SEOM – INSARAP: Sentinel-1 InSAR Performance Study with TOPS Data

ESA-ESRIN Contract 4000110587/14/I-BG

Special Considerations in the TOPS Case

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Knowledge for Tomorrow

Coregistration and Azimuth Shifts*

*F. De Zan, P. Prats-Iraola, R. Scheiber, A. Rucci
Interferometry with TOPS: coregistration and azimuth shifts
EUSAR 2014, Berlin, Germany.

Impulse response and interferometric phase

- Impulse response (zero-Doppler focusing geometry)

$$s(\tau,t;r_0) = s_r(\tau-\tau_0)\cdot s_a\big(t-t_0-k\cdot(\tau-\tau_0)\big)\cdot \exp\left[-j\frac{4\pi}{\lambda}r_0\right]$$

$$\cdot\ \xcancel{\exp[j2\pi f_0\cdot(\cos\beta-1)\cdot(\tau-\tau_0)]}\ \cdot\ \boxed{\boldsymbol{\exp[j2\pi f_{dc}\cdot(t-t_0)]}}$$

True range position of scatterer within resolution cell

- Interferometric phase for azimuth shifts
  - $\Delta\phi = 2\pi\cdot f_{DC}(t)\cdot\Delta t$
  - Variable Doppler centroid (TOPS)
    - Constant shift => azimuth phase ramp in each burst
    - Local shift => local phase contribution (bug or feature?)

One could estimate the azimuth shifts…

- Phase error due to azimuth mis-registration (in presence of Doppler centroid)

$$\sigma^2_{\varphi_{AZ}} \approx 6 \left(\frac{f_{dc}}{B_d} \right)^2 \frac{1-\gamma^2}{N\,\gamma^2}$$

    - Azimuth coregistration performance depends on coherence, samples and Doppler bandwidth
    - The phase error depends on Doppler centroid (and coregistration error)

- Performance of (range) phase measurement, the well known CRB

$$\sigma^2_{\varphi_{IF}} \approx \frac{1}{2}\;\frac{1-\gamma^2}{N\,\gamma^2}$$

- On the same resolution (same *N*) the coregistration-related term will always dominate in the TOPS case! (as soon as the Doppler centroid is comparable to the bandwidth)

Two cases: systematic shifts & geophysical shifts

- Systematic shifts:
    - Orbital accuracy, timing errors, (Earth tides)*
    - Can be corrected to sub-centimetric accuracy

- Geophysical shifts:
    - The effect on the phase should only be correctly interpreted
    - Users (and their models) should be aware

♦M. Eineder *et. al.*, “Imaging Geodesy – Toward Centimeter-Level Ranging Accuracy with TerraSAR-X,” *IEEE Trans. on Geoscience and Remote Sensing*, vol. 49, no. 2, Feb. 2011.

Systematic azimuth shifts

- Systematic shifts:
  - Orbital accuracy, timing uncertainty
  - One single value for a long scene (tens of kilometers)
  - Lots of averaging opportunities
    - Many independent samples
    - Burst edges and overlaps (high sensitivity)
    - Elimination of outliers might be necessary

- Sub-centimetric accuracy (for Sentinel-1, 20m azimuth resolution)
  - Coregistration accuracy $\sigma_x = \sqrt{\frac{3}{2N}\frac{1-\gamma^2}{(\pi\gamma)^2}}\rho_{az} = 1\text{cm @ } 1000\ \text{km}^2 (\gamma = 0.25)$
  - Resulting phase accuracy $\sigma_\varphi = 360\frac{f_{dc}}{v}\sigma_x = 3\ \text{deg}\ (f_{dc} = 6\text{kHz}, \text{v=7000 m/s})$

- Long wavelength signals in azimuth direction, e.g. Earth tides, will be absorbed in this correction (they end up in the shift information)

Geophysical shifts

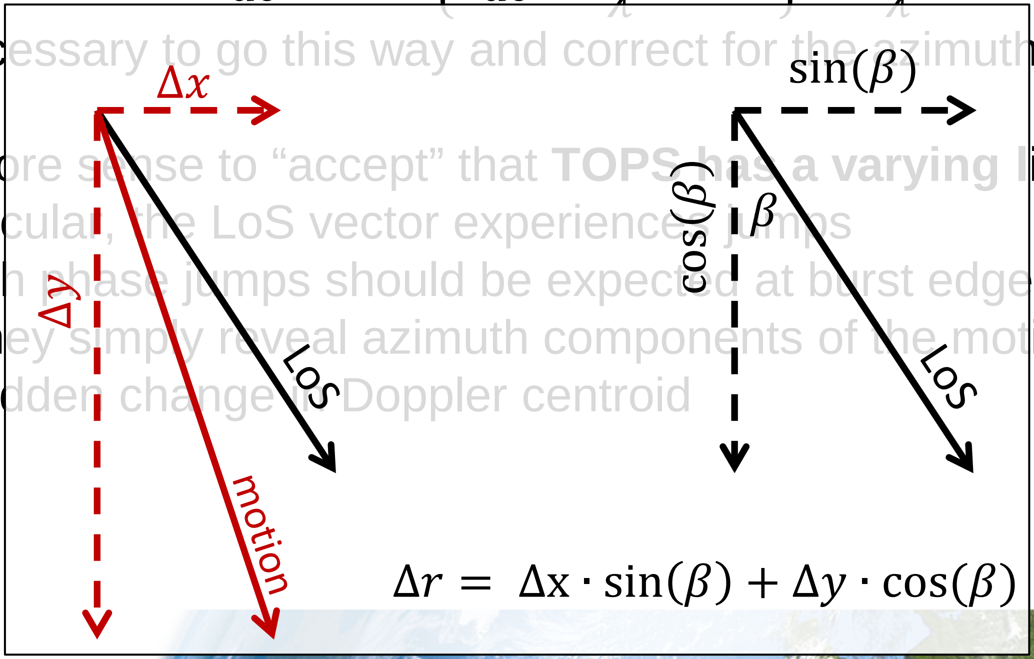
- It is not possible to compensate satisfactorily local shifts (at the scale of the interferometric product)

- The correction is really an attempt to separate azimuth and zero-Doppler component for a slightly squinted geometry

$$\Delta\,\phi = 2\,\pi\cdot f_{\mathrm{dc}}\cdot\Delta t = \left\{f_{\mathrm{dc}} = \frac{2v}{\lambda}\sin\beta\right\} = \frac{4\pi}{\lambda}\cdot\Delta x\cdot\sin\beta$$

- But is it necessary to go this way and correct for the azimuth LoS component?

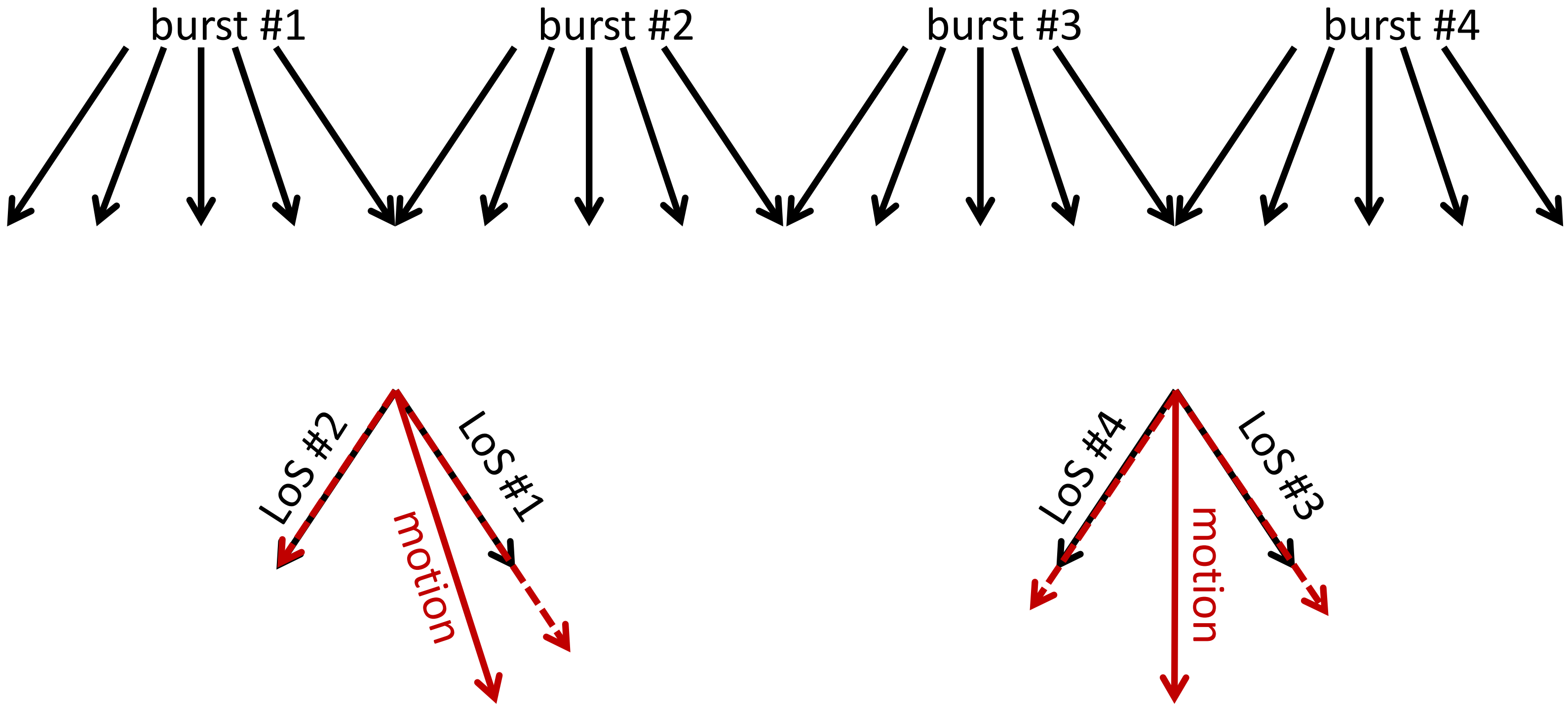
- It makes more sense to “accept” that **TOPS has a varying line of sight!**
  - In particular, the LoS vector experiences jumps
  - Azimuth phase jumps should be expected at burst edges
    - They simply reveal azimuth components of the motion, sensed by a sudden change in Doppler centroid



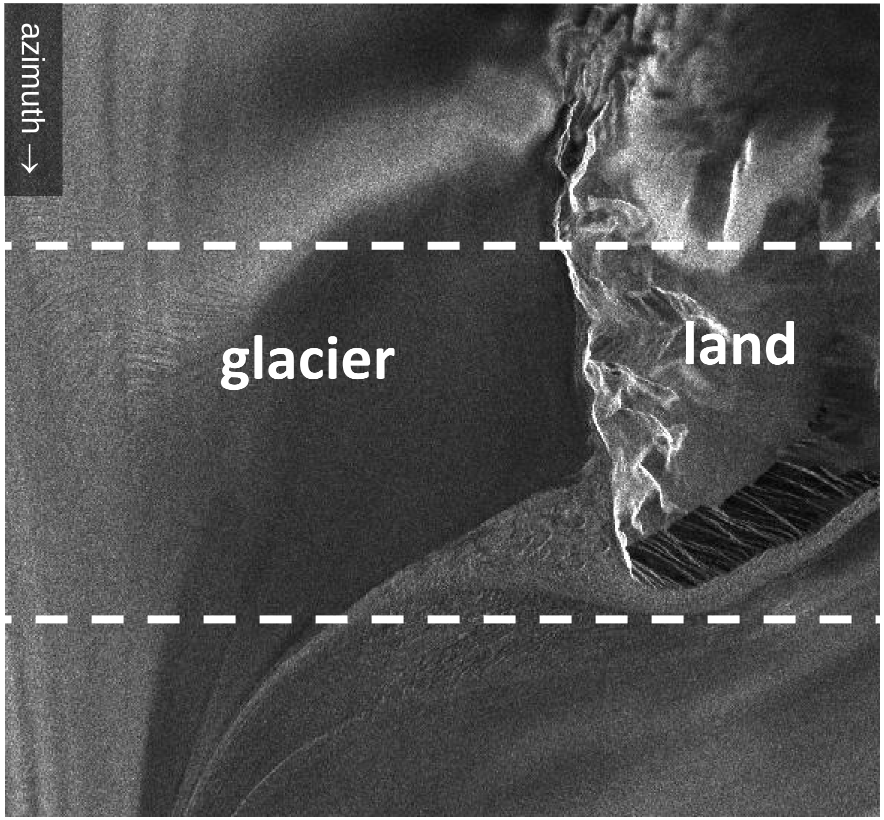
$$\Delta r = \Delta\mathrm{x}\cdot\sin(\beta) + \Delta y\cdot\cos(\beta)$$

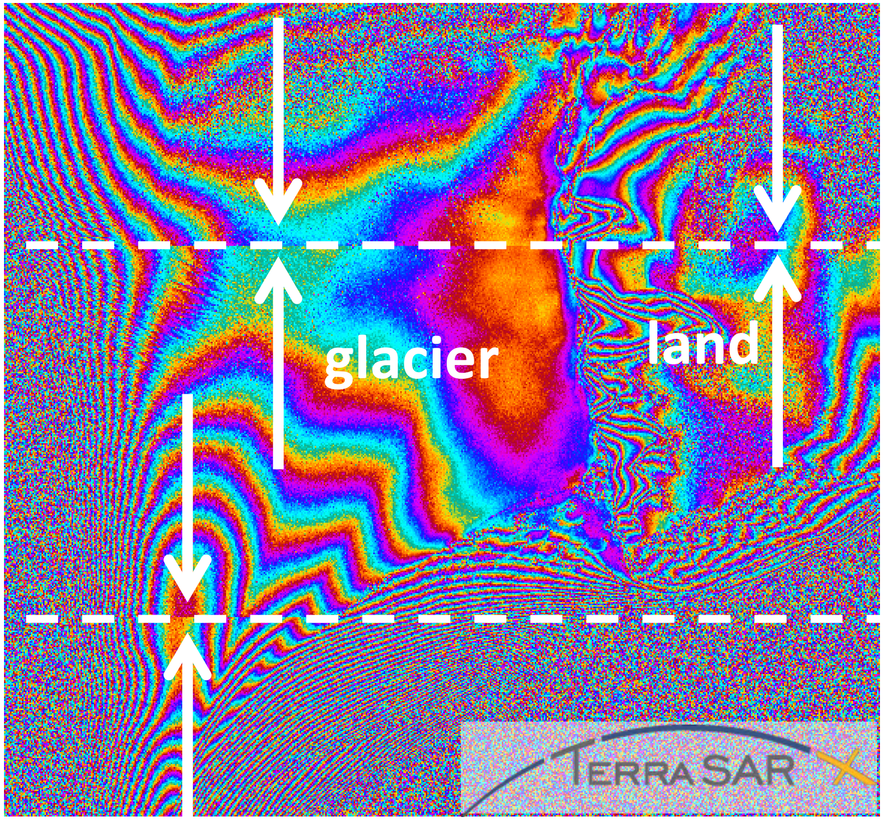
Variation of line of sight along azimuth

- SAR interferometry is sensitive to motion in line of sight
- Discontinuities in LoS are likely to appear in the interferogram
- Jumps in the interferograms will be normal (small or large)

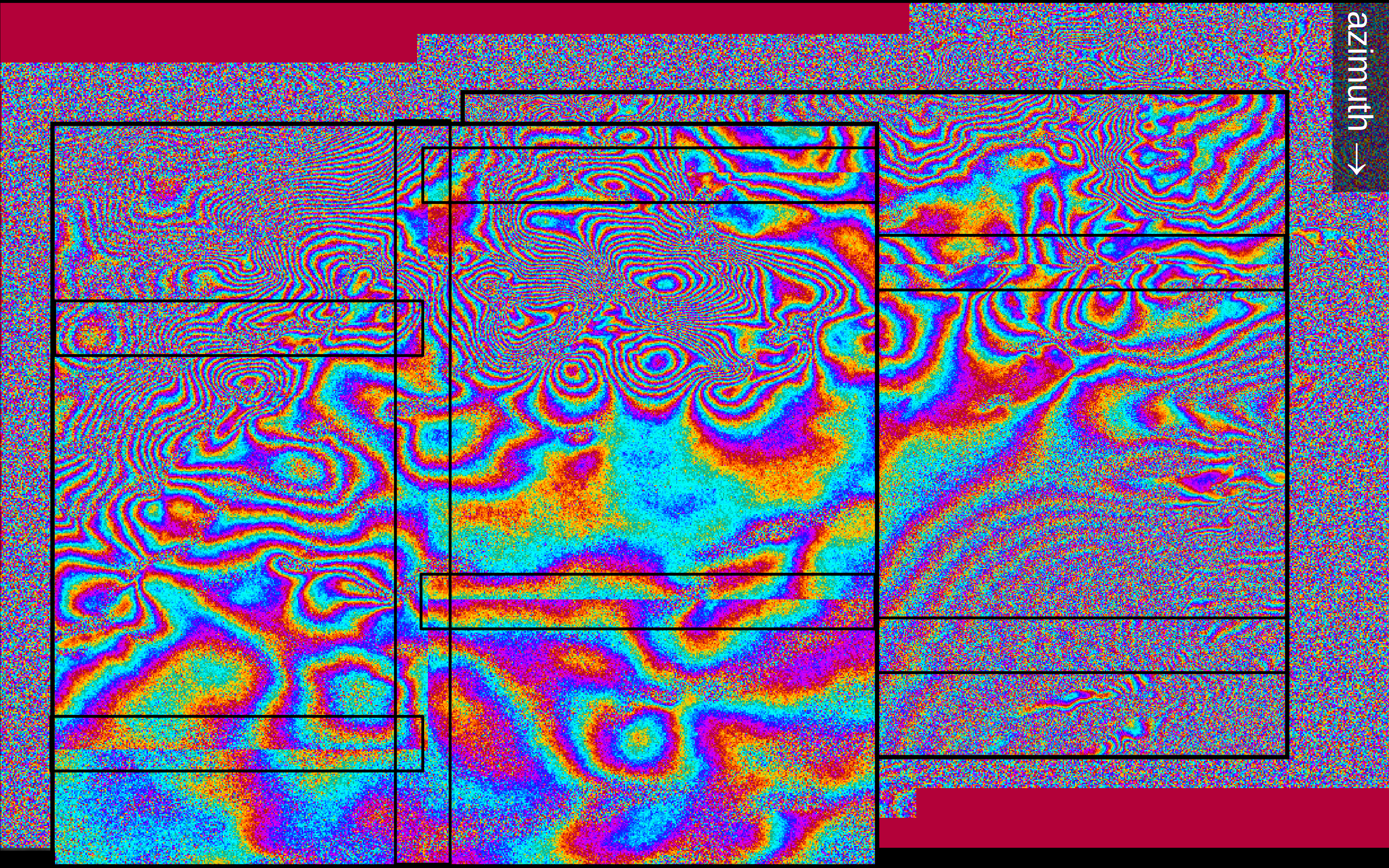


Example With TerraSAR-X Data





Phase Discontinuities over Pine Island Glacier



Proposed methodology

- Correct with Enhanced Spectral Diversity for a constant shift or slow varying term (geolocation/timing error)
  - Burst-periodic phase ramps should disappear
  - Optionally, assume global offset is small enough to be ignored (with precise orbits)

- For phase variations or jumps due to local azimuth shifts
  - Models / users should be aware of the azimuth-varying line of sight
  - They should take care in phase unwrapping if the phase discontinuity is significant
    - Estimating the local azimuth shift, coregistering, unwrapping, reinserting the removed phase
    - Unwrapping each burst independently and solving for phase ambiguity, e.g. with the help of radargrammetry
  - Only large azimuth shifts will affect phase unwrapping: 75 cm (azimuth) → 180 deg phase jump. Earthquakes, glaciers…

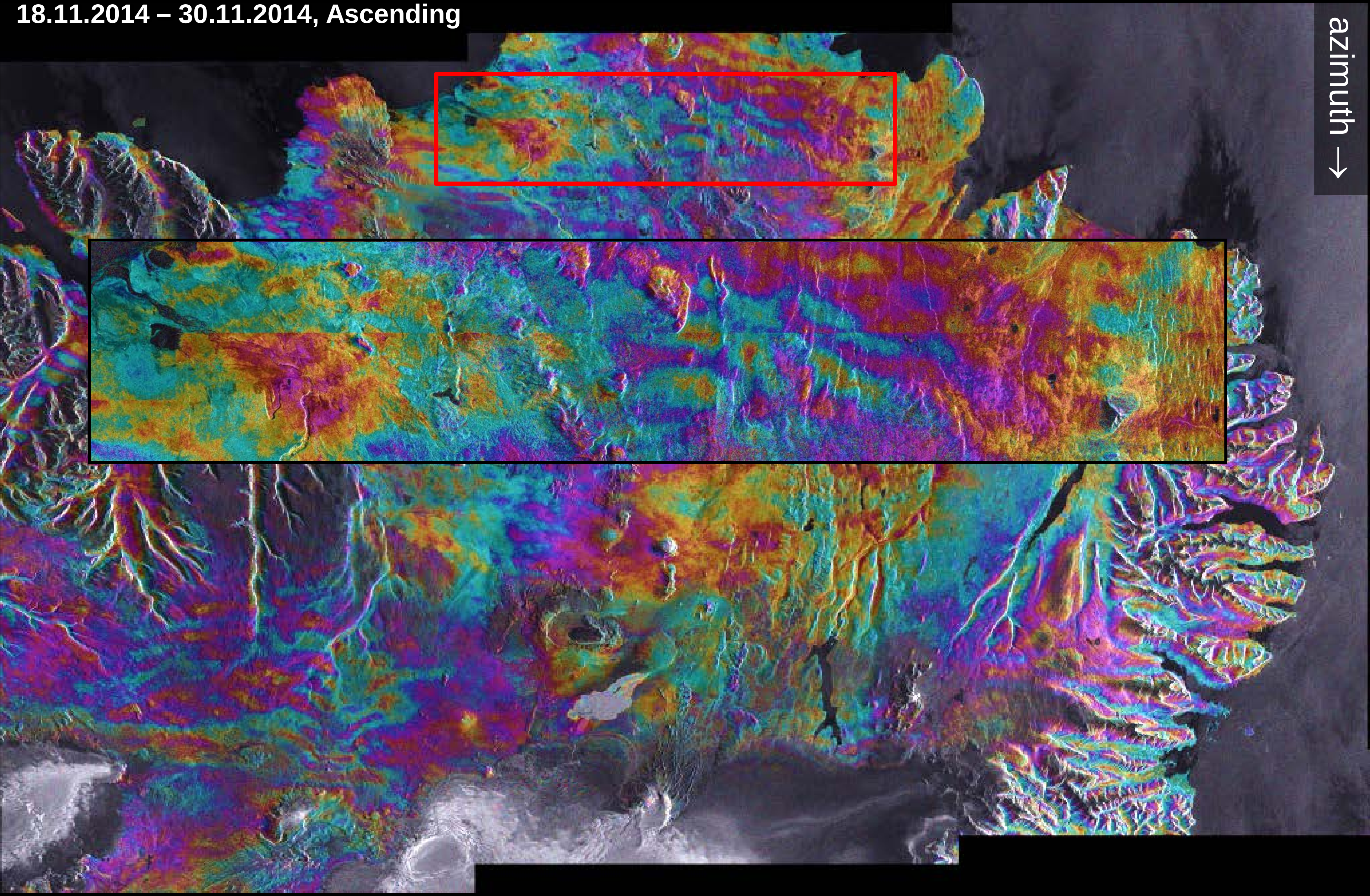
Ionospheric Scintillations & TOPS

Ionospheric Scintillations and TOPS

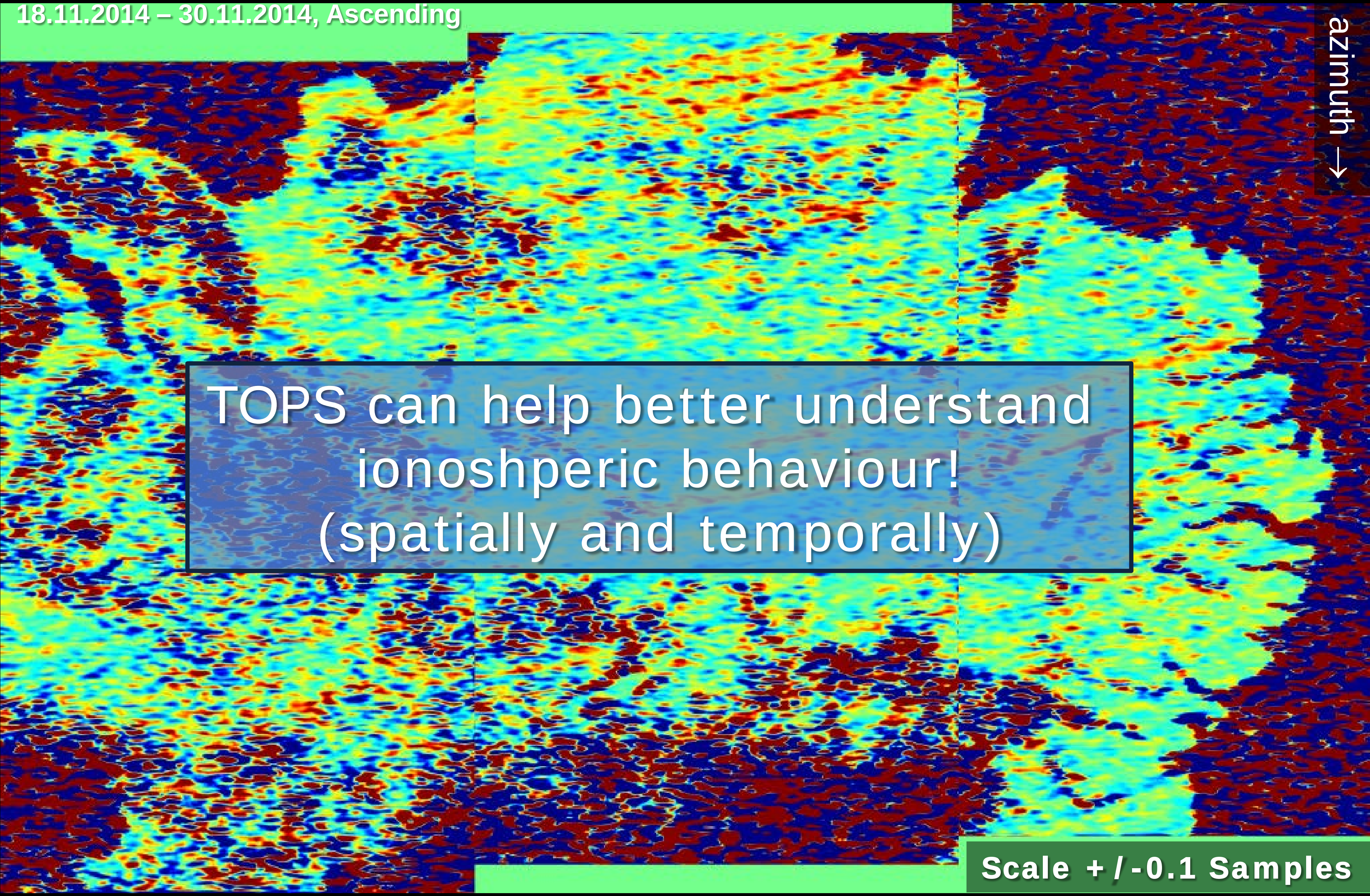
- Ionospheric scintillations are specially intense and frequent close to the equator, but also at higher latitudes.
- Lower frequency bands are more affected.
- They can introduce azimuth shifts locally up to decimeters at C-band.
- For TOPS, the azimuth shifts will turn into phase jumps at burst edges.
- In the following an example with Sentinel-1 data over Iceland is shown.

Iceland

18.11.2014 – 30.11.2014, Ascending



Iceland: Estimated azimuth offsets



18.11.2014 – 30.11.2014, Ascending

TOPS can help better understand ionoshperic behaviour! (spatially and temporally)

Scale + / -0.1 Samples

Speckle Tracking with TOPS Data*

*R. Scheiber, M. Jäger, P. Prats-Iraola, F. De Zan, D. Geudtner
Speckle Tracking and Interferometric Processing of TerraSAR-X TOPS Data for Mapping Nonstationary Scenarios
IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, online, early access.

Speckle Tracking with TOPS

- **Large azimuth offsets cause spectral decorrelation**

$$\Delta f_{shift} = \frac{K_a K_{rot}}{K_a - K_{rot}} \Delta_{az}/\mathrm{v_g}$$

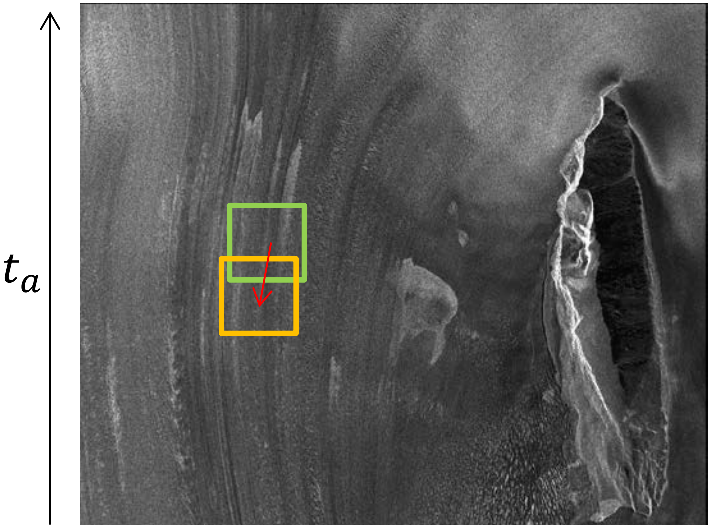
Δf_{shift}: Spectral shift

K_{rot}: Rotation rate (steering)

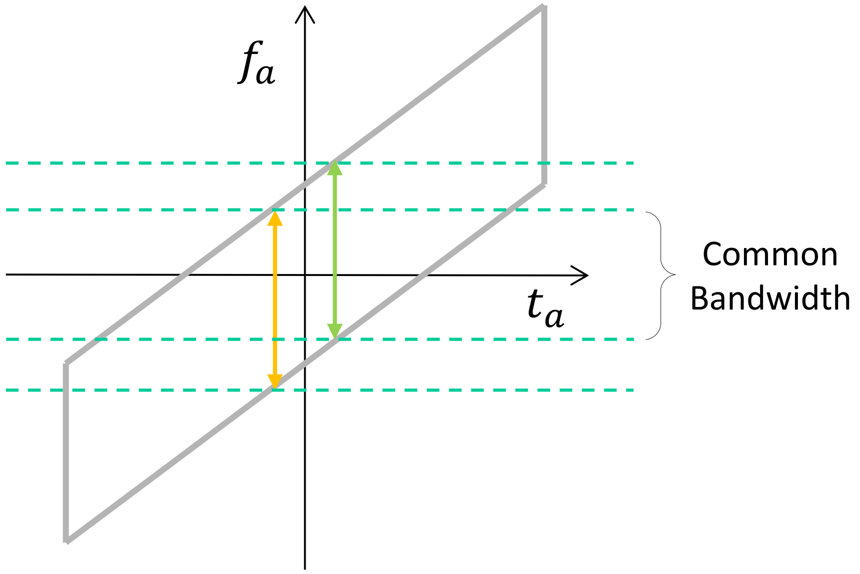
K_a: Target Doppler rate

$\mathrm{v_g}$: Ground Velocity

Δ_{az}: Azimuth displacement (metres)



🟩 : Master Patch 🟨 : Slave Patch

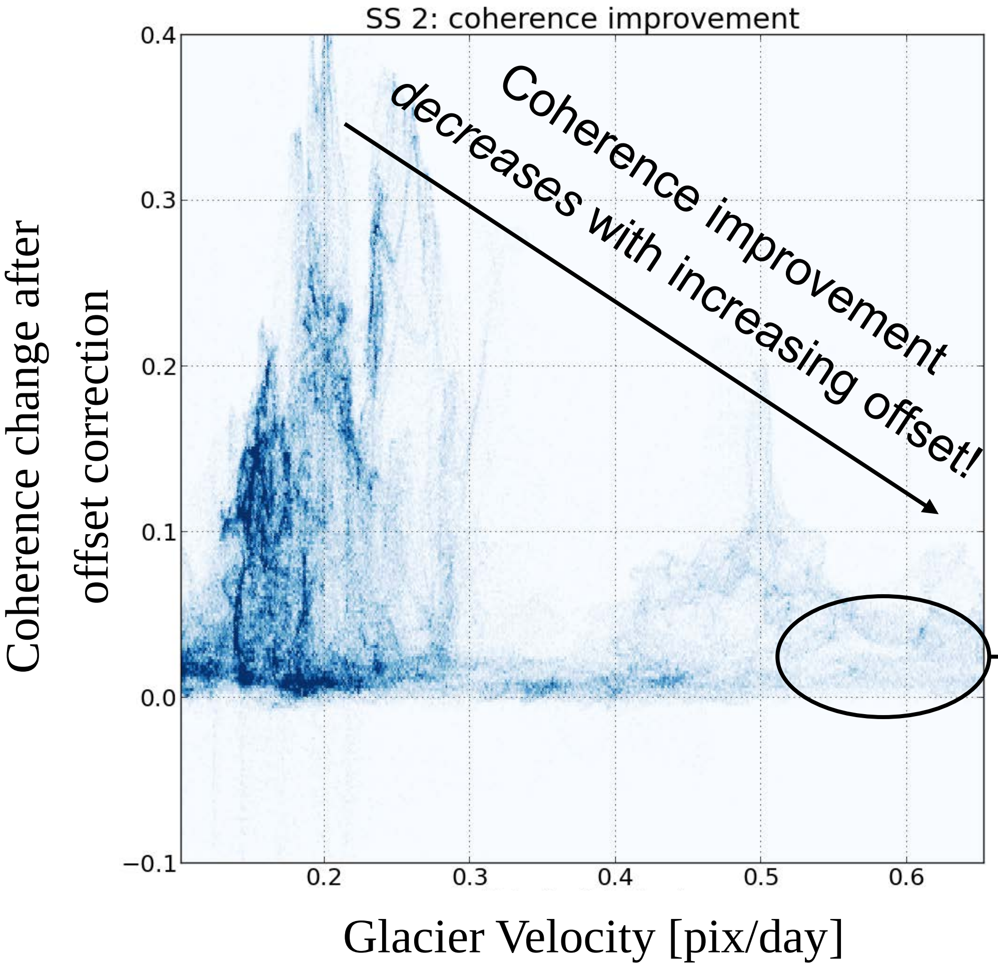


- Total decorrelation in Sentinel-1 for 1.3 km azimuth displacement (~100 az. samples).
- Three step processing: estimate + filter + re-estimate

Time-series Evaluation – Temporal decorrelation

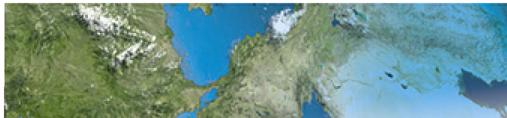
Analysis with TerraSAR-X Data

- Expectation: The larger the offset, the more coherence improves after coregistration. But…



Coherence improvement decreases with increasing offset!

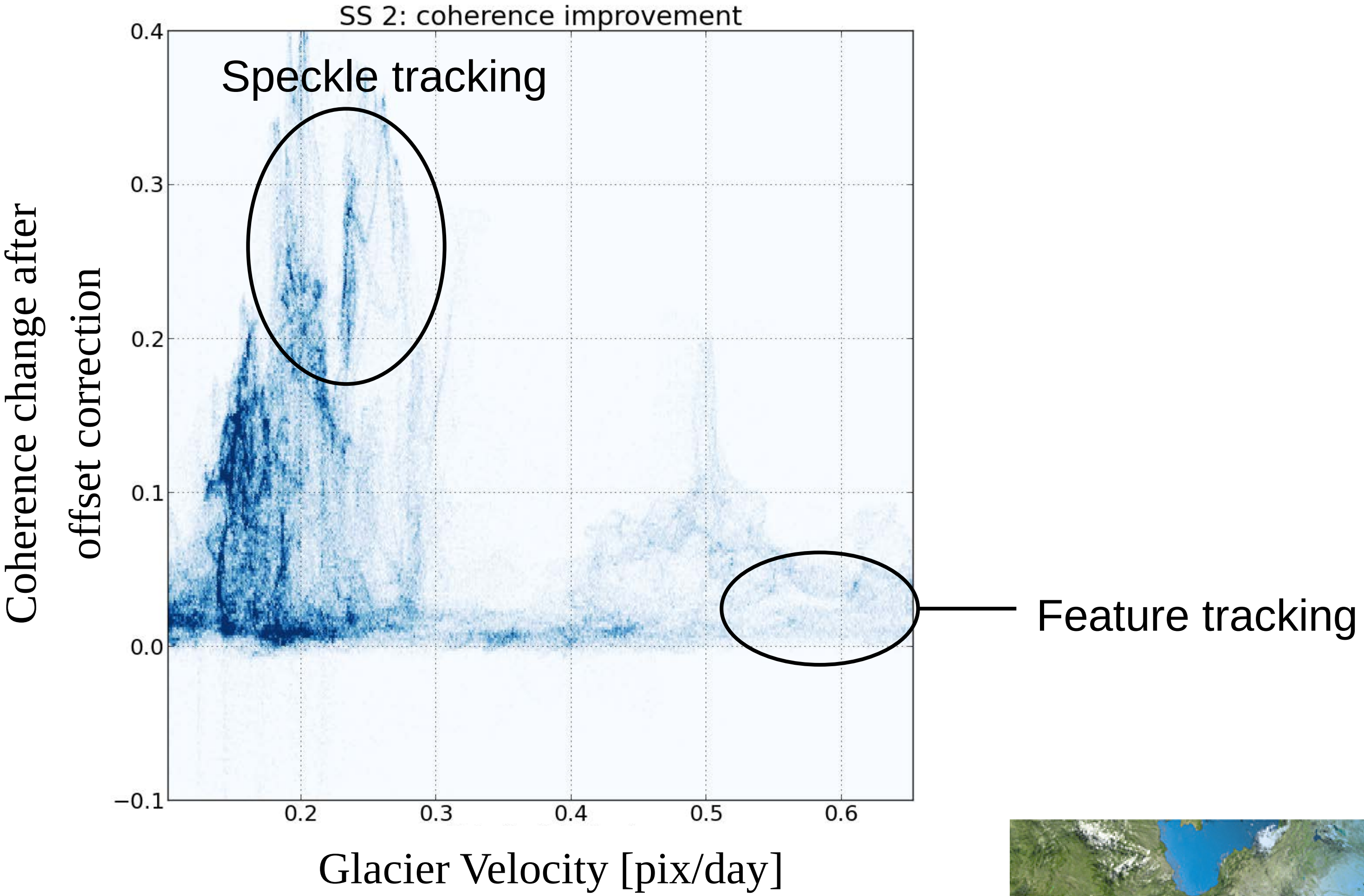
Spectral decorrelation likely due to large acceleration or rotation



Timeseries Evaluation – Temporal decorrelation

Analysis with TerraSAR-X Data

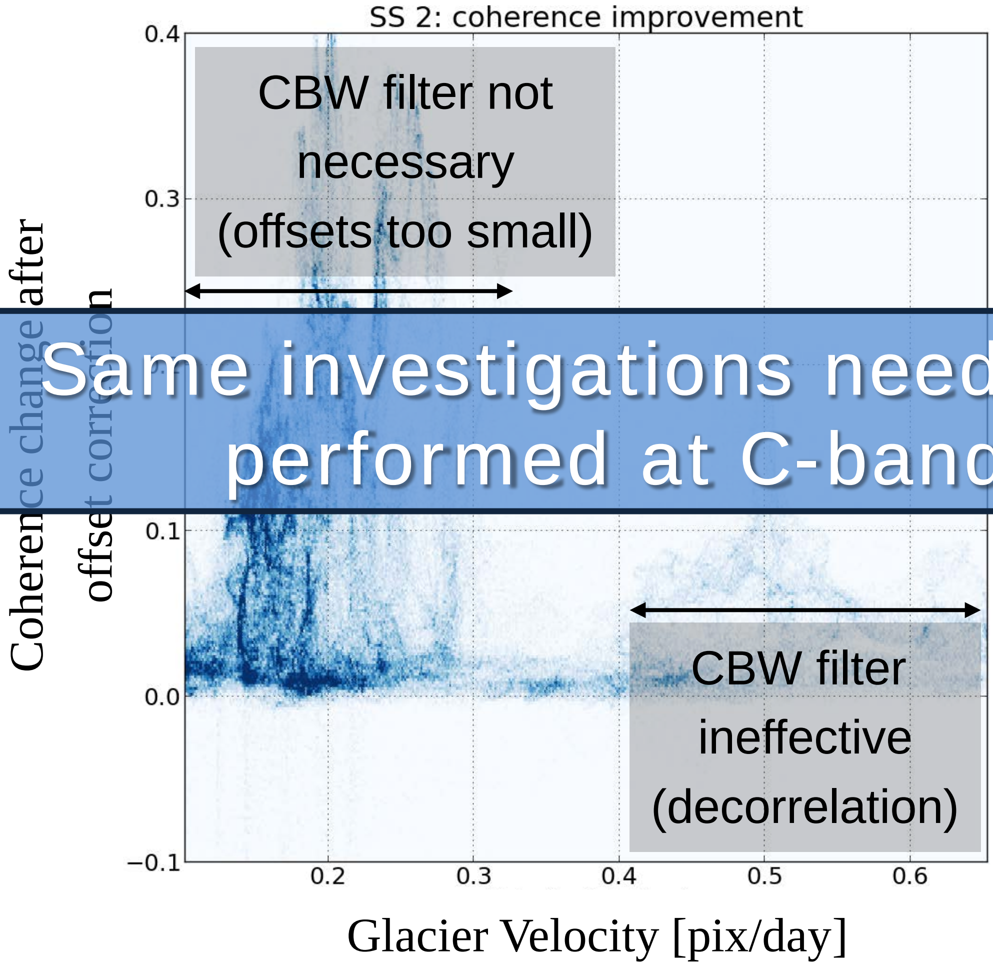
- Feature tracking occurs where the correction of large offsets yields little coherence improvement:



Timeseries Evaluation – Temporal decorrelation

Analysis with TerraSAR-X Data

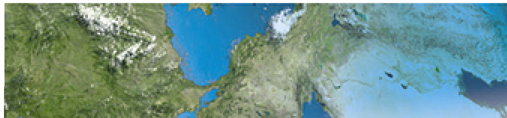
- Implications for the azimuth common bandwidth filter:



CBW filter not necessary (offsets too small)

CBW filter ineffective (decorrelation)

Same investigations need to be performed at C-band!



Role of the Orbital Tube

The Orbital Tube

- Sentinel-1 is controlled to follow an orbital tube of 50 m radius.
- The size of the tube can have a critical role in terms of **azimuth spectral decorrelation** and **azimuth coregistration accuracy** for the TOPS mode.
- The baseline components can be described using the **Clohessy-Wiltshire** equations:

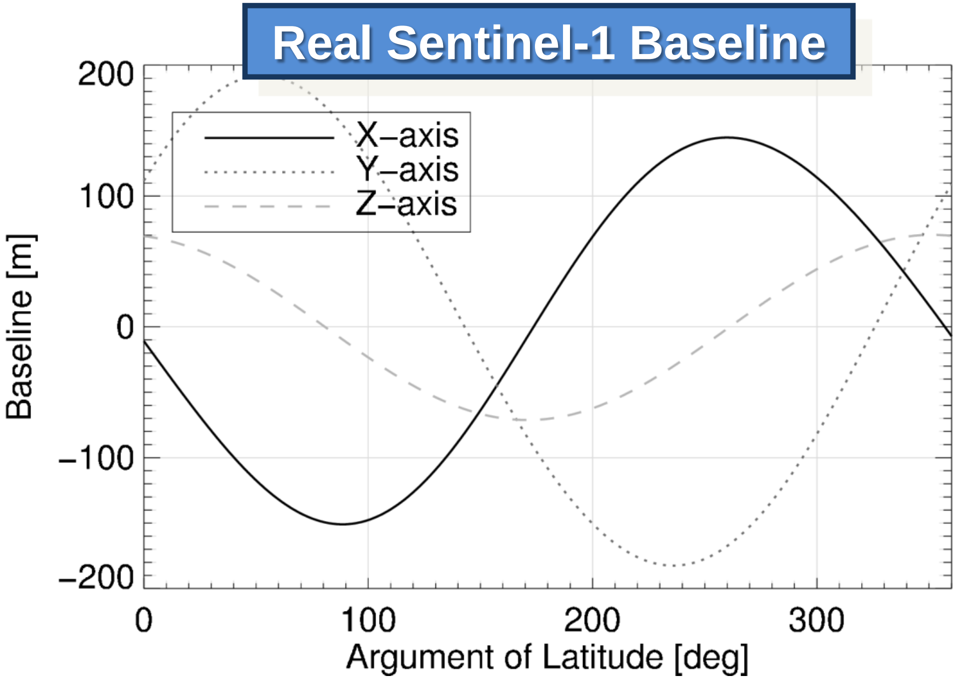
$$\Delta x(t) = \Delta x_0 + 2 \cdot \boxed{A} \cdot \sin(\phi_{lat} + \alpha)\,,$$

$$\Delta y(t) = -\boxed{B} \cdot \cos(\phi_{lat})\ \ ,$$

$$\Delta z(t) = -\boxed{A} \cdot \cos(\phi_{lat} + \alpha)$$

Depends on difference between orbit eccentricities

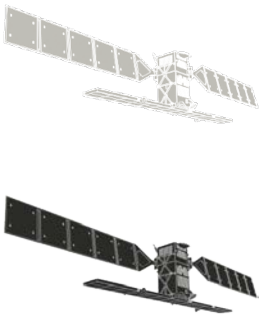
Depends on difference between inclination vectors



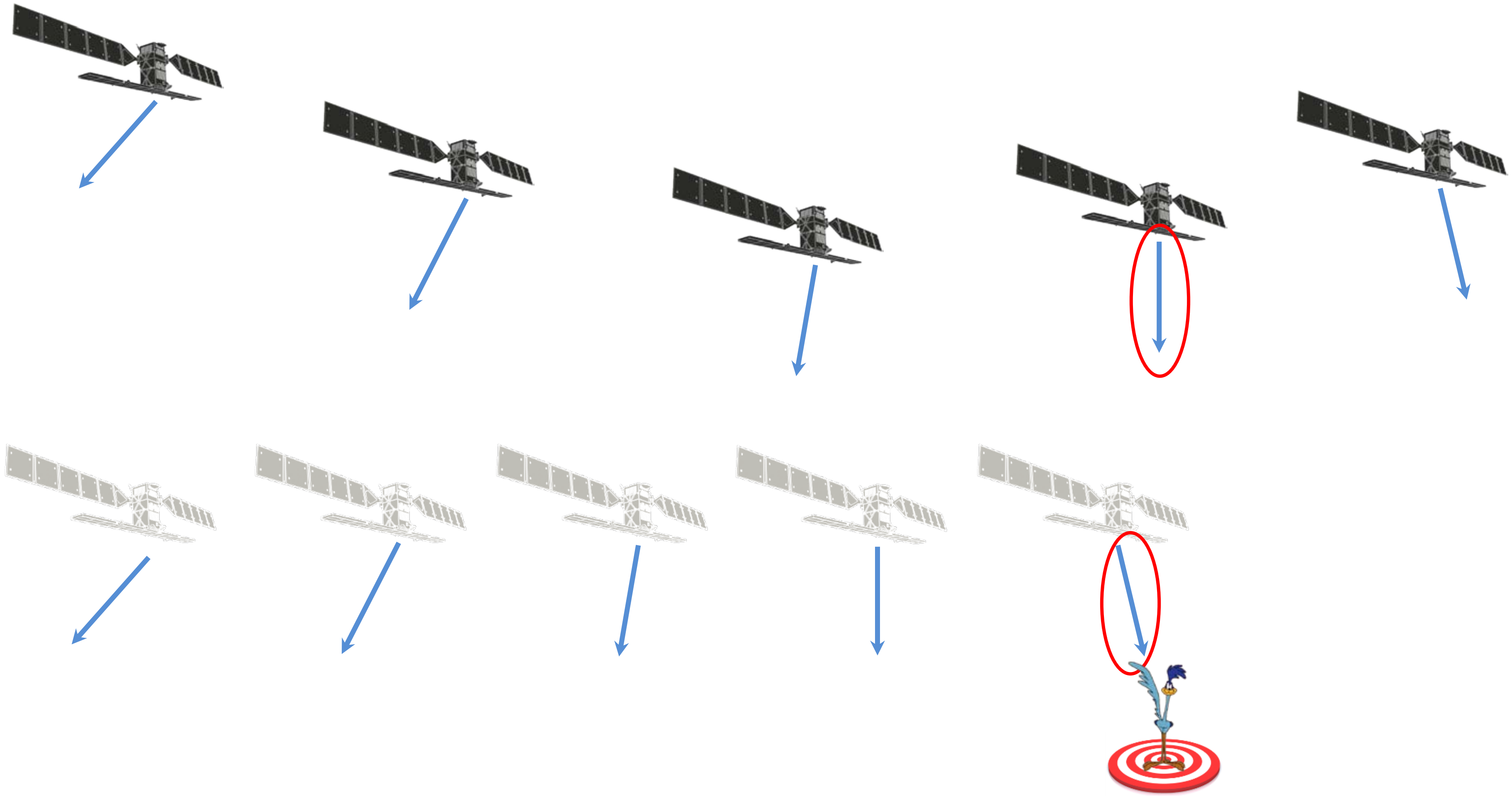
Real Sentinel-1 Baseline

Burst Synchronization for Long Data Takes

- Sentinel-1 can synchronize with very good accuracy at the beginning of the data take (2-3 ms std. dev.).
- However, this does not guarantee perfect synchronization during the data take. Sentinel-1 can potentially acquire **25 minutes** per orbit.
- The **along-track component** of the baseline introduces azimuth spectral decorrelation, as the targets are observed under a different squint angle due to **TOPS scanning pattern**.



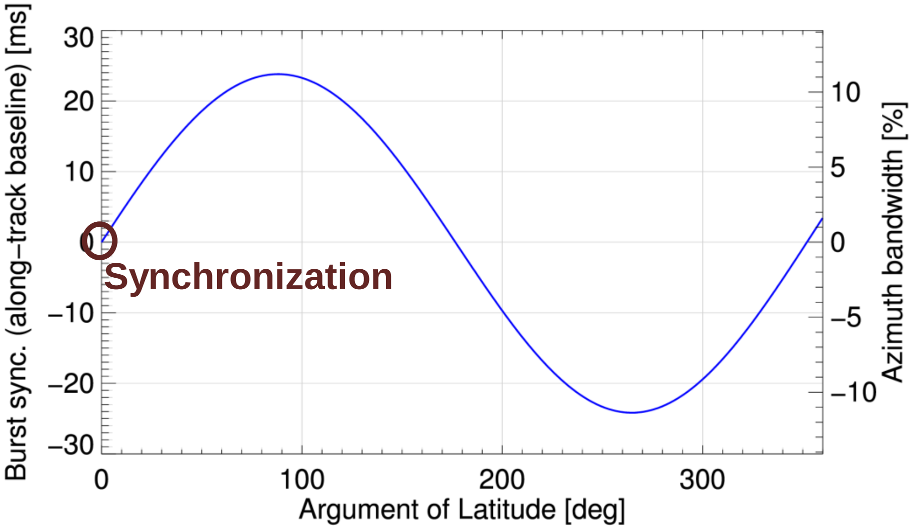
Burst Synchronization for Long Data Takes



Target observed under different Doppler centroids = Azimuth spectral decorrelation!

Burst Synchronization for Long Data Takes

- Numerical evaluation using Sentinel-1 real orbits:

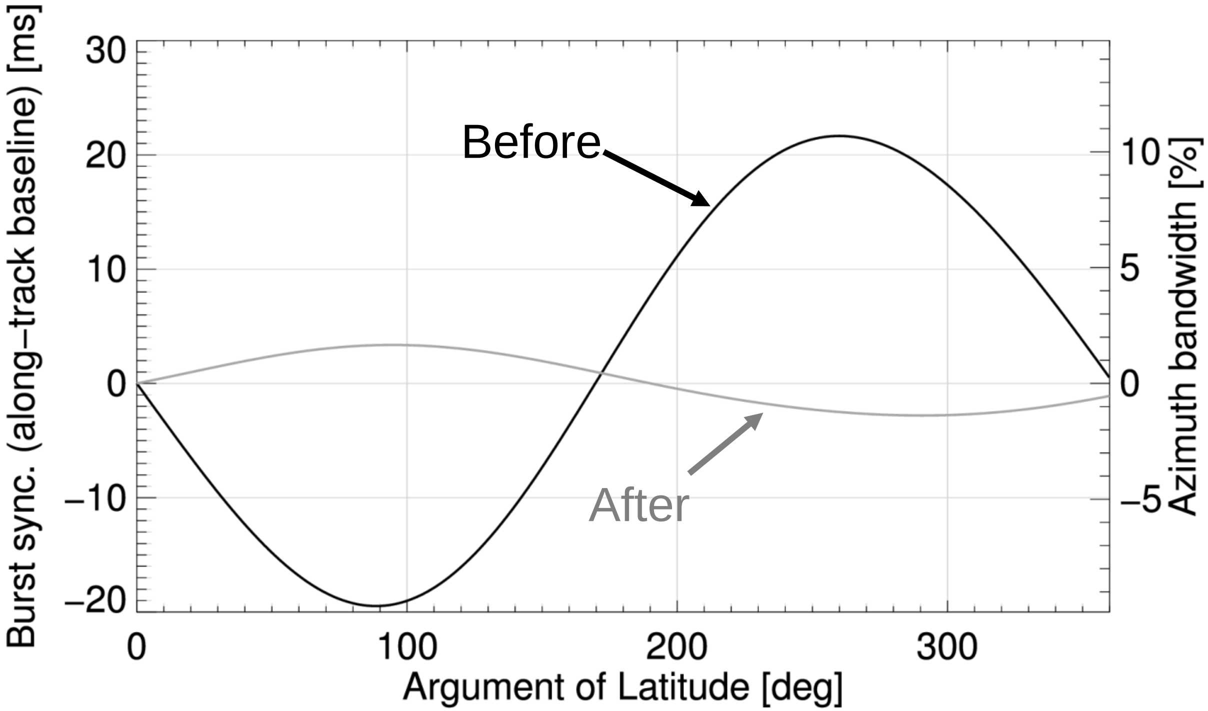


- Observations:
  - For a 25 minutes data take (a quarter of orbit), up to 30 ms mis-synchronization at the end of the data take $\Rightarrow$ 15 % azimuth bandwidth (30% worst case in stacks!)
  - Drift depends on latitude: (±0.4 ms/deg). Worst case at equator.

- Along-track component depends on radial tube dimension $\Rightarrow$ Radius of radial tube, A, depends on difference between orbit eccentricities $\Rightarrow$ Tighter orbit eccentricity control to mitigate effect (not necessariliy more maneuvers or fuel!)

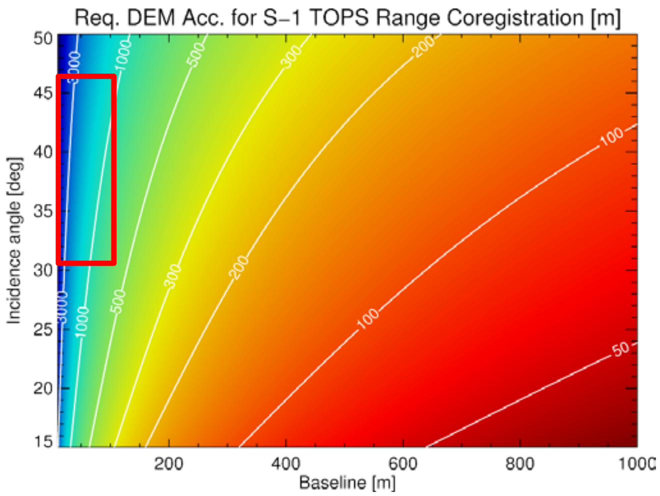
Burst Synchronization for Long Data Takes

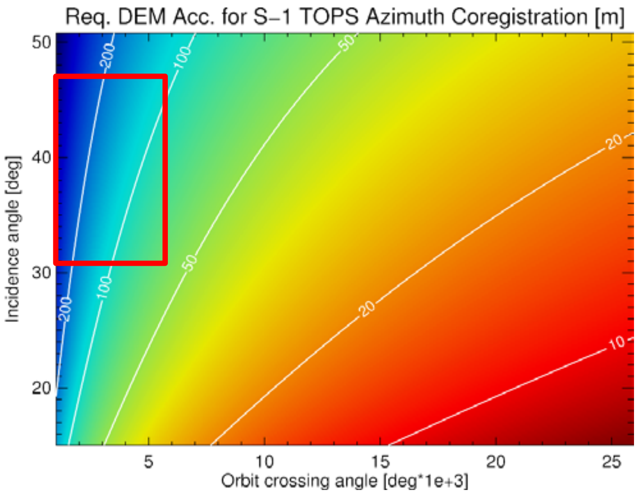
- Reduction of radial tube size implemented in Sentinel-1:



Crossing Angle – DEM Requirements for Coregistration

- Geometric coregistration: use the external DEM to compute the offsets between image pairs (nominal coregistration), rather than estimate them from the data.
- The non-parallel orbit increases the requirement in the DEM accuracy when it is used for coregistration*.





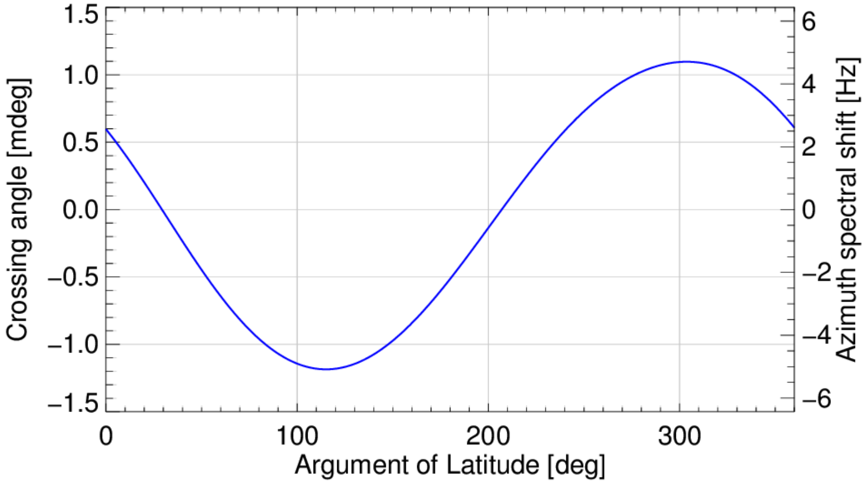
Range: Small orbital tube of S-1 (50m in diameter). No stringent requirement.

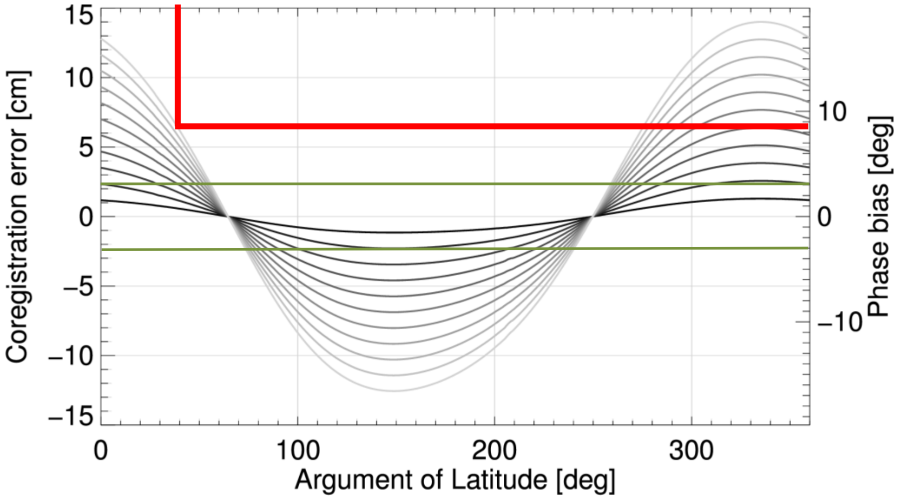
Azimuth: Small S-1 orbit crossing angles anticipated (0.001° worst case). SRTM/ASTER DEMs sufficiently accurate!

*E. Sansosti, P. Berardino, M. Manunta, F. Serafino, G. Fornaro, "Geometrical SAR Image Registration," *IEEE Trans. on Geosci. and Remote Sens., vol. 44, no. 10, Oct. 2006.*

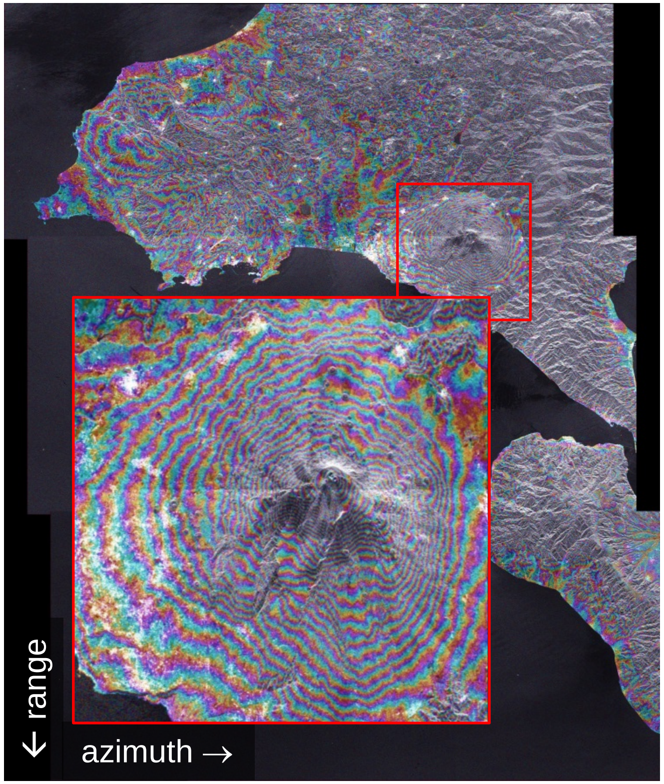
Crossing Angle – DEM Requirements for Coregistration

- Accurate computation of DEM requirement using Sentinel-1 orbits.
- The larger the variation in across-track (B variable in the Clohessy-Wiltshire equations), the larger the crossing angle will be.
- The plot on the right shows the azimuth coregistration error for different error heights (ranging from 300m to 3300 m) using real Sentinel-1 orbits.
- Errors in the DEM up to 600m produce less than 3º phase error. DEM requirement proportional to cross-track dimension of tube.





Case Example: Mount Etna Example

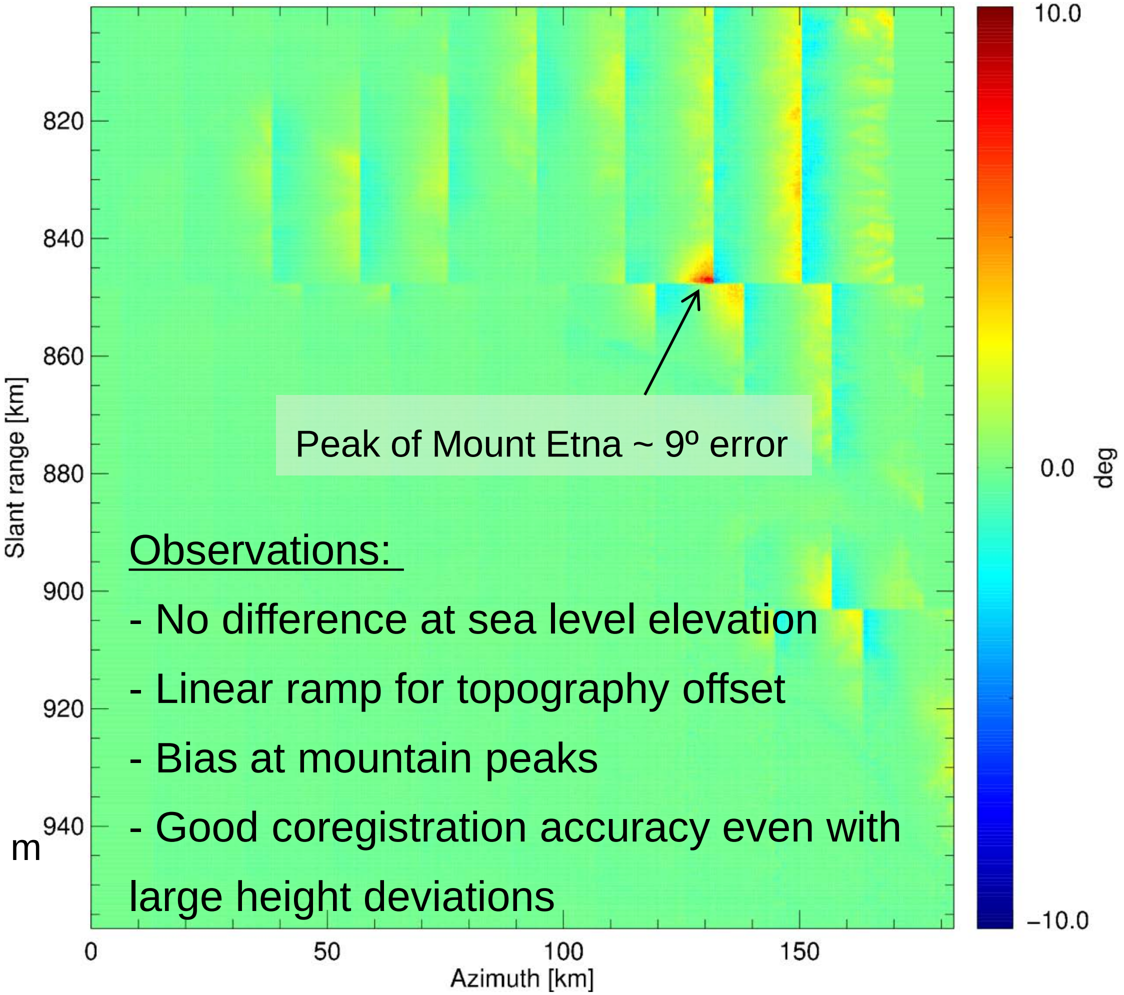


Orbit crossing angle: ~0.3 mdeg

Bperp (per Sub-swath): 140.5 / 129.4 / 118.2 m

Burst mis-sync: 3ms

Difference of Slaves co-registered with and without DEM (reference = 0m)



Peak of Mount Etna ~ 9º error

Observations:

- No difference at sea level elevation
- Linear ramp for topography offset
- Bias at mountain peaks
- Good coregistration accuracy even with large height deviations