North-South ground displacement retrieval with burst-mode SAR Systems: Experimental modes and results with TerraSAR-X

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MDIS 2017. Besse-en-Chandesse.

Outline

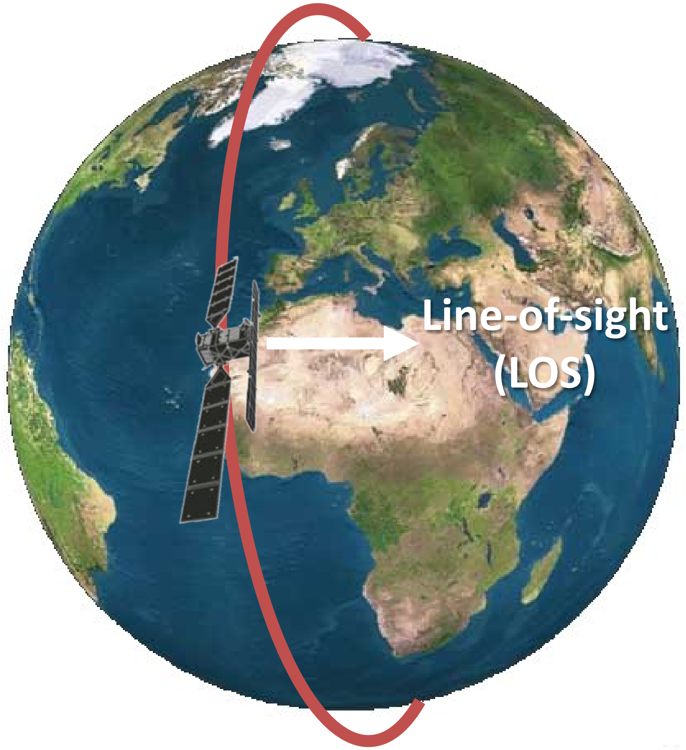
- Motivation: the North-South sensitivity problem

- Two-looks TOPS experimental mode with TerraSAR-X

- Along-track motion estimation performance with **Pairs** of images
- Experimental results over the Petermann glacier (Greenland)

- Along-track motion estimation performance with **Time-Series**
- Experimental results. Postseismic Deformation Balochistan.

- Conclusions



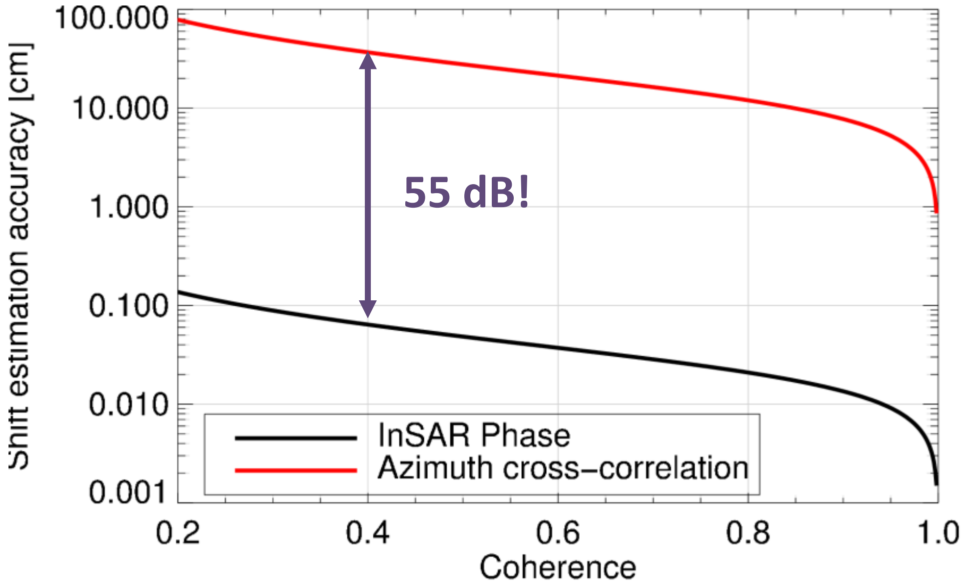
Motivation (I): the NS-Problem

- Sensitivity to NS possible by exploiting **cross-correlation techniques** between pairs in the azimuth dimension. BUT performance is much worse than in line-of-sight:

$$\sigma_{\Delta r}^2 = \left(\frac{\lambda}{4\pi}\right)^2 \frac{1}{2 \cdot N} \frac{1-\gamma^2}{\gamma^2} \quad [\mathrm{m}]$$

$$\sigma_{cc}^2 = \frac{3}{2 \cdot N} \frac{1-\gamma^2}{\pi^2 \gamma^2} \delta x^2 [\mathrm{m}]$$

$$\frac{\sigma_{cc}^2}{\sigma_{\Delta r}^2} = \frac{48 \cdot \delta x^2}{\lambda^2} \approx 55 \text{ dB } [\text{X–Band}, \delta x = 2.5 \text{ m}]$$

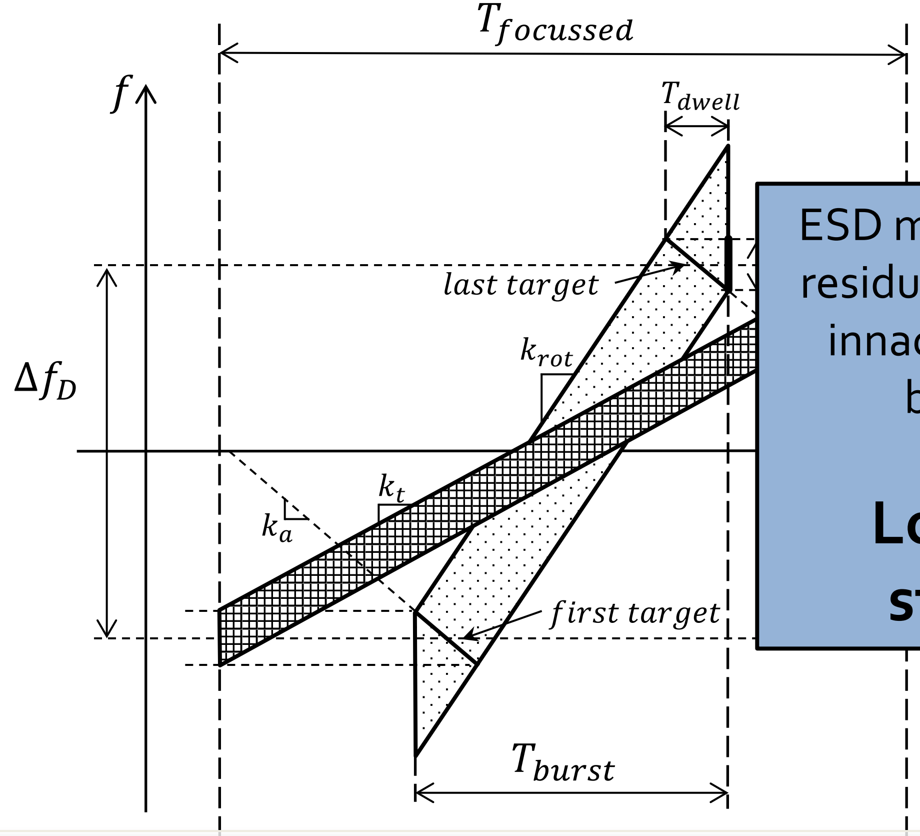


X-band; 2.5 m az. Resolution; $N_{looks} \sim 40$ (for 100 m resolution)

R. Bamler and M. Eineder, “Accuracy of differential shift estimation by correlation and split-bandwidth interferometry for wideband and Delta-k SAR systems,” IEEE Geosci. Remote Sens. Lett., vol. 2, no. 2, pp. 151–155, Apr. 2005.

Motivation (II): burst-modes and azimuth shifts

Spectrum of a TOPS burst



ESD method able to retrieve (rigid) residual azimuth shifts due to orbit innacuracies / timing errors with burst-mode acquisitions

Local shifts for non-stationary scenes?

- **InSAR phase** error due to an **azimuth** misregistration[1], Δt:

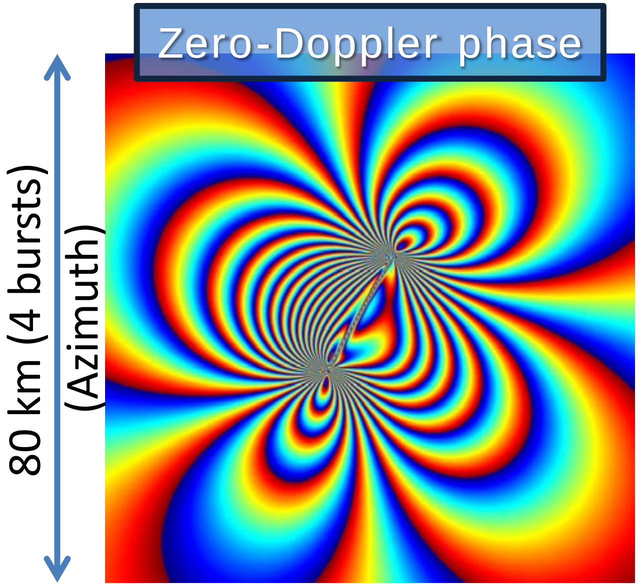
$$\Delta\phi_{error} = 2\pi\Delta f_D \Delta t$$

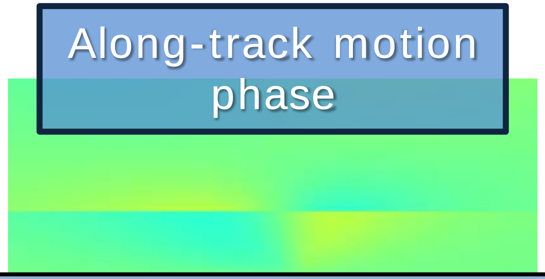
	S1 TOPS IW mode
Azimuth resolution	20 m
Azimuth pixel spacing	14.1 m
Needed Azimuth co-registration accuracy*	~0.0009 pixel (1.3 cm)

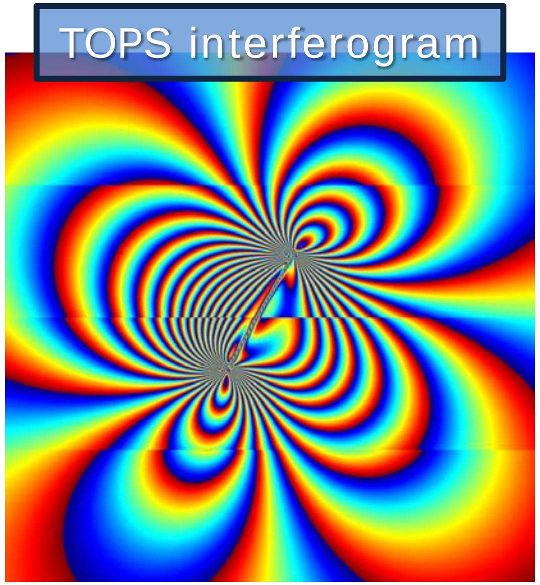
*Limiting $\Delta\phi_{burst}$ = 1/100 cycle = 3.6°

[1] R. Scheiber, A. Moreira. Coregistration of Interferometric SAR Images using Spectral Diversity", *IEEE TGRS. 2000*

Motivation (II): burst-modes and azimuth shifts

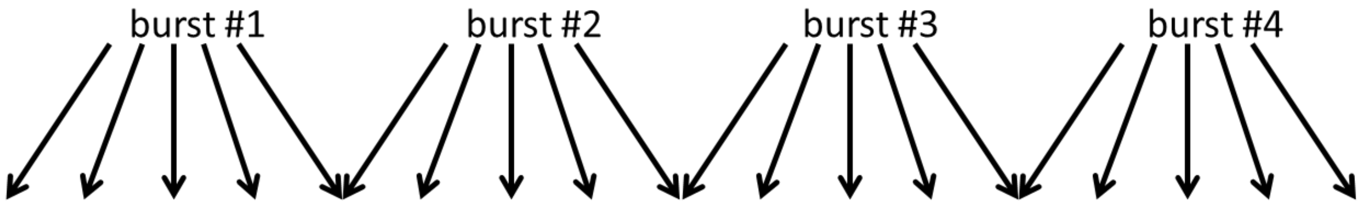






Phase jumps at the burst transitions are legitimate, due to the LOS change.

Phase Unwrapping issues at burst edges?



Goals

- **Goal 1**: improve the estimation accuracy of the along-track motion when compared to the one given by the azimuth resolution of the mode.
- **Goal 2:** circumvent phase jumps between bursts in non-stationary scenes.
- Options to improve the along-track motion sensitivity:
  - Increase azimuth resolution
  - Increase angular diversity (in azimuth)

Angular (Squint) Diversity

- SAR measures line-of-sight distances
- Going away from zero-Doppler geometry increases sensitivity to the azimuth component
- But we need (at least) **two** different **line-of-sight** to decouple cross-track and along-track components of the motion ⇒ the **dual-beam concept** [1]:

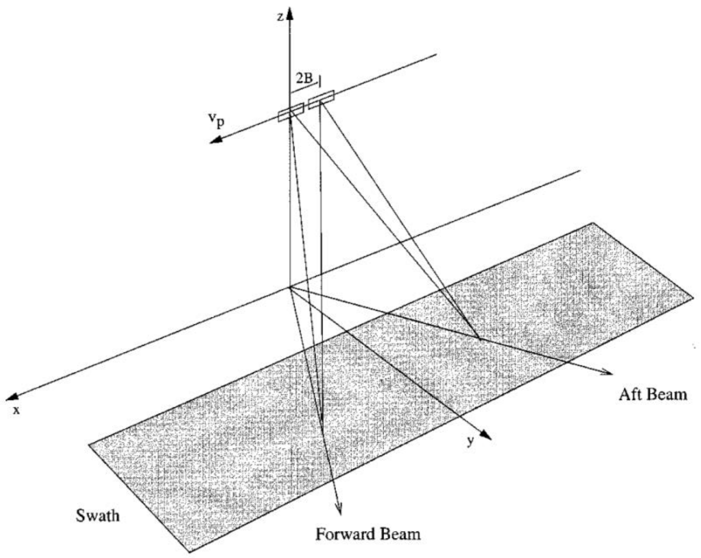


Fig. 1. Dual-beam interferometer system geometry. Image source: [1]

Besides the dual-beam concept, **burst-mode acquisitions** offer also an opportunity to achieve angular diversity.

[1] S. J. Frasier and A. J. Camps, “Dual-beam interferometry for ocean surface current vector mapping”,IEEE Transactions on Geoscience and Remote Sensing. 2001.

Experimental modes

(I) BiDirectional SAR (BiDiSAR)

- Same idea as the dual-beam concept, but exploiting a **phased array antenna**.

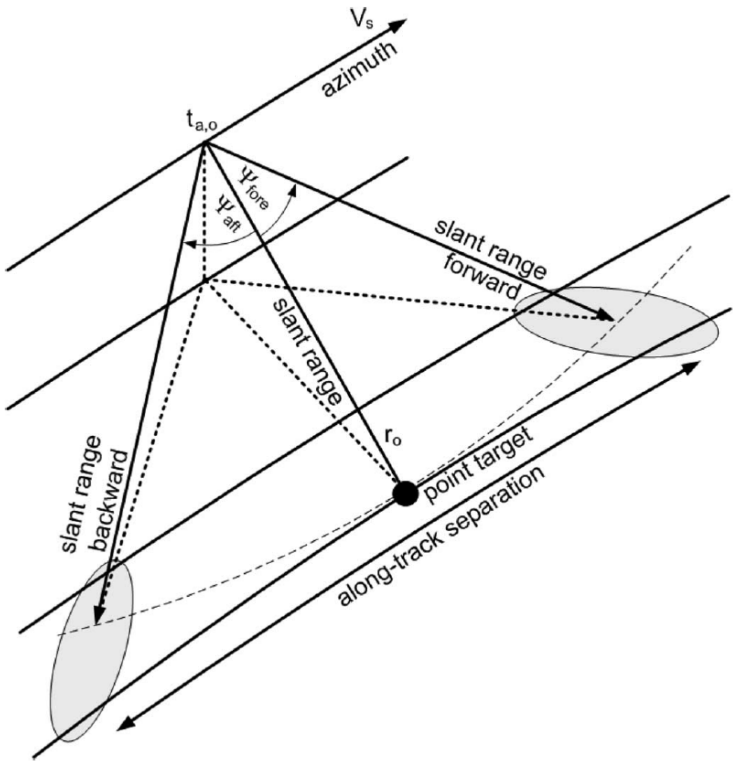
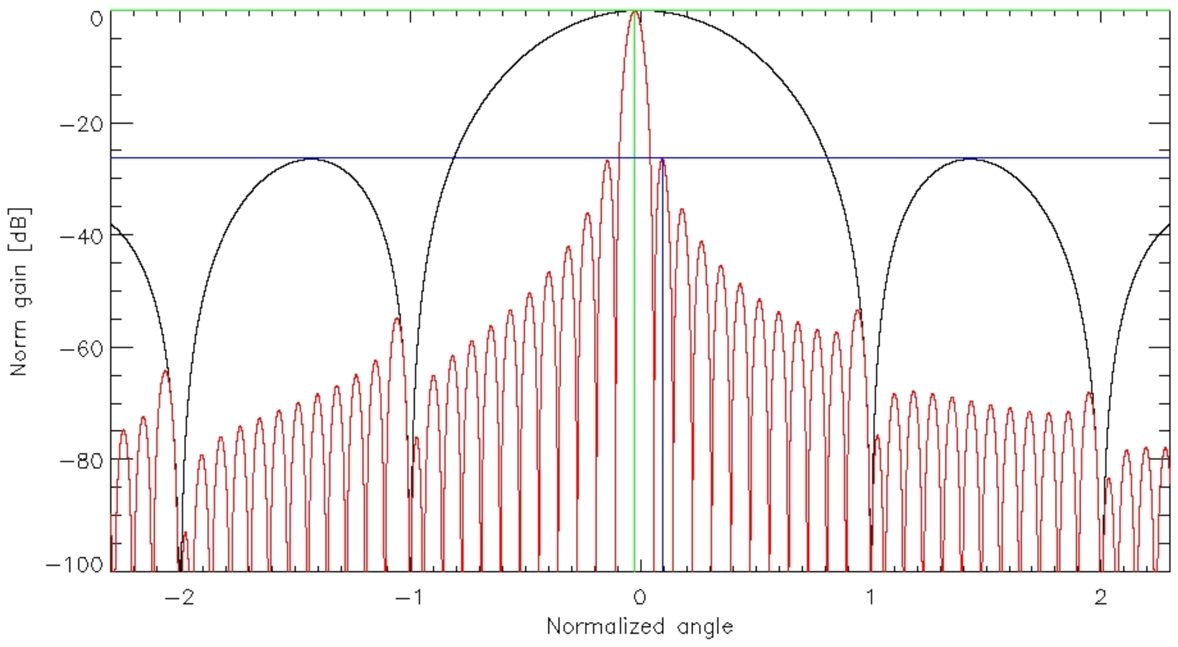


Fig. 1. BiDi acquisition geometry example with simultaneous fore and aft acquisitions.

Image source: [1]



[1] Josef Mittermayer et. al., "Bidirectional SAR imaging mode," IEEE Trans. Geosci. Remote Sens., vol. 51, no. 1, pp. 601–614, Jan. 2013.
[2] P. Lopez-Dekker et.al. Experimental bidirectional SAR ATI acquisitions of the ocean surface with TanDEM-X," Proceedings of EUSAR 2014.

(I) BiDirectional SAR (BiDiSAR)

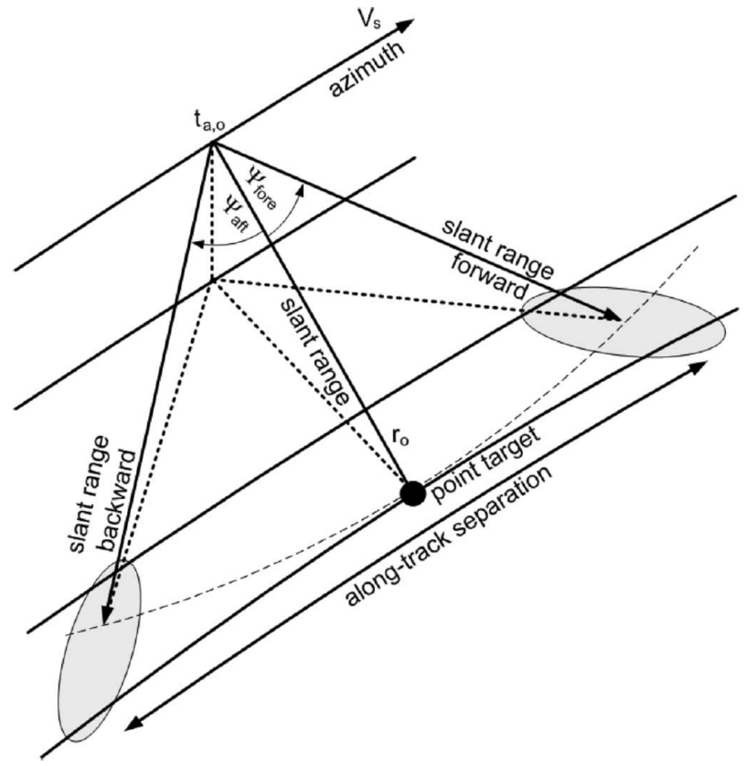
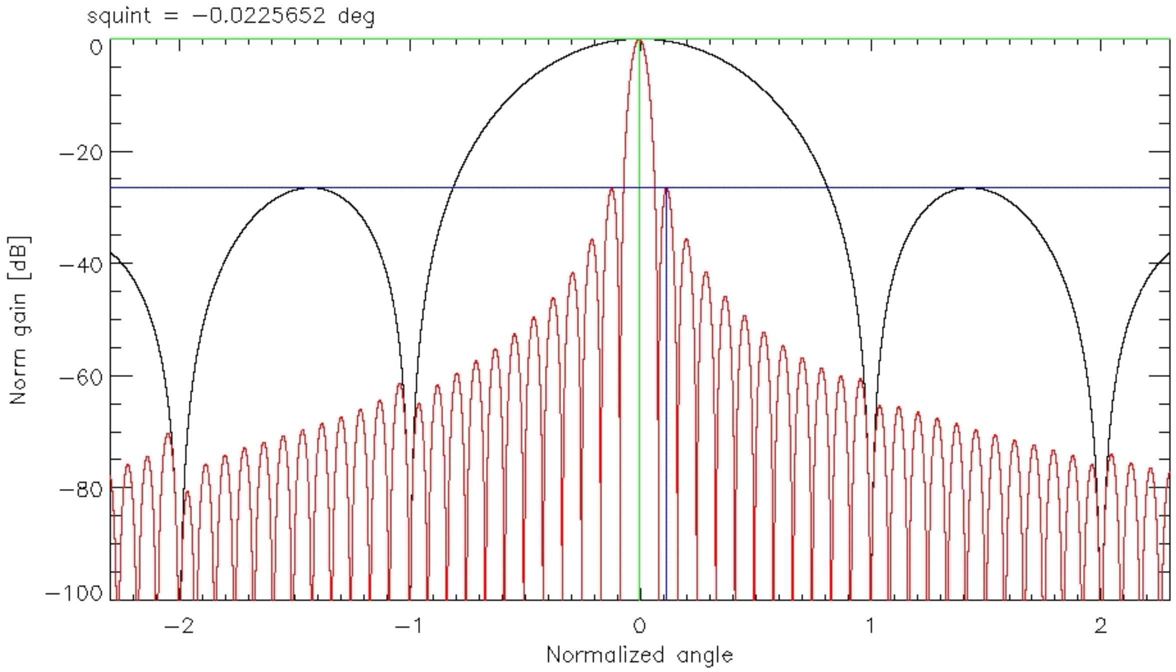


Fig. 1. BiDi acquisition geometry example with simultaneous fore and aft acquisitions.

Image source: [1]

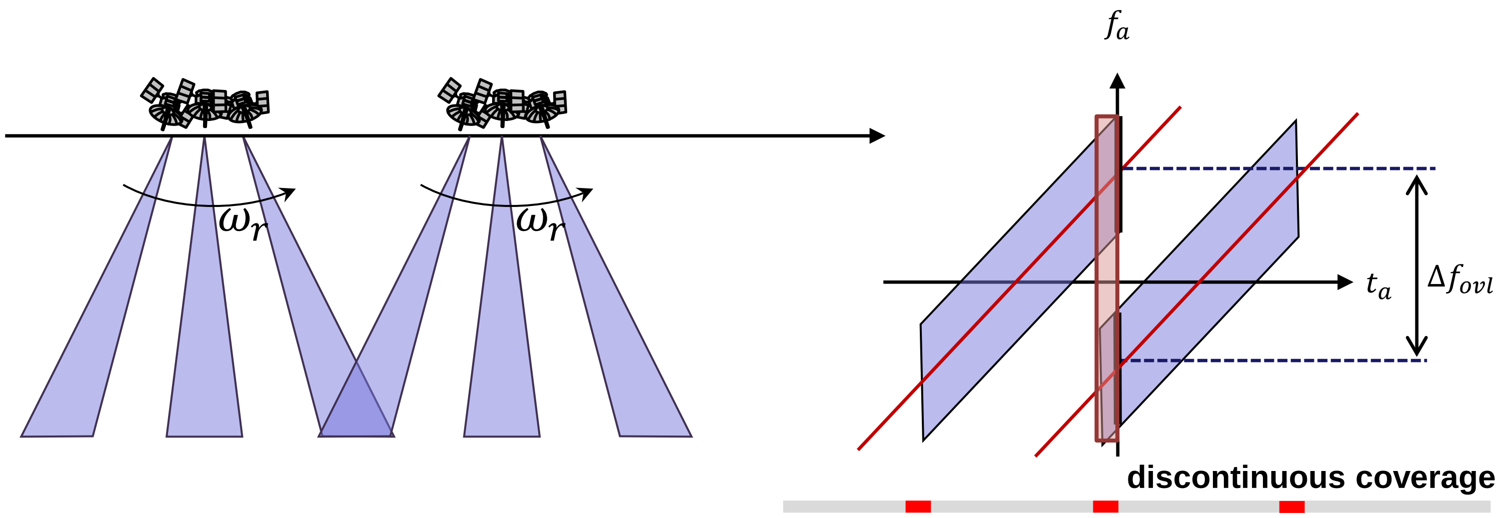
- Same idea as the dual-beam concept, but exploiting a **phased array antenna**.
- Two beams available by exploiting the grating lobe
- Simultaneous acquisition of both beams with the same antenna.
- Requires doubling PRF ⇒ Range ambiguities!
- ATI-BiDiSAR already demonstrated with TSX/TDX [2]
- Stri calloping effe
- Oth
  - ed PRF
  - eous ward, e.g.,

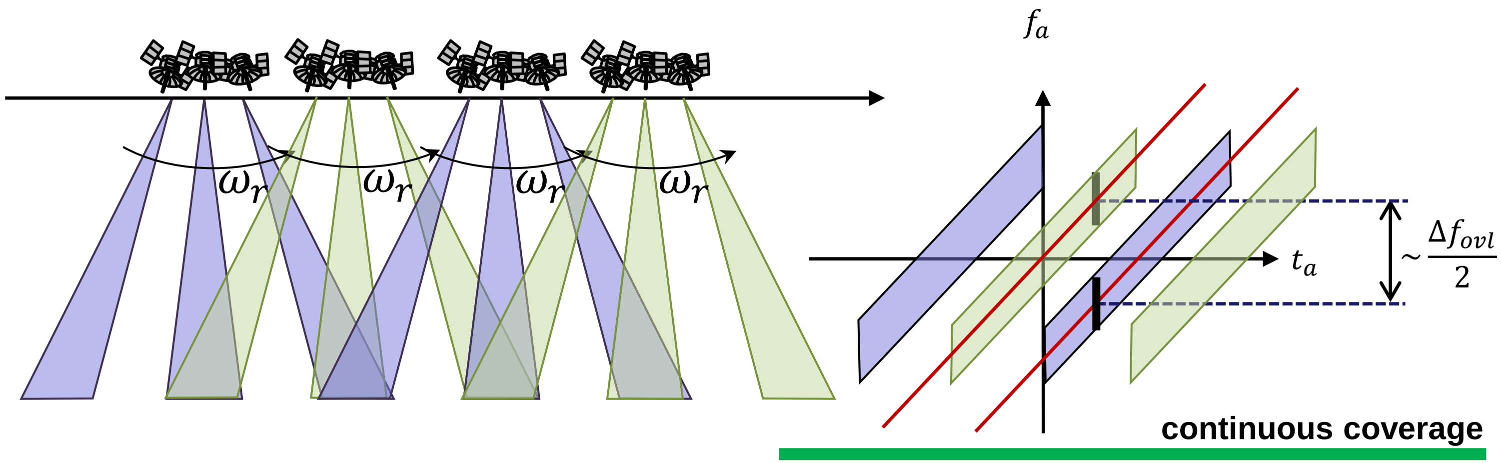


[1] Josef Mittermayer et. al., "Bidirectional SAR imaging mode," IEEE Trans. Geosci. Remote Sens., vol. 51, no. 1, pp. 601–614, Jan. 2013.
[2] P. Lopez-Dekker et.al. Experimental bidirectional SAR ATI acquisitions of the ocean surface with TanDEM-X," Proceedings of EUSAR 2014.

(II) The 2-Look TOPS mode

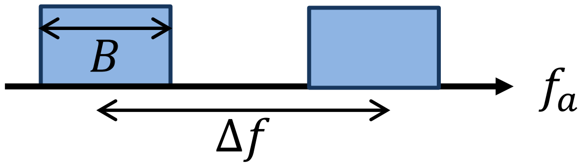
- 1-look burst-mode acquisition: each target observed once (except at overlap area).
- 2-look burst-mode acquisition: each target observed twice under two different squint angles ⇒ possibility to exploit squint diversity! [2]
- Half of the spectral separation than overlap area of 1-look and lower azimuth resolution ☹
- BUT: continuous azimuth coverage! ☺
- AND: the number of looks is kept when compared to the 1-look! ☺





[2] R. Scheiber and A. Moreira, “Coregistration of interferometric SAR images using spectral diversity,” IEEE TGRS., vol. 38, no. 5, pp. 2179–2191, July 2000.

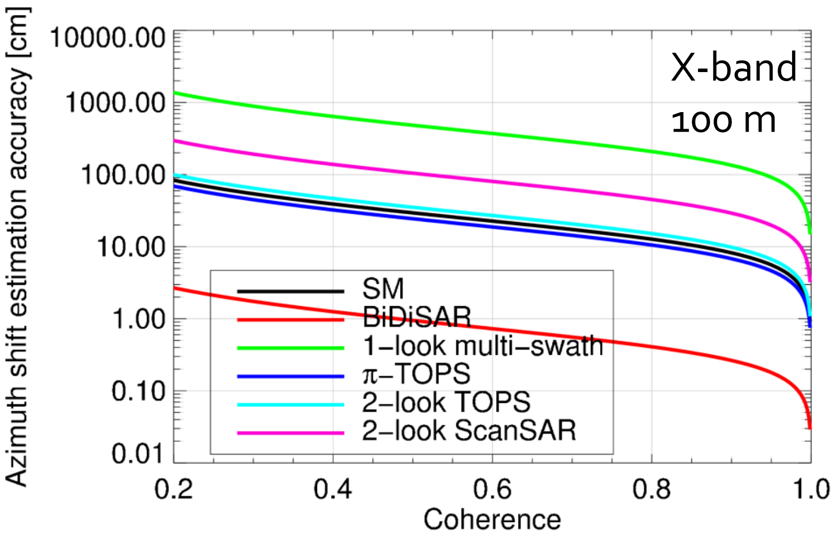
Along-Track Motion Estimation Performance



$$\sigma_{SD} = \frac{\sqrt{2}\cdot\sigma_\varphi}{2\pi\cdot\Delta f} v_g = \frac{\sqrt{2}}{2\pi\cdot\Delta f}\frac{1}{\sqrt{2N}}\frac{\sqrt{1-\gamma^2}}{\gamma} v_g \ [m]$$

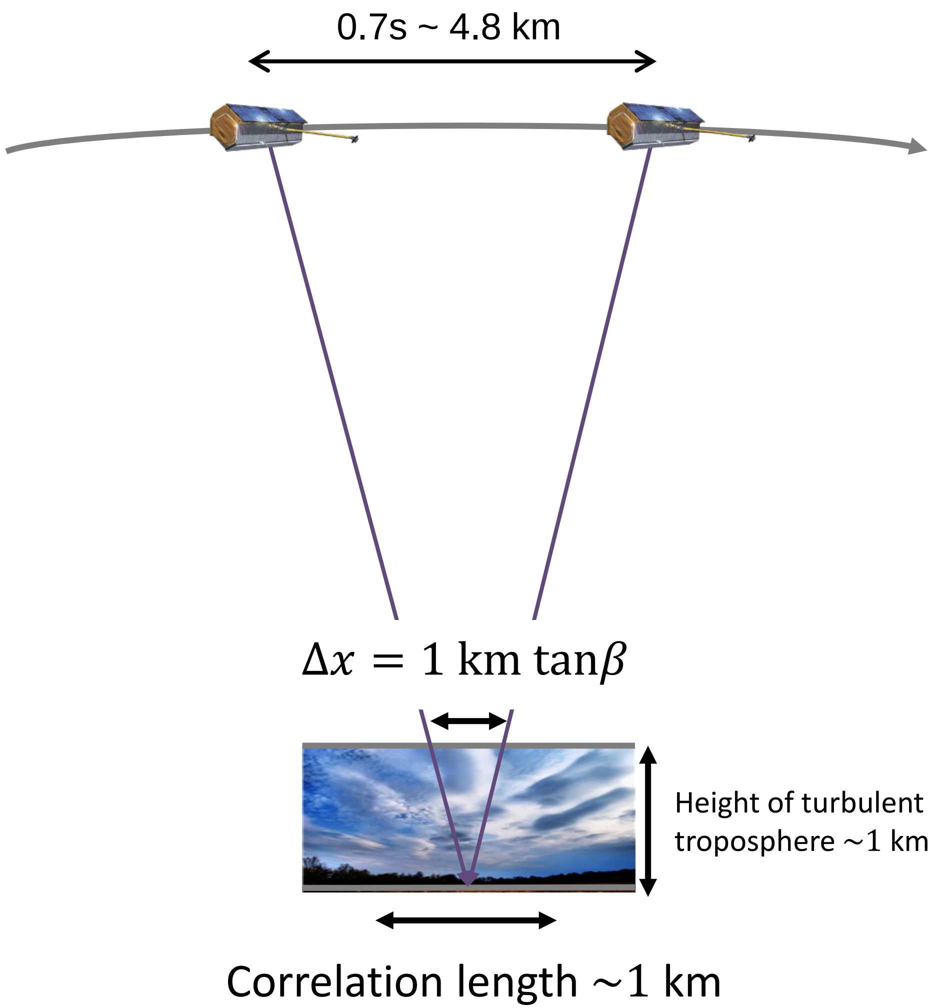
- Performance evaluation for the different experimental modes and comparison with stripmap:

Mode	$B\ [Hz]$	$\Delta f\ [Hz]$	$\rho_{x\ vs\ SM}\ [dB]$
BiDiSAR	2000	38900	29.8
π –TOPS	445	3200	1.63
SM	**2765**	**1843**	**0**
2-look TOPS	222.5	3200	-1.55
2-look ScanSAR	205	800	-11.01
1-look burst mode	445	297	-24.31



- Relative performance between any given two modes: $\rho = 10\cdot\log_{10}\frac{\Delta f_1^2\cdot B_{look,1}}{\Delta f_2^2\cdot B_{look,2}}$

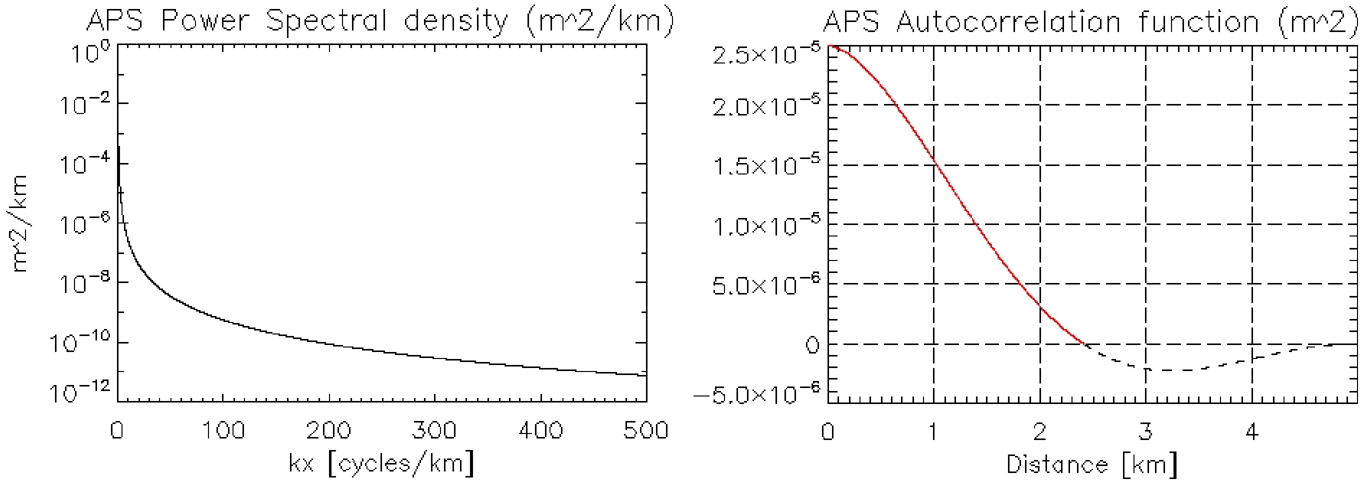
Role of the Troposphere: turbulent component correlation



- Turbulent troposphere spatially modeled as a fractal process (power law or $1/f^{\alpha}$ noise)
- Kolmogorow Power spectrum of the APS delay signal*:

$$P_S(k_x) \propto k_x^{-8/3}$$

(for a 1D profile over the 2D surface – AT direction)



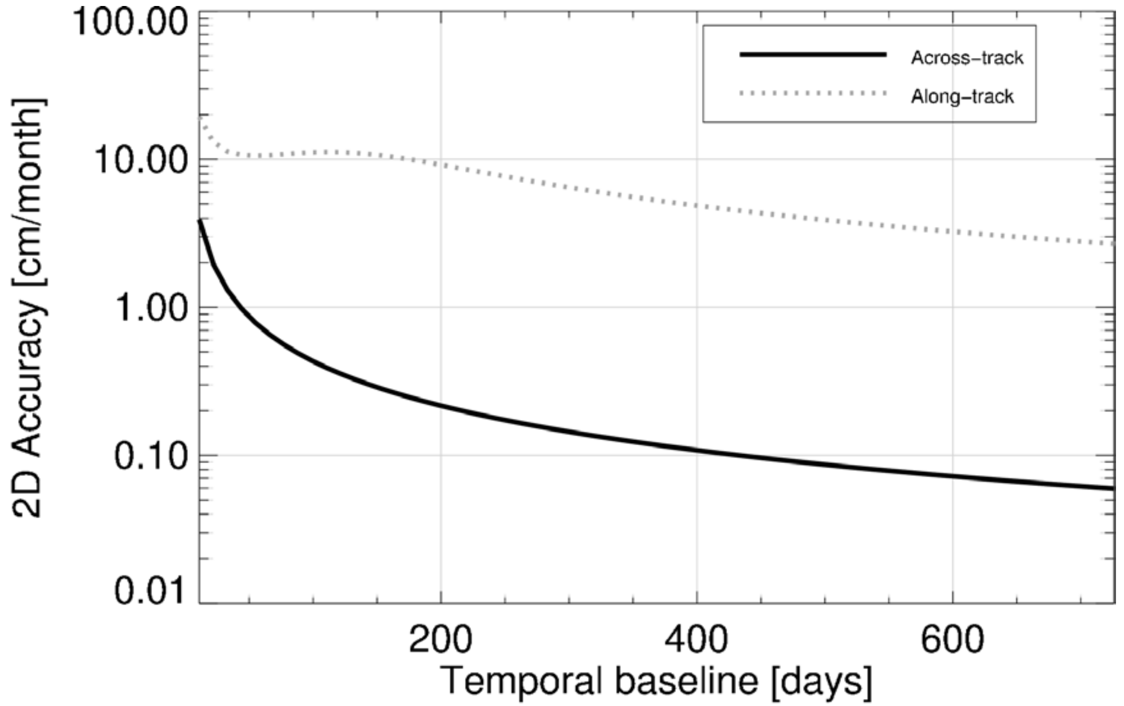
*R. F. Hanssen. Radar Interferometry. Data Interpretation and Error Analysis. 2001

2D and 3D Expected Performances

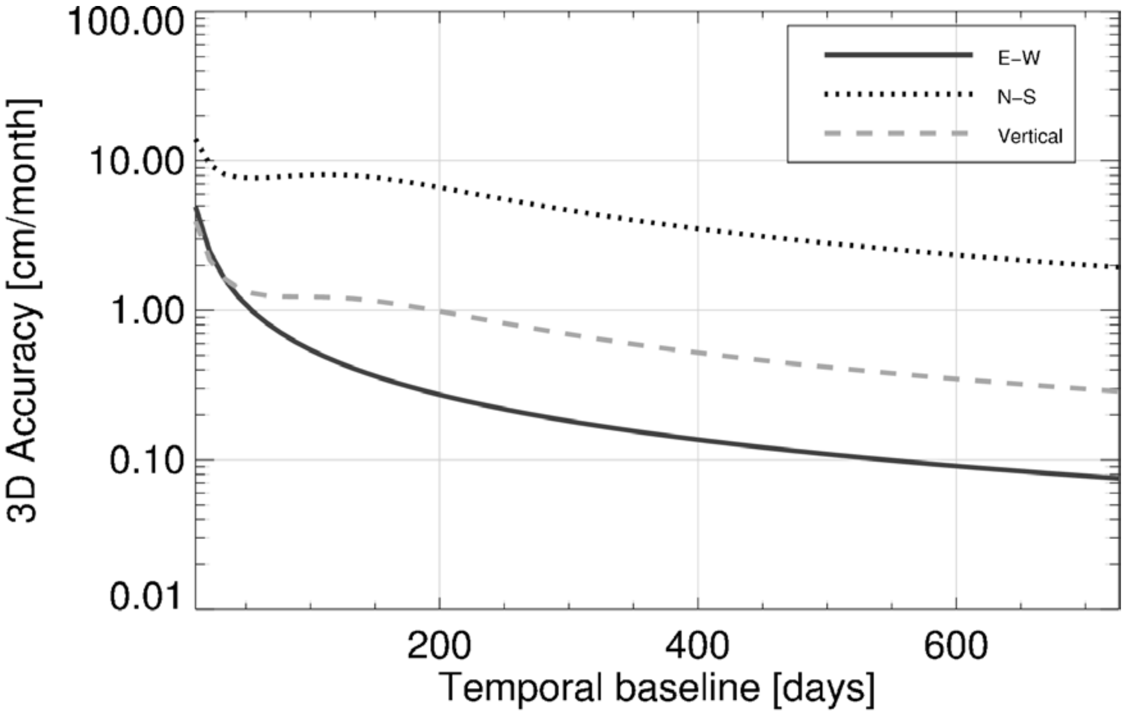
$\sigma_{atm} = 1$ cm
$\tau = 40$ days
$\gamma_{inf} = 0.1$
$N_{look} = 200$

2 Images Asc & 2 Images Desc
2 Subswaths (~85 Km ground coverage)

2D



3D

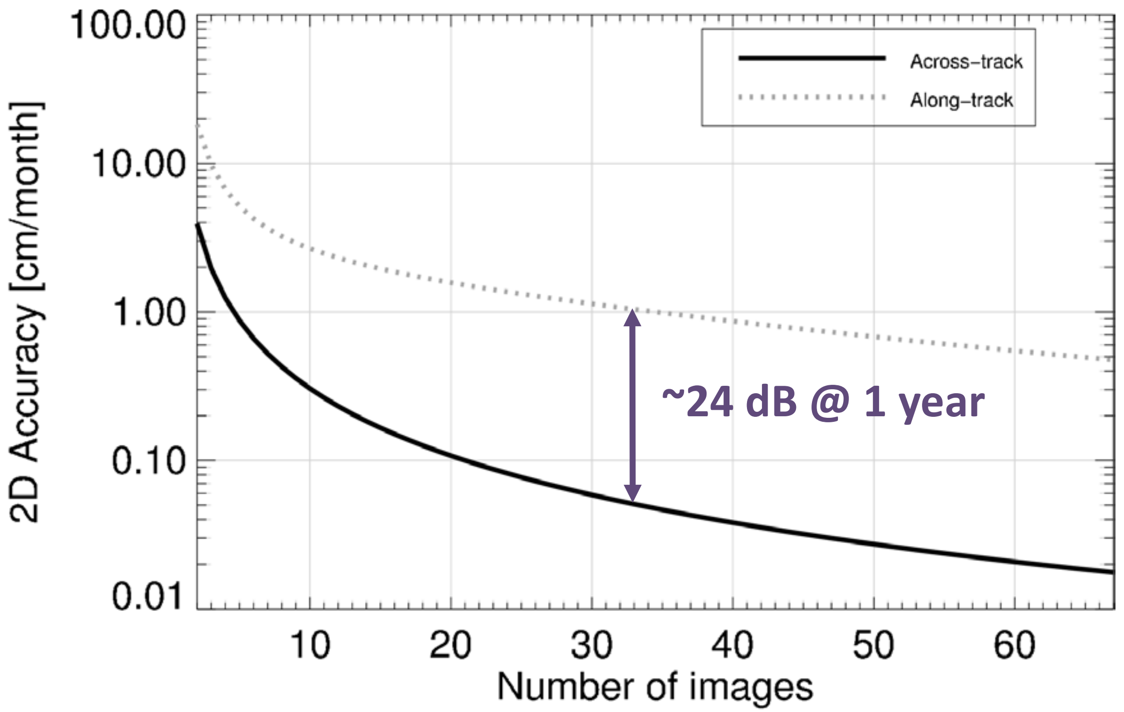


Along-track component insensitive to APS!
Closer perf. of 3D comp. for short temp. baselines.
Afterwards temporal decorrelation dominates.

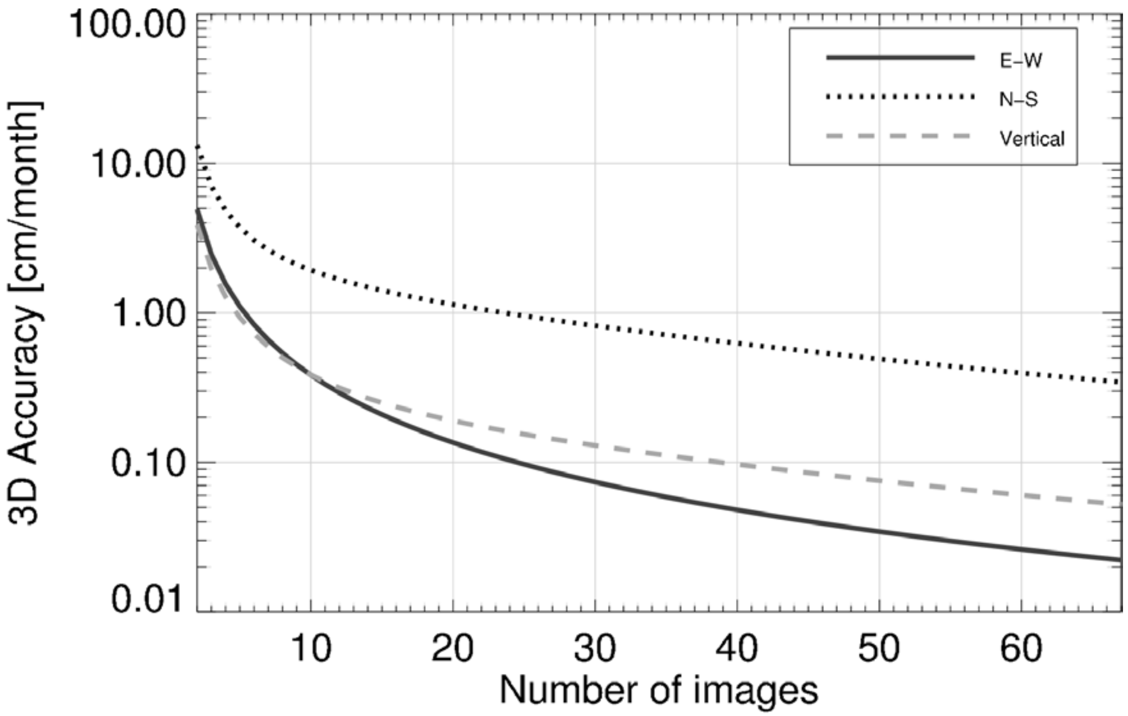
$\sigma_{atm} = 1$ cm
$\tau = 40$ days
$\gamma_{inf} = 0.1$
$N_{look} = 200$
$T_{cycle} = 11\ days$

Time Series Asc & Desc (up to 2 years)
2 Subswaths (~85 Km ground coverage)

2D



3D



Closer performances for short temp. baselines.
Afterwards temporal decorrelation dominates.

Results with pairs of TerraSAR-X 2-looks TOPS

Test Site: Petermann Glacier, Greenland

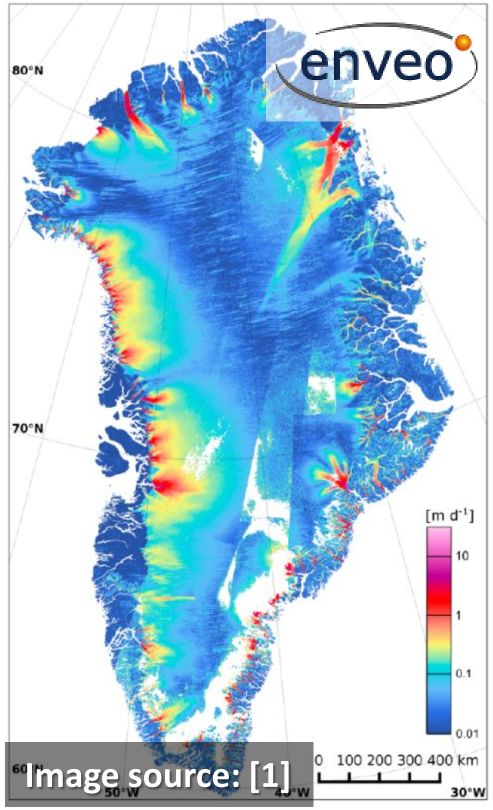
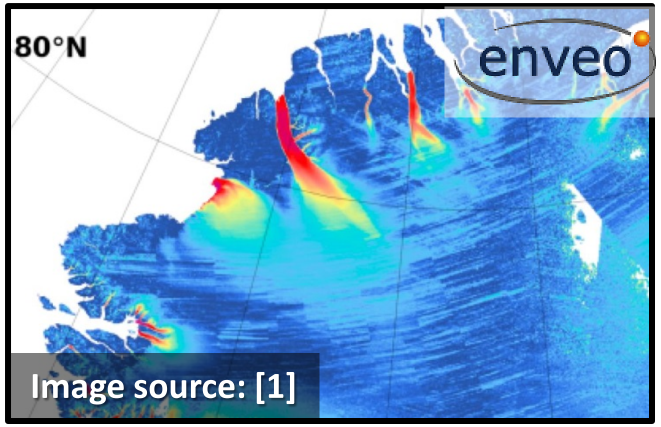
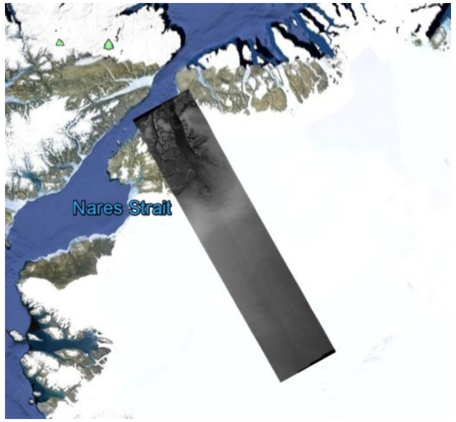
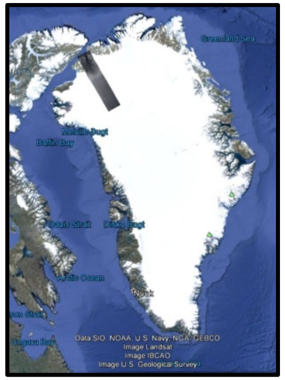
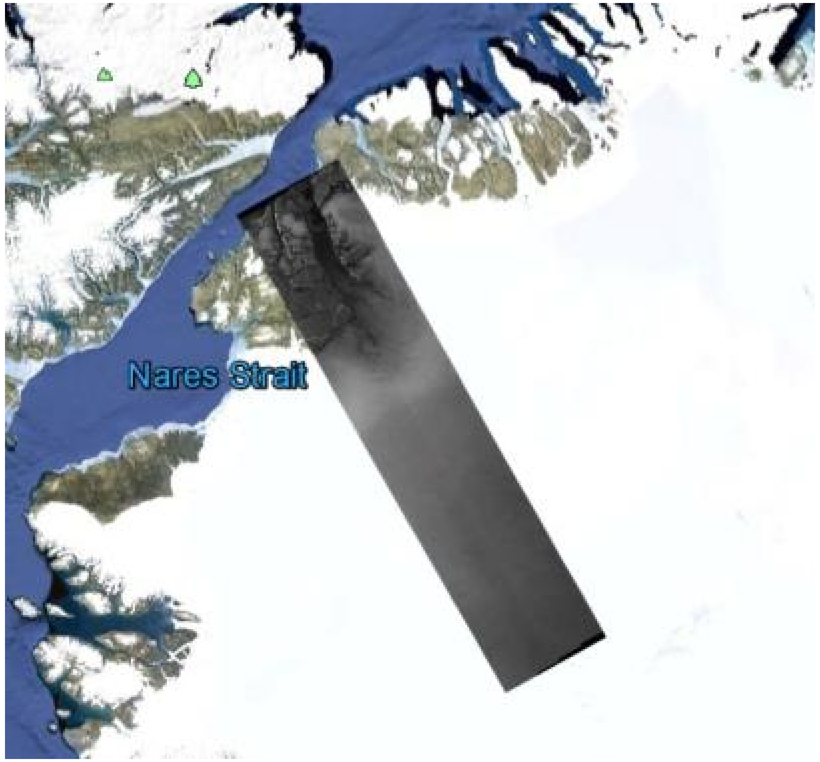


Figure 1. Ice velocity map (magnitude, in logarithmic scale) of the Greenland Ice Sheet derived from SAR data of the Sentinel-1A satellite, acquired in Interferometric Wide Swath Mode (IW) between January and March 2015.







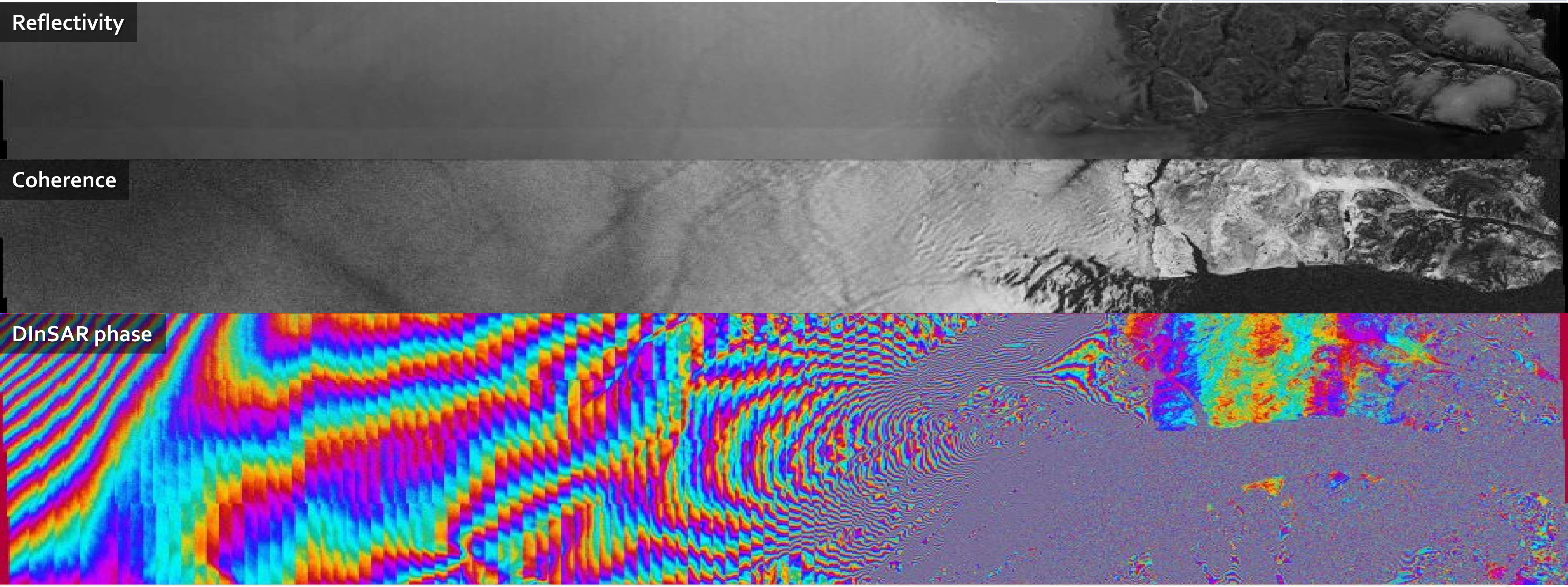


Master Acq.	Slave Acq.	Coverage
16-10-2015	27-10-2015	500 x 100 km (4SS) (40 m resolution)

[1] Thomas Nagler, Helmutt Rott, Markus Hetzenecker, Jan Wuite, Pierre Potin, “The Sentinel-1 Mission: New Opportunities for Ice Sheet Observations,” Remote Sensing, 2015, 7, 9371-9389.

Two-looks TOPS results over Peterman Glacier. 40 m azimuth resolution

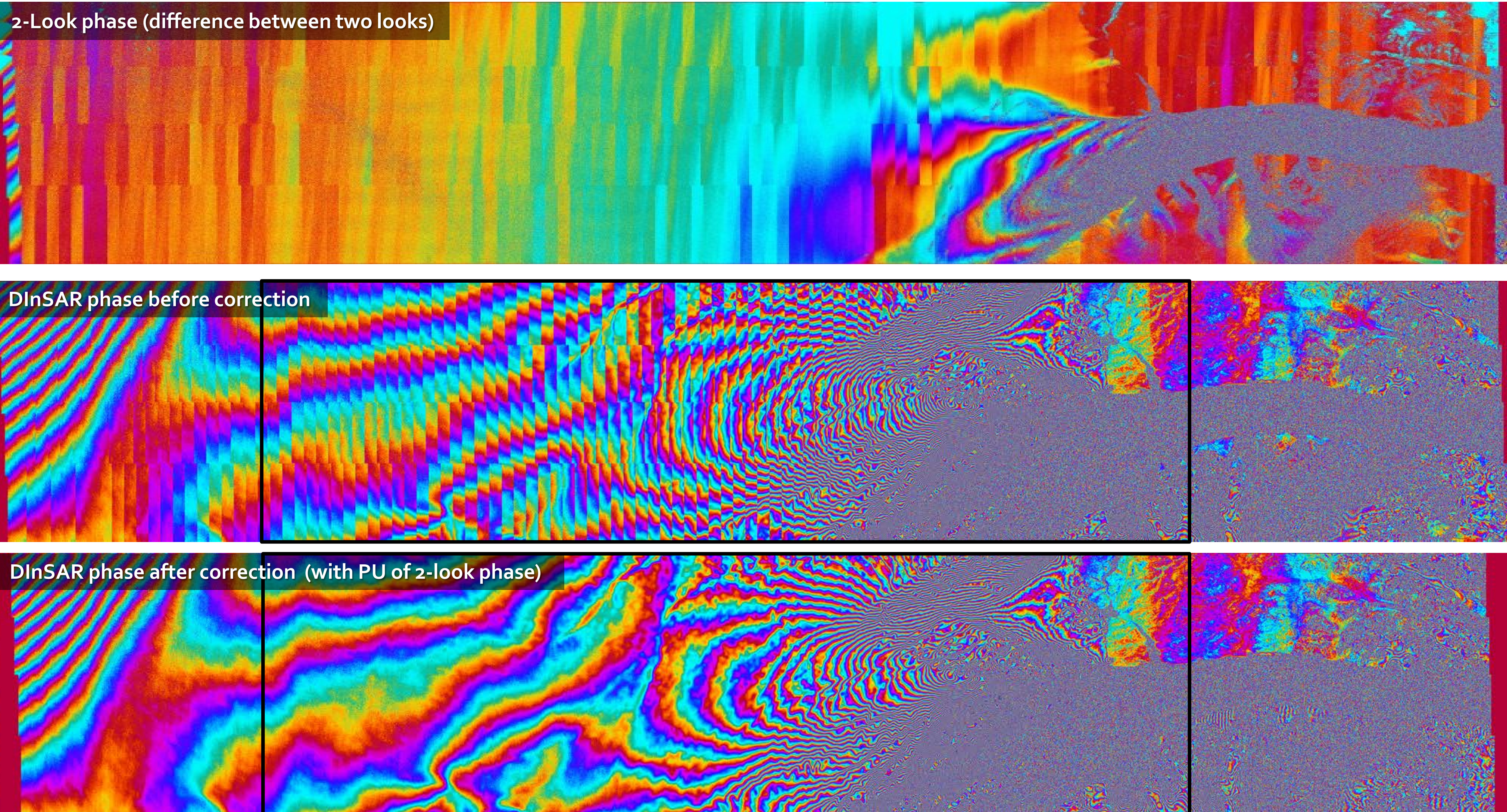
Master Acq.	Slave Acq.	Coverage
16-10-2015	27-10-2015	500 x 100 km (4SS) (40 m resolution)

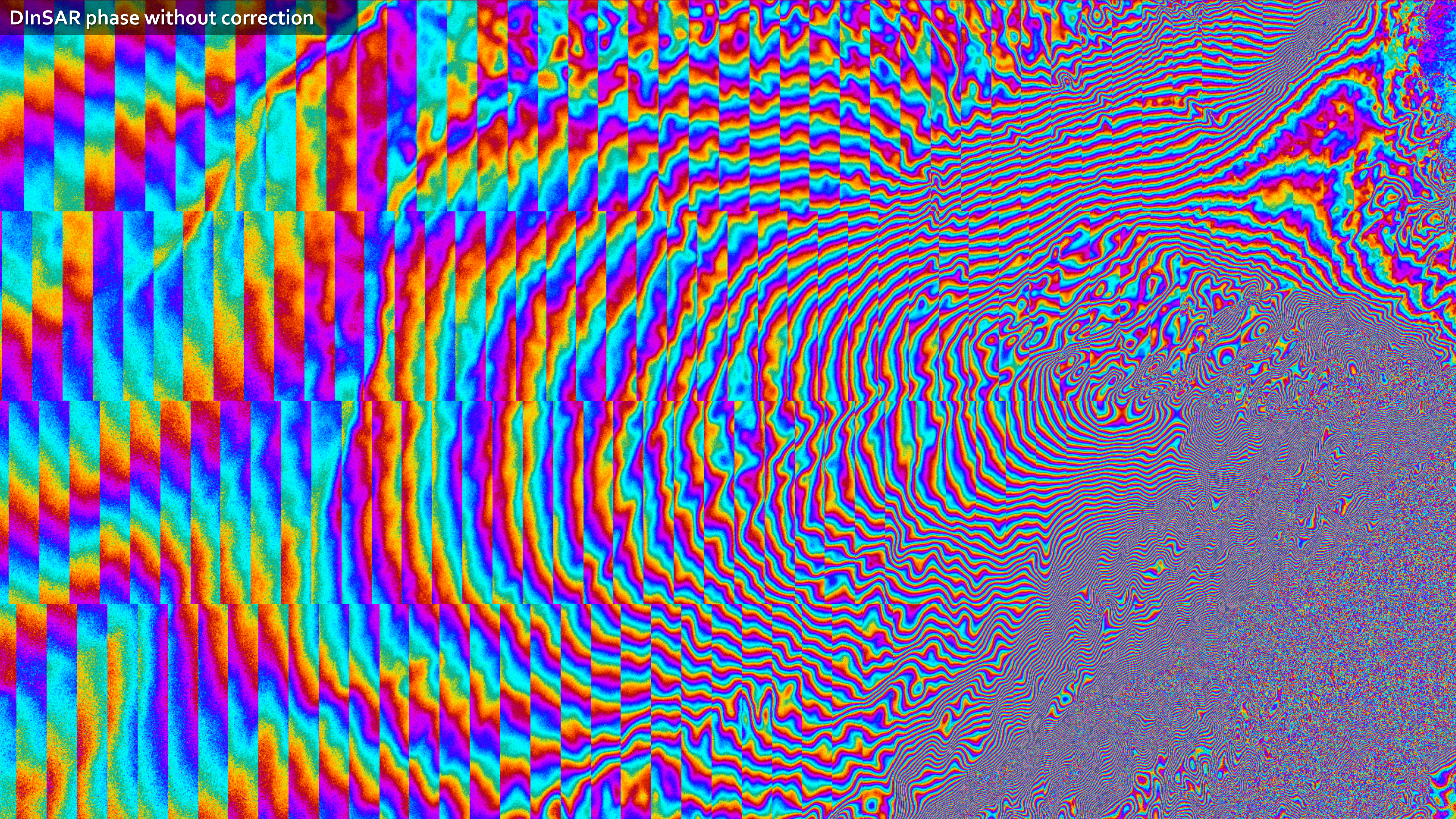


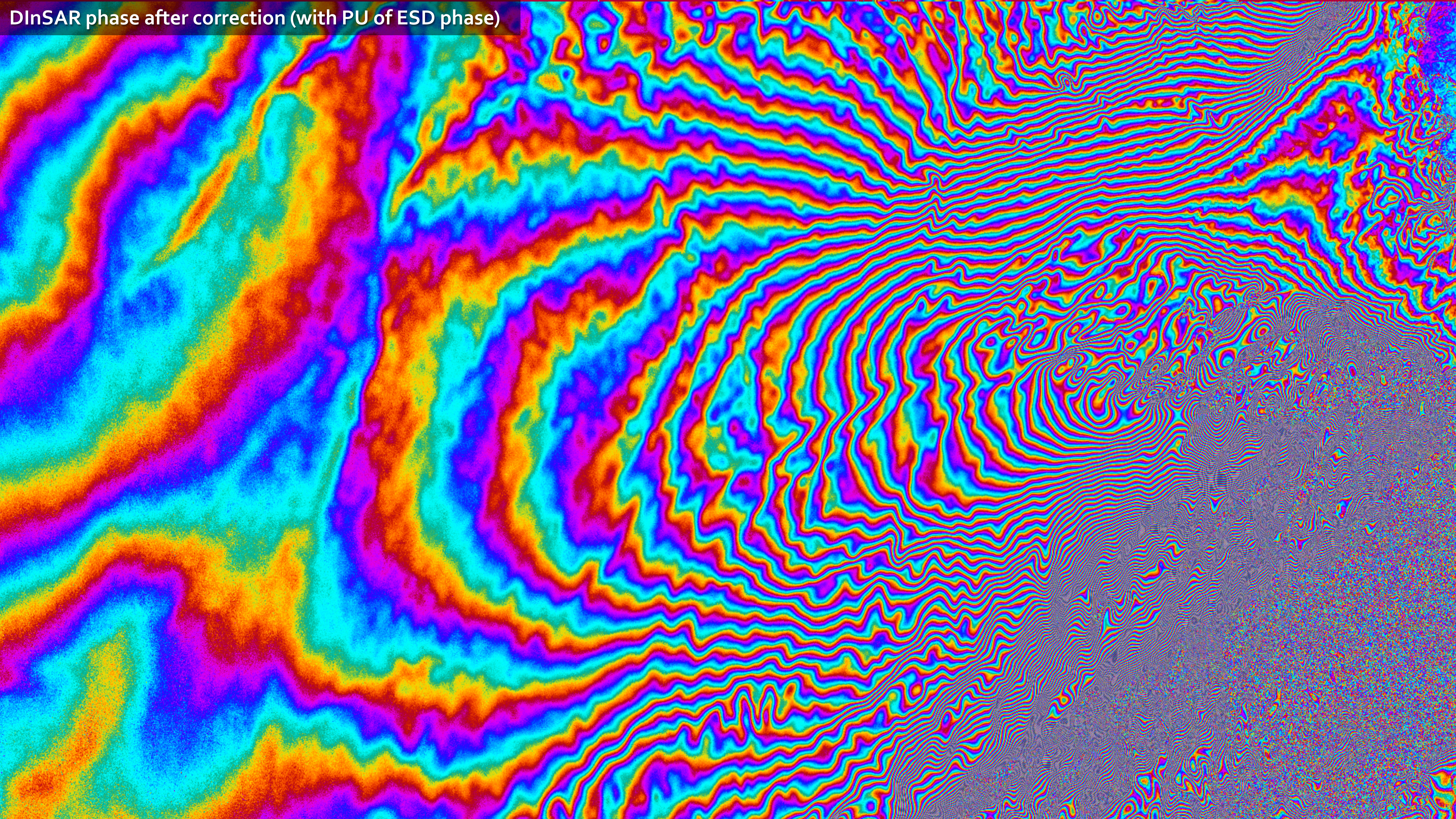
(1) Prats-Iraola et al. Repeat-pass interferometric experiments with the TanDEM-X constellation for accurate along-track motion estimation. IGARSS 2015

(2) Prats-Iraola et al. Demonstration of the Applicability of 2-Look Burst Modes in Non-Stationary Scenarios with TerraSAR-X. EUSAR 2016

(3) Yague-Martinez et al. Experimental Validation with TerraSAR/TanDEM-X of advanced interferometric modes for accurate retrieval of azimuthal displacements. IGARSS 2016

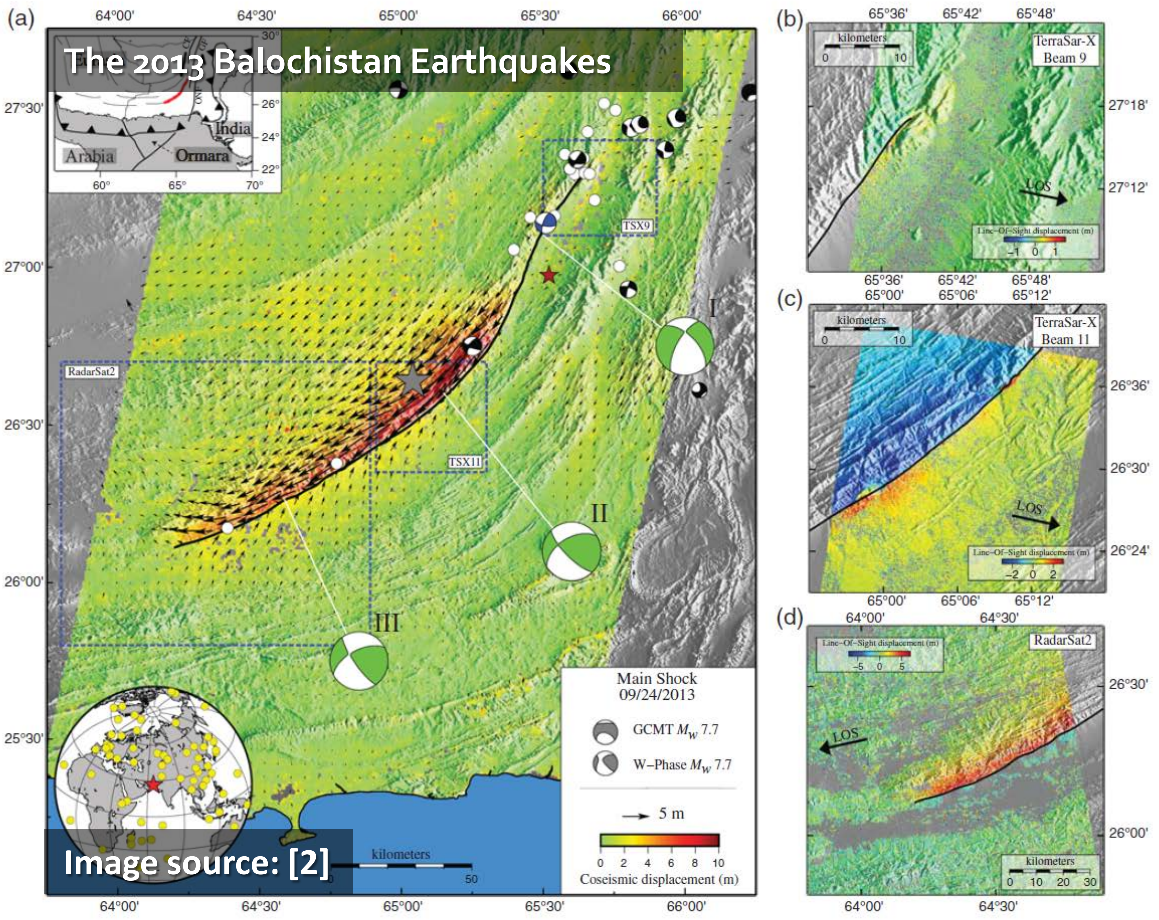

2-Look phase (difference between two looks)
DInSAR phase before correction
DInSAR phase after correction (with PU of 2-look phase)

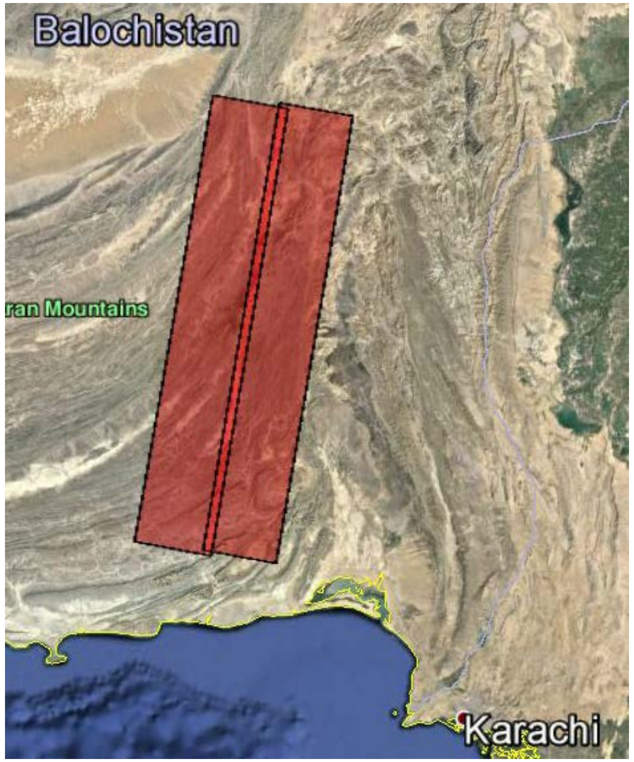

DInSAR phase without correction


DInSAR phase after correction (with PU of ESD phase)

Time-series evaluation of TerraSAR-X 2-looks TOPS

Test site: Balochistan, Pakistan (Post-seismic)

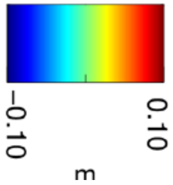




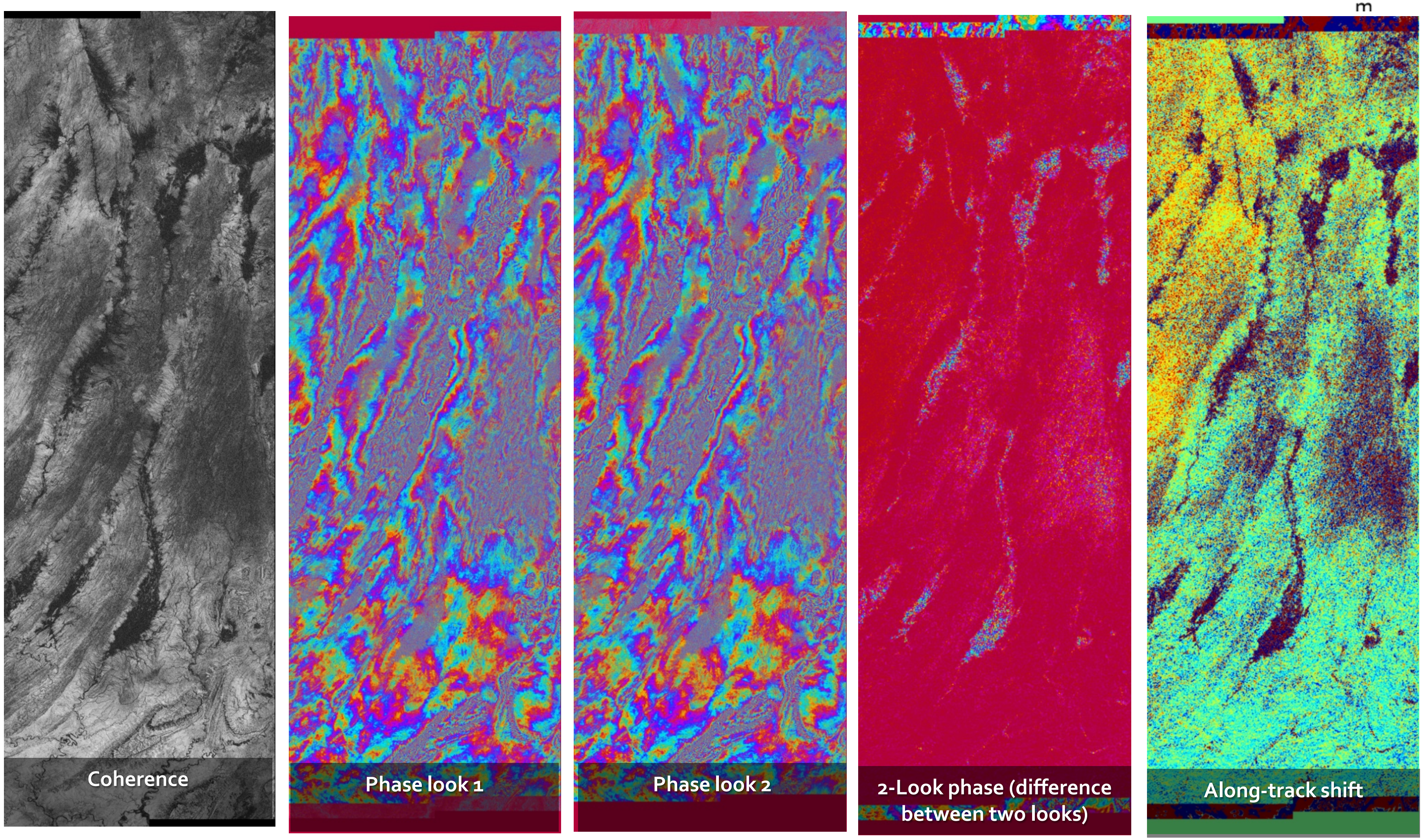
	Coverage	#images
Desc	265 x 83 km (2SS) (18m az resolution)	45 (~1,5 years) (**201604**19-20170816)
Asc	265 x 85 km (2SS) (18m az resolution)	31 (~1 year) (**201608**24 – 20170731)

[1] Avouac, J-P; Ayoub, F.; Wei, S.; Ampuero, J-P.; Meng, L.; Leprince, S.; Jolivet, R.; Duputel, Z.; Helmberger, D. (2014), "The 2013, Mw 7.7 Balochistan earthquake, energetic strike-slip reactivation of a thrust fault" (PDF), Earth and Planetary Science Letters.
[2] Jolivet, R.; Duputel, Z.; Riel, B.; Simons, M.; Rivera, L.; Minson, S. E.; Zhang, H.; Aivazis, M. A. G.; Ayoub, F.; Leprince, S.; Samsonov, S.; Motagh, M.; Fielding, E. J. (2014), "The 2013 Mw 7.7 Balochistan earthquake : Seismic potential of an accretionary wedge", Bulletin of the Seismological Society of America, Seismological Society of America.

Along-track deformation. Balochistan. Pair 20160807 – 20170520 (9.5m)



- High coherence after 9.5 months
- No evident deformation fringes in each LoS
- Tropospheric disturbances in each look phase
- **2-look phase free of tropospheric effects**



Estimation of the mean az velocity. Periodogram applied to ESD phases

- Estimation of the mean azimuth velocity applying the periodogram on the ESD phases of the time-series

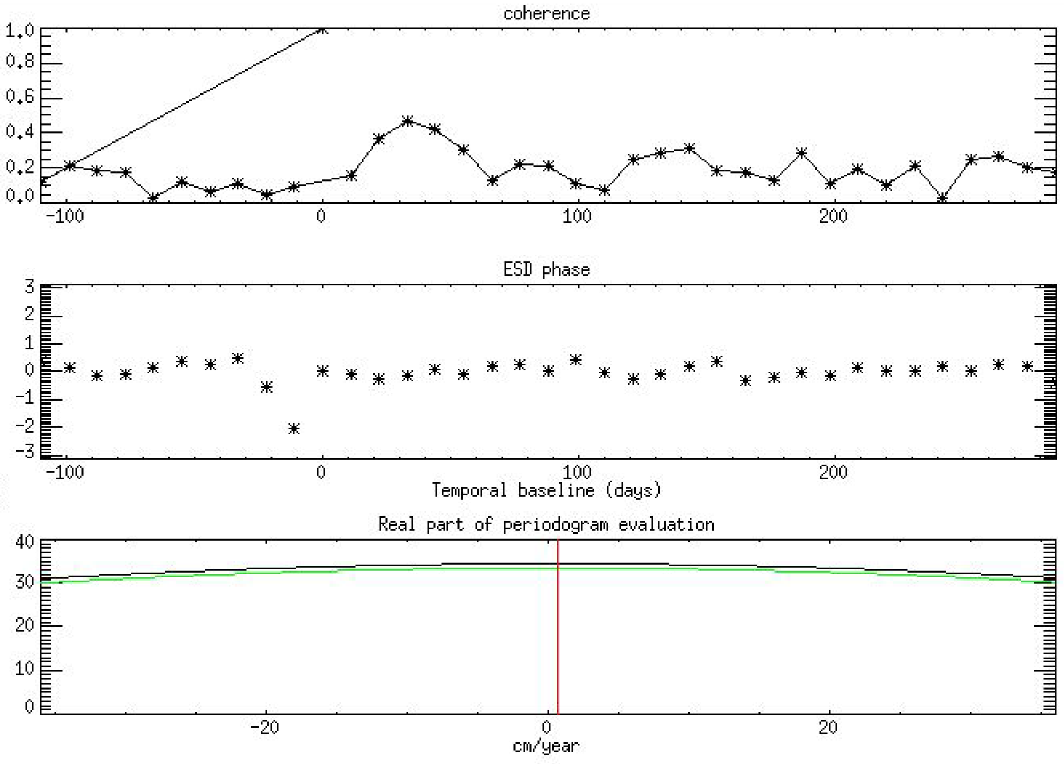
- ESD phases **not affected by troposphere**

- Periodogram evaluation:

$$\arg\max_{v_a}\left\{\mathbb{R}\left\{\sum e^{j(\phi_{ESD}-2\pi\,\Delta f\,v_a T_i)}\right\}\right\}$$

- v_a: $mean\ azimuth\ velocity$
- T_i: $temporal\ baseline$
- Δf: $spectral\ separation$

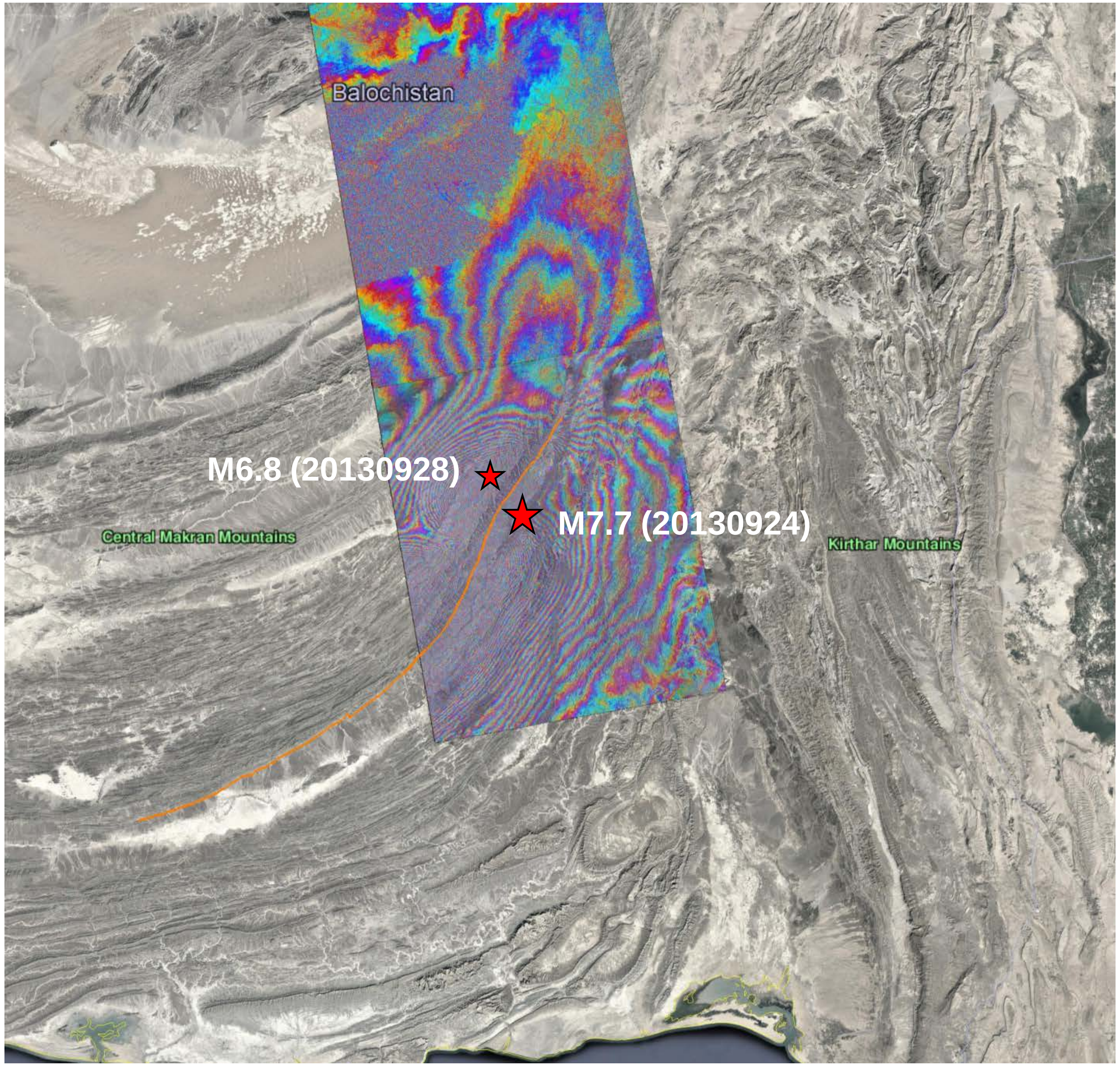
- **Multilooked** pixelwise estimation



2013 M7.7 and M6.8 Balochistan EQ

- Main shock: M7.7 on 20130924
- Aftershock: M6.8 on 20130928

- TanDEM-X ScanSAR Coseismic Interferogram (21.11.2011- 25.10.2013)



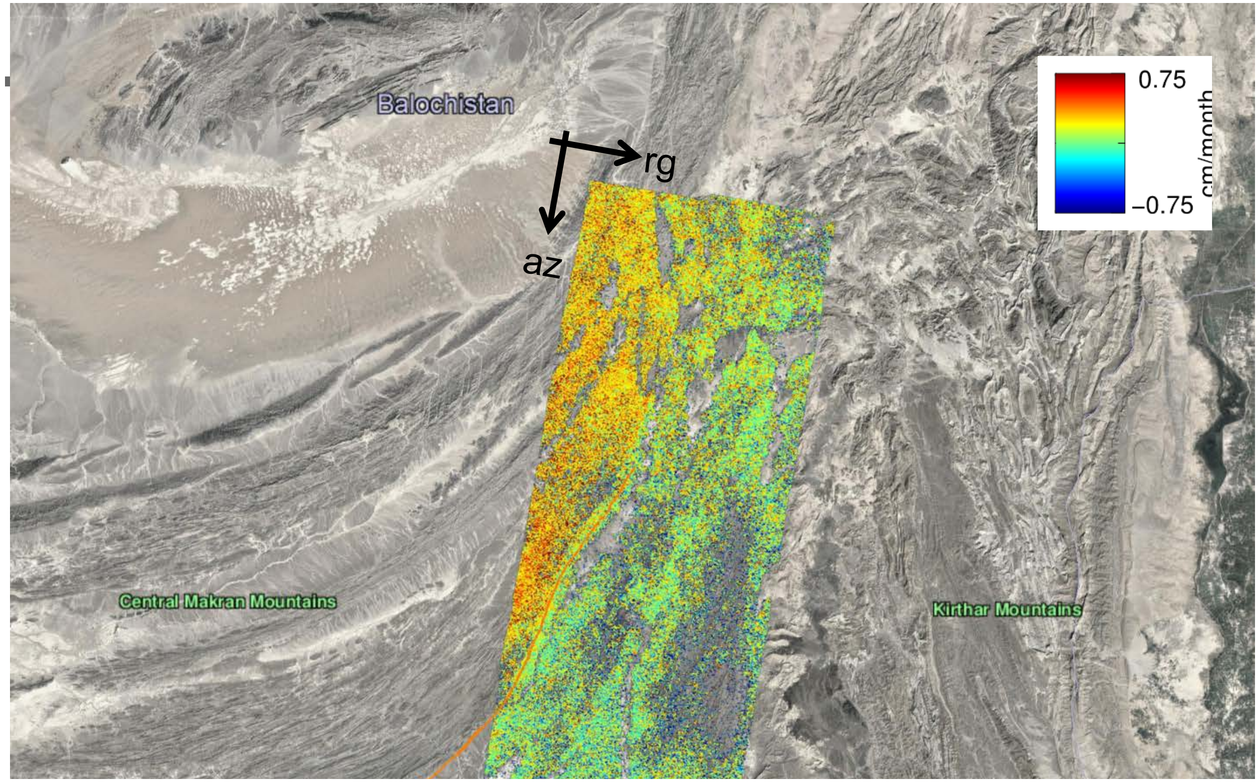
GROUND DISPLACEMENT MEASUREMENT OF THE 2013 M7.7 AND M6.8 BALOCHISTAN EARTHQUAKE WITH TERRASAR-X SCANSAR DATA

N. Yague-Martinez, E. Fielding, M. Haghshenas-Haghighi, X.Y. Cong, M. Motagh, U. Steinbrecher, M. Eineder, T. Fritz

(IGARSS 2014, Quebec, Canada)

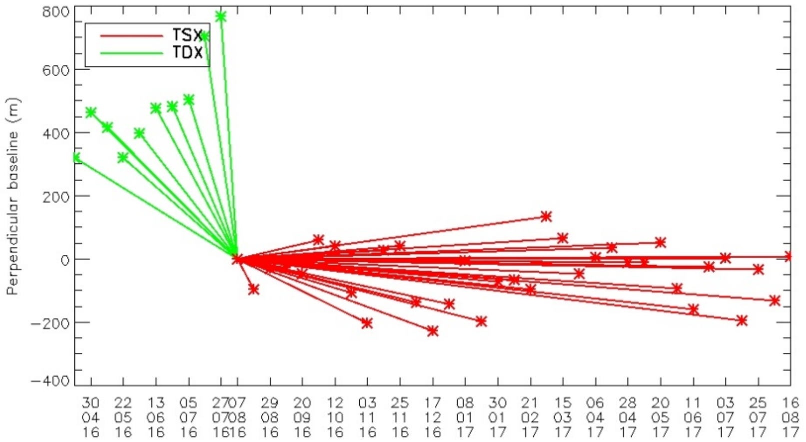
- Acknowledgment to Ken Hudnut, Caltech: Surface rupture line from Landsat pixel offsets.

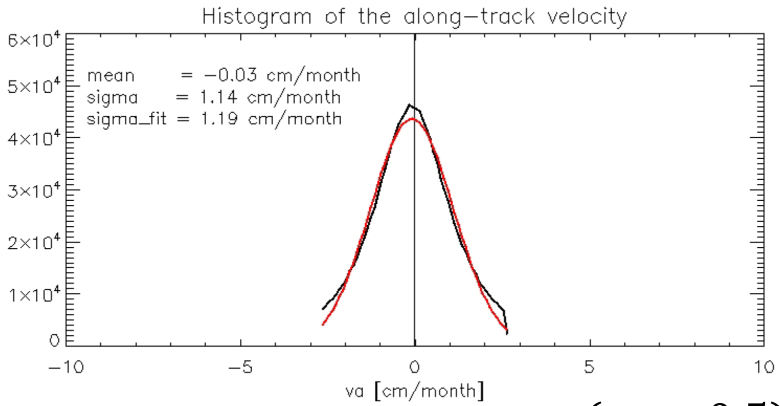
Postseismic along-track deformation. Balochistan. Descending

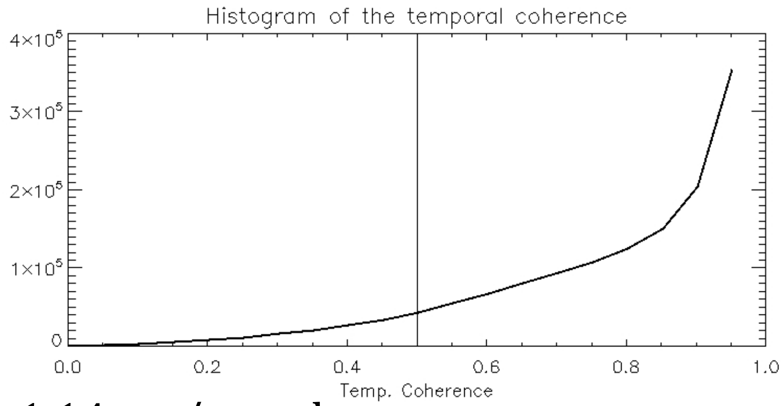


Dataset:

- 2-looks TOPS, 2SS@18m azRes
- Descending
- 45 images
- 19.04.2016 – 16.08.2017 (~1,5 y)
- Master: 07.08.2016







$$\sigma_{v_a}(\gamma_t > 0.5) = 1.14\ \mathrm{cm/month}$$

Conclusions

- **2-looks TOPS mode** provides an opportunity to improve the performance of the **along-track** displacement estimation keeping **wide coverage**.
- Performance of azimuth motion estimation gets closer to the across-track one due to the **correlated tropospheric signal** for both lines of sight.
- Demonstration with experimental **TerraSAR-X 2-looks TOPS** data reveals:
  - Applicability to pairs of images for mapping fast moving sites (glaciers, seismic events).
  - Applicability to time series for mapping of slow moving areas, e.g. postseismic events.
  - Obtained accuracy with real data is similar to the expected one using periodogram on ESD phases
- The comparison of mean azimuth velocities between **TSX 2-looks** and **Sentinel-1** at the overlap areas reveals consistency between both systems.
- Ionospheric effects should be further analyzed