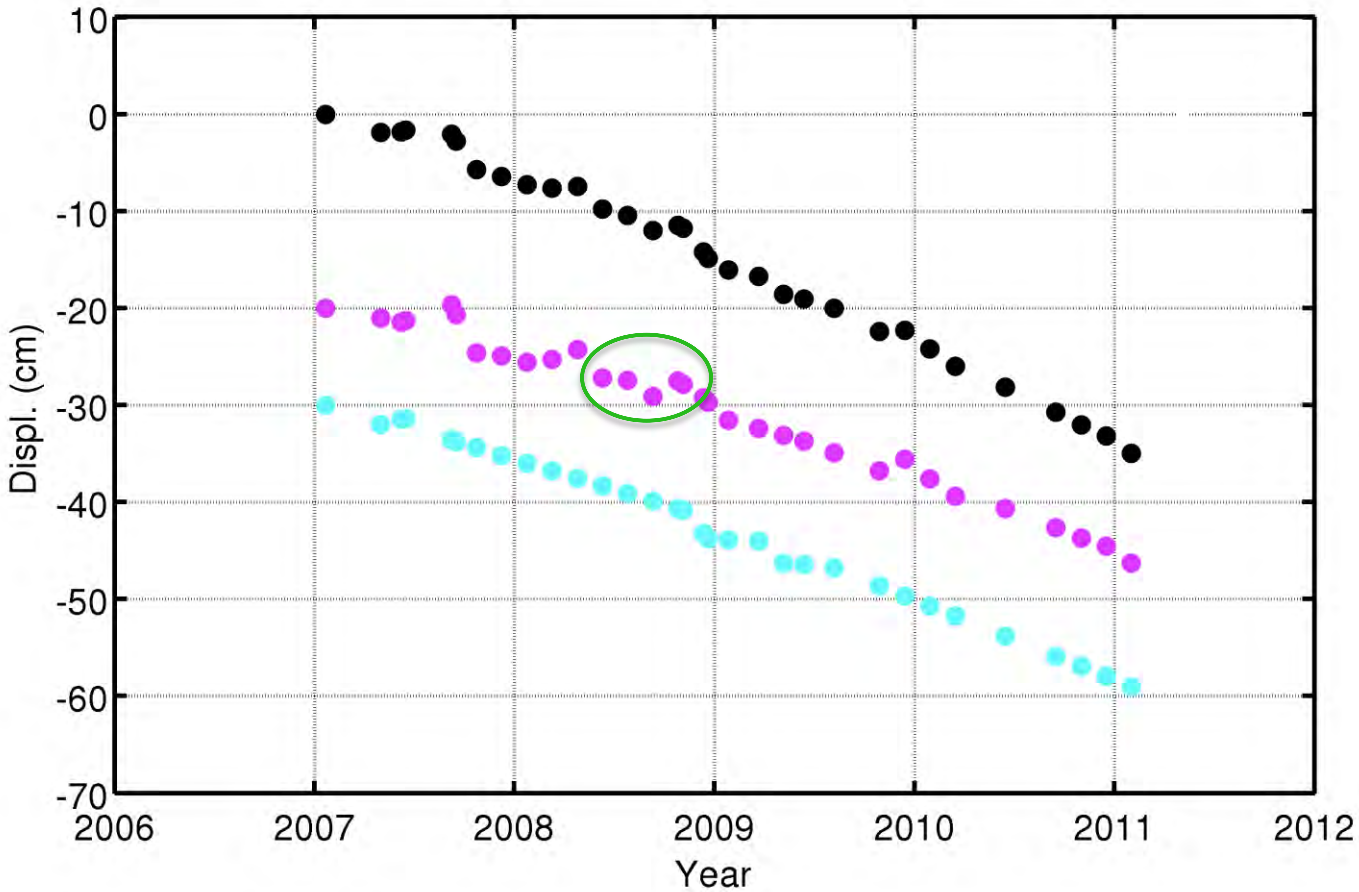


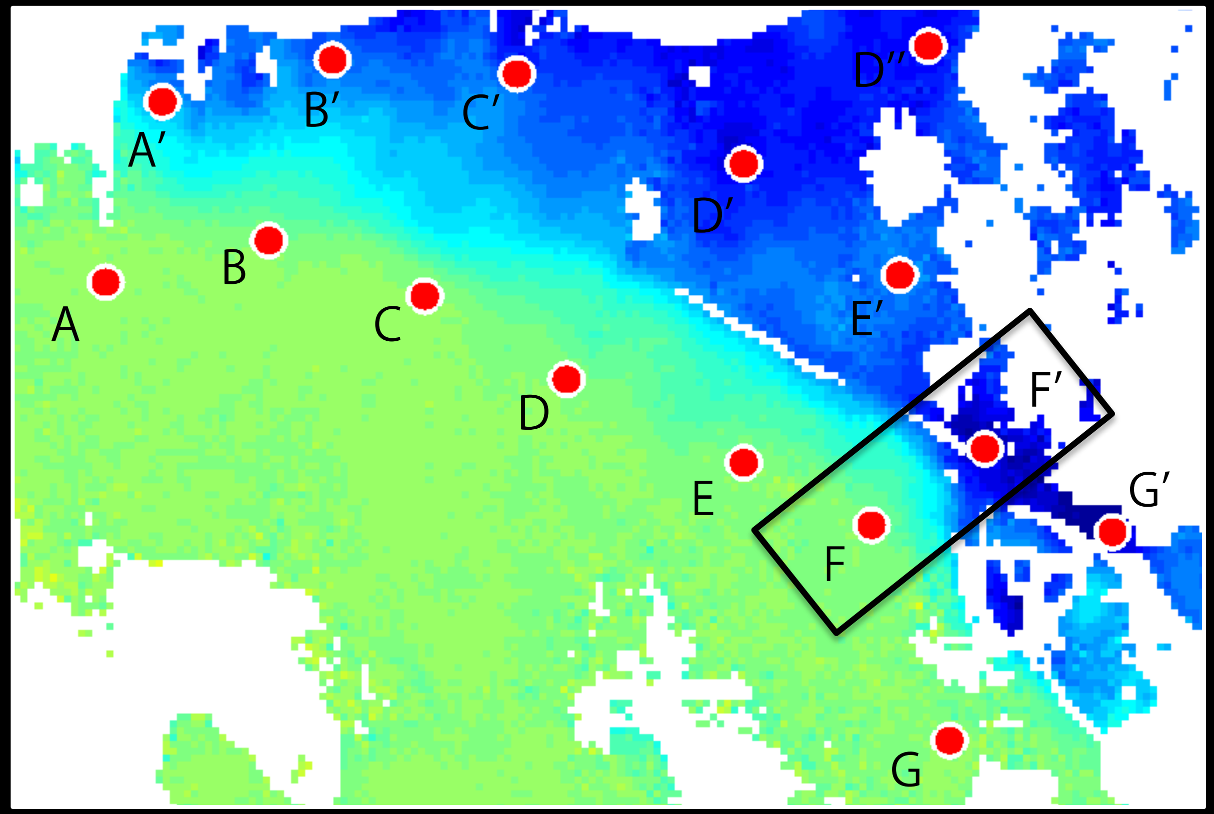


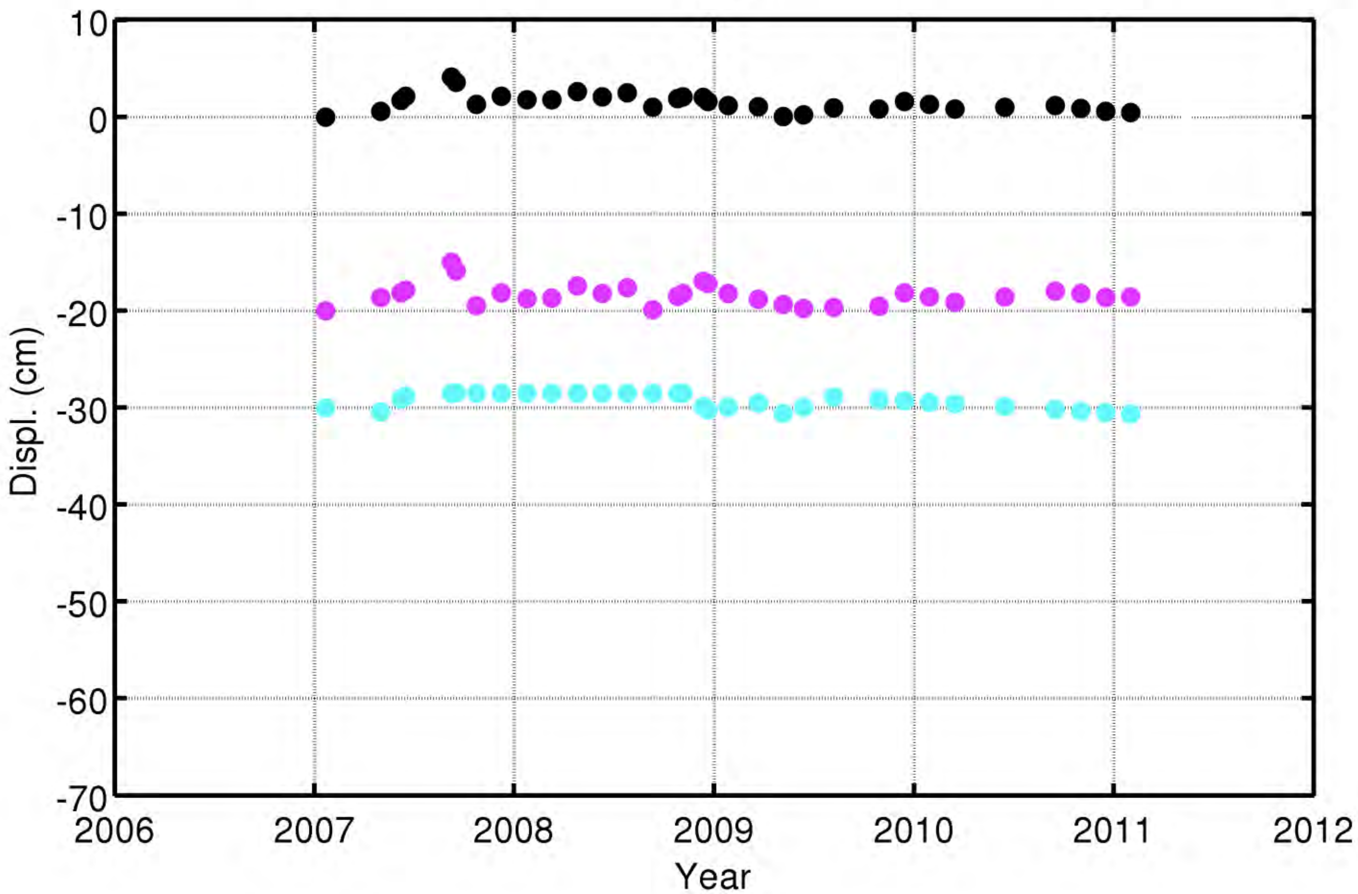


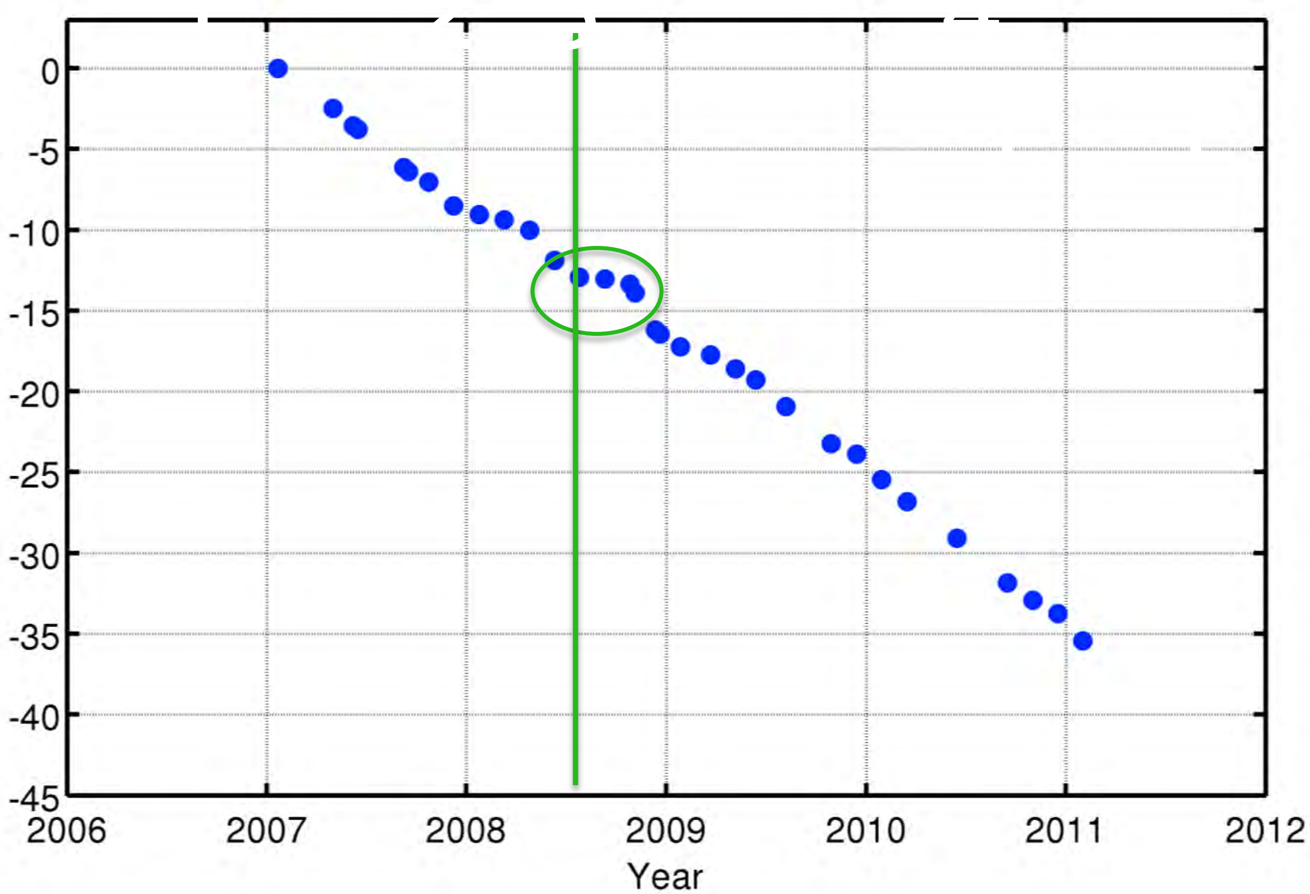


Profiles at Selected Points









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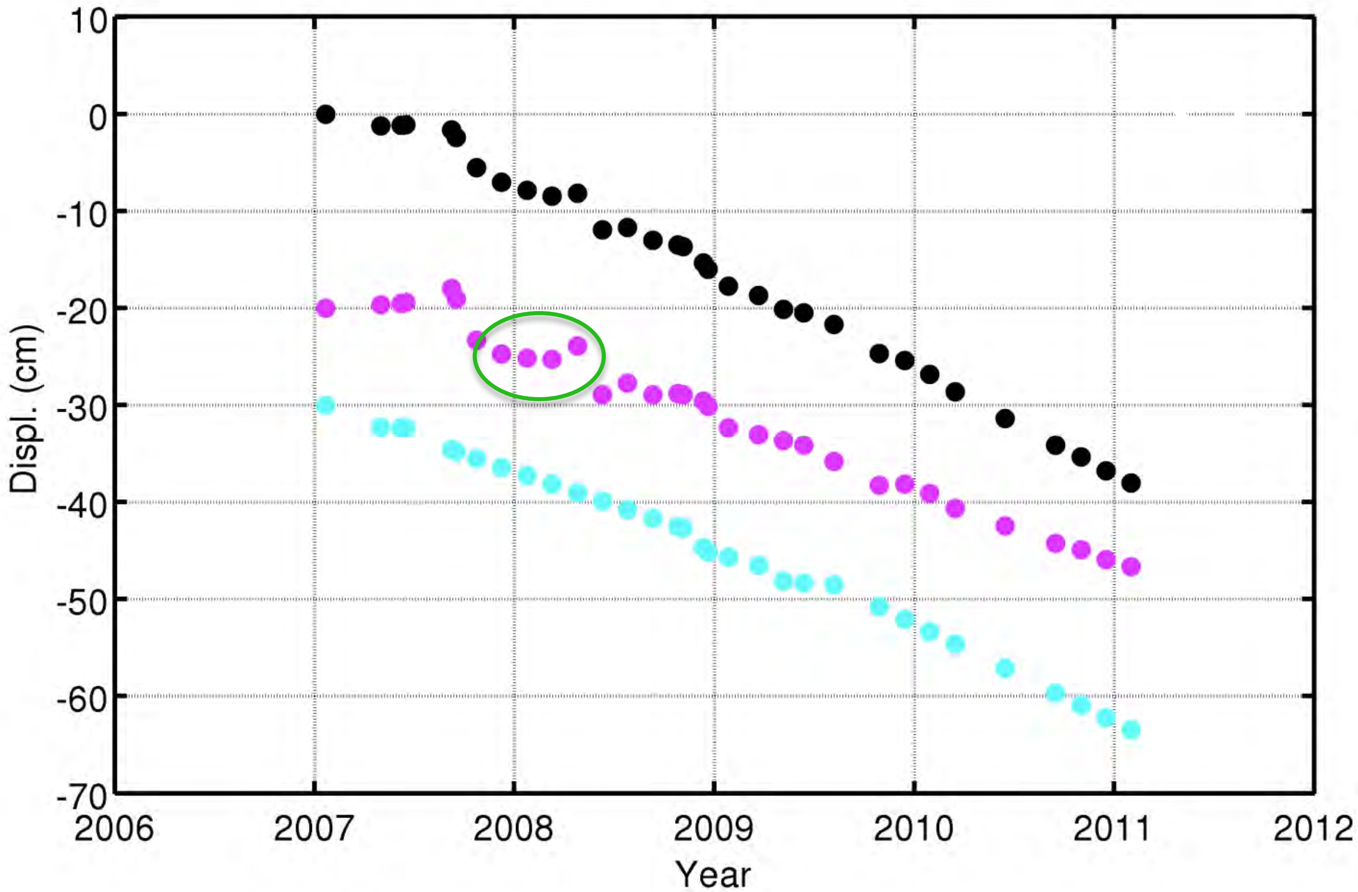
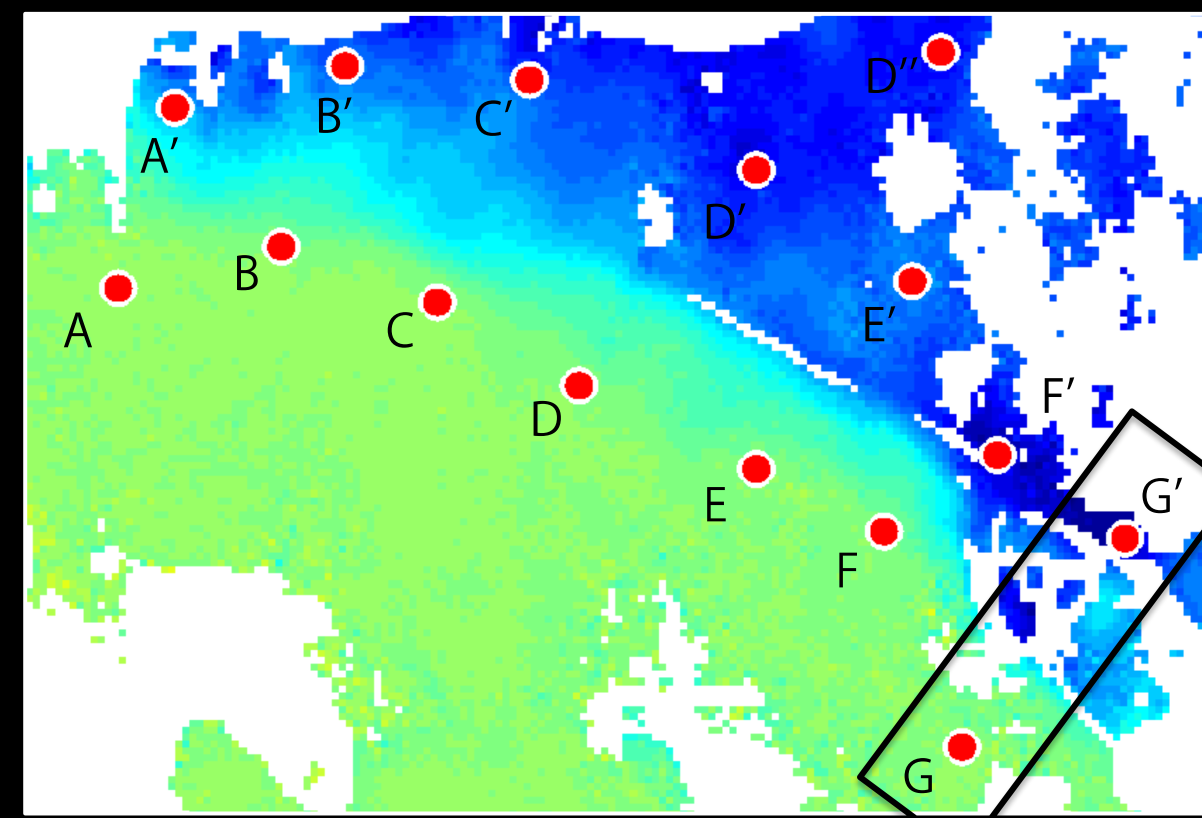
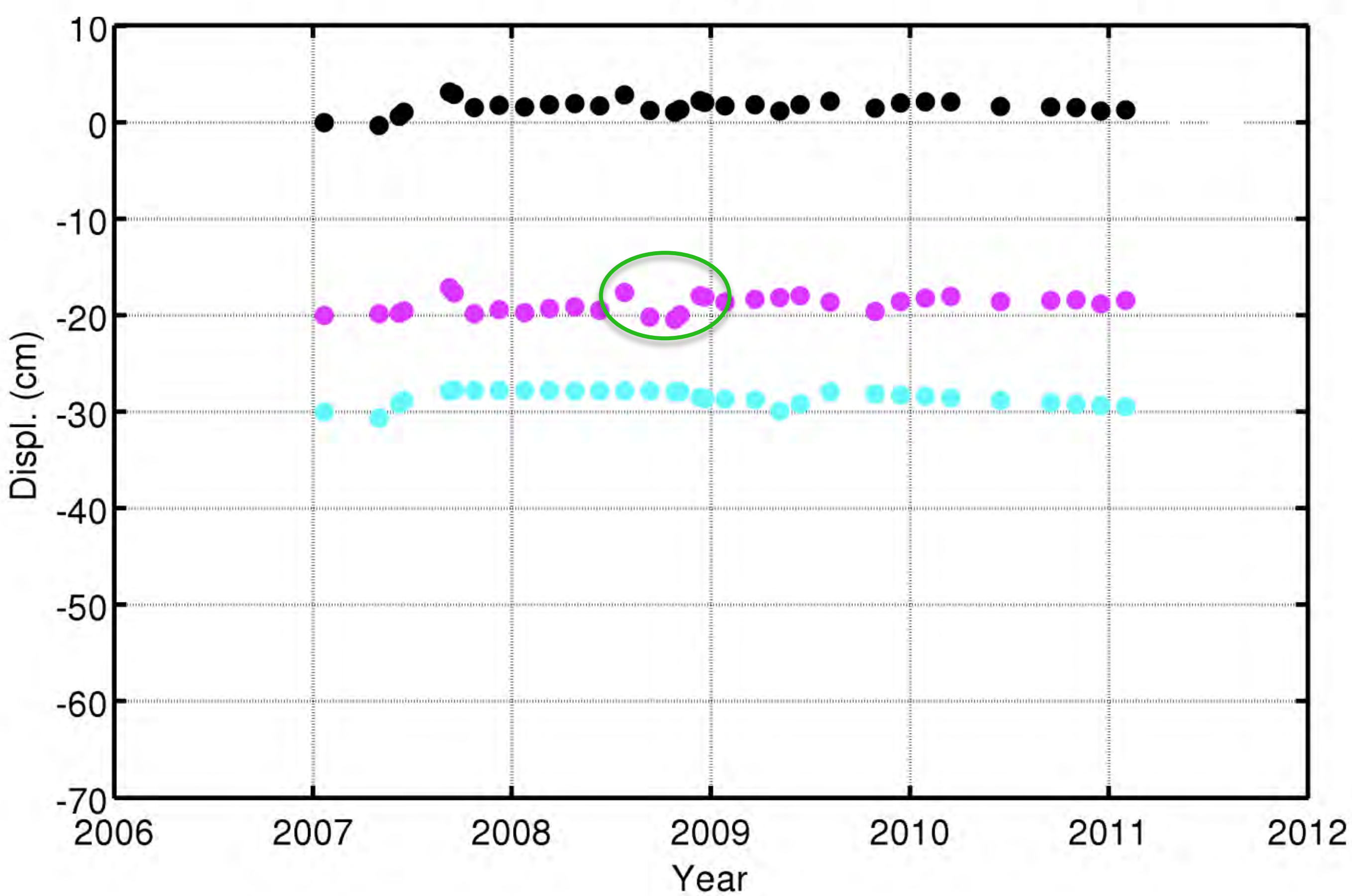
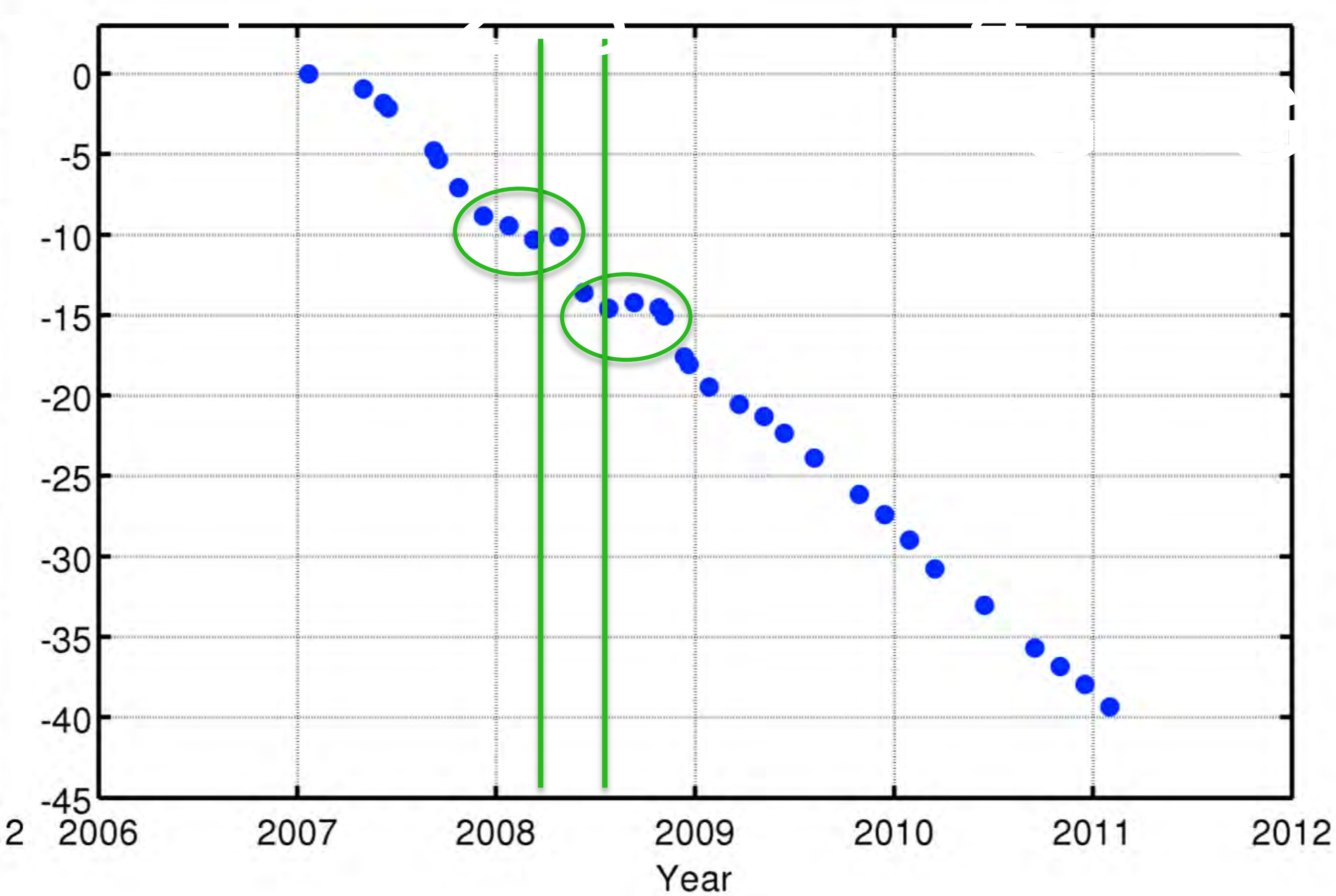


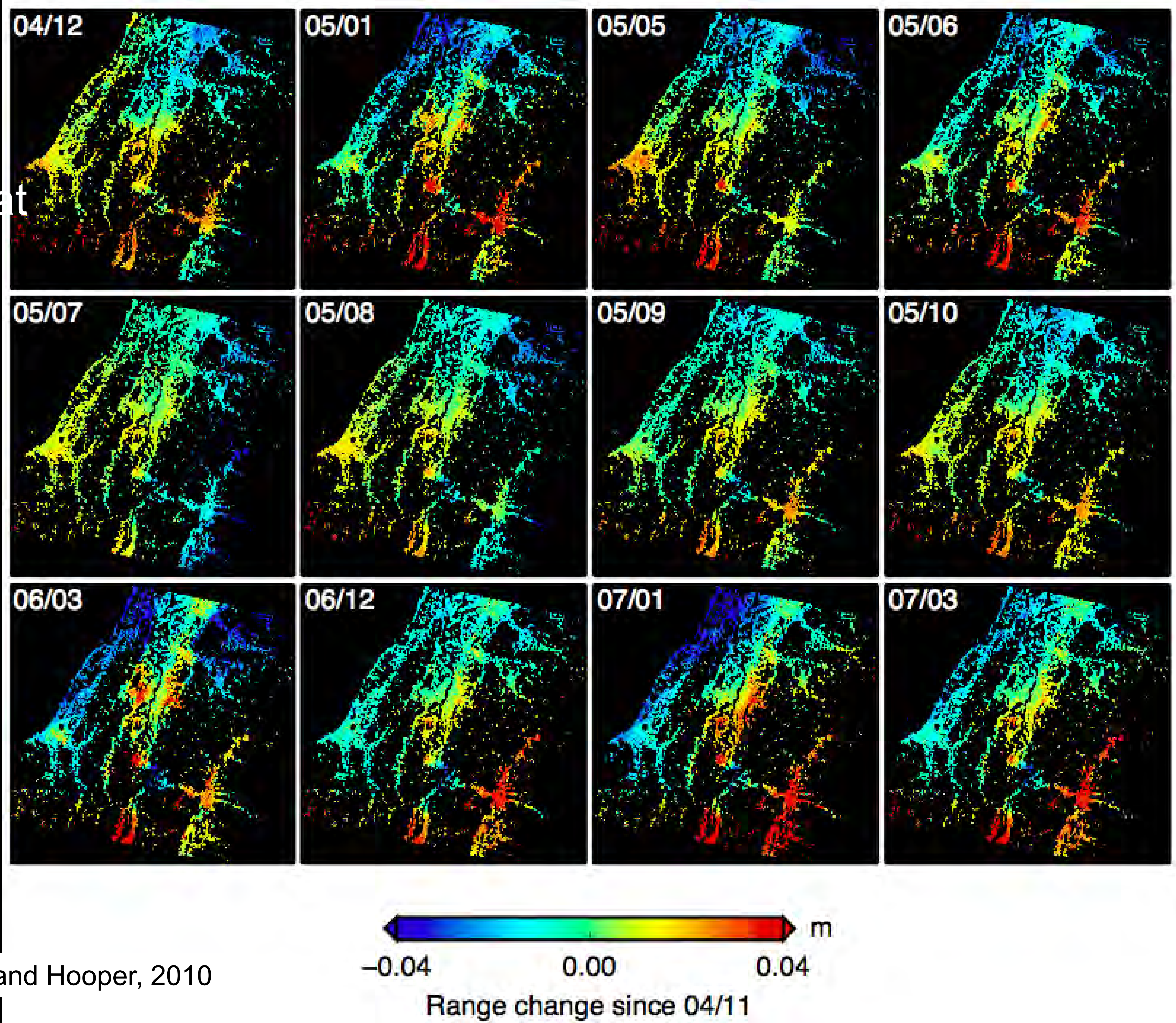






StaMPS result

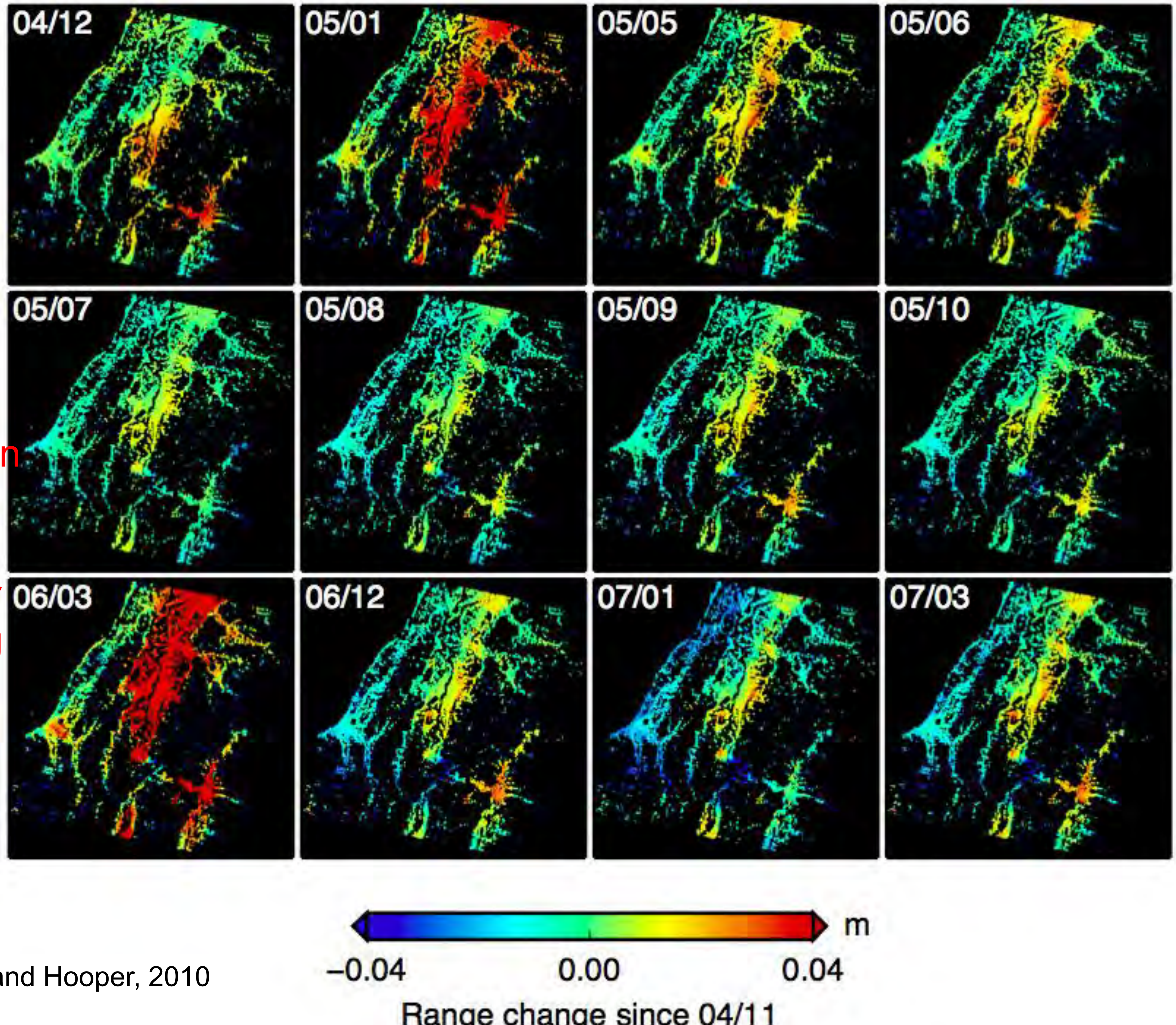
data: Envisat



Fukushima and Hooper, 2010

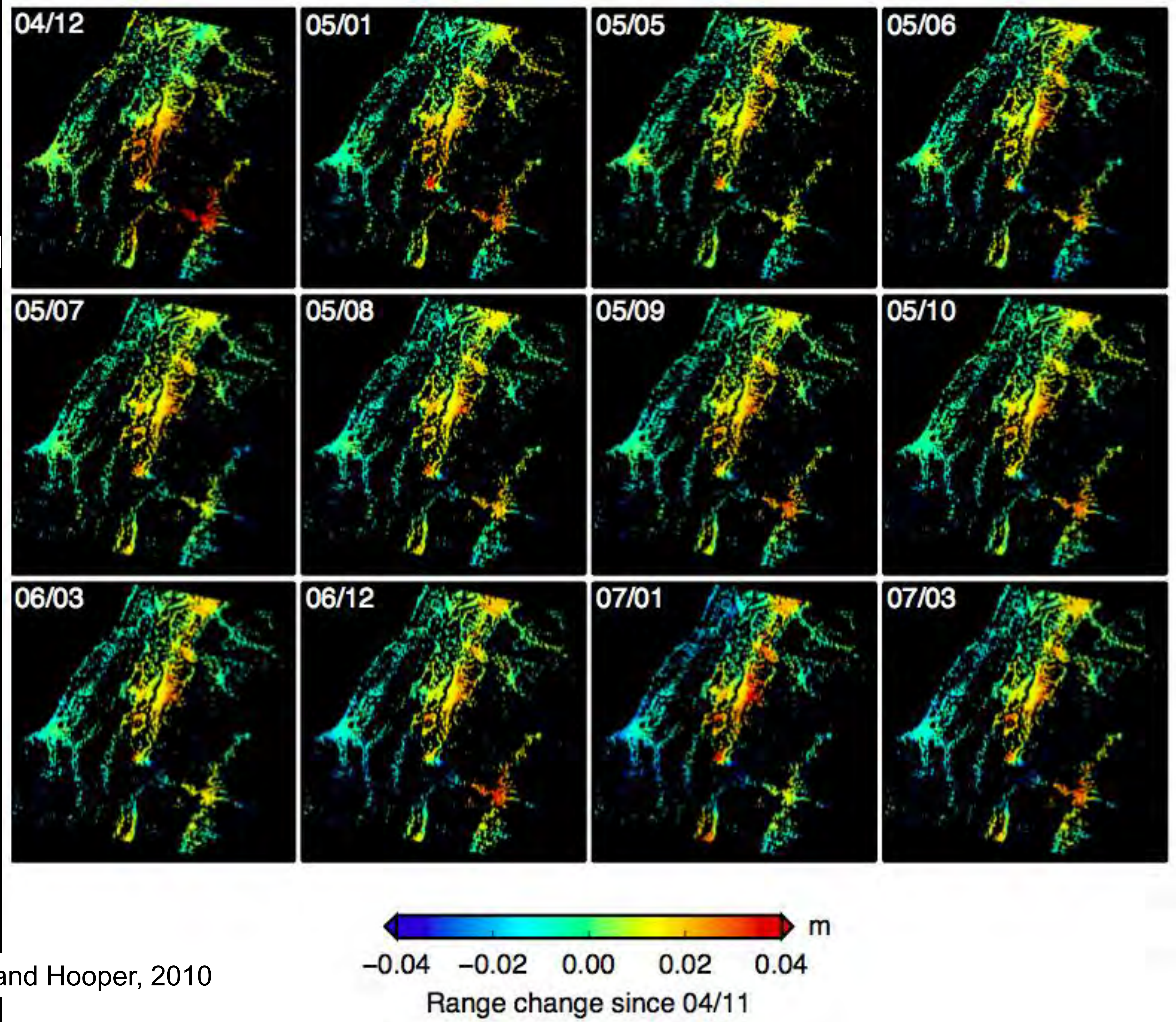
Long-wavelength trend and topo-correlated phase corrected using GPS

Subsidence in winter due to water extraction for snow melting

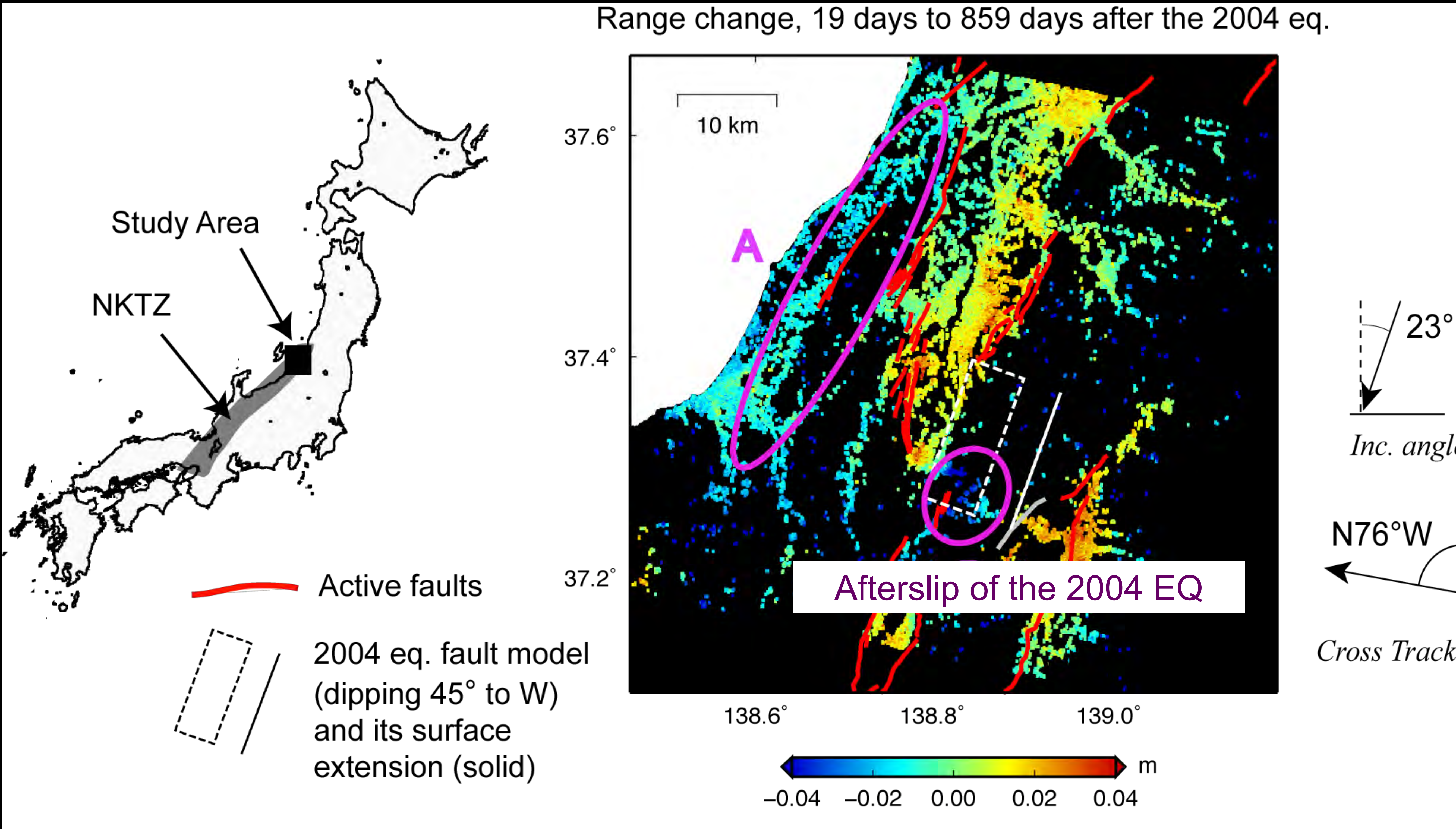


Fukushima and Hooper, 2010

+ PCA to get rid of the seasonal signals and see the tectonic signals



Fukushima and Hooper, 2010



Range change, 19 days to 859 days after the 2004 eq.
Study Area
NKTZ
Active faults
2004 eq. fault model (dipping 45° to W) and its surface extension (solid)
10 km
37.6°
37.4°
37.2°
A
Afterslip of the 2004 EQ
138.6°
138.8°
139.0°
m
−0.04
−0.02
0.00
0.02
0.04
23°
Inc. angle
N76°W
Cross Track

Summary

- Efforts have been made for measurements of small displacements at various scales. This includes
  - Automatic InSAR processing with robustness and accuracy
  - Atmospheric noise reduction
  - Algorithm development to solve for the displacement time-series (including post-processing)