Tomographic calibration and processing for Repeat-pass Bistatic Airborne SAR: A case study on New ESA TomoSense L-band Data

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Outline

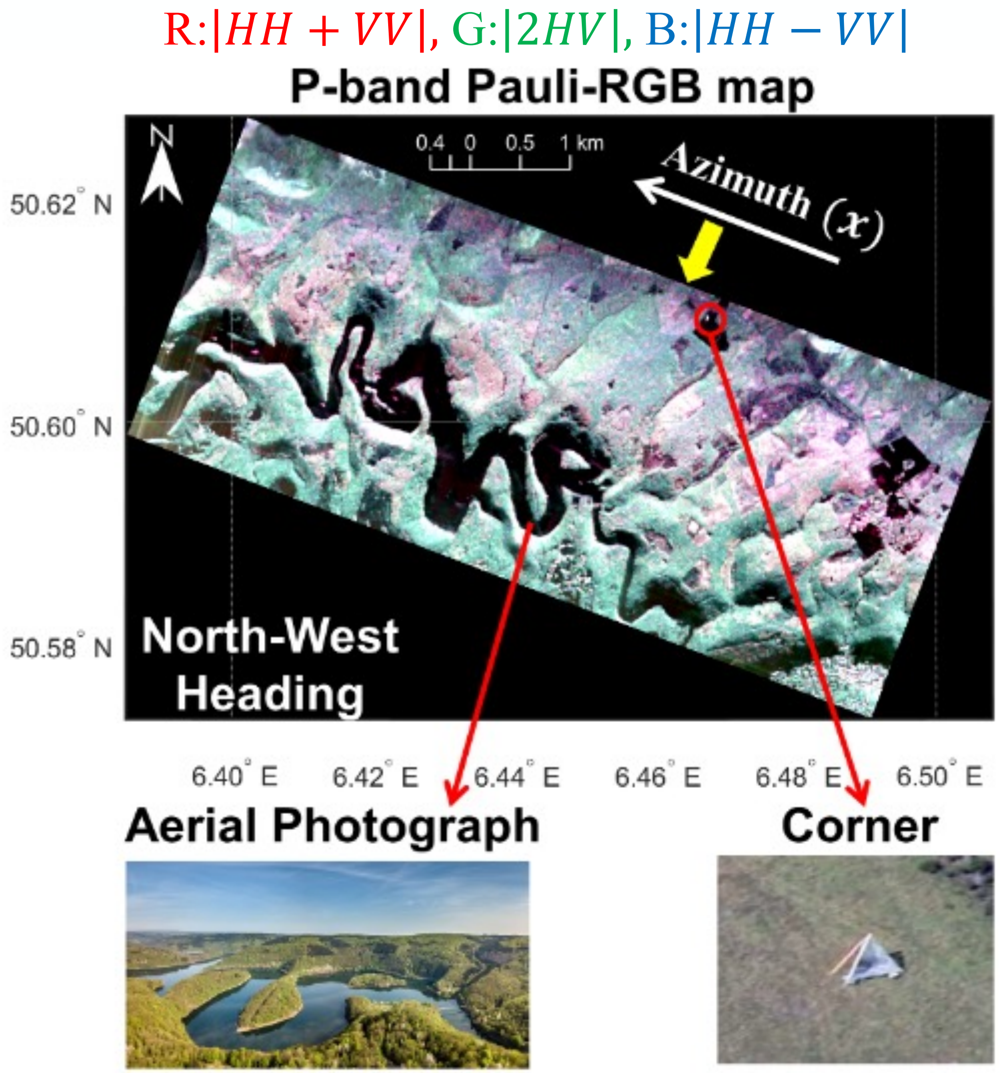
- Brief introduction to ESA TomoSense Campaign
- Challenges for SAR tomography on L band data
- Tomographic calibration and processing
- Conclusion

ESA TomoSense Campaign

esa

- A new 3D remote sensing dataset featuring a temperate forest (Kermeter forest) in Germany[1]:

  - P band monostatic SAR data (BIOMASS);
  - L band mono- and bi-static SAR data (Rose-L) ;
  - C band mono- and bi-static SAR data (Harmony);
  - Terrestrial, UAV-based, Airborne LiDAR measurements;
  - In-situ forest census (AGB、DBH…)



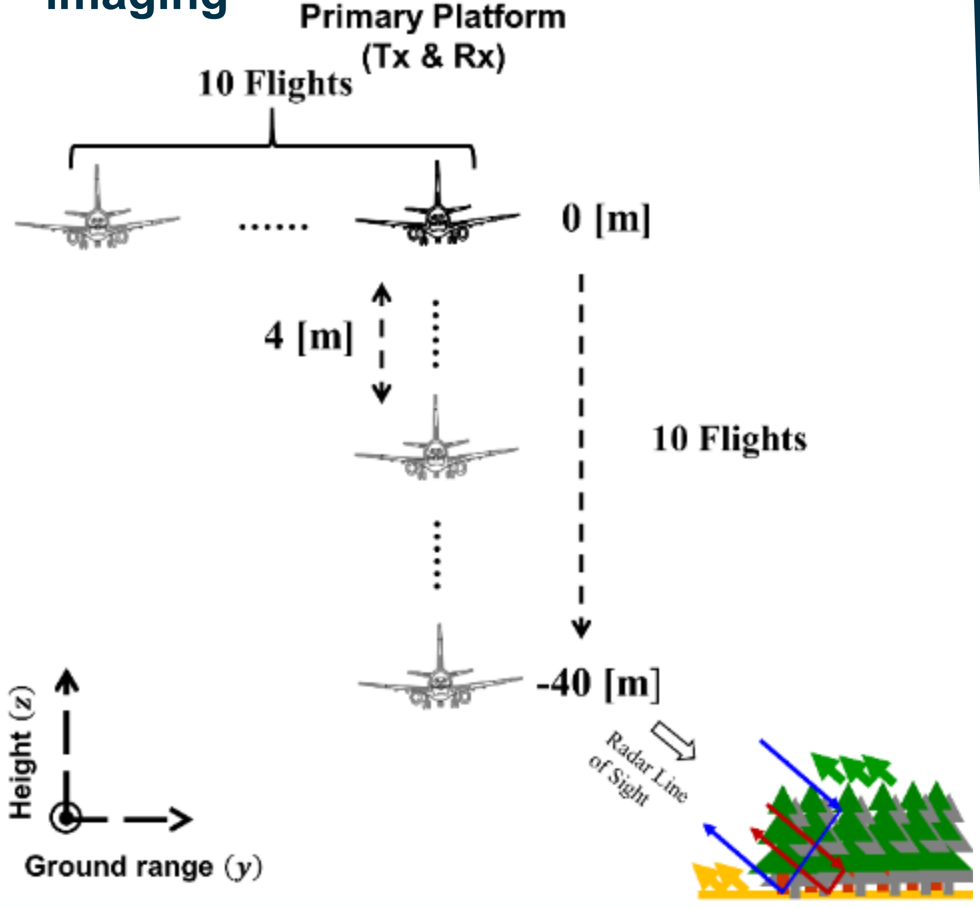
For more details, please go to:

[1] Tebaldini, S., d'Alessandro, M. M., Ulander, L. M., Bennet, P., Gustavsson, A., Coccia, A., ... & Scipal, K. (2023). TomoSense: A unique 3D dataset over temperate forest combining multi-frequency mono-and bi-static tomographic SAR with terrestrial, UAV and airborne lidar, and in-situ forest census. *Remote Sensing of Environment*, *290*, 113532.

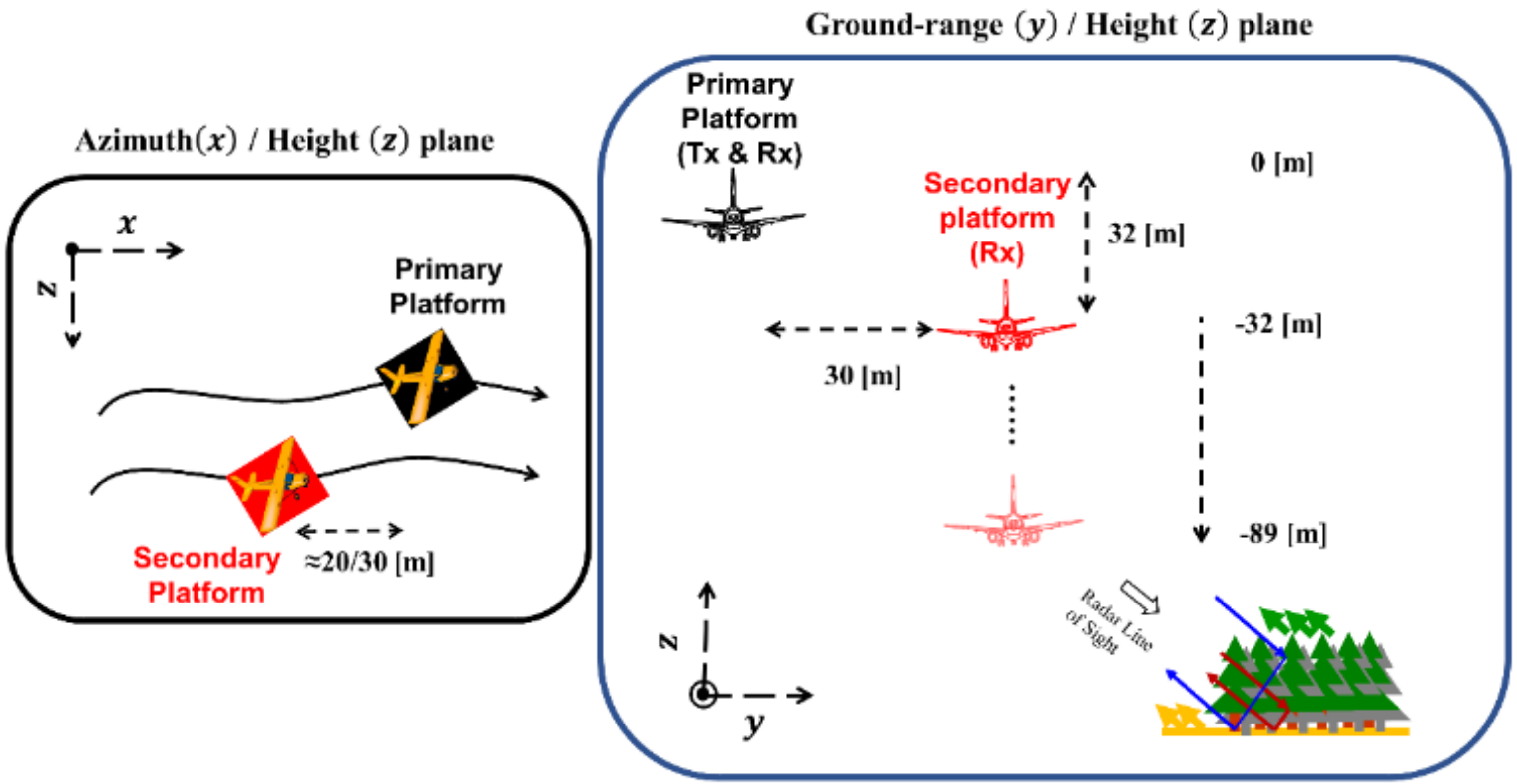
ESA TomoSense L band data

Acquisition Geometry

- Repeat-Pass acquisitions for TomoSAR imaging



- Single-pass bistatic configuration for each flight



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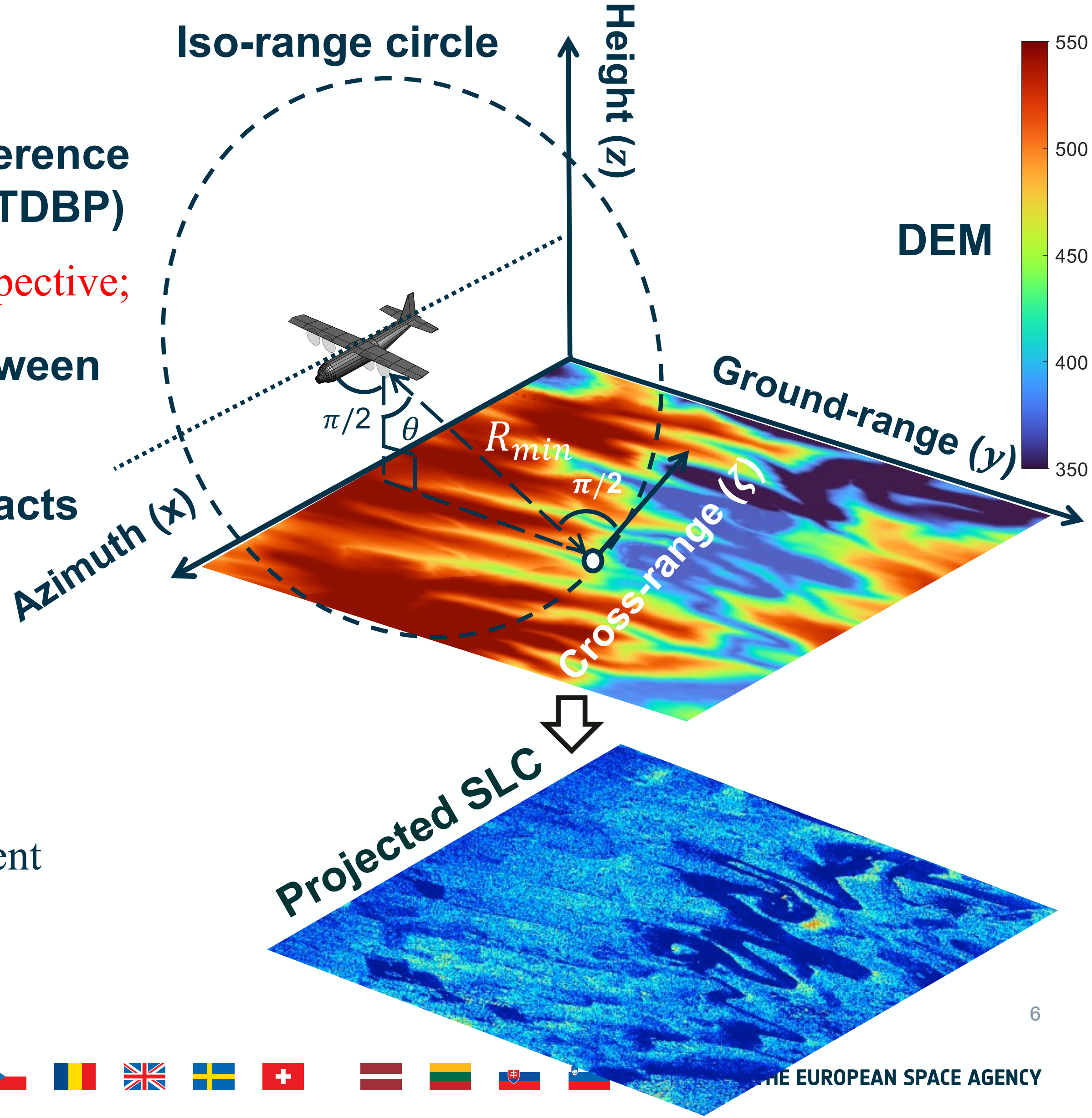
Challenges

☐ Starting Stage after pre-processing

- ➢ **Initially SLCs are generated by projecting onto a reference topography using 2D time-domain back-projection (TDBP)**
  - ✓ focusing and coregistration from a purely geometrical perspective;
- ➢ **No dedicated communication link was deployed between primary and secondary platforms.**
- ➢ **Unwanted phase disturbances and geometrical artifacts are mainly attributed to:**
  - ✓ Uncertainties in provided navigational data
  - ✓ A potential presence of clock drift errors
  - ✓ Even inaccurate topography information (height-dependent coregistration offsets, not a big problem here)

  …



Chanllenges

◻ Major Challenges

✓ **Residual positioning errors for dual platforms in provided navigational data:**

- Varying positioning errors along flight direction:

=> Locally spatially-varying imaging shifts;
=> Fast varying phase disturbances;

- Positioning errors along baseline direction:

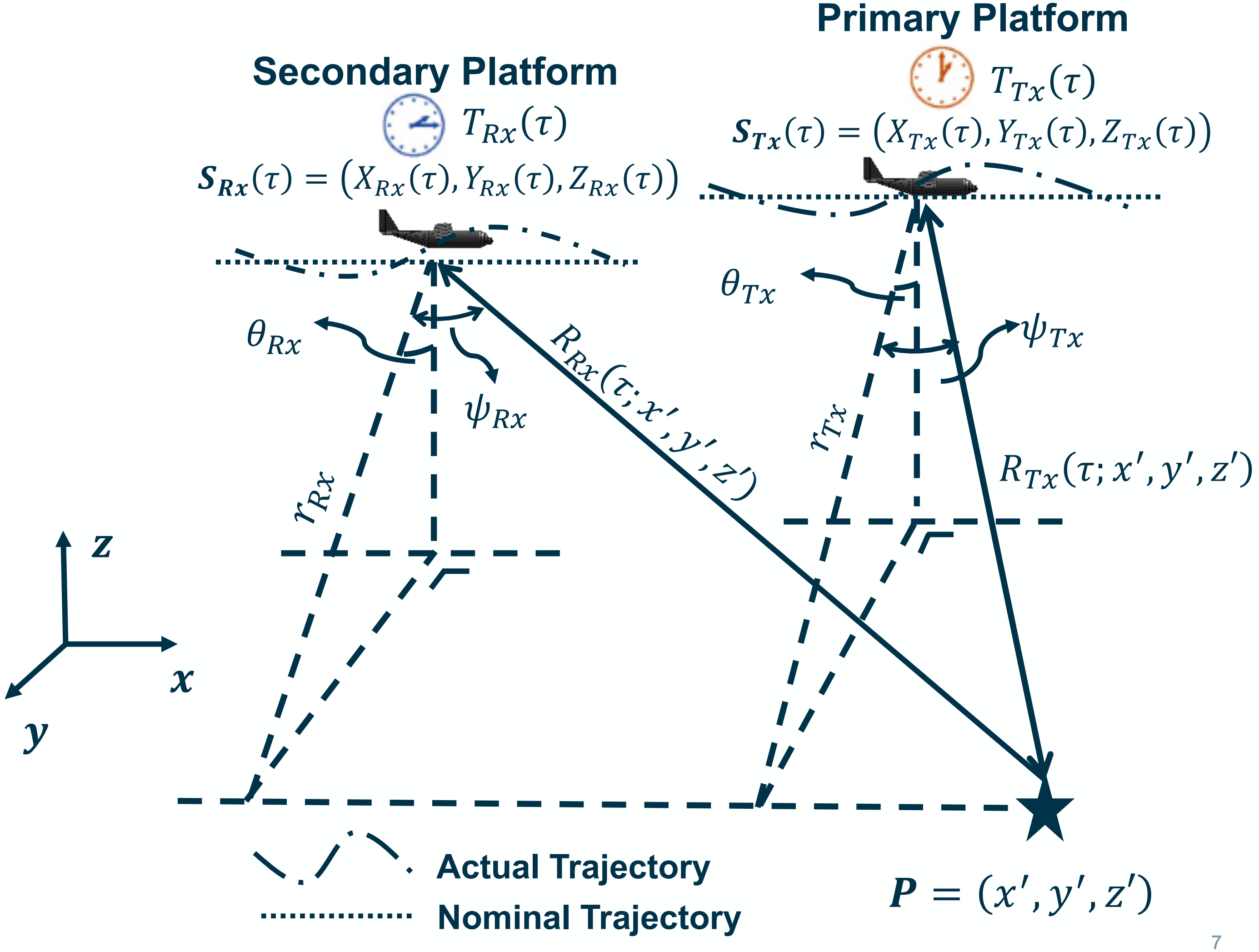
=> slowly-varying phase screen;
=> vertical imaging shifts;
=> tomographic imaging defocusing;

✓ **A potential presence of clock drift error:**

- Manifest as a varying function of flight time:

=> Additional phase modulation along flight direction;
=> Azimuthal imaging shifts in SLCs;

$$\delta_{cd}(\tau) = T_{Rx}(\tau) - T_{Tx}(\tau)$$



ESA TomoSense Campaign

- Given the performance of current navigational system and oscillator, only sub-pixel imaging shifts, and phase residuals arise:

  ☺ Proper 2D focusing.

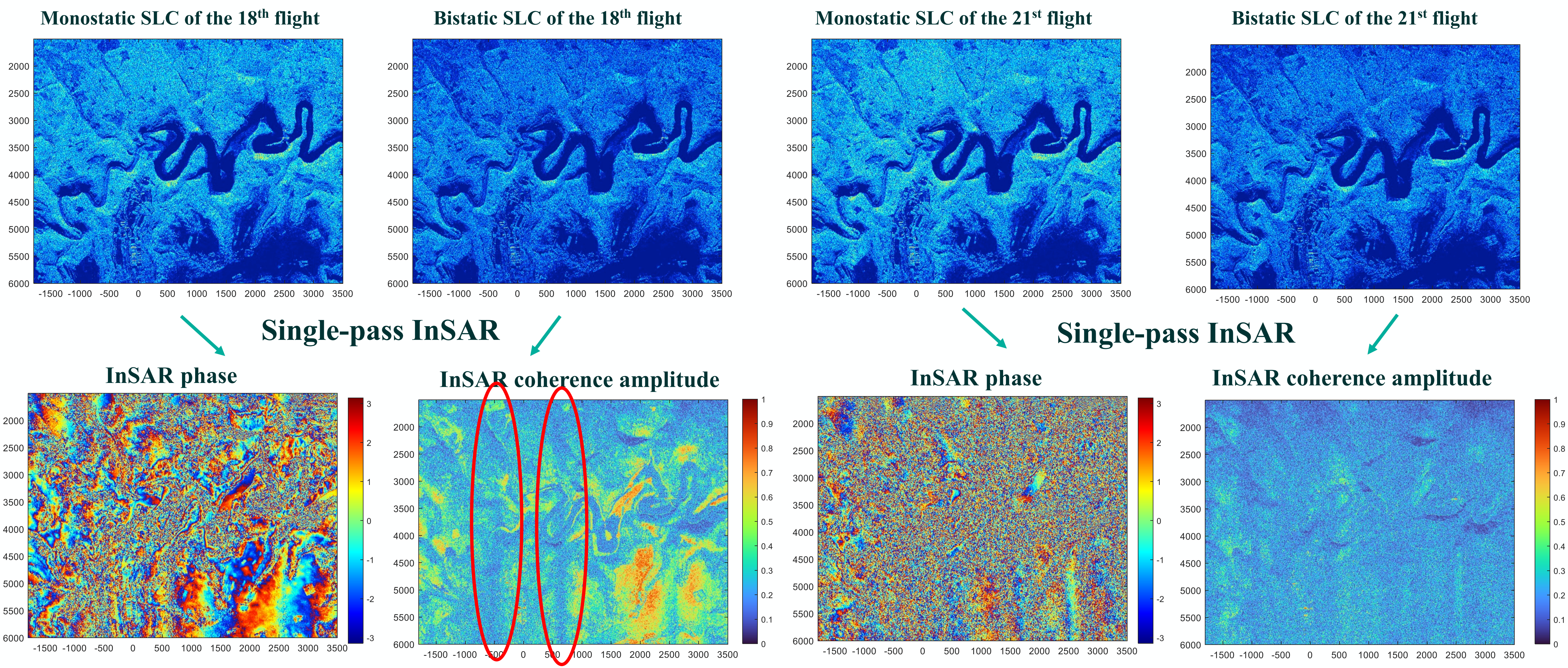
  ☹ Interferometric and tomographic performances.

- SAR interferometry is a relevant tool to sense and invert these errors, because
  - Highly sensitive to sub-pixel coregistration errors;
  - Demanding accurate phase information.

- Following content is going to exhibit:
  - Two InSAR examples to infer the presence of the errors;
  - An InSAR based calibration;

Used SAR data: TomoSense L-band SAR data in North-west heading

First InSAR example



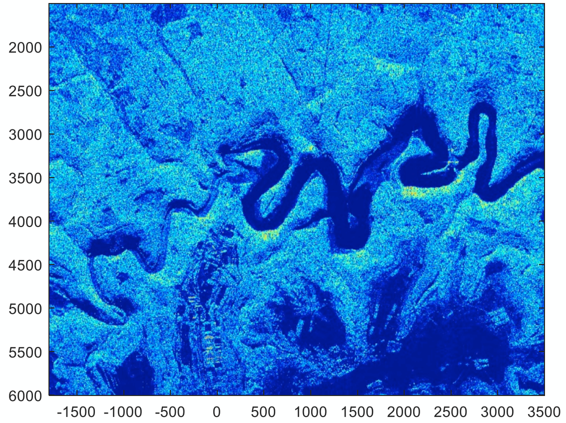
Partially coherent with!

Totally decorrelated!

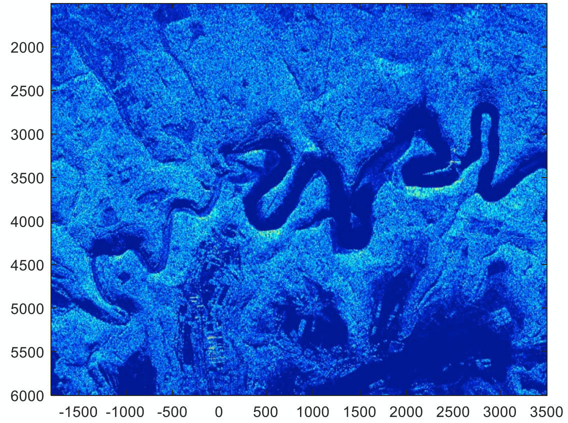
→ THE EUROPEAN SPACE AGENCY

First InSAR example

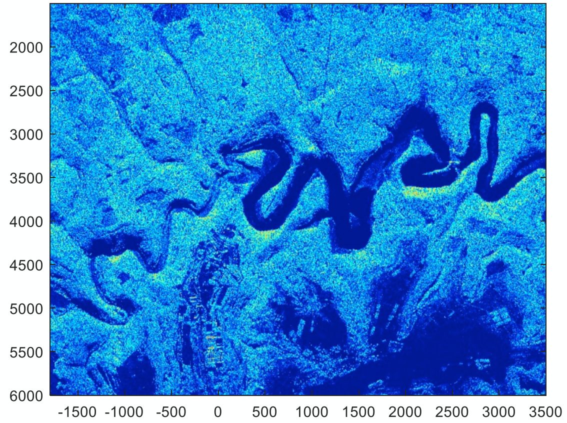
Monostatic Image of the 18th flight



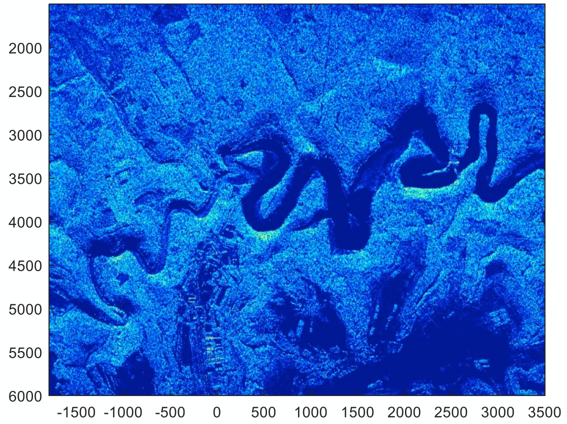
Bistatic Image of the 18th flight



Monostatic Image of the 21st flight

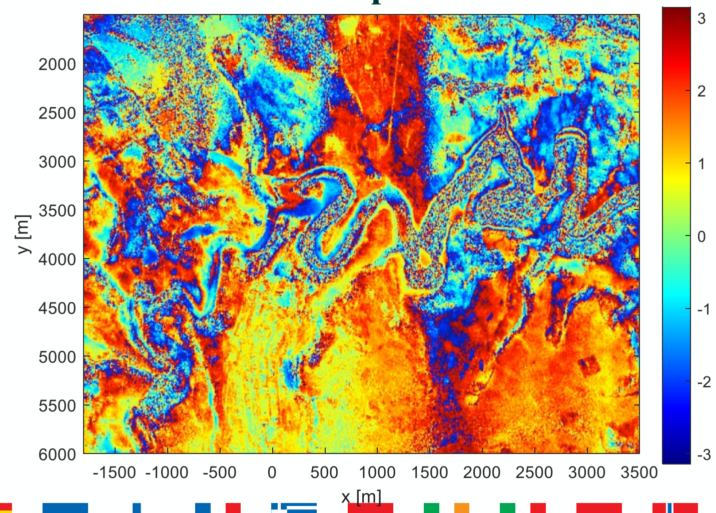


Bistatic Image of the 21st flight

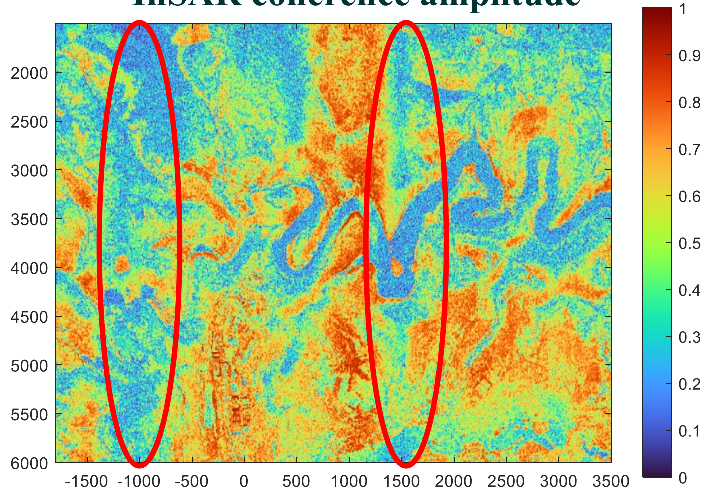


Repeat-pass InSAR for monostatic data

InSAR phase



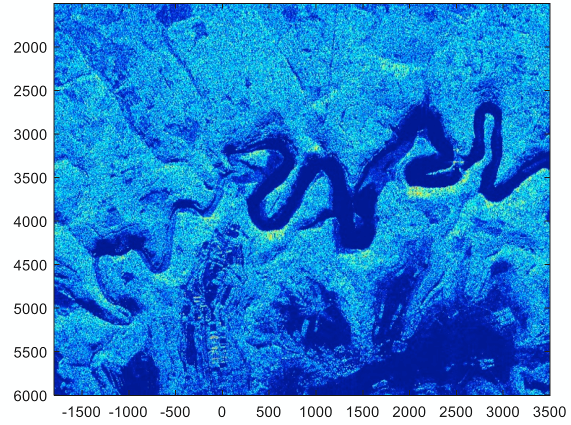
InSAR coherence amplitude



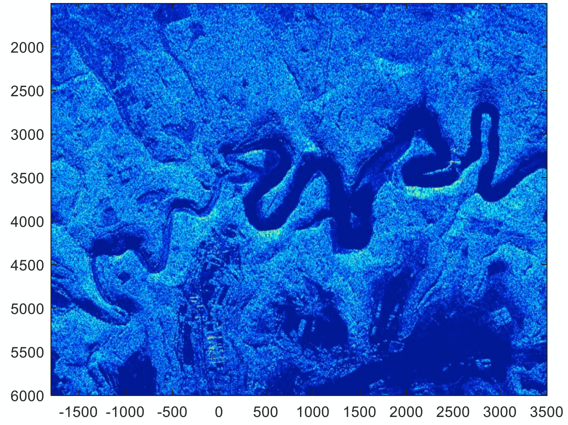
Highly coherent despite some local coherence fluctuation due to residual time-varying baseline errors!

First InSAR example

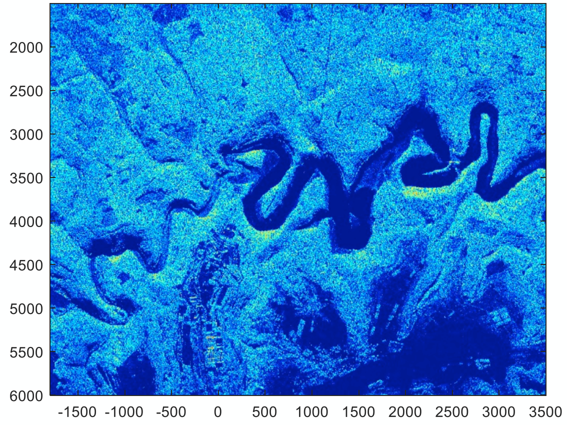
Monostatic Image of the 18th flight



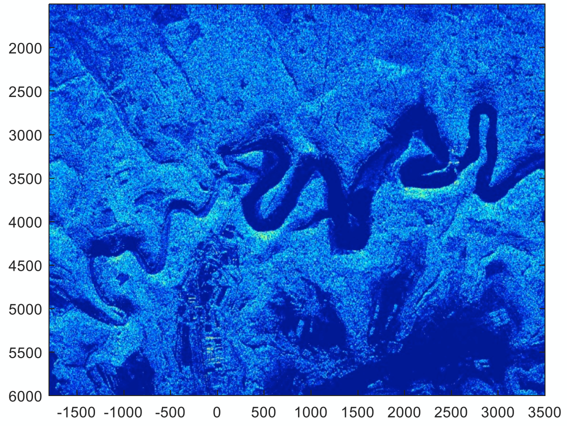
Bistatic Image of the 18th flight



Monostatic Image of the 21st flight

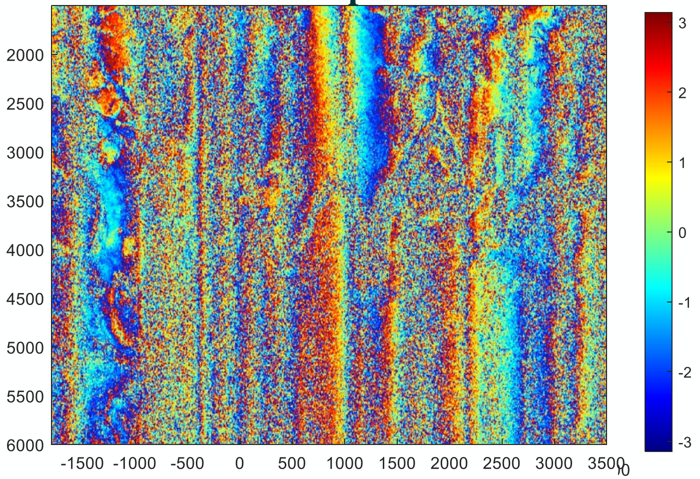


Bistatic Image of the 21st flight



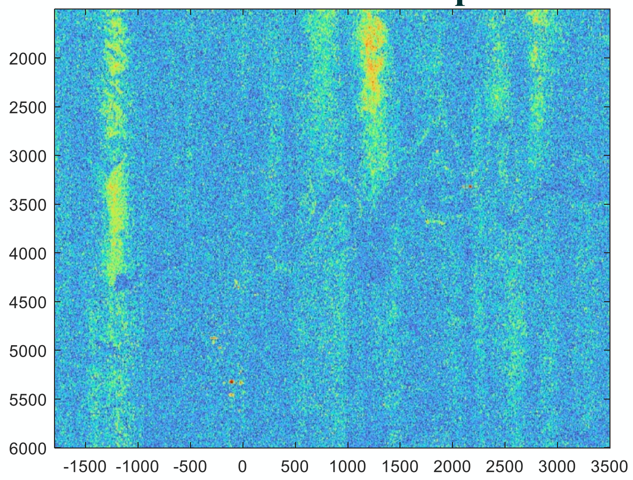
Repeat-pass InSAR for Bistatic data

InSAR phase



Fast phase modulation along flight direction!

InSAR coherence amplitude

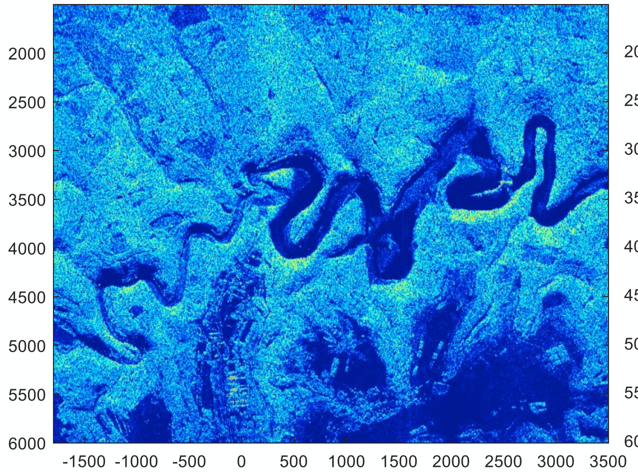


Totally Decorrelated!

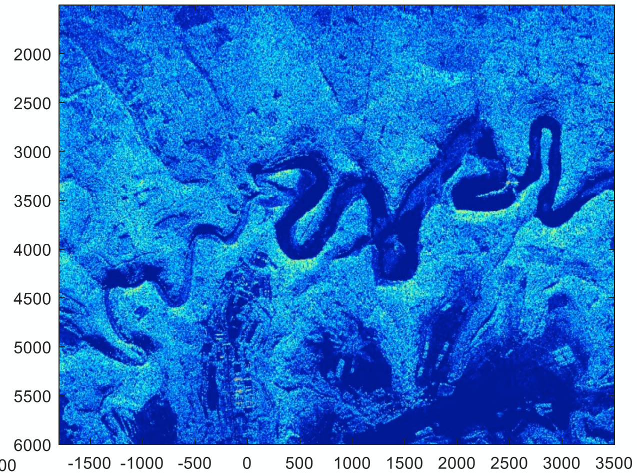
Besides the confirmed presence of baseline errors, clock-drift error is suspected to be involved.

Second InSAR example

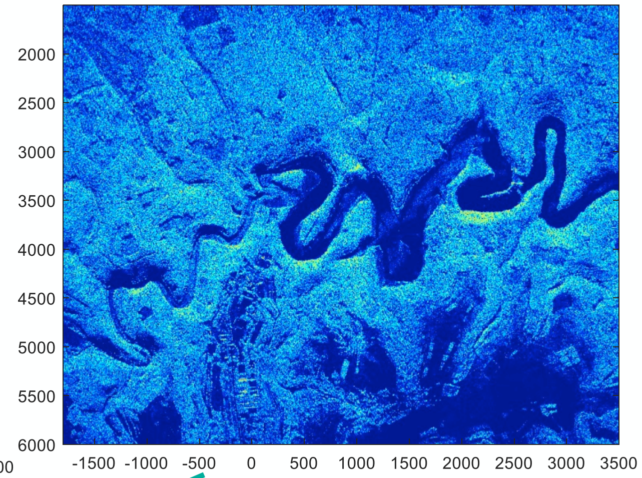
Monostatic SLC of the 3rd flight



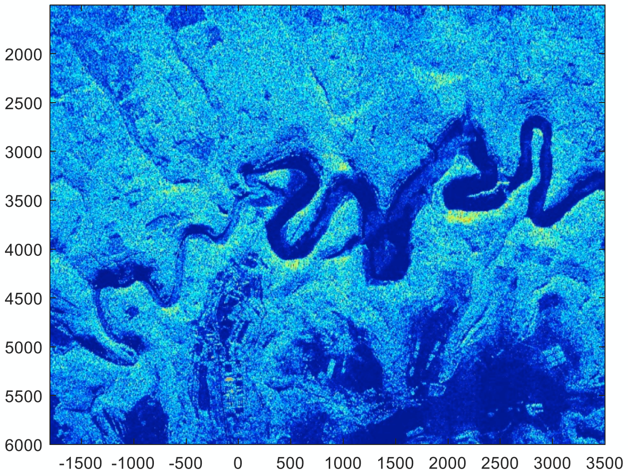
Bistatic SLC of the 3rd flight



Monostatic SLC of the 4th flight

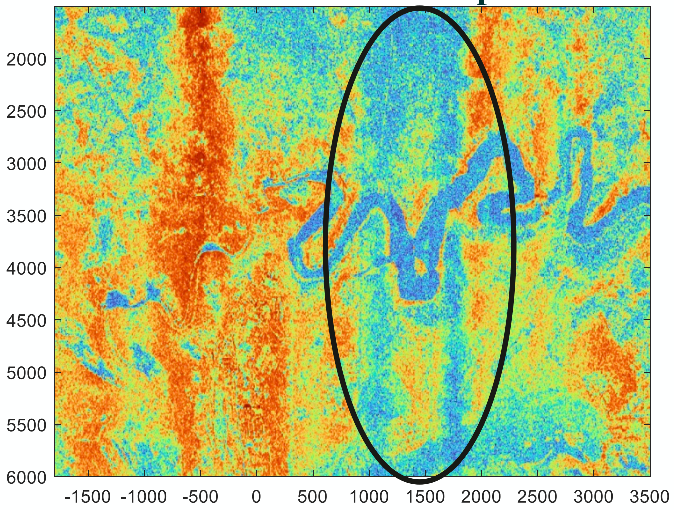


Bistatic Image of the 4th flight



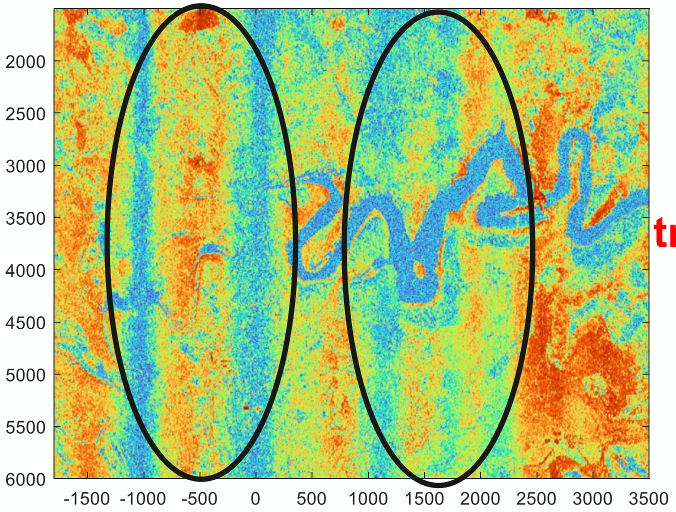
Repeat-pass InSAR for monostatic data

InSAR coherence amplitude



Repeat-pass InSAR for bistatic data

InSAR coherence amplitude



Subject to coupled trajectory errors from dual platforms!

Calibration and imaging

◆ A cascadedcalibration approach with following three steps:

➢ **Single-pass Multi-Squint InSAR for each mono- and bi-static InSAR pair**

- ✓ Capture the potential clock drift like term in each bistatic image;
- ✓ Inverse time-varying baseline errors between two platforms for each pass;
- ✓ Defocus and refocus each bistatic SLCs with clock drift like phase compensations terms and updated trajectories.

➢ **Multi-baseline multi-squint InSAR for both mono- and bi-static data stack**

- ✓ Inverse $(N-1)$ passes of time-varying trajectory errors for both platforms out of all coherent InSAR pairs;
- ✓ the objective is to achieve better coregistration of ensemble tomographic dataset in the presence of large spatial and temporal separations for InSAR pairs;
- ✓ Defocus and refocus the mono- and bi-static SLCs using corrected trajectories.

➢ **Bistatic version of Phase Center Double Localization (PCDL)[1]**

- ✓ Retrieve $(N-1)$ passes of positioning errors along baseline direction for both platforms out of all coherent InSAR pairs;
- ✓ Guarantee consistent phase centers for both mono- and bi-static imaging modes;

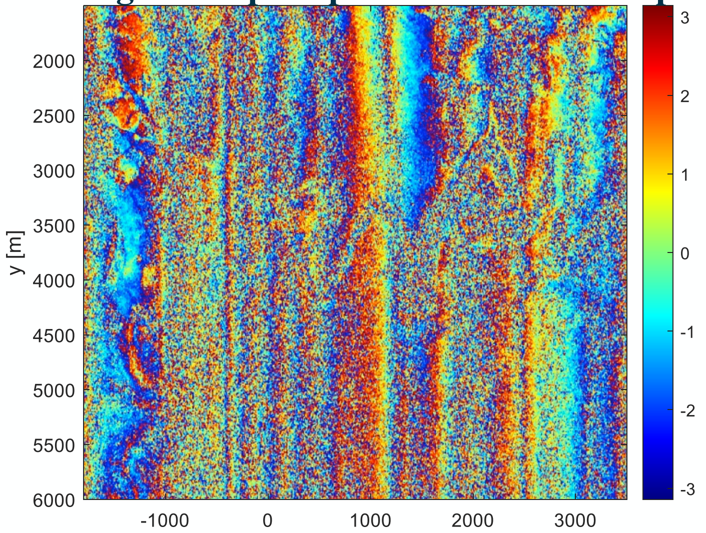
◆ Tomographic Imaging formation

➢ Defocusing the initial mono- and bi-static SLCs and directly project onto 3D space using corrected trajectories and phase compensation terms via 3D TDBP[2].

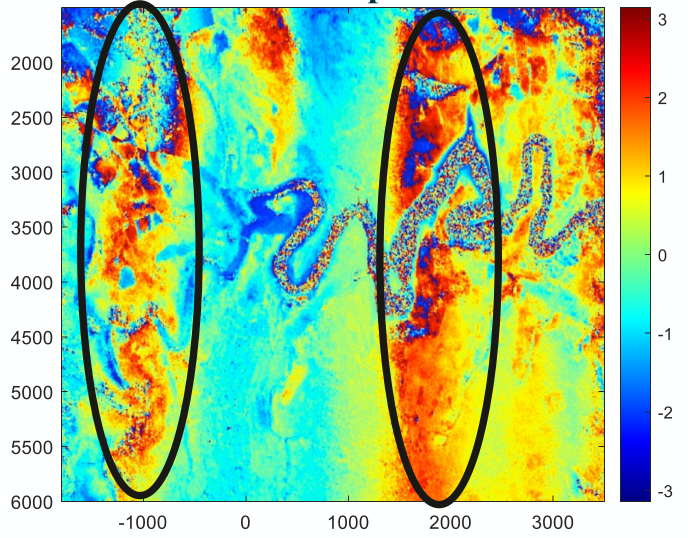
[1] Tebaldini, S., Rocca, F., d'Alessandro, M.M. and Ferro-Famil, L., 2015. Phase calibration of airborne tomographic SAR data via phase center double localization. IEEE Transactions on Geoscience and Remote Sensing, 54(3), pp.1775-1792.
[2] Yu, Y.; d'Alessandro, M.M.; Tebaldini, S.; Liao, M. Signal Processing Options for High Resolution SAR Tomography of Natural Scenarios. Remote Sens. 2020, 12, 1638.

Interferometric performance enhancement

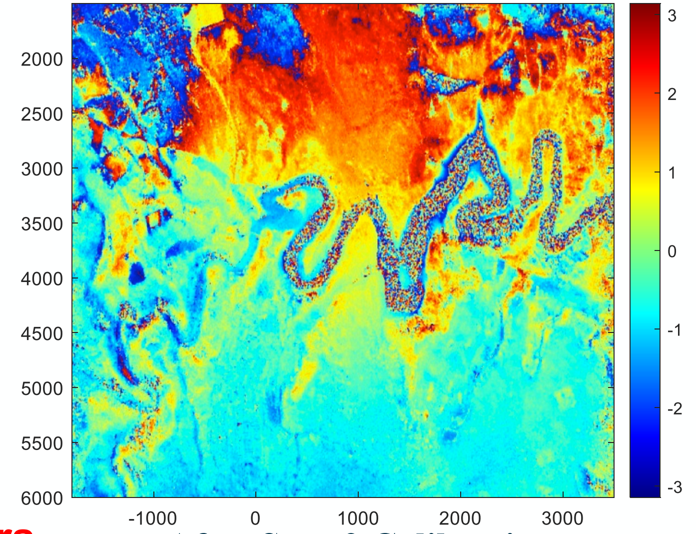
Original Repeat-pass Bistatic InSAR phase



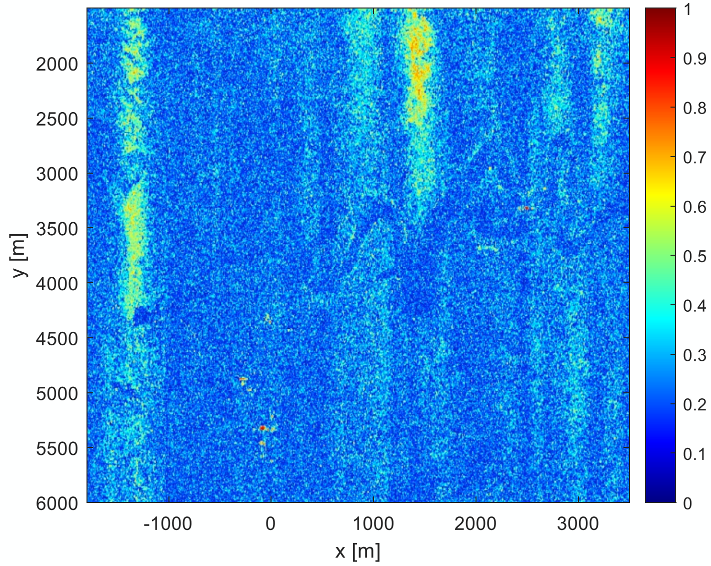
After Step-1 Calibration



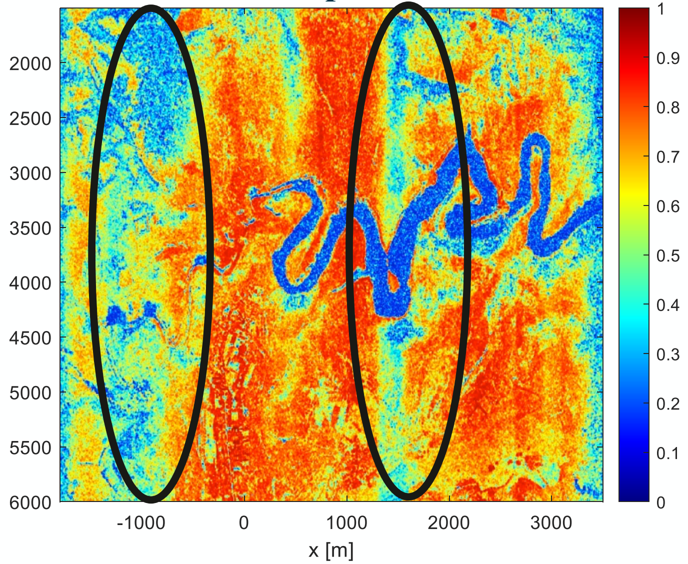
After Step-2 Calibration



Original Repeat-pass Bistatic InSAR coherence amplitude

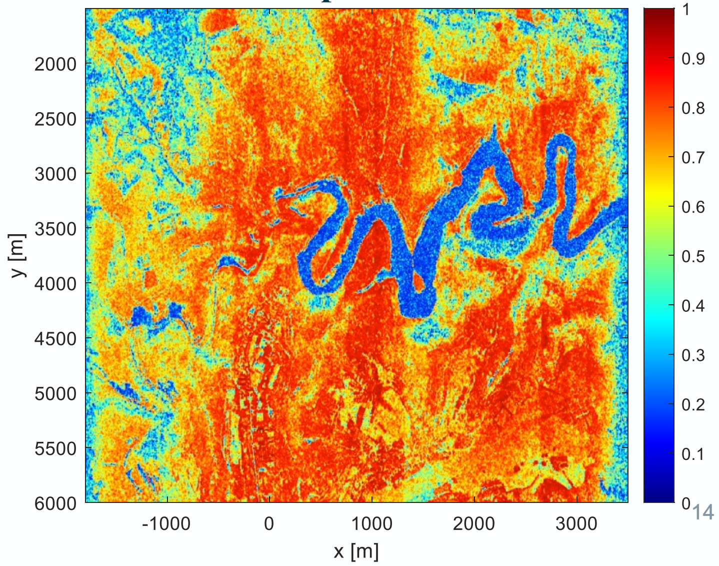


After Step-1 Calibration



Residual motion errors remain!

After Step-2 Calibration

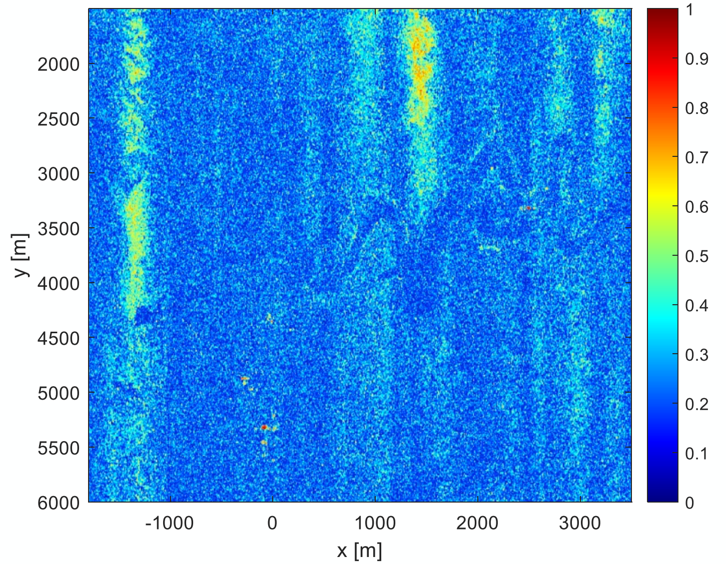


Interferometric performance enhancement

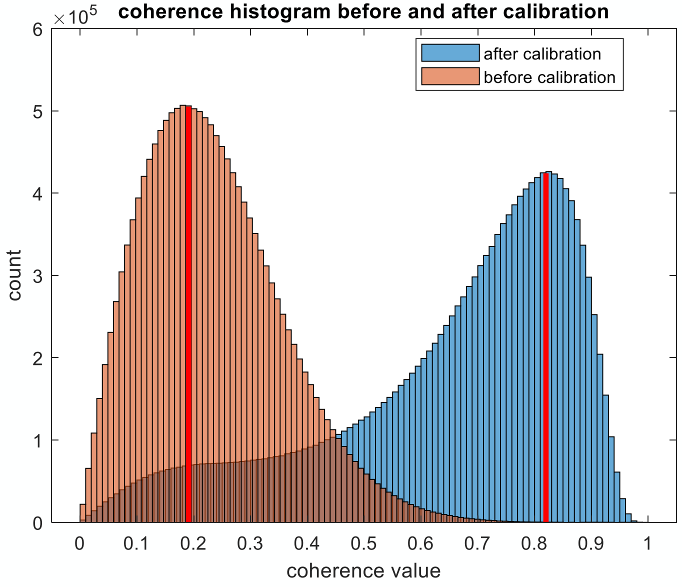
Coherence amplitude value:

mostly below 0.25 ⇨ mostly above 0.75

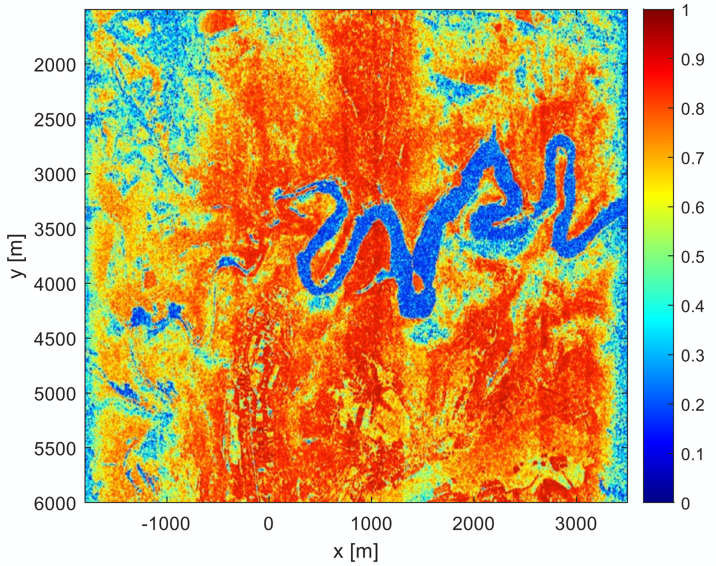
Original repeat-pass Bistatic InSAR coherence



Before calibration (orange) vs After calibration (blue)



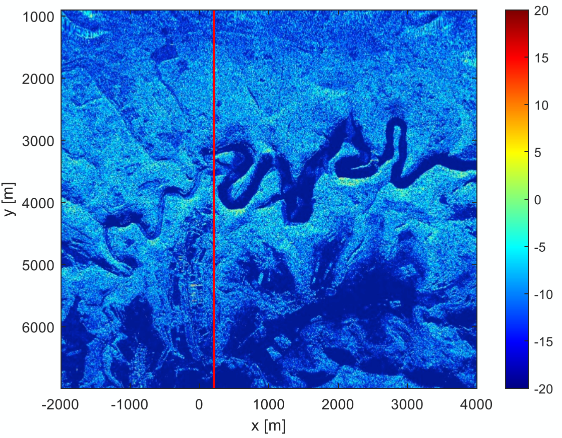
After Step-2 Calibration

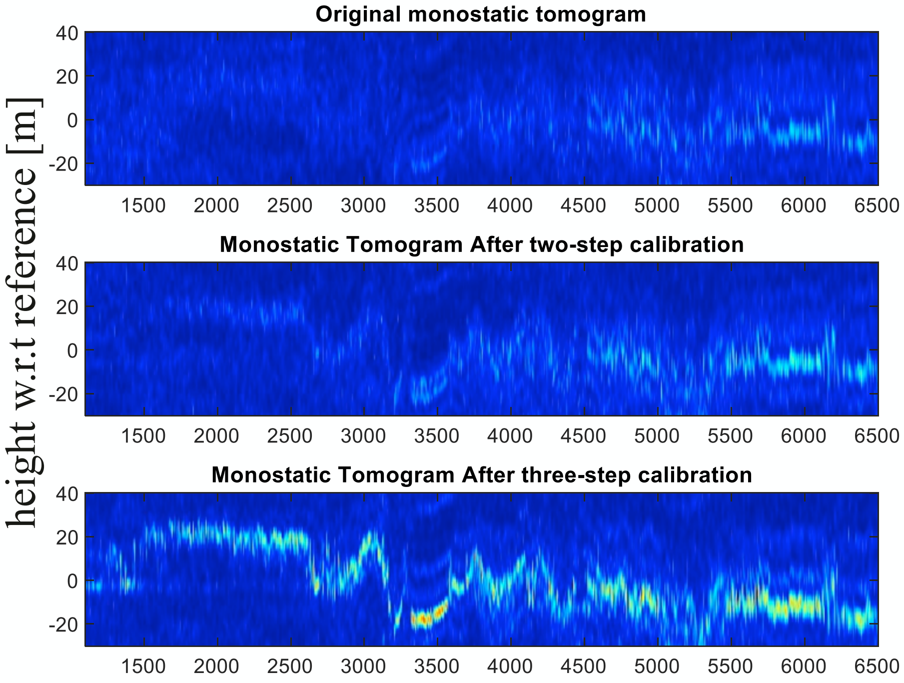


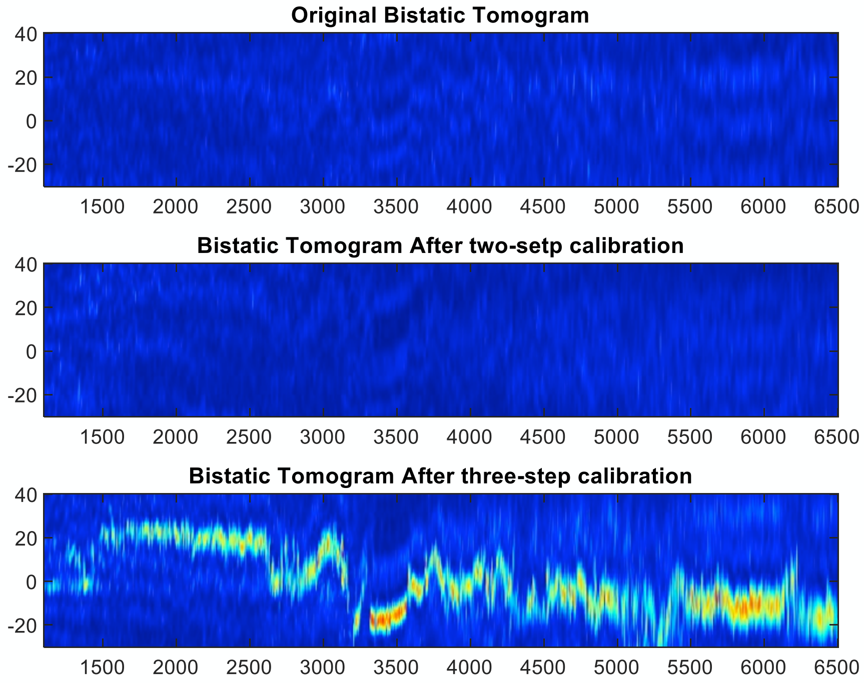
From totally decorrelated to fully correlated!

Tomographic performance enhancement

☐ Tomographic performance during calibration







- ➢ Tomographic imaging metric:

$$\gamma_{tomo,k}(x,y,z) = \frac{N^2 \cdot \left|\sum_{n=1}^{N} y_n^k(x,y,z)\right|^2}{\sum_{n=1}^{N} \left|y_n^k(x,y,z)\right|^2}$$

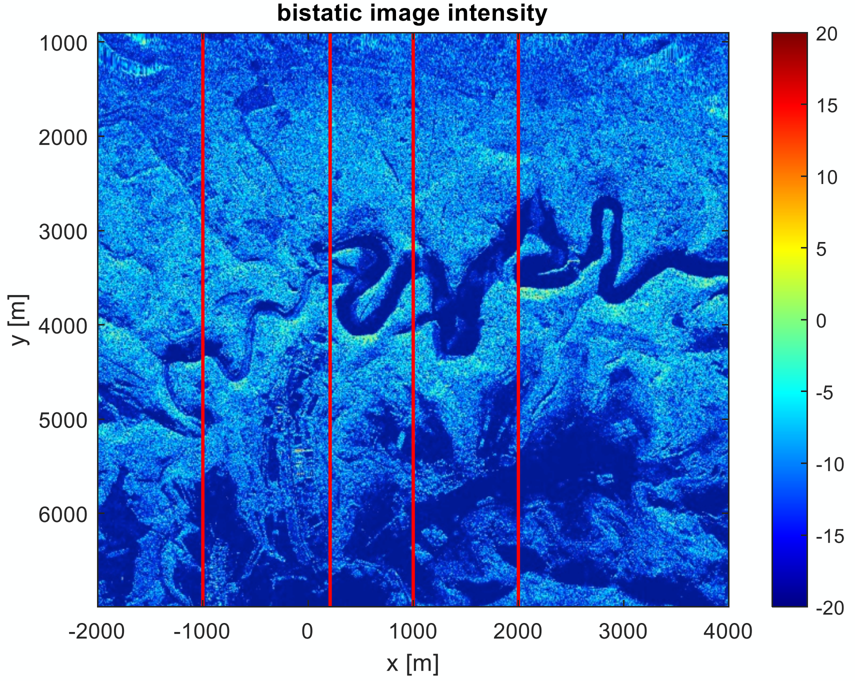
with k=mono- or bi-static imaging mode

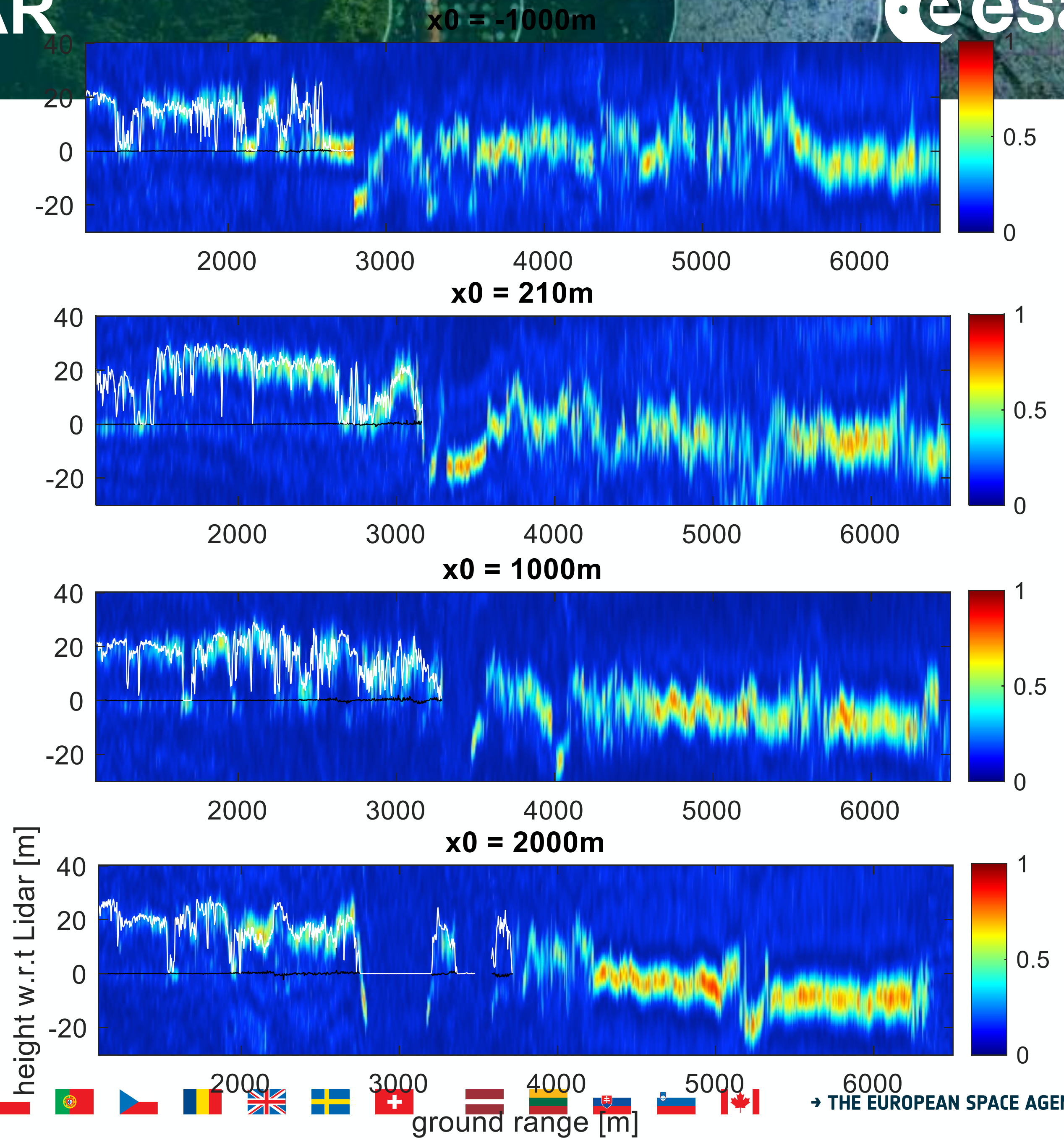
0: decorrelated for whole data stack(☹)

1: fully coherent for whole data stack(☺, point target)

Tomographic profiles VS LiDAR

- Comparing tomographic section along azimuth direction with LiDAR measurements

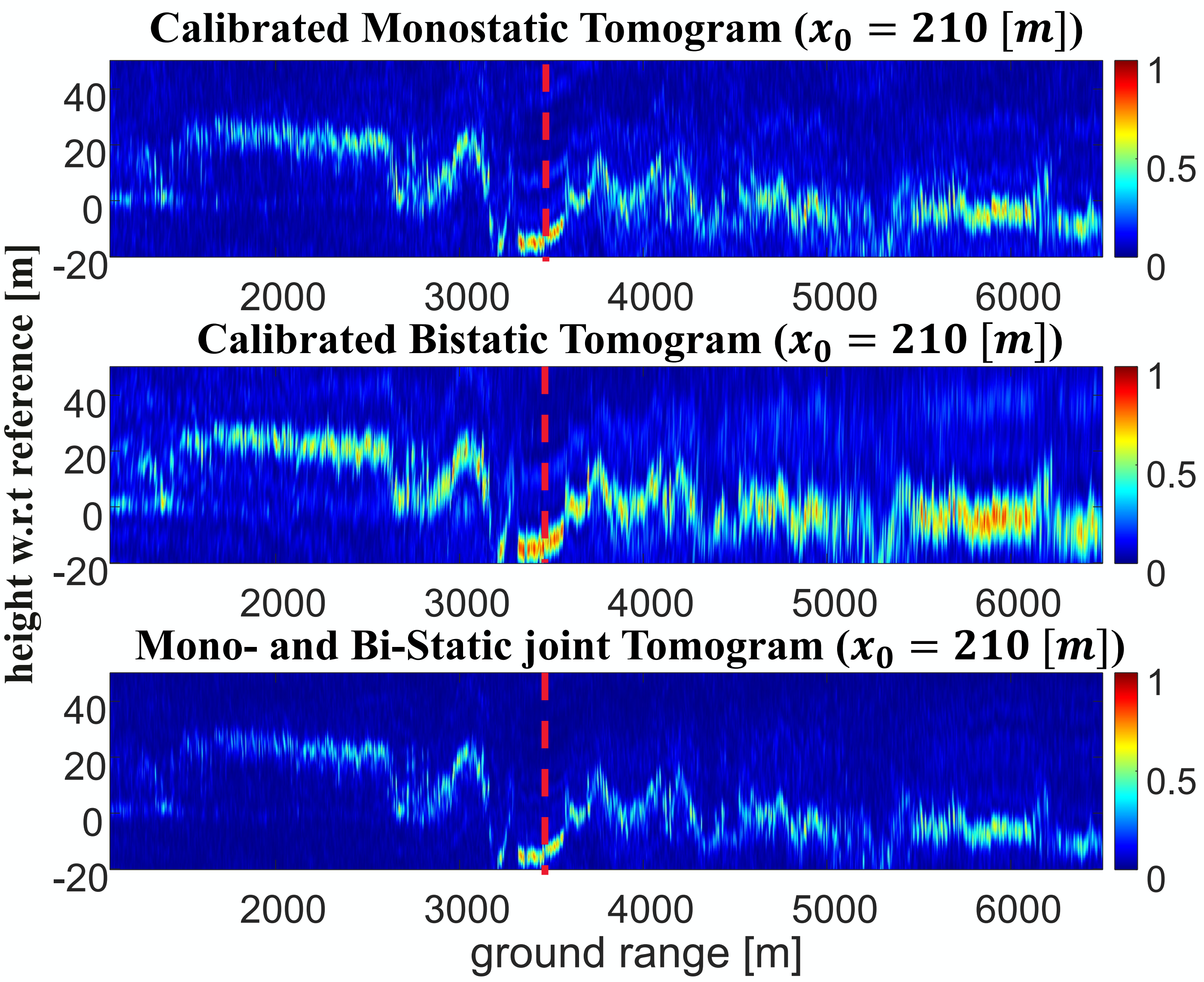


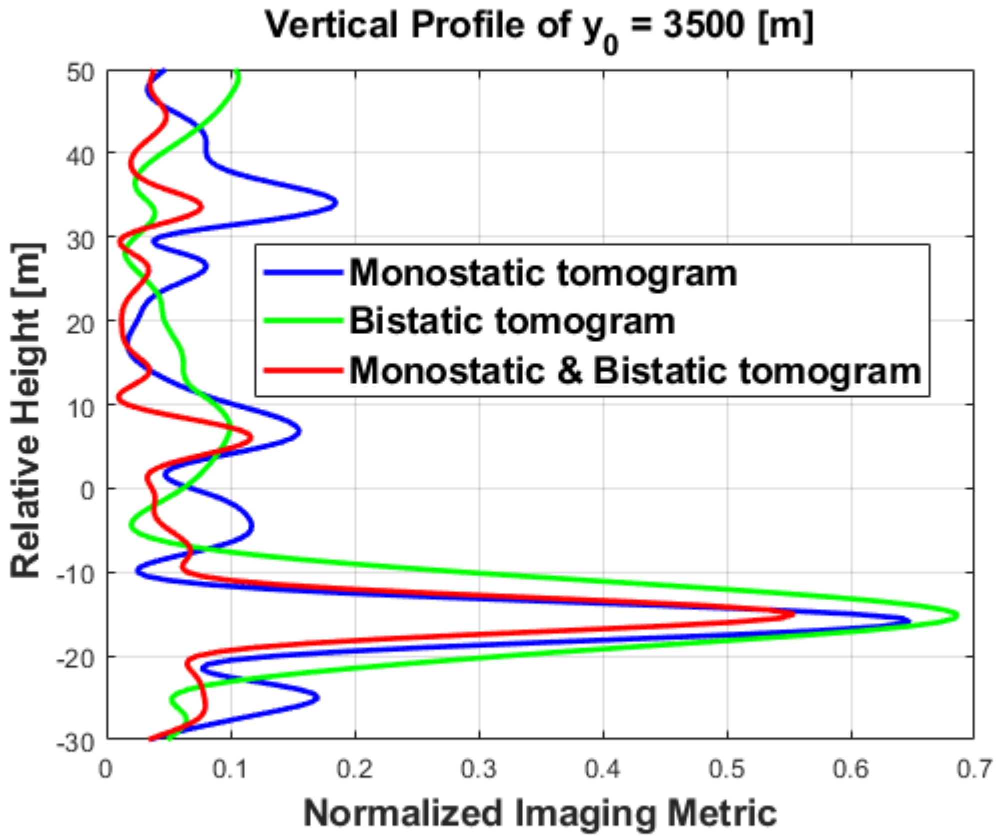


Mainly focusing on bistatic data

LiDAR DSM in white lines
LiDAR DTM in black lines
In a good agreement!

A synergy of mono- and bi-static Imaging





Enable a joint imaging mode with higher vertical resolution!

Conclusion

The TomoSense campaign provides a rich remote sensing data featuring a temperate forest site, including multi-frequency and bistatic tomographic SAR acquisitions and a large amount of reference data.

Particularly, the L-band bistatic data could motivate a series of advanced technologies and scientific applications. In any case, a fundamental requirement is the accurate measurement of sensor-to-target distances within the synthetic apertures along flight and/or baseline directions.

L-Band calibration was carried out in cascaded fashion with three steps:

- Single-pass Bistatic multi-squint InSAR processing:

⇔ Correction of potential clock drift errors and baseline errors between two platforms along flight direction

- Multi-baseline multi-squint InSAR processing for both mono- and bi-static data stack:

⇔ Correction of coregistration errors for both data stacks and fast-varying residual phase errors

- Bistatic version of Phase Center Double Localization:

⇔ Determination of positioning errors of two platforms along baseline direction, and correction of slow-varying residual phase errors

The resulting 3D L-Band reconstruction is observed to be in excellent agreement with aerial Lidar data;

Our calibration enable a joint imaging mode (using both mono- and bi-static data) with higher vertical resolution;

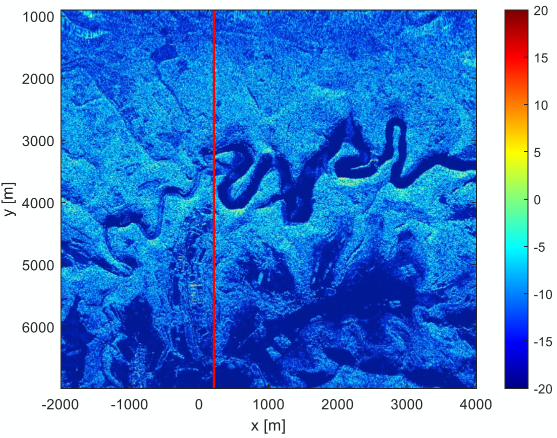
Conclusion

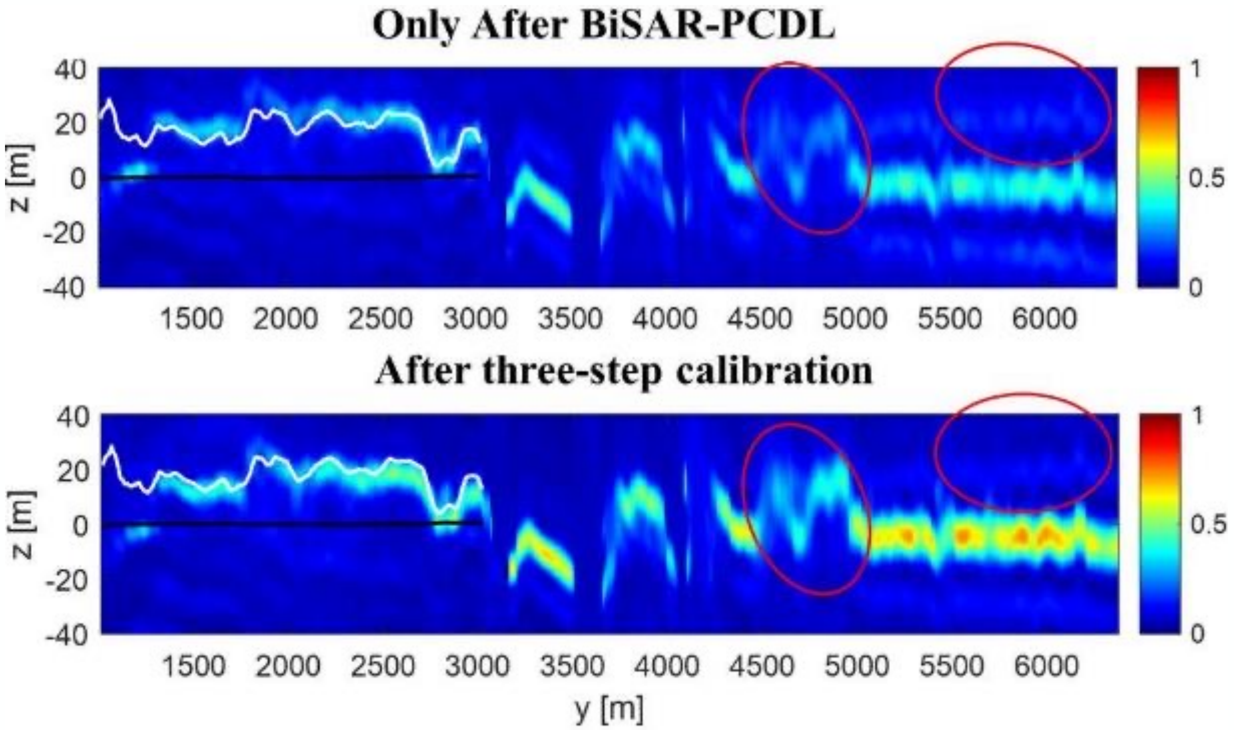
Thank you for Attention!

Special thanks to ESA and Meta-Sensing for providing such a nice dataset!

Tomographic performance enhancement

☐ Tomographic performance during calibration





First two steps lead to sidelobes suppressing and better final focusing

- ➢ Tomographic imaging metric:

$$\gamma_{tomo,k}(x,y,z) = \frac{N^2 \cdot \left|\sum_{n=1}^{N} y_n^k(x,y,z)\right|^2}{\sum_{n=1}^{N}\left|y_n^k(x,y,z)\right|^2}$$

with k=mono- or bi-static imaging mode

0: decorrelated for whole data stack(☹)

1: fully coherent for whole data stack(☺, point target)