2025 DRAGON 6 SYMPOSIUM

14-18 JULY 2025

PROJECT ID. 95358

GEOPHYSICAL AND GEODETICS RETRIEVAL FROM SAR DATA STACKS OVER NATURAL SCENARIOS





Dragon 6 Batch-2 Project Overview

ID. 95358

PROJECT TITLE: GEOPHYSICAL AND GEODETICS RETRIEVAL FROM SAR DATA STACKS OVER NATURAL SCENARIOS

PRINCIPAL INVESTIGATORS: PROF. MINGSHENG LIAO, PROF. STEFANO TEBALDINI

CO-AUTHORS:

- ***PROF. DEREN LI, PROF. JIANYA GONG, PROF. JIANSI YANG, CHUANJUN WU, YONGQIAN CHEN, XIN ZHAO, JIE DONG, WUHAN UNIVERSITY, CHINA***
- ***PROF. FABIO ROCCA, MARCO MANZONI, NAOMI PETRUSHEVSKY, PIETRO GRASSI, YANGHAI YU, POLITECNICO DI MILANO, ITALY***
- ***PROF. DONGHAI ZHENG, INSTITUTE OF TIBETAN PLATEAU RESEARCH, CHINESE ACADEMY OF SCIENCES CHINA***
- ***PROF. LAURENT FERRO-FAMIL, ISAE SUPAERO, FRANCE***

PRESENTED BY: PROF. MINGSHENG LIAO

Project objectives

The aim of this project focuses on the development and application of processing methodologies to address the 3D characterization of sub-surface targets using stacks of spaceborne SAR data acquired over natural scenarios, including 3D imagery of forests, ice sheets, and desert areas.

The topics above are of fundamental importance in the context of present and future spaceborne SAR missions, which will allow increasingly more systematic use of multiple acquisitions thanks to improved hardware stability and more strict orbital control.

Specifically, the proposed activities are intended to support use of multi-pass data stacks from:

- the upcoming P-Band mission BIOMASS.
- in-orbit L-Band missions, such as the Argentinian SAOCOM constellation, the Chinese missions LuTan-1 & LuTan-4, and potentially ALOS-4 and NISAR.

Remote sensing data

ESA Missions:

- BIOMASS P-Band data stacks, to be made available after launch in April 29, 2025

Chinese Missions:

- LuTan L-Band interferometric and bistatic data

Other Missions:

- SAOCOM L-Band data

ESA campaigns

- TomoSense, AfriSAR, AfriSAR 2023, AlpTomoSAR

Remote sensing data

A few specific sites have been identified at the time this proposal is being prepared.

Site 1: the forested area of Paracou, French Guiana. This site was investigated in the context of the ESA campaign TropiSAR in 2009, and it is suitable to be further investigated using spaceborne data from BIOMASS and L-Band missions.

Site 2: the forested area of Lopé, Gabon. This site was investigated in the context of the ESA campaign AfriSAR and AfriSAR-2 in 2015 and 2022, and it is suitable to be further investigated using spaceborne data from BIOMASS and L-Band missions

Site 3: Bayi Glacier (39°01.00'N, 98°53.53'E) is located in the middle part of the Qilian Mountains. The glacier is an ice cap-type glacier developed on the top of a gently sloping mountain. According to the glacier cataloging data, the Bayi Glacier is the largest glacier in the headwaters area of the main stream of the Heihe River, with a length of 2.2 km and an area of 2.81 km2, with the end of the glacier at an elevation of 4,520 m, and the highest point at an elevation of 4,828 m.

Site 4: the forested area at the Kermeter site, Germany. This site was investigated in the context of the ESA campaign TomoSense in 2020, and it is suitable to be further investigated using spaceborne data from L-Band missions (BIOMASS being blocked by SOTRs over Europe).

Site 5: the desert area of Merzouga, Morocco. This site was investigated in the context of an ASI helicopter-borne P-Band campaign in 2017, providing evidence of sub-surface penetration. It is suitable to be further investigated using spaceborne data from BIOMASS and L-Band mission.

Site 6: tbd areas Antarctica.

Project contributions

The activities will be concentrated on processing SAR image stacks to extract information about vertical vegetation structure and sub-surface terrain topography in forested areas, and also about the internal structure of sand dunes in desert area as well as snow-ice volume in glacier area.

Estimation and compensation of ionospheric and tropospheric propagation effects will be investigated as well.

Leveraging the unprecedented availability of P-Band spaceborne data from the BIOMASS mission, the research will as well be extended to investigating the 3D of the ionosphere.

Work plan



Activities:

1. Data procurement
2. Pre-processing: area selection, co-registration, spectral filtering
3. Estimation and compensation of atmospheric phase screens
4. Characterization of internal structure of forested areas, ice bodies, and sand dunes
5. Validation against campaign data

Milestones:

1. Development of methods for estimation of atmospheric phase screens, application to spaceborne data, validation.
2. Development of methods for internal structure characterization, application to spaceborne data, validation.

Project schedule

2025

- Procurement of satellite stacks.
- Acquisition of campaign data.
- Data pre-processing, preliminary analysis.
- Presentation at Dragon symposium 2025.

2026

- Advanced analysis of satellite data.
- Advanced analysis of campaign data.
- Presentation at Dragon symposium 2026.
- Preparation of one or more journal papers

2027

- Advanced data analysis.
- Presentation at Dragon symposium 2027.

2028

- Presentation of final results
- Presentation at Dragon symposium 2028.
- Preparation of one or more journal papers

Young Scientists

Continuing on the success story of young scientists supported by Dragon Program, we intend to focus on the support of young scientists in Dragon-6.

With solid supports from the Chinese Scholarship Council (CSC), but in the framework of Dragon, 1-2 PhD student from LIESMARS and CAS will work in POLIMI.

On the European side, the activities are currently planned to get started with three funded European Young Scientists from Politecnico di Milano.

Chinese YS	Institution	Current position
Yongqian Chen	Wuhan University, *Academic exchange at PoliMi for a period of two years(since Jan 2025)*	**Ph.D. student**
Yanghai Yu	National Space Science Center, Chinese Academy of Science *Academic exchange at PoliMi for a period of three years(since July 2024)*	**Post doc researcher**
European YS	**Institution**	**Current position**
Marco Manzoni	Politecnico di Milano	**Post doc researcher**
Naomi Petrushevsky	Politecnico di Milano	**Post doc researcher**
Pietro Grassi	Politecnico di Milano	**Ph.D. student**

Preliminary results - BIOMASS



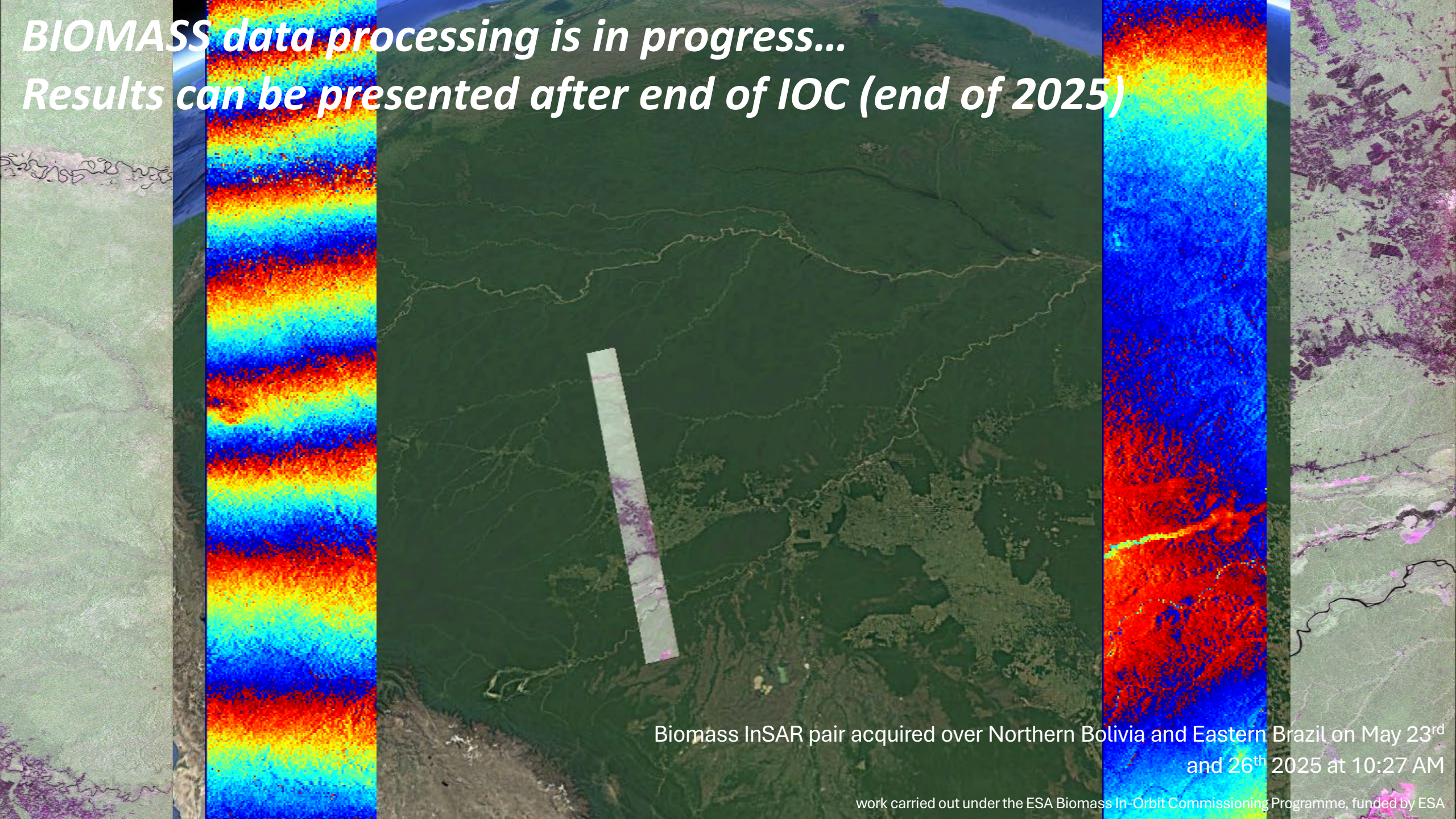
***BIOMASS*:**

- Successfully launched on April 29th 2025
- First P-Band SAR mission in orbit
- Will provide unprecedented data for monitoring the world's forests

Unique data:

- P-Band (435 MHz) waves provides sensitivity to the whole vertical structure of the vegetation, even in dense tropical forests.
- Orbit designed to illuminate the same scenes 3 or 7 times with 3 days separation to enable polarimetry, polarimetric interferometry, tomography

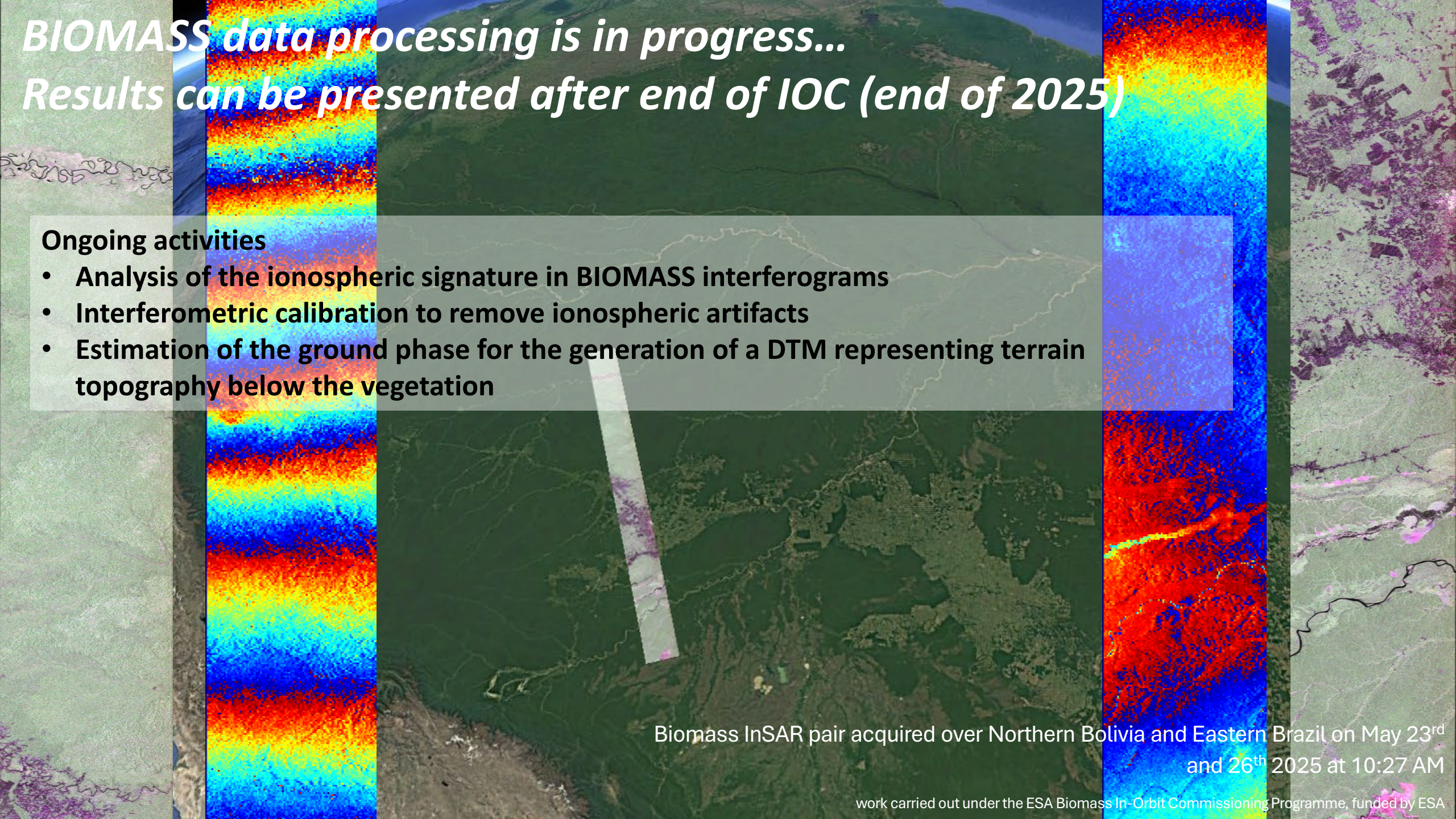



BIOMASS data processing is in progress…
Results can be presented after end of IOC (end of 2025)
Biomass InSAR pair acquired over Northern Bolivia and Eastern Brazil on May 23rd and 26th 2025 at 10:27 AM
work carried out under the ESA Biomass In-Orbit Commissioning Programme, funded by ESA

BIOMASS data processing is in progress…
Results can be presented after end of IOC (end of 2025)

Ongoing activities

- **Analysis of the ionospheric signature in BIOMASS interferograms**
- **Interferometric calibration to remove ionospheric artifacts**
- **Estimation of the ground phase for the generation of a DTM representing terrain topography below the vegetation**



Biomass InSAR pair acquired over Northern Bolivia and Eastern Brazil on May 23rd and 26th 2025 at 10:27 AM

work carried out under the ESA Biomass In-Orbit Commissioning Programme, funded by ESA

BIOMASS INTERFEROMETRIC STACK PHASE CALIBRATION: METHODS AND SIMULATED RESULTS

Generation of BIOMASS products requires starting from coregistered and calibrated stacks, so that main disturbances affecting data have been removed. These include orbital inaccuracies, ionosphere and troposphere.

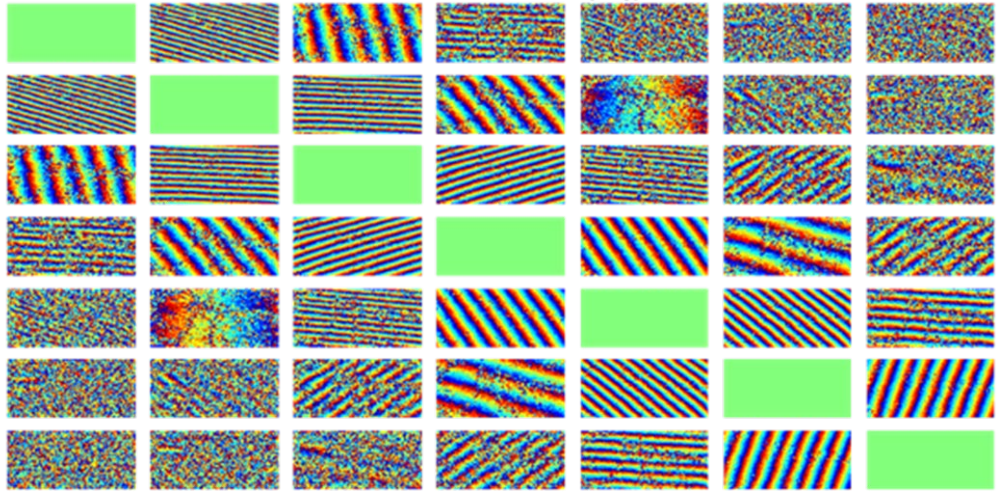
The main blocks addressed are:

- **Split-spectrum** for slow-varying ionosphere removal. The method exploits the dispersive nature of propagation through the ionospheric layer.
- **Multi-squint interferometry** for fast-varying ionosphere and orbital errors removal. The technique separates the squint-dependent components (fast ionosphere, orbital error) from other effects (topography, troposphere).
- **Sum of Kronecker Products (SKP):** uses the multi-baseline and multi-polarimetric covariance matrix for a decomposition of ground and volume contributions.

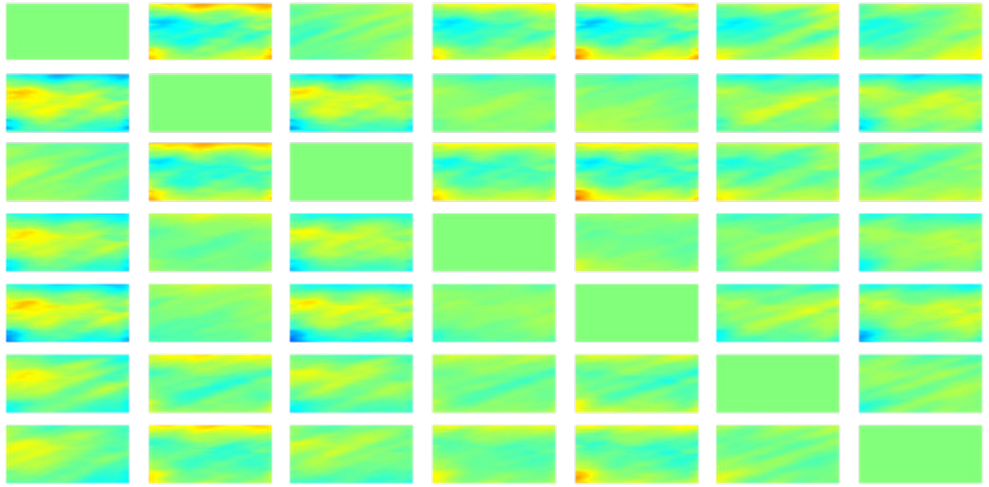
Preliminary results - BIOMASS

Split-spectrum for slow-varying ionosphere removal. The method exploits the dispersive nature of propagation through the ionospheric layer.

Perturbed phase



Corrected

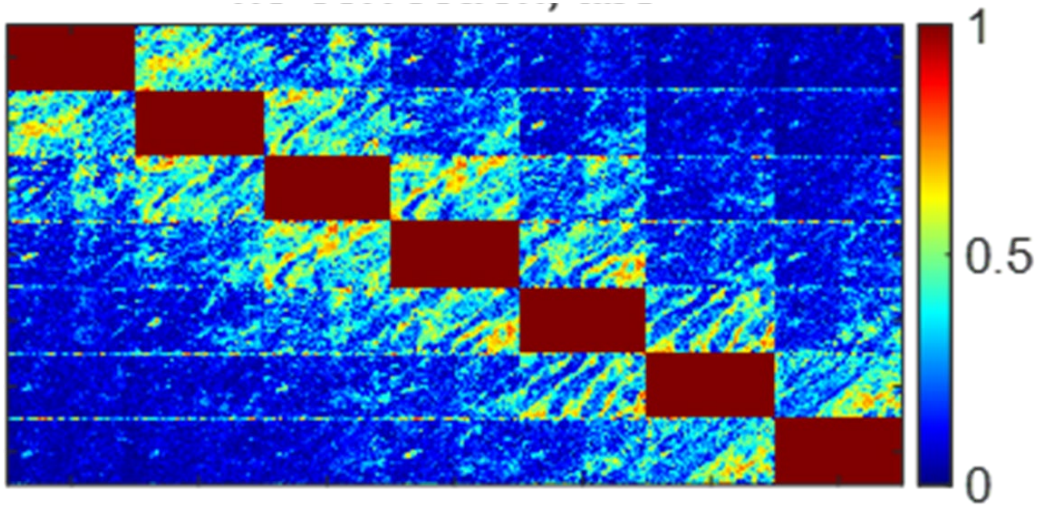


*N.B.: results from **simulated** data (real data can only be shown after end of the commissioning phase)*

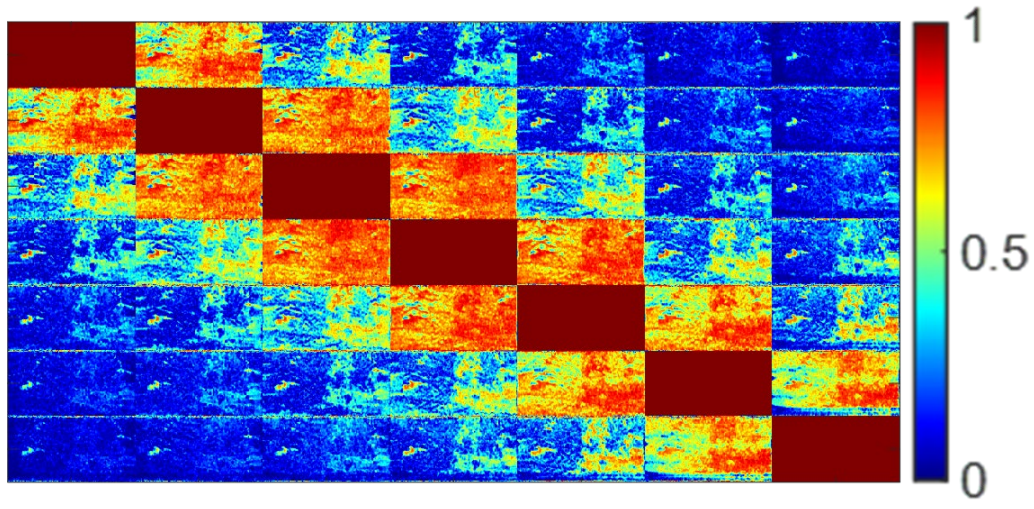
Preliminary results - BIOMASS

Multi-squint interferometry for fast-varying ionosphere and orbital errors removal

Perturbed coherence



Corrected

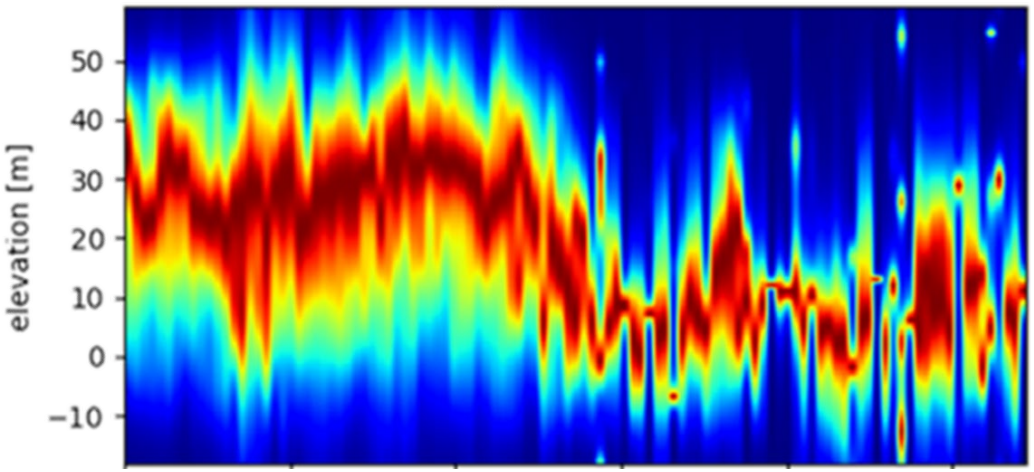


*N.B.: results from **simulated** data (real data can only be shown after end of the commissioning phase)*

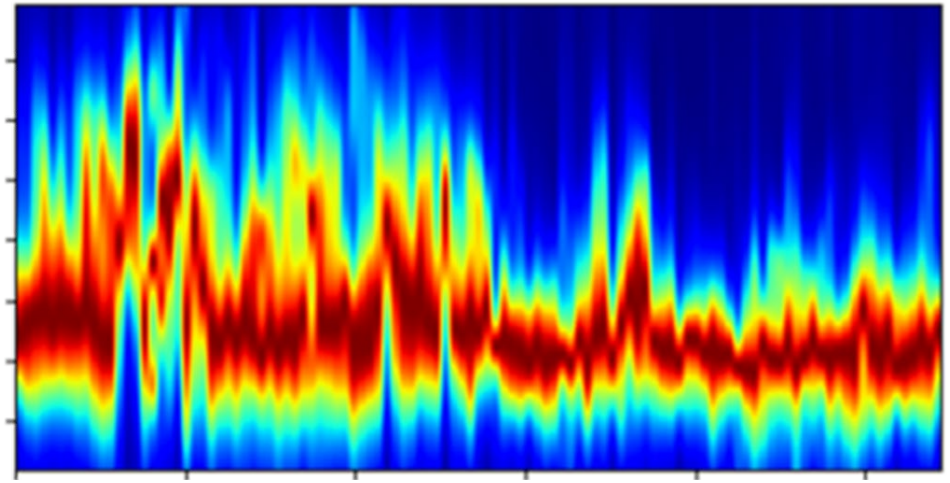
Preliminary results - BIOMASS

- **Sum of Kronecker Products (SKP):** covariance matrix for a decomposition of ground and volume contributions to estimate the ground phase

Perturbed tomogram



Corrected



*N.B.: results from **simulated** data (real data can only be shown after end of the commissioning phase)*

Preliminary results - SAOCOM

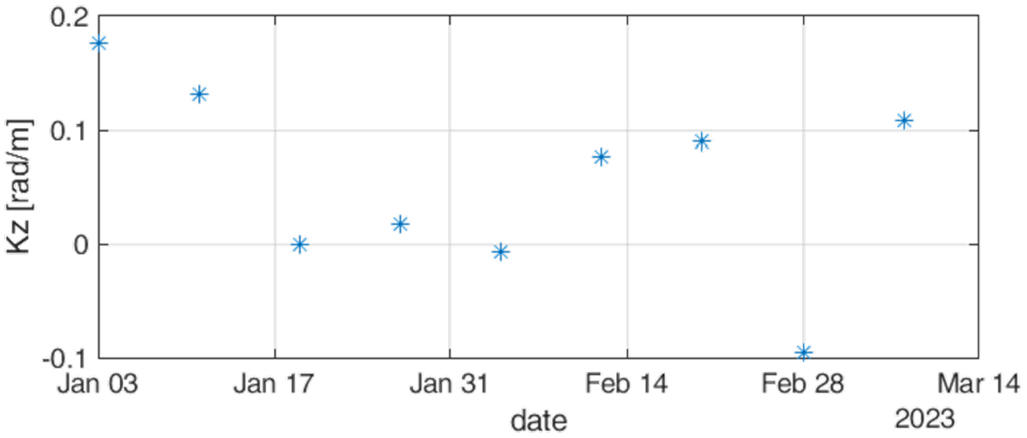
SAR Tomography of forested areas from repeat pass SAOCOM data

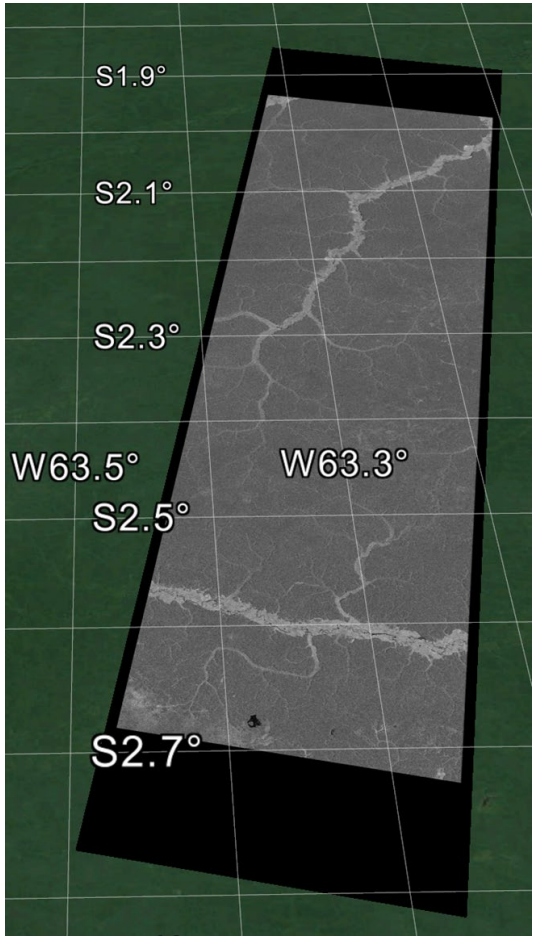
The area is located in Amazonas, the largest Brazilian state, mostly covered by tropical jungle.

The climate is tropical with all-year consistent precipitations, topography is moderately flat and average tree height is around 25 m to 35 m.

9 HH acquisition from SAOCOM A/B operating at L-band with a carrier of λ = 23.5 cm, in Stripmap mode, average look angle of 22◦ and pulse bandwidth of 25 MHz.

The temporal span ranges over two months, sampled regularly at 8 days, which is well within the reported forest decorrelation time.

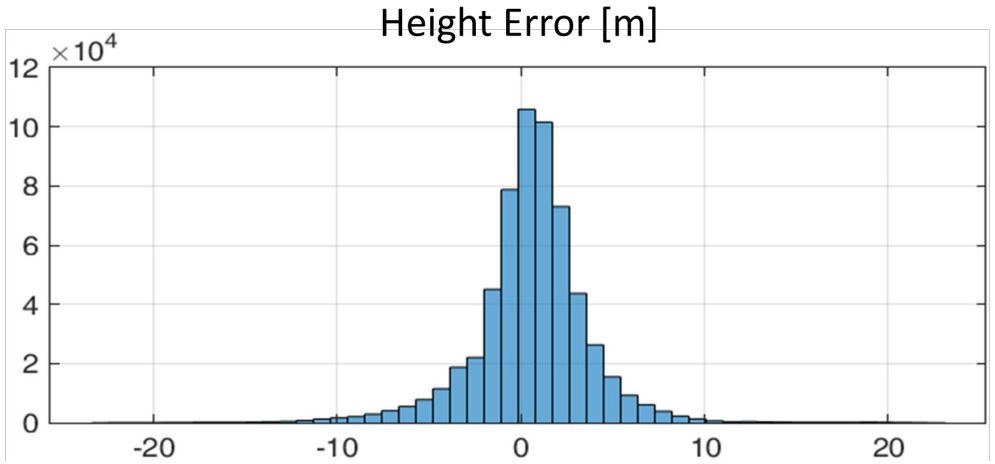


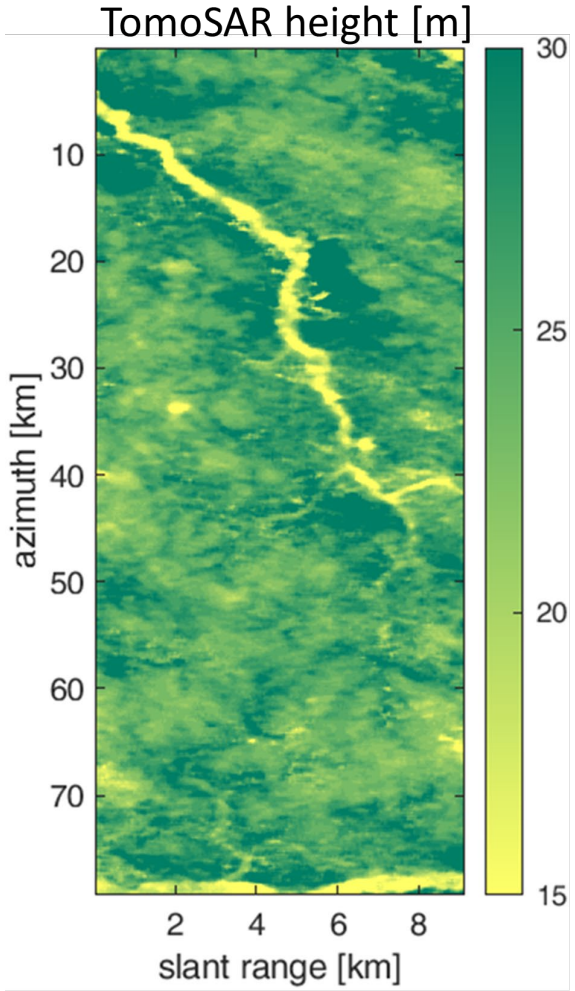


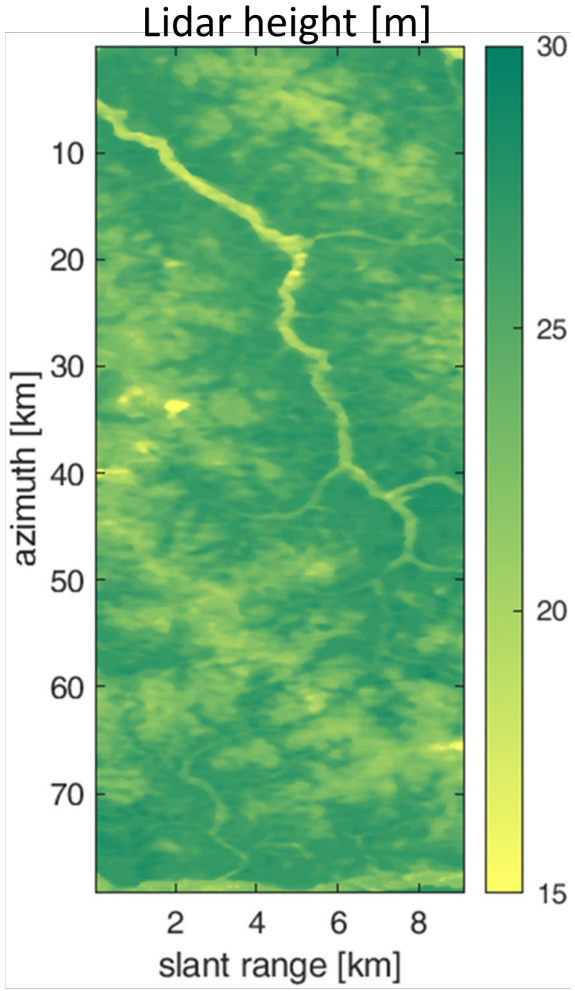
Preliminary results - SAOCOM

SAR Tomography of forested areas from repeat pass SAOCOM data

Reference tree canopy height is provided by UMD GLAD, by integrating GEDI and Landsat.

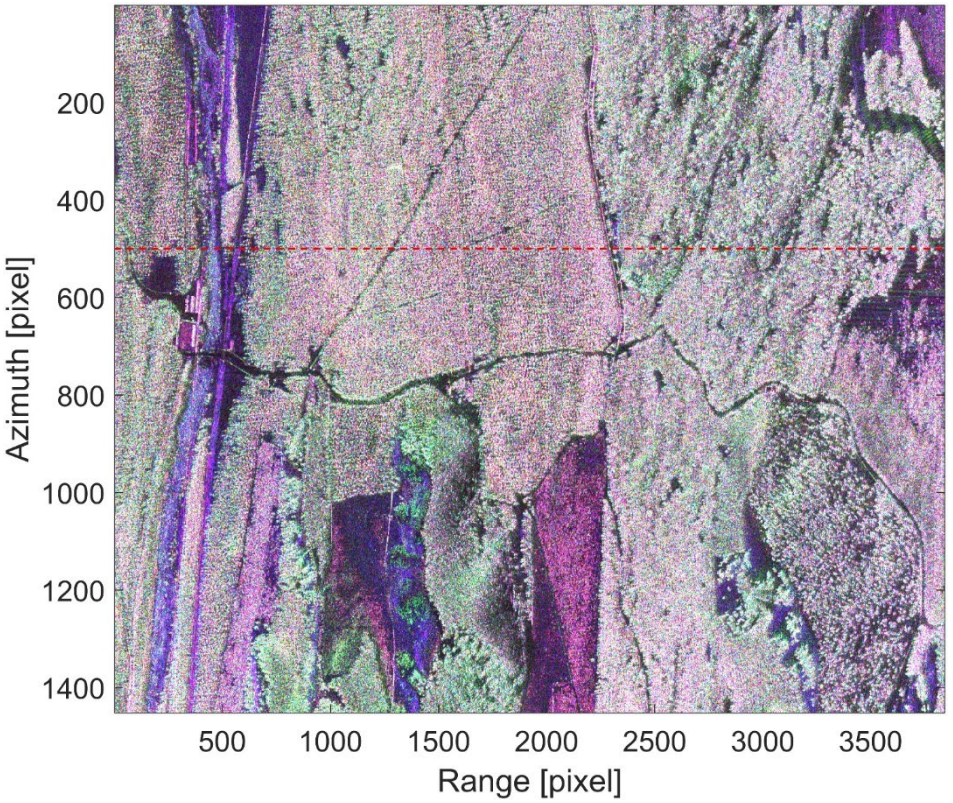




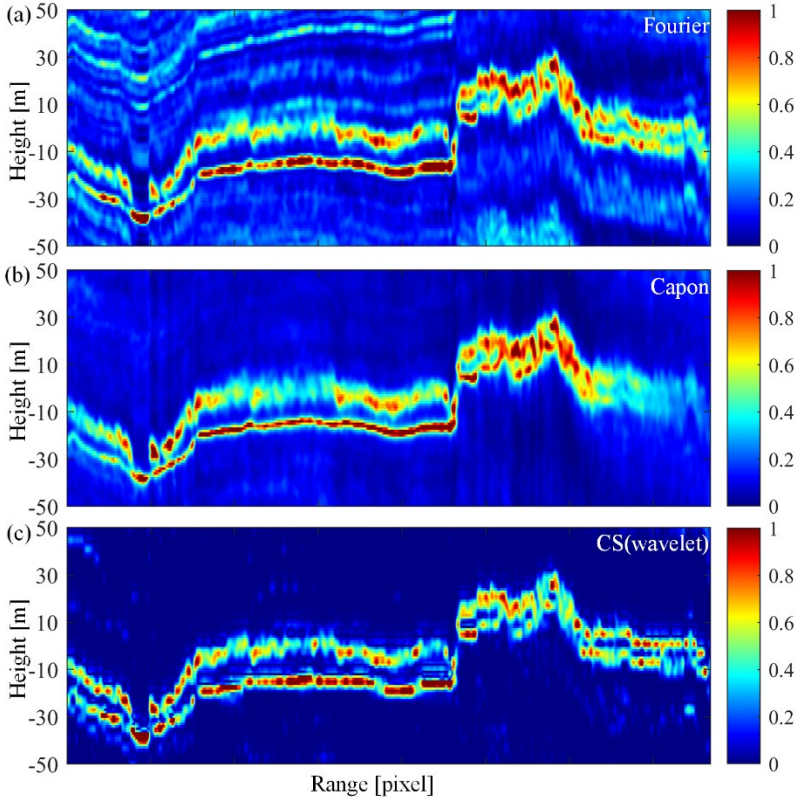


Preliminary results – *YSs research*

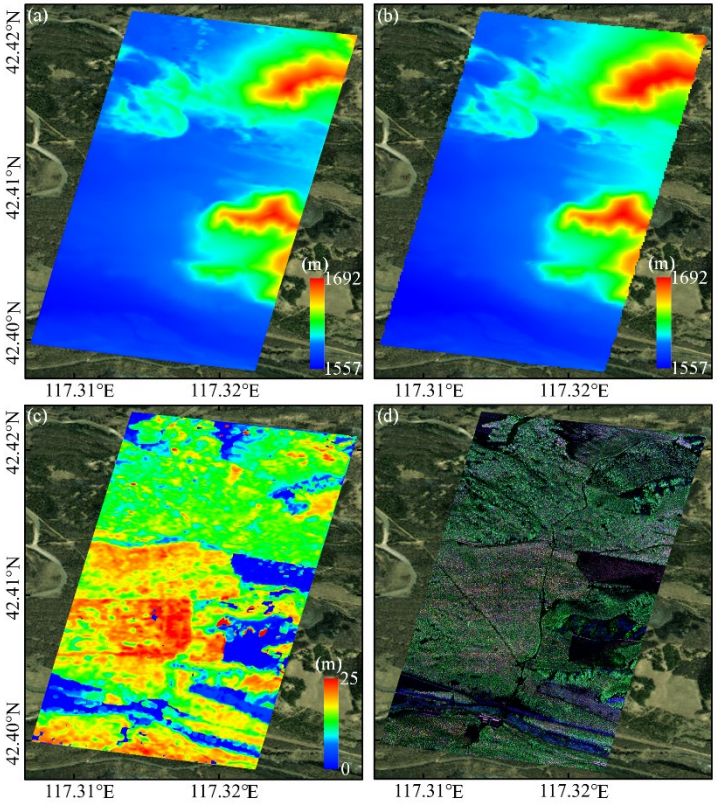
Forest parameters inversion by TomoSAR with Chinese P-band airborne data in Saihanba



Reference image in Pauli false color



TomoSAR result with different methods (a) Fourier transform method; (b) Capon method; (c) Compressive sensing method;



Retrieved underlying topography and forest height by TomoSAR (a) Retrieved underlying topography; (b) Underlying topography by airborne LiDAR; (c) Retrieved Forest height; (d) Reference image in Pauli false color

Preliminary results - *YSs research*

TomoSense data

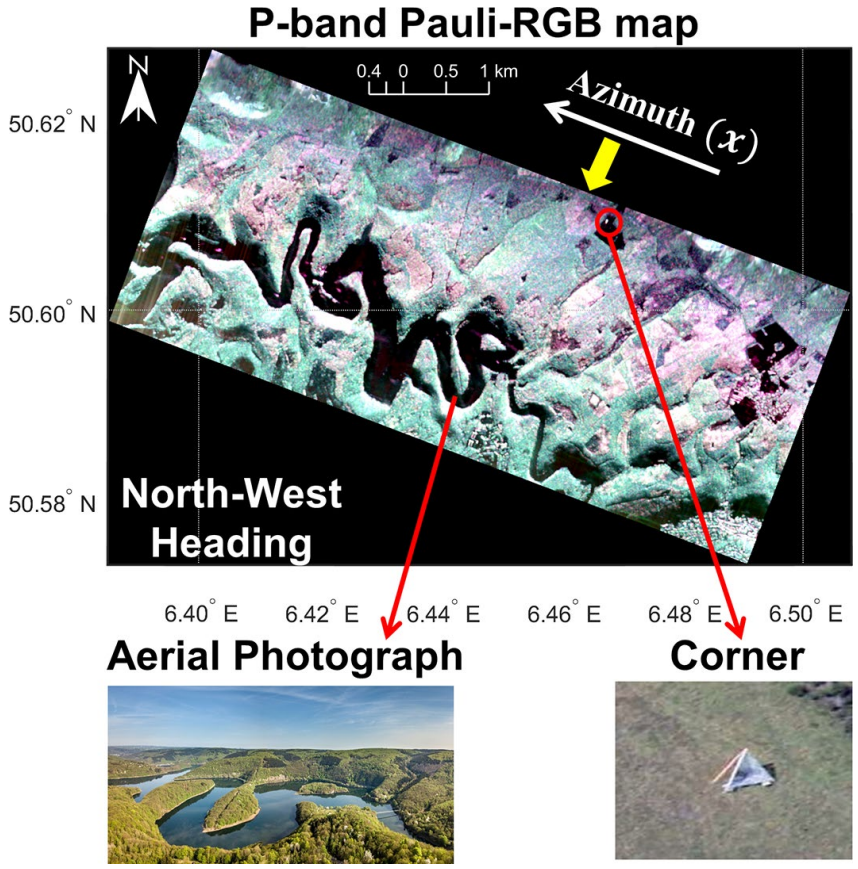


Table 1
Summary of SAR data.

	P-Band	L-Band	C-Band
Polarization	Full-pol	Full-pol	Full-pol
Bandwidth	30 MHz	50 MHz	100 MHz
Along-track resolution	≈ 1 m	≈ 1 m	≈ 0.6 m
Flight heading	North-West and South-East	North-West and South-East	North-West and South-East
Number of passes per heading	28 monostatic	30 monostatic 30 bistatic	17 monostatic 17 bistatic
Vertical resolution in the main area of interest	≈ 5 m to 10 m	< 5 m	< 5 m
Bistatic along track baseline	Not applicable	50 to 150 m	50 to 150 m

Error sources:

Navigational errors (P & L-band data)

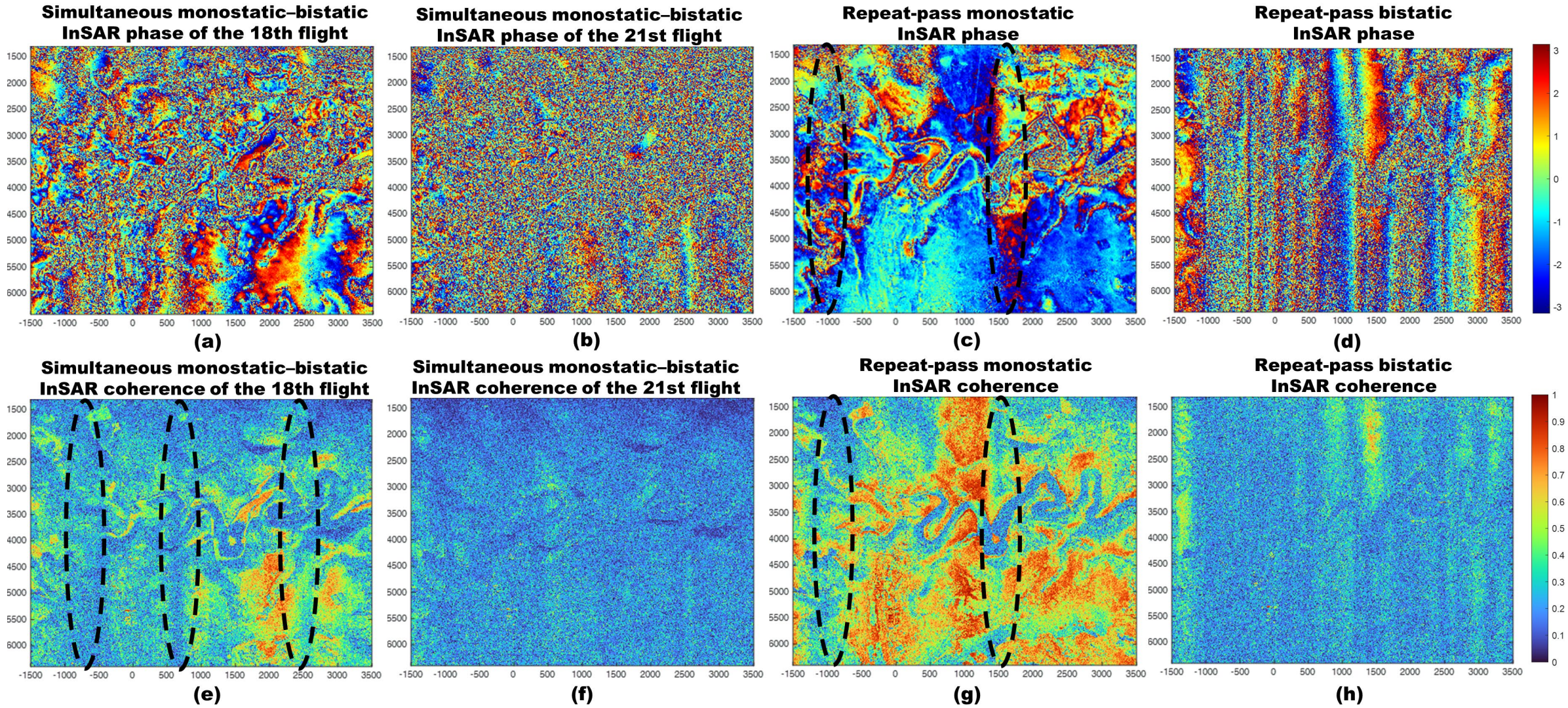
Clock synchronization errors (L-band data)

C-band data are affected by temporal decorrelation.

Preliminary results - *YSs research*

TomoSense L-band Interferograms

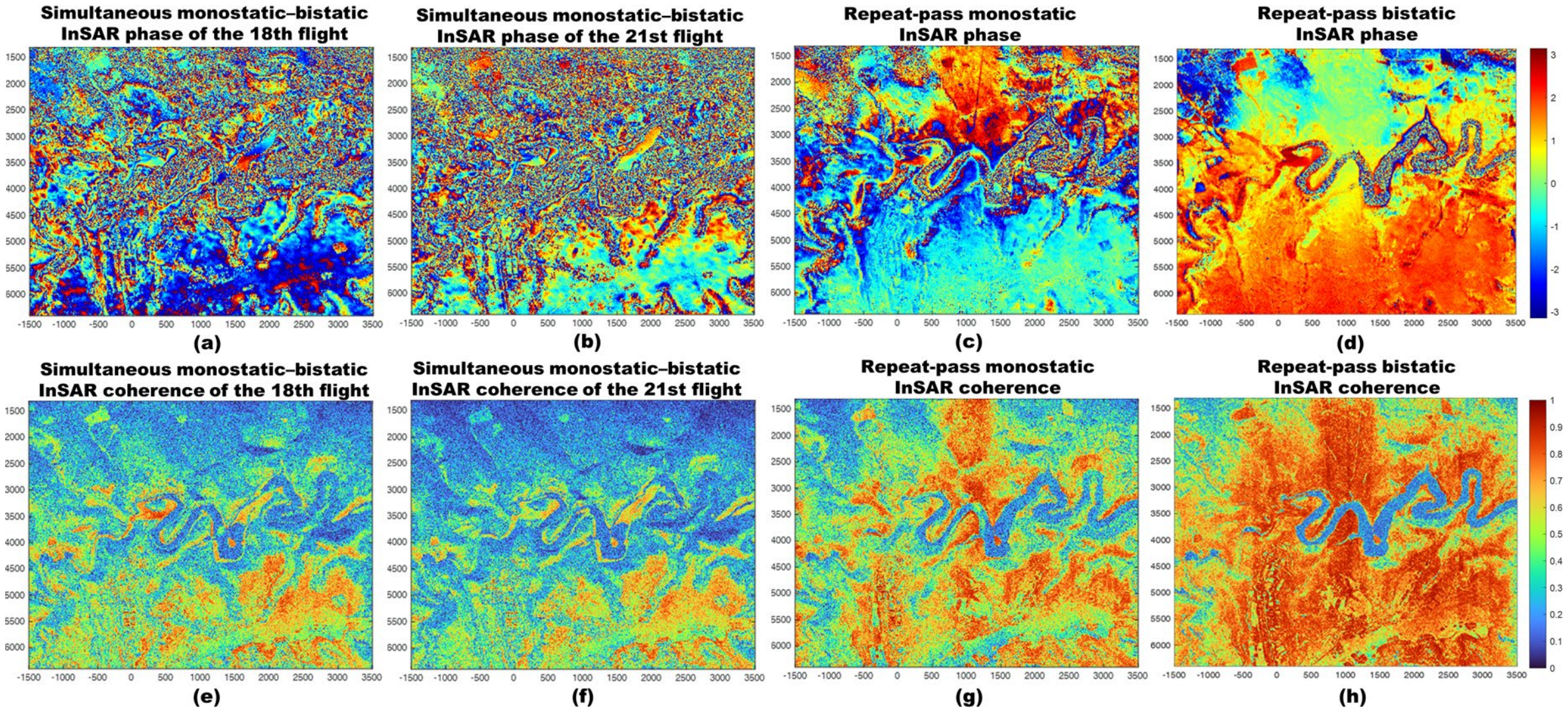
Before Calibration



Preliminary results - *YSs research*

TomoSense L-band Interferograms

After Calibration

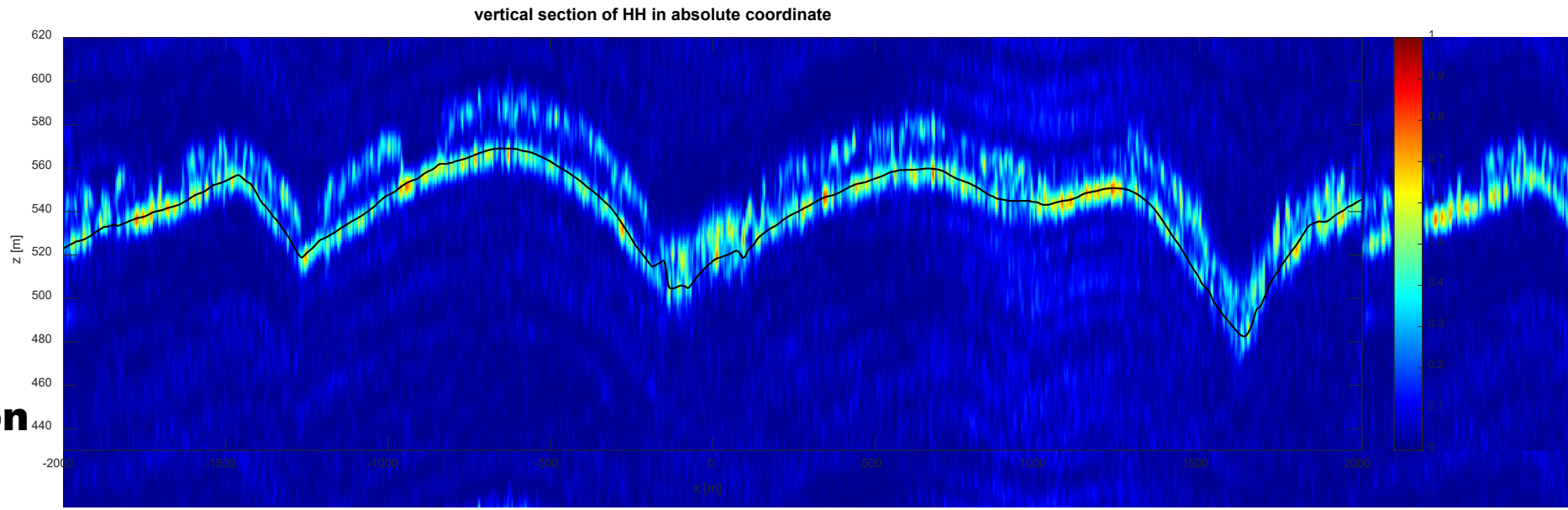


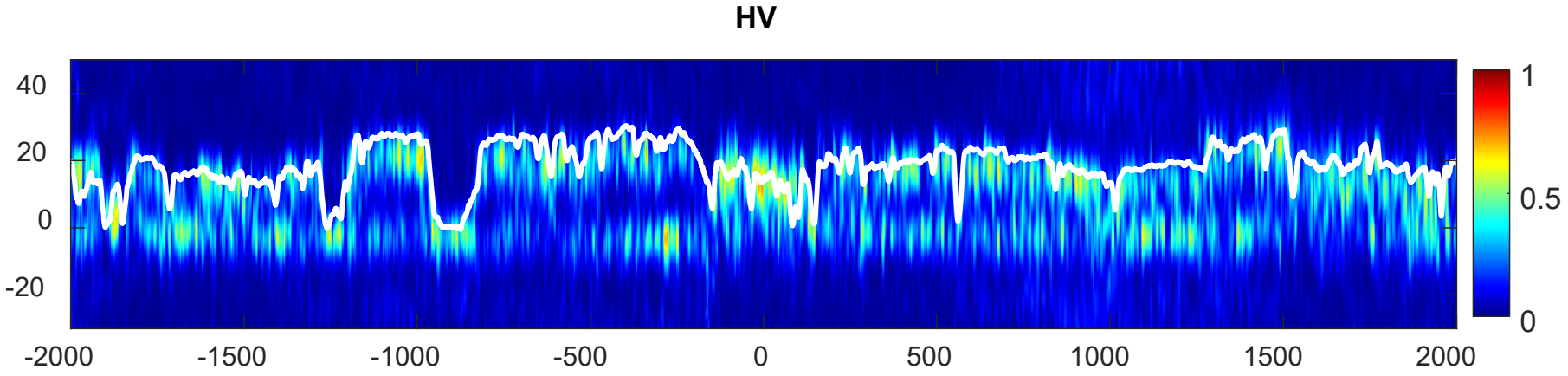
Preliminary results - *YSs research*

TomoSense P-band

Investigating:

- **Underlying ground**
- **Forest canopy position**





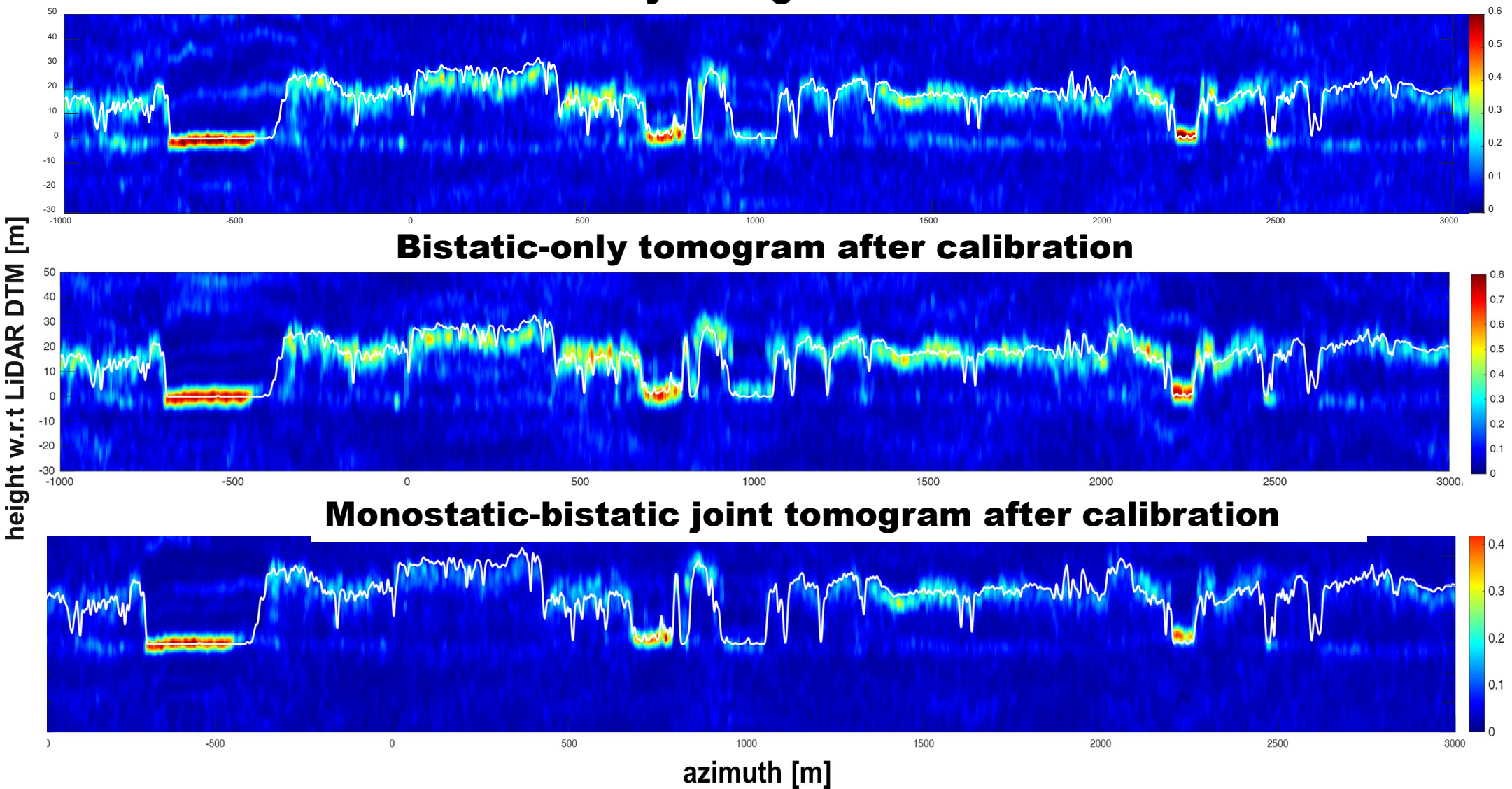
Black Line: Airborne LiDAR DTM

White Line: Airborne LiDAR DSM

Preliminary results - *YSs research*

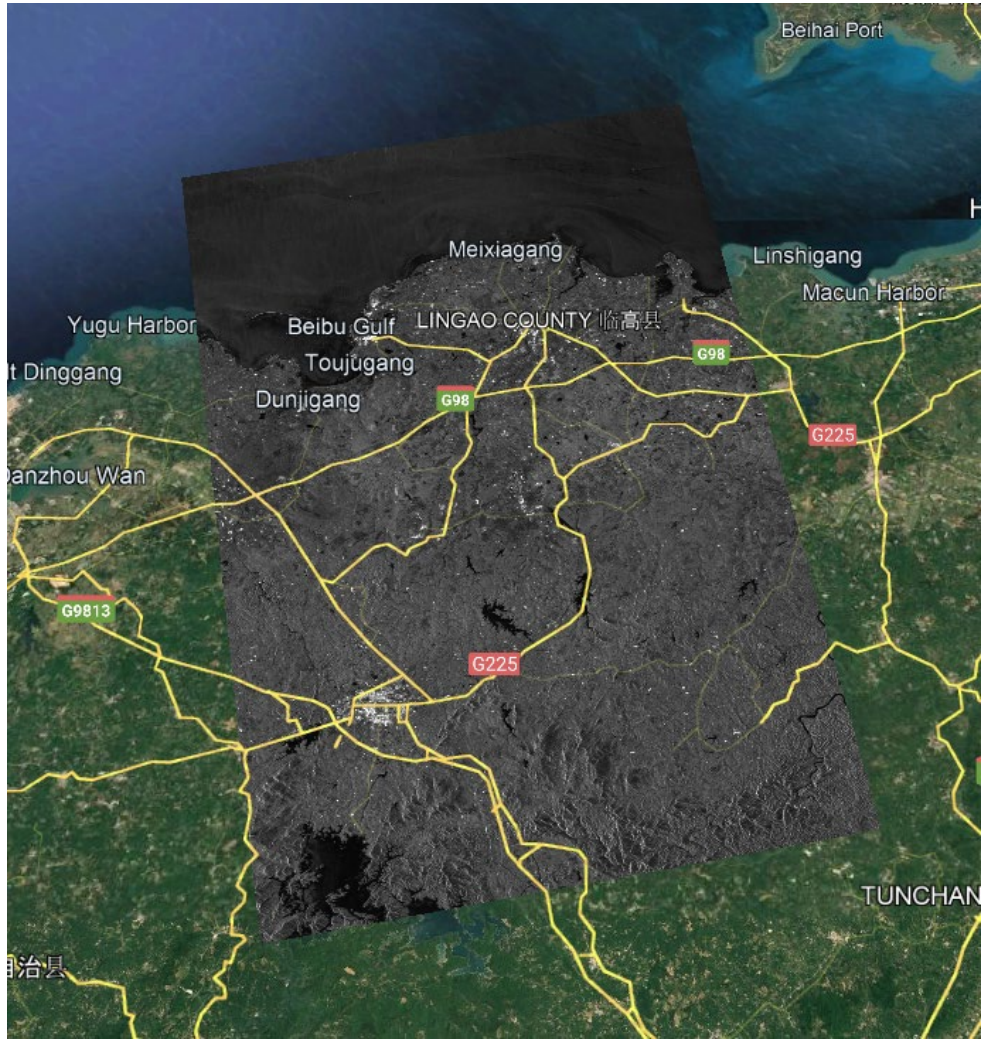
TomoSense L-band Tomograms

White Line: Airborne LiDAR DSM



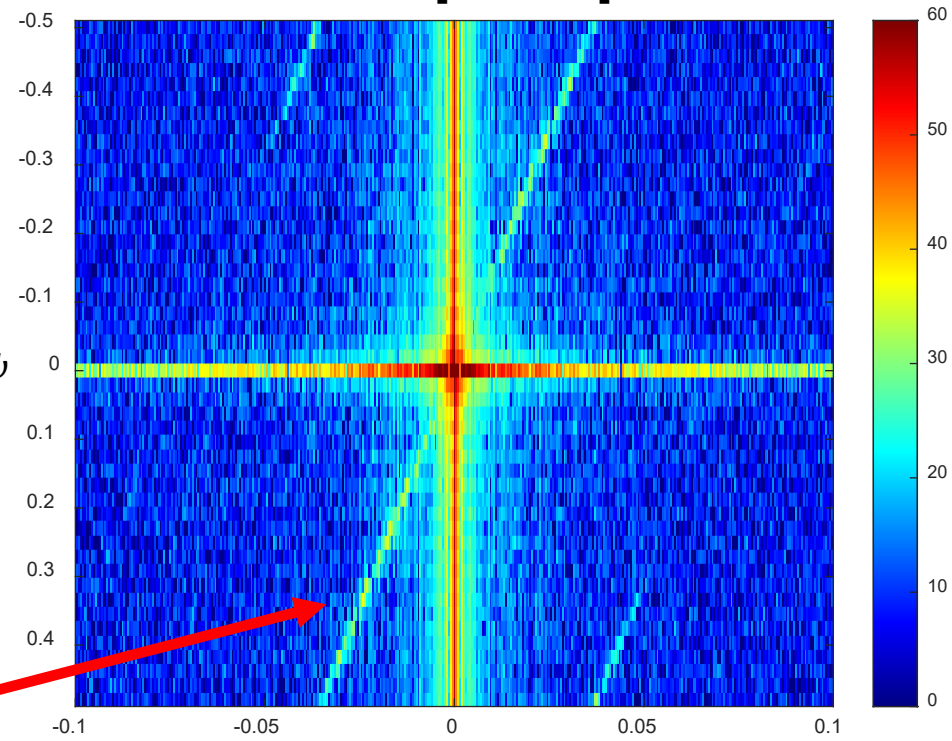
Preliminary results - *YSs research*

Chinese Lutan-1 bistatic InSAR data



- **Although equipped with clock synchronization hardware, we still detect synchronization errors using multi-squint InSAR.**
- **On going analysis and calibration this error.**

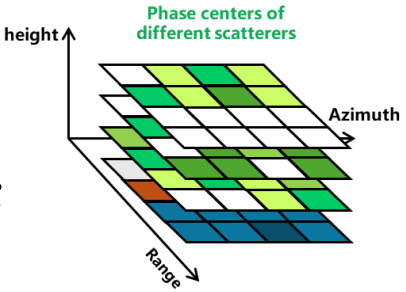
multi-squint spectrum



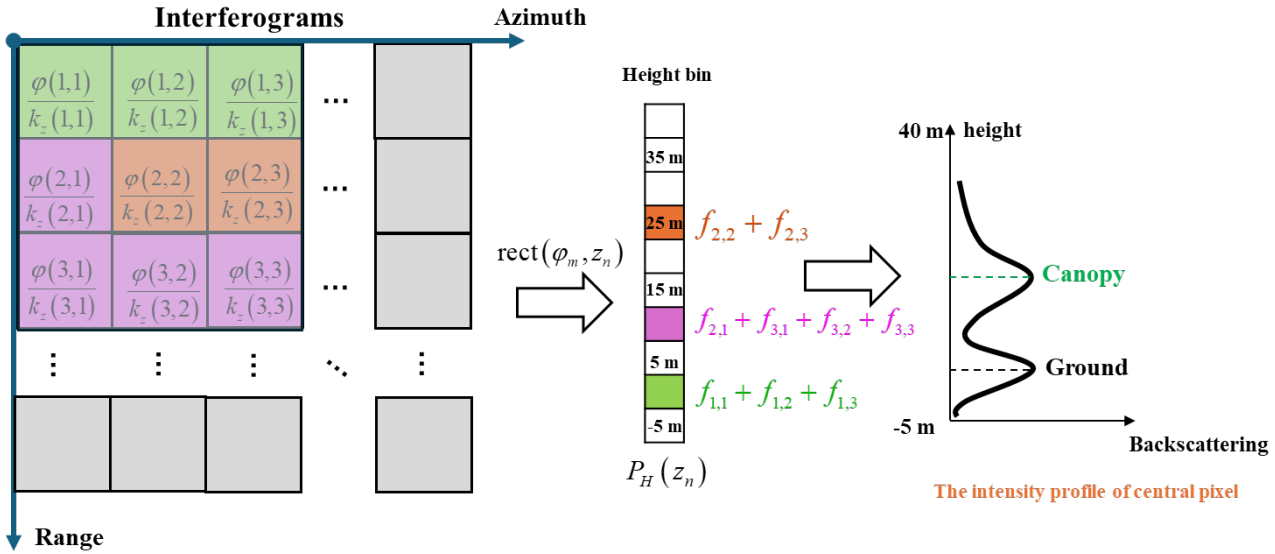
Preliminary results - *YSs research*

For Single-baseline and Single-polarization InSAR data:

- **Phase histogram** (PH) is a light-weight solution for approximating forest vertical structure using spatial horizontal InSAR phase center;
- Explore PH technique to extract biophysical parameters.



3D vertical structure



?



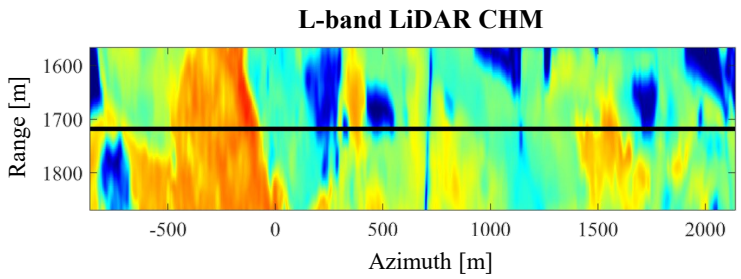
Forest height



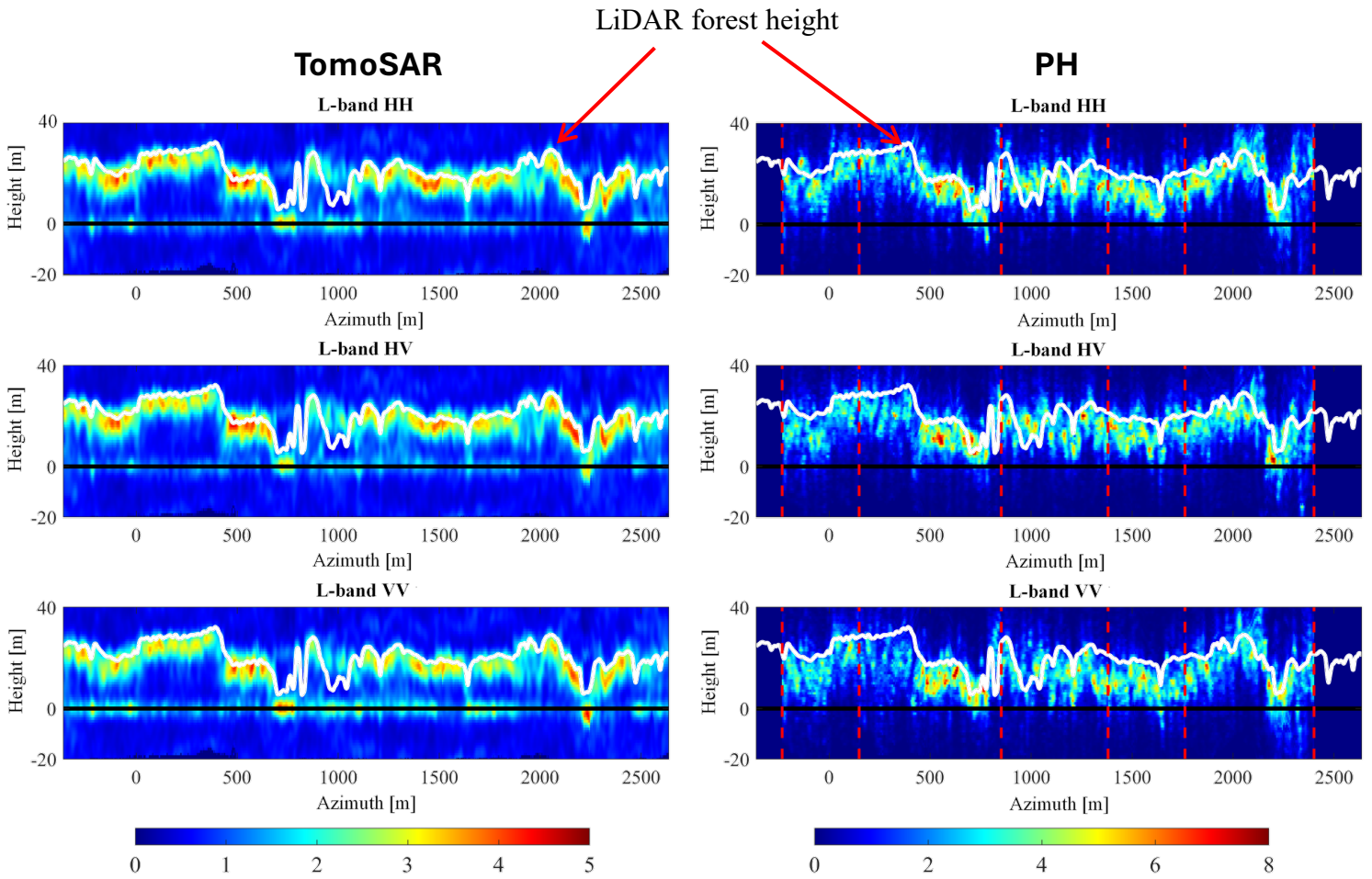
AGB

Preliminary results - *YSs research*

1. Evaluating PH technique on L-Band monostatic SAR

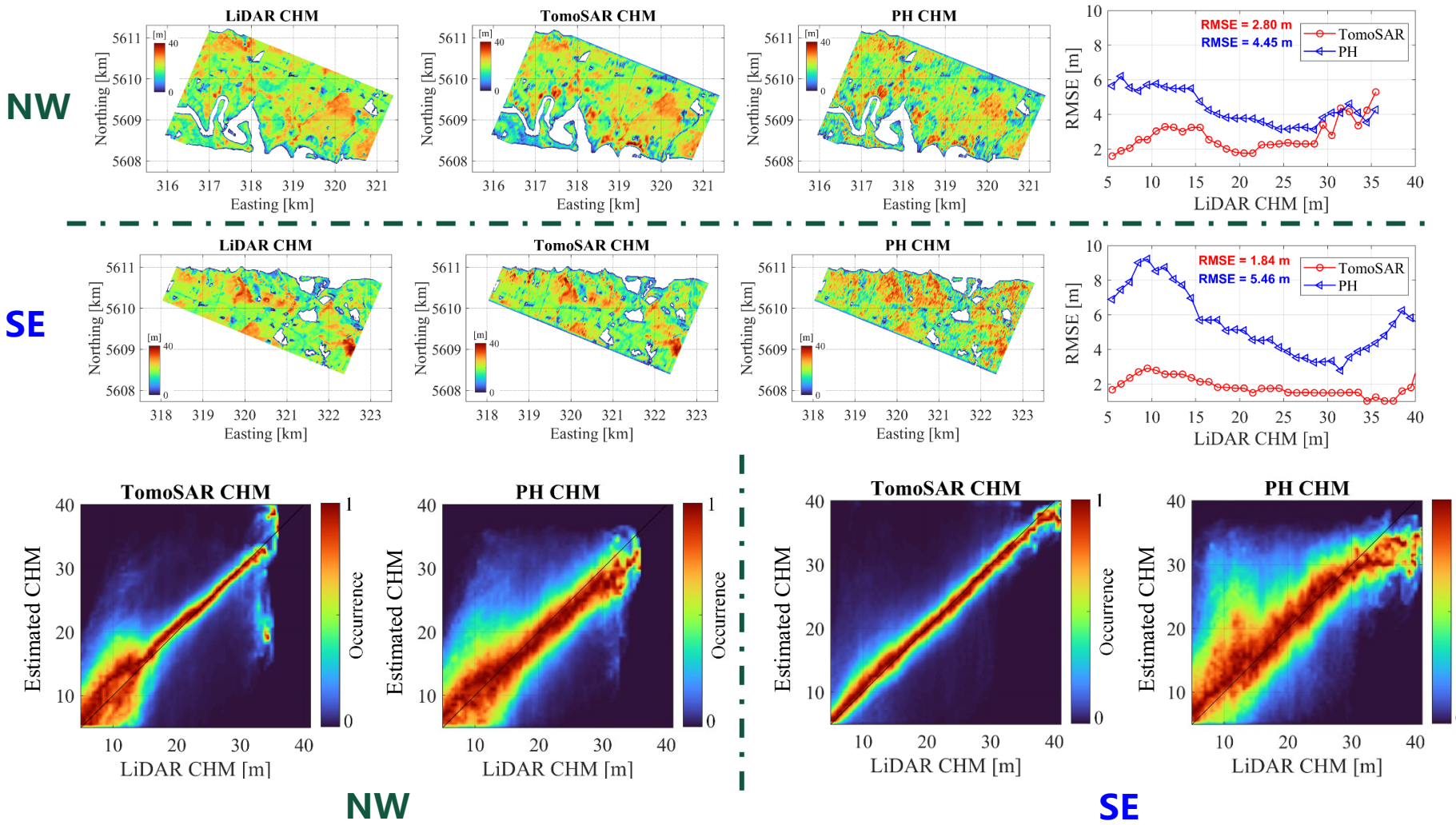


- TomoSAR effectively distinguishes ground and canopy scattering;
- PH profiles exhibit single-layer scattering somewhere between forest canopy scattering and ground signal scattering.



Preliminary results - *YSs research*

1.Evaluating Phase Method in Forested Areas Using L-Band SAR: Theoretical Modeling and Experimental Results



Compared with LiDAR CHM, the average RMSE

- **TomoSAR CHM**

NW：2.80 m

SE：1.84 m

- **PH CHM**

NE：4.45 m

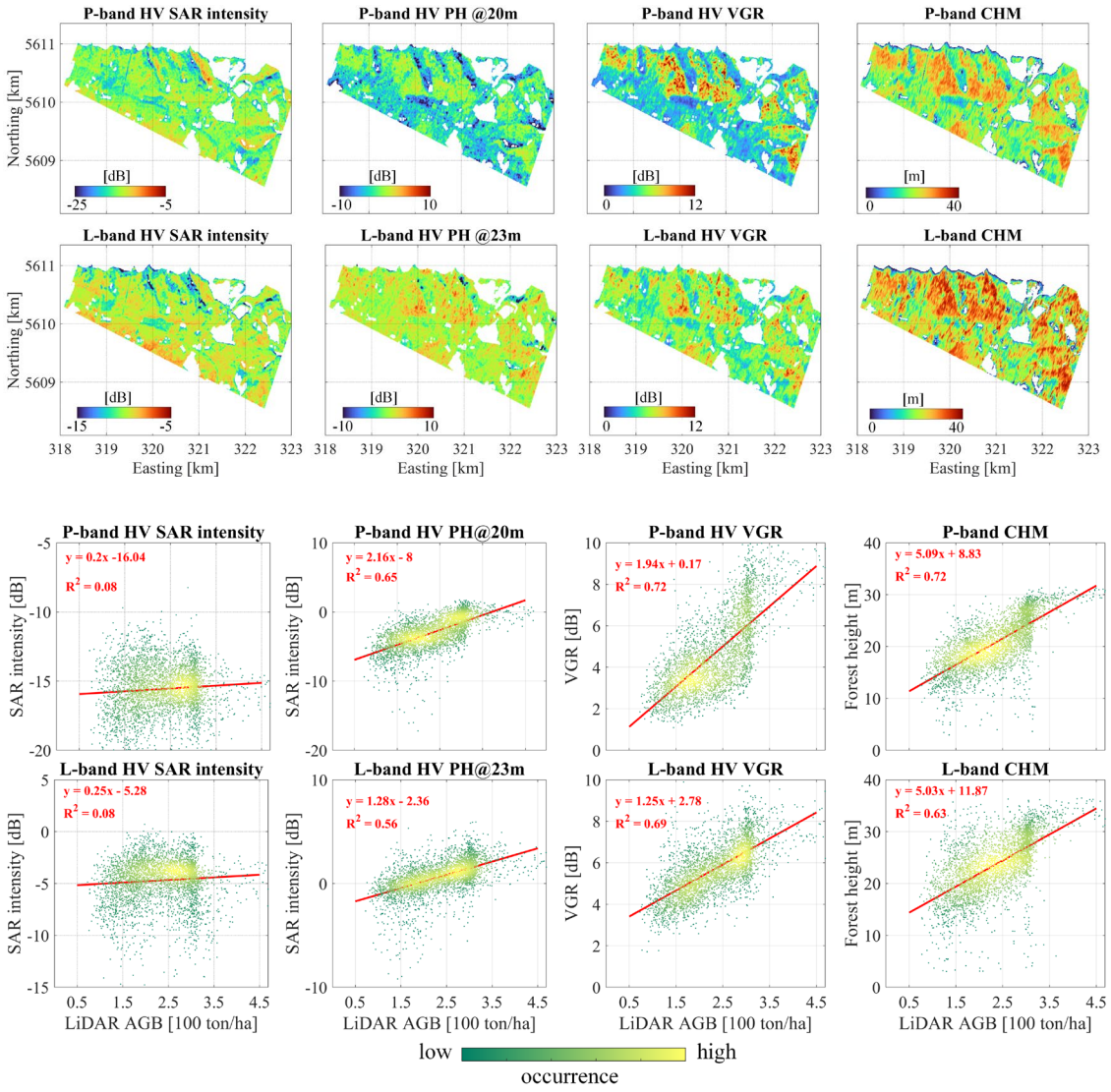
SE：5.46 m

Preliminary results - *YSs research*

2. PH Based Estimates of Above-Ground Biomass

The 3D parameters derived from PH technique present:

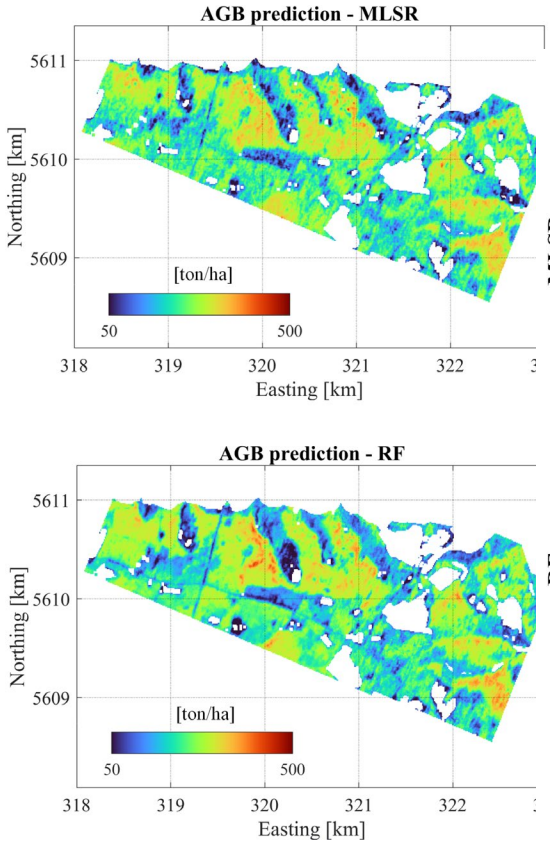
- **a high correlation with AGB;**
- **improved accuracy in forest AGB estimation;**

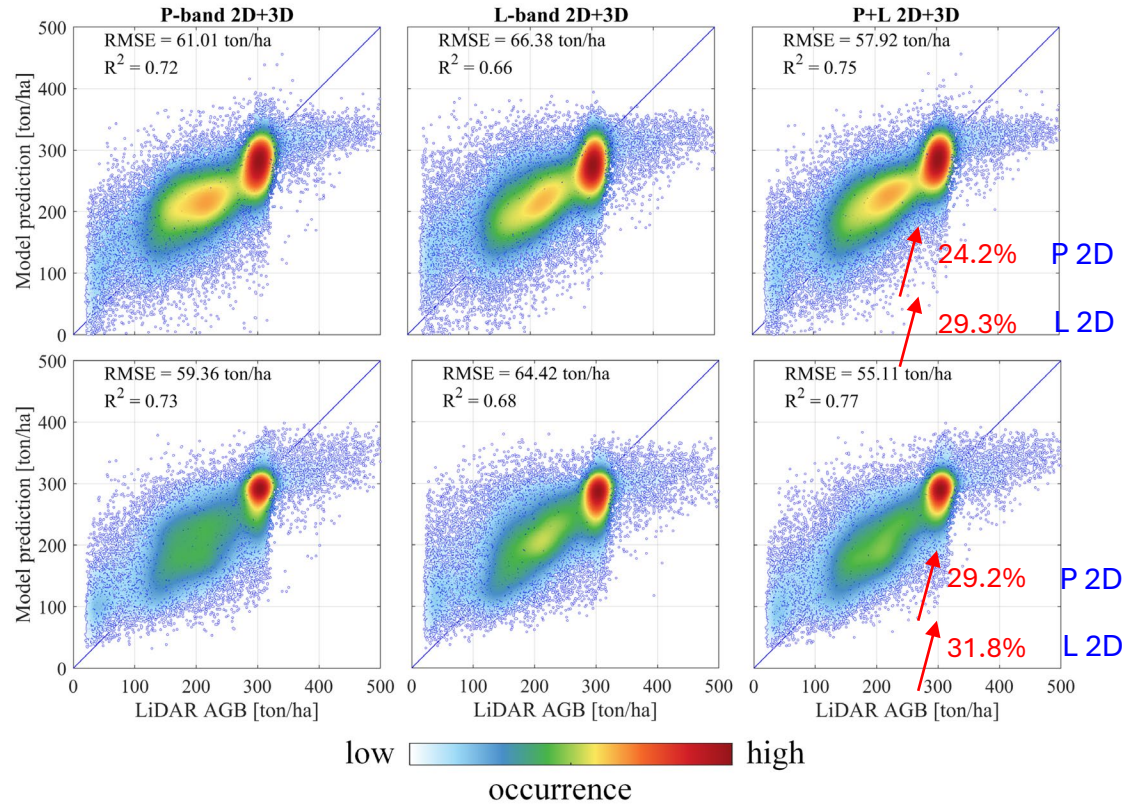


Preliminary results - *YSs research*

2. InSAR-Based Estimation of Forest Above-Ground Biomass Using Phase Histogram Technique

- **Higher accuracy of AGB estimates is achieved by combining 3D parameters from multi-frequency observations.**



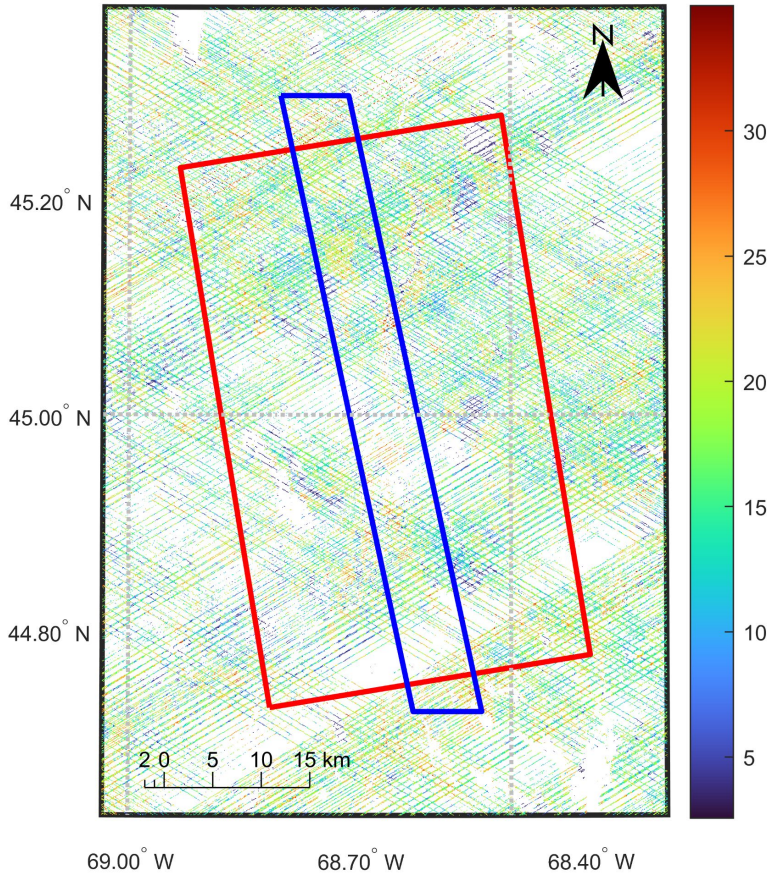


Preliminary results - *YSs research*

Combine TanDEM-X and spaceborne LiDAR data

- **Integrate sparse GEDI data and TanDEM-X to invert ground elevation based on PH technique.**
- **Invert the forest height based on RVoG model.**
- **Promising to add high-resolution information to future BIOMASS coarse-resolution products.**

GEDI Samples of canopy height

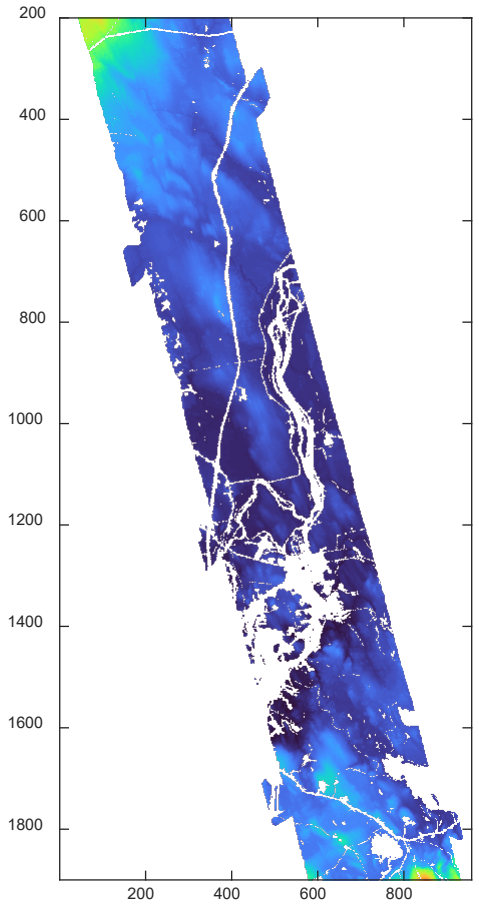


Red box: TDX scene

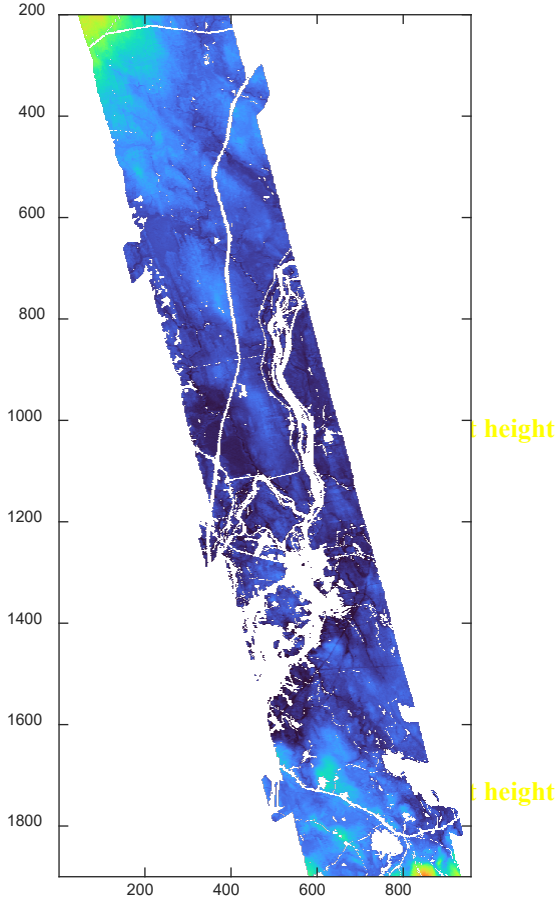
Blue box: LVIS airborne LiDAR

Preliminary results - *YSs research*

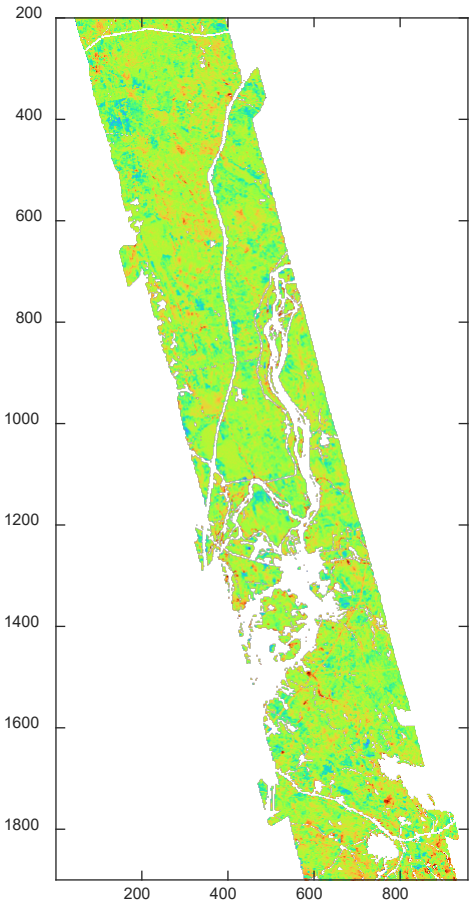
LVIS LiDAR DTM



Our Derived DTM

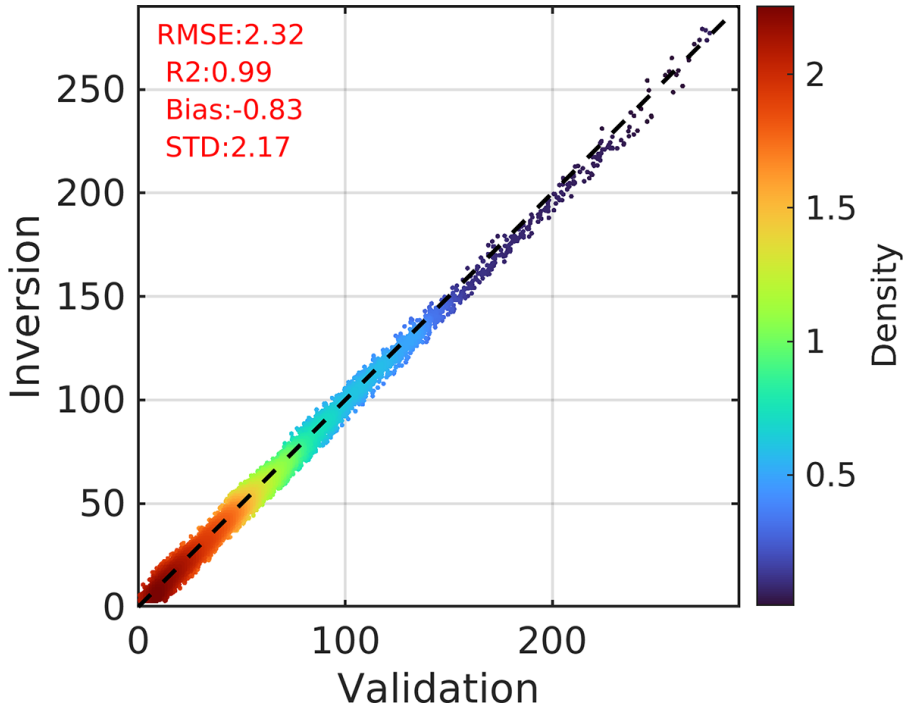


LVIS DTM - Our Derived DTM



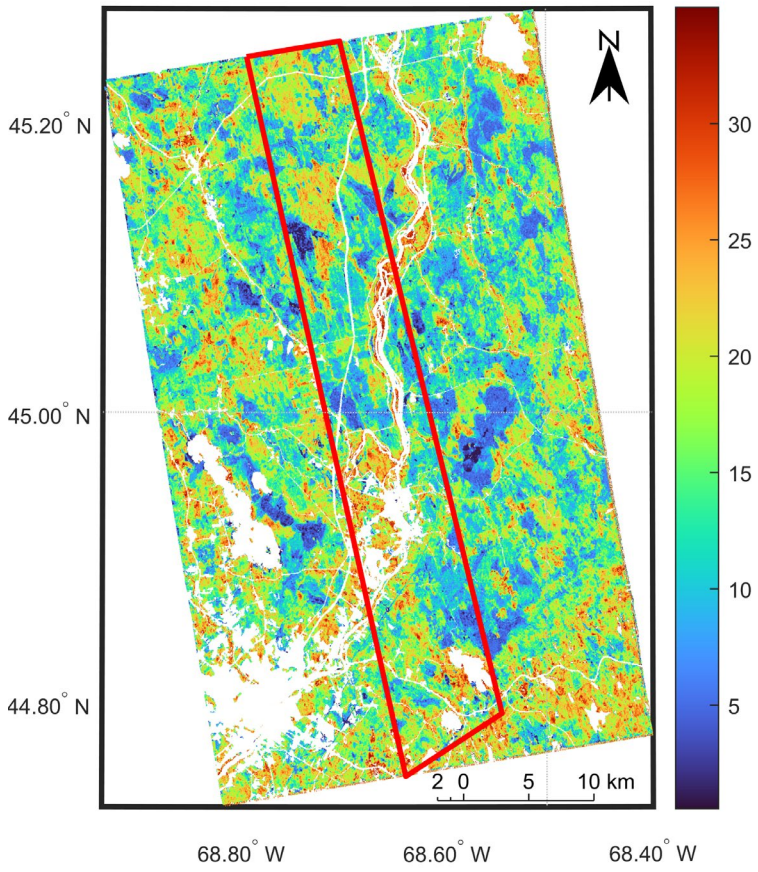
Accuracy Assessment

Statistical pixel size ~0.81ha

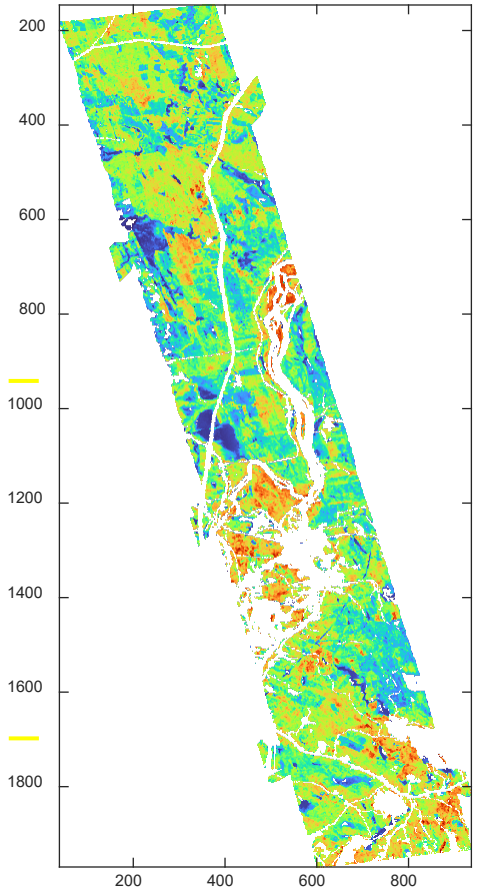


Preliminary results - *YSs research*

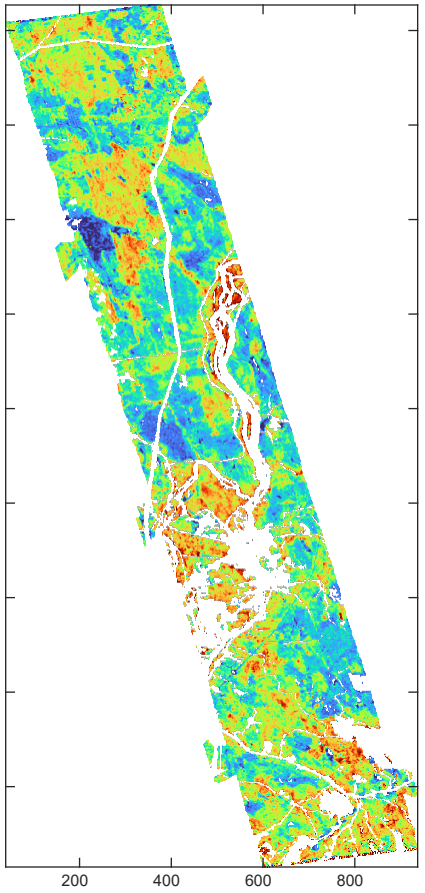
RVoG inversion



LVIS Airborne CHM

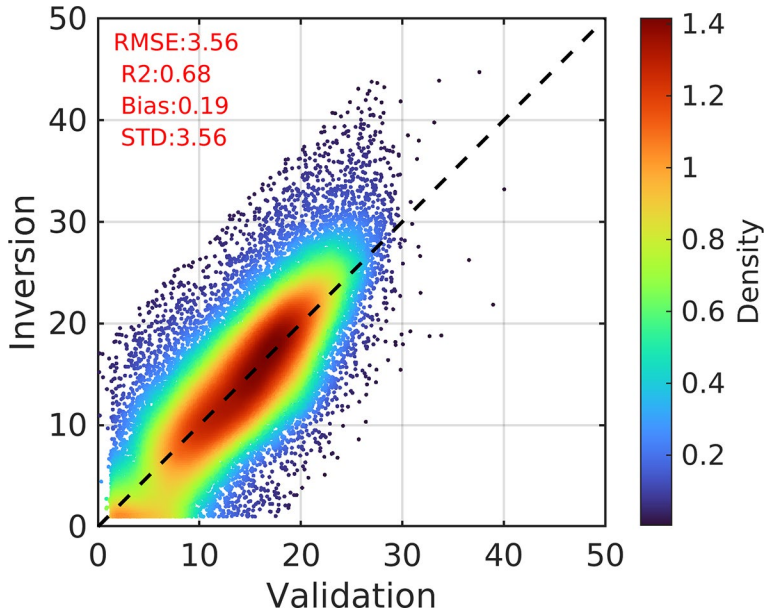


Our Inversion



Accuracy Assessment

Statistical pixel size ~0.81ha

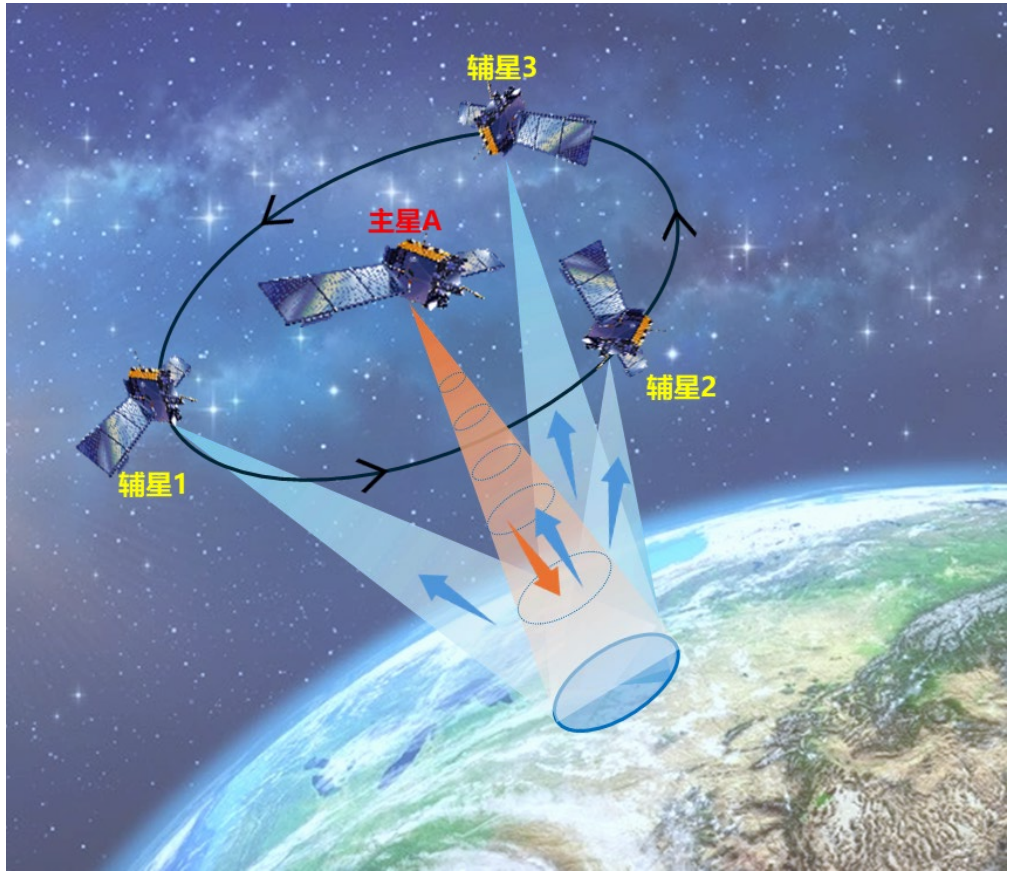


Red box: validation site

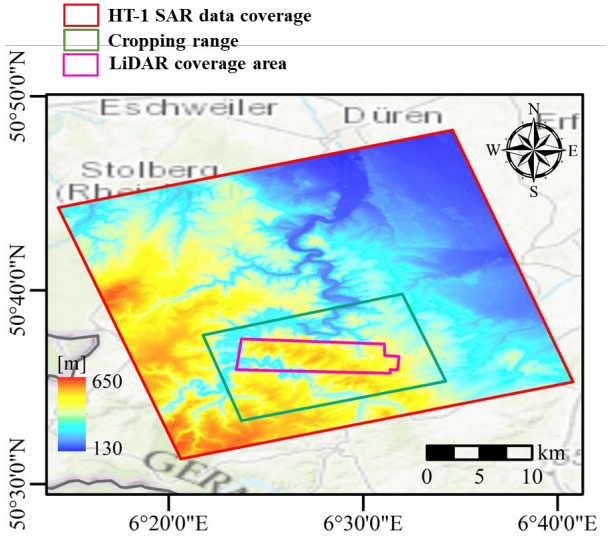
@30m spatial resolution

3. Spaceborne exploration of SAR Phase Histogram Technique

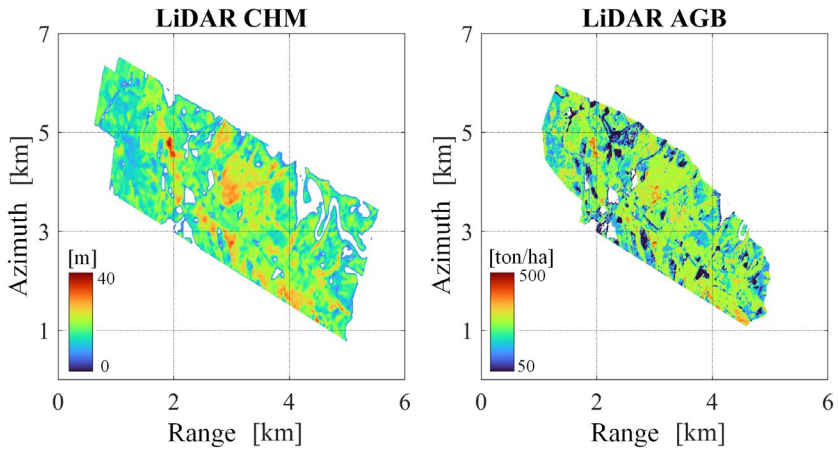
HT-1 SAR satellites flying in a cartwheel formation



The SAR and LiDAR coverage



LiDAR dataset (SAR coordinate)

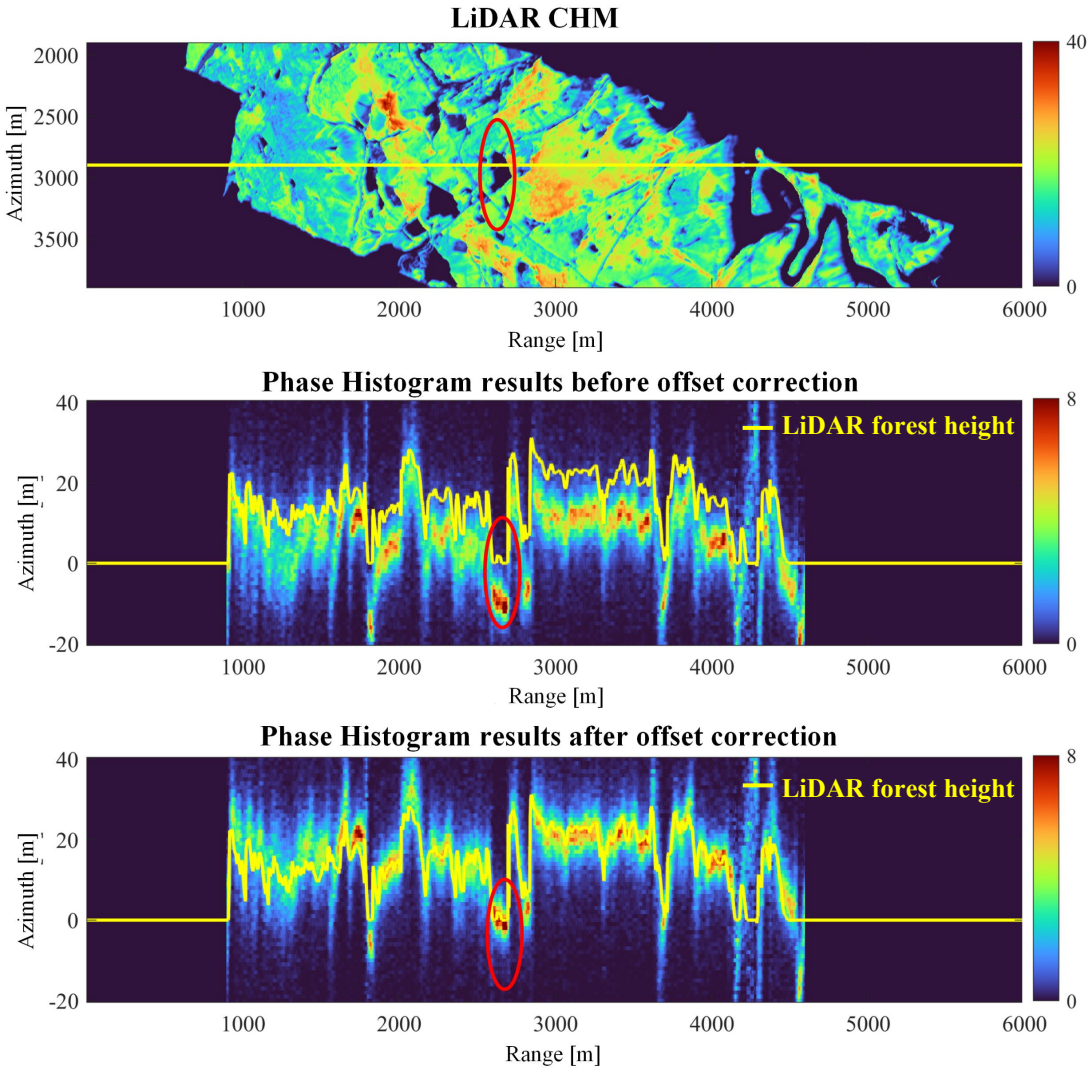


- X-band spaceborne SAR (center frequency of 9.6GHz, chirp bandwidth of up to 600 MHz).
- Four radar satellites flying in a cartwheel formation.
- **Single-transmit, quad-receive** configuration mitigates the effects of **temporal decorrelation** and **atmospheric disturbances**.

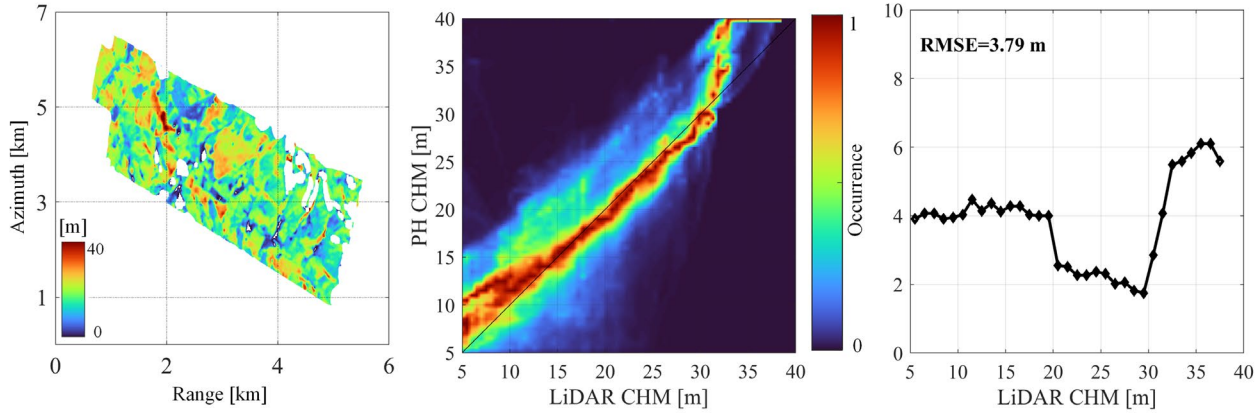
Preliminary results - *YSs research*

3. Verification and Evaluation of Spaceborne SAR Phase Histogram Technique

PH backscatter profiles acquired with the assistance of LiDAR DTM



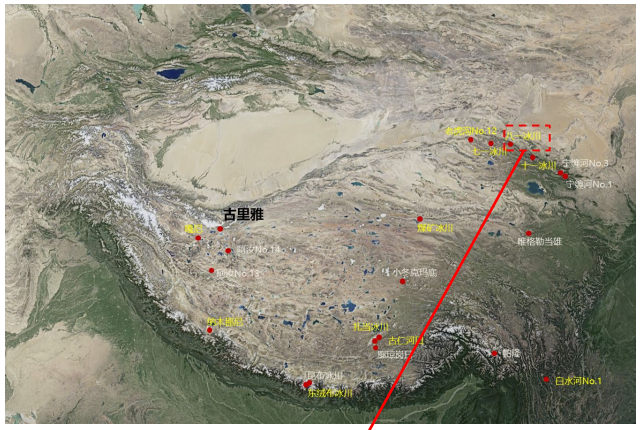
The results of estimated CHM



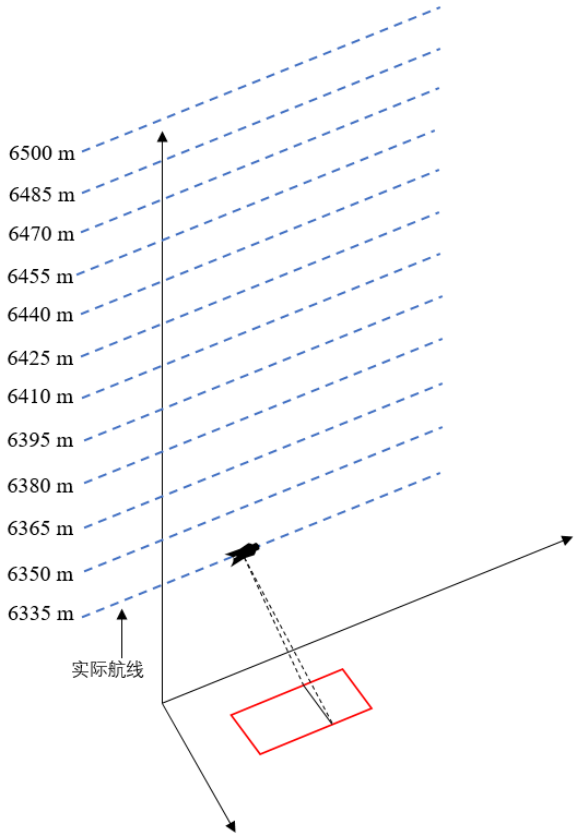
- The PH technique can capture vertical forest structure dominated by canopy scattering.
- In areas with uniform and tall forest canopies, the backscattered energy is more concentrated.
- Sparse forest regions exhibit notable height dispersion.
- With accurate terrain support, the PH technique can provide reasonably accurate forest height products.
- Compared to LiDAR-derived CHM, the PH CHM achieves an average RMSE of 3.79 m.

Preliminary results – *YSs research*

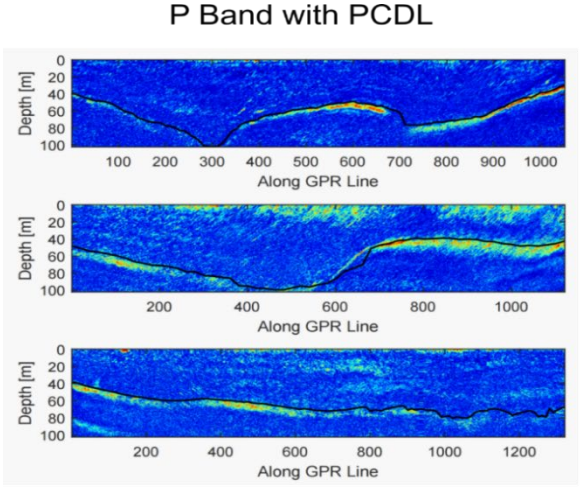
Imaging the Bedrock of a Tibetan Glacier via Chinese L- and P-Band Airborne SAR Tomography

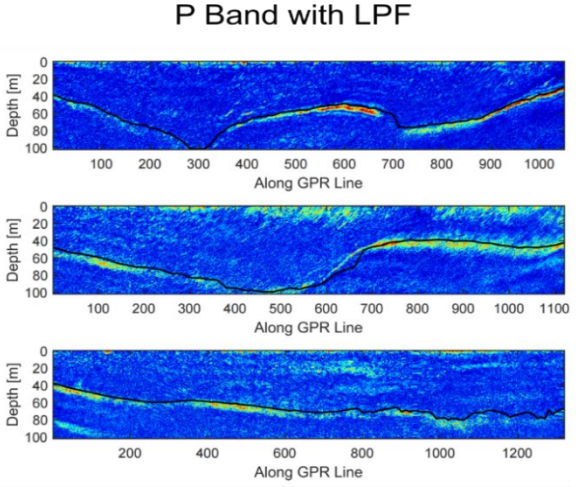


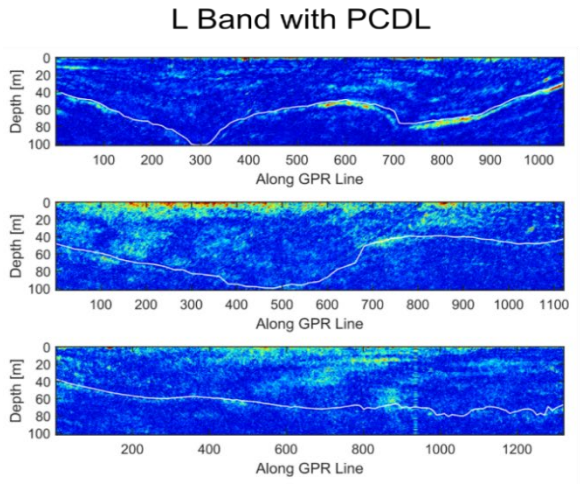
Study Area: Bayi Glacier

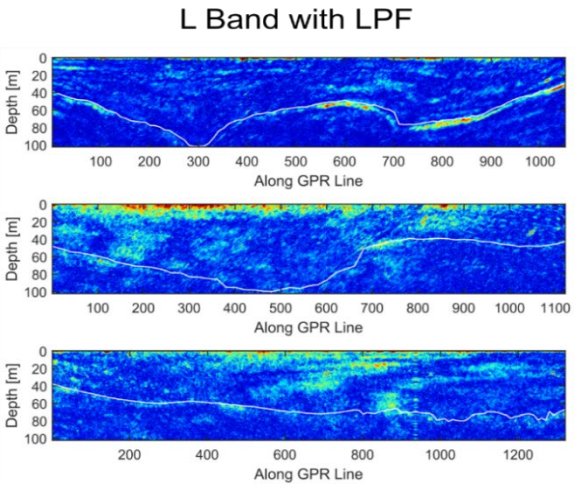


TomoSAR Experiment: 12 flight altitudes with total vertical baseline of 180 m









Preliminary results: 1) P-band is better especially when the depth>50m; 2) PCDL is comparable to LPF method to calibrate the phase errors.

Preliminary results - *YSs research*



P-band SAR imaging results of Saihanba forest based on GPU-accelerated TDBP



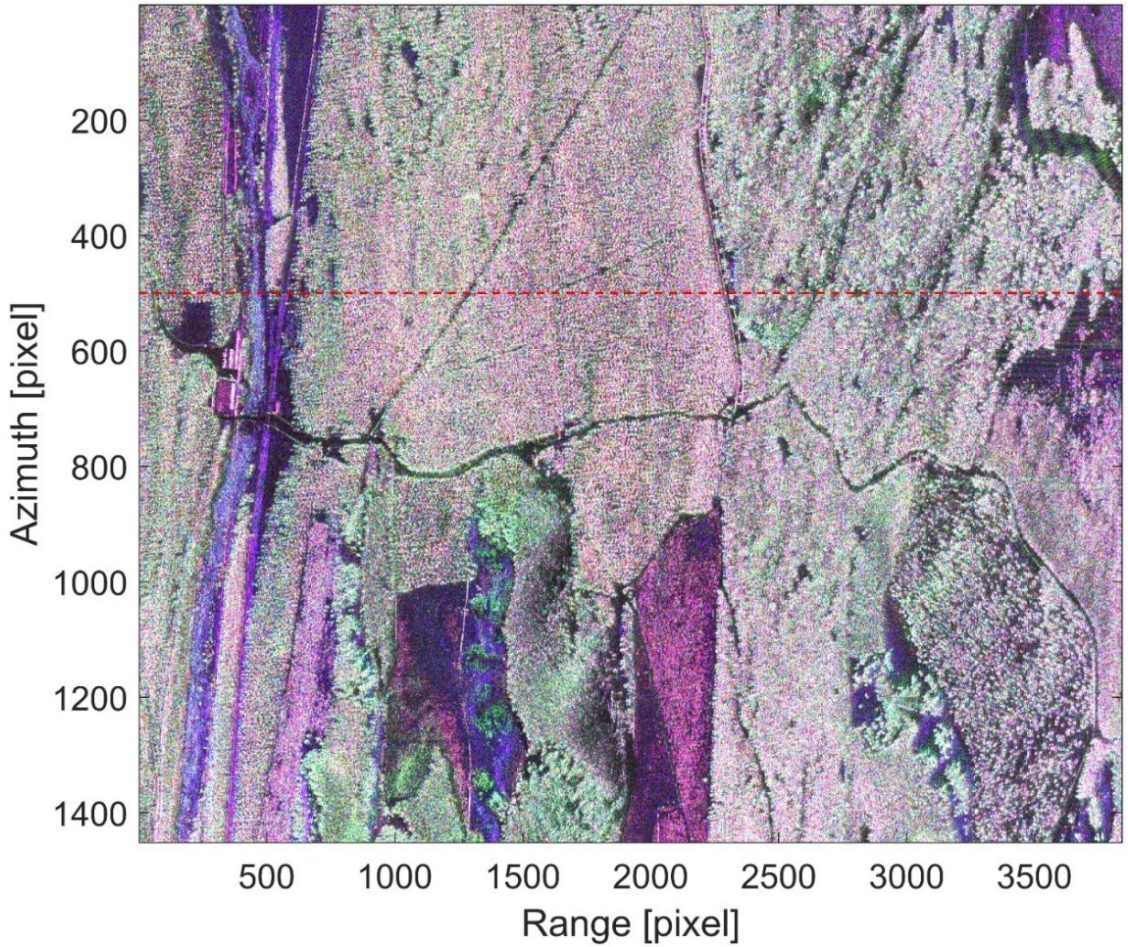
Zoomed-in view of the red box

- Resolution (azimuth x ground range): 0.9m x 1m
- Sampling (azimuth x ground range): 0.5m x 0.5m

- Block size: 1024 x 1024
- CPU(i7-12700F):323s → GPU(RTX3070):14s
- Speedup of 22×
- C++ & CUDA

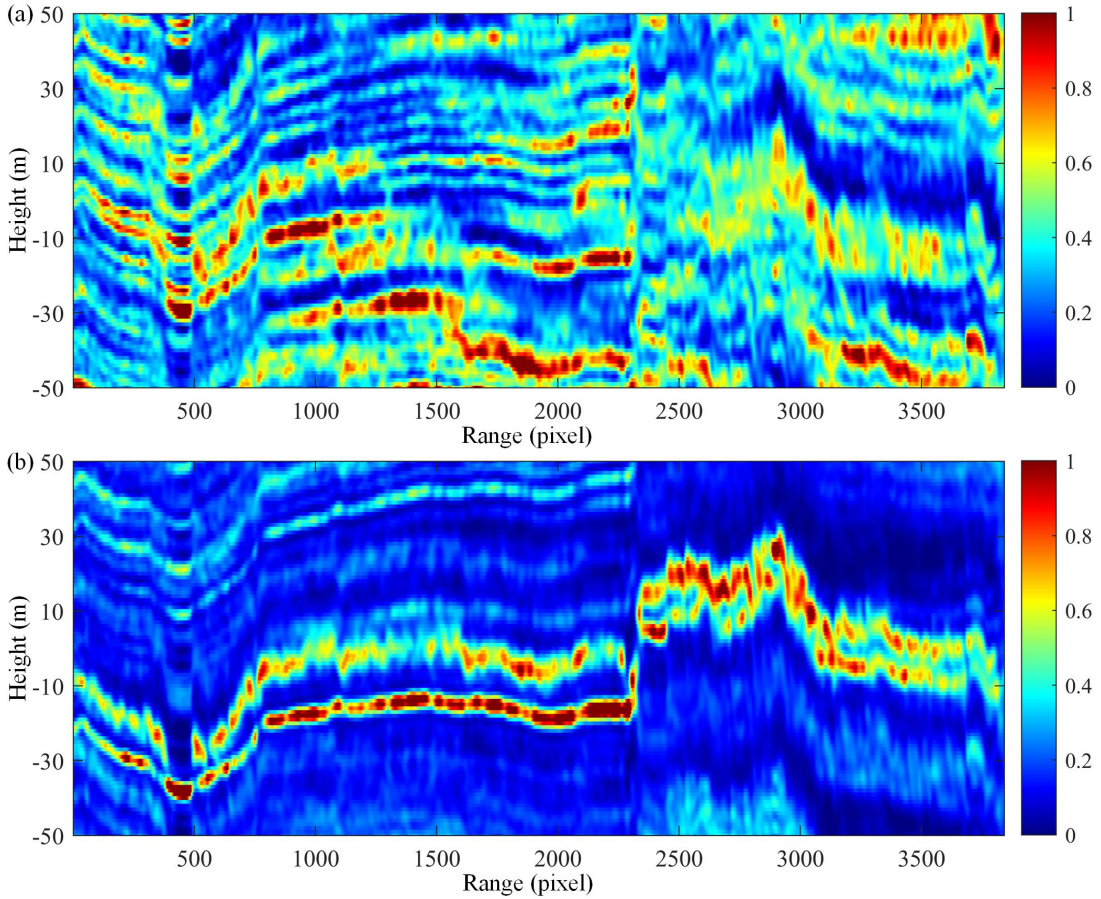
GPU-based TDBP algorithm for SAR imaging

Preliminary results - *YSs research*



SAR reference image in Pauli false color

- 12 flights to achieve TomoSAR imaging
- Resolution of 0.9 m (azimuth) × 0.75 m (range) × 5 m (elevation)

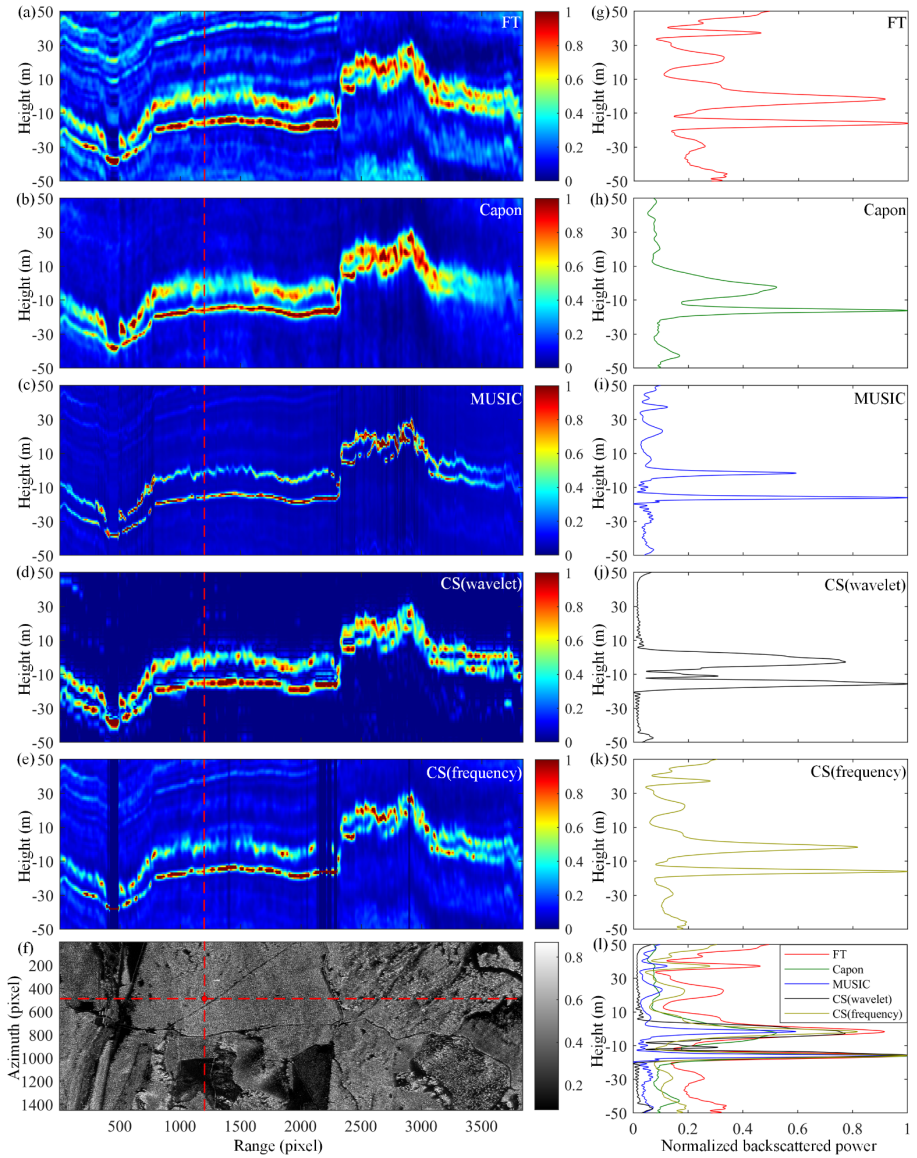


TomoSAR vertical profile of the read dashed line by Fourier transform (a) without phase calibration and (b) with phase calibration by PCDL.

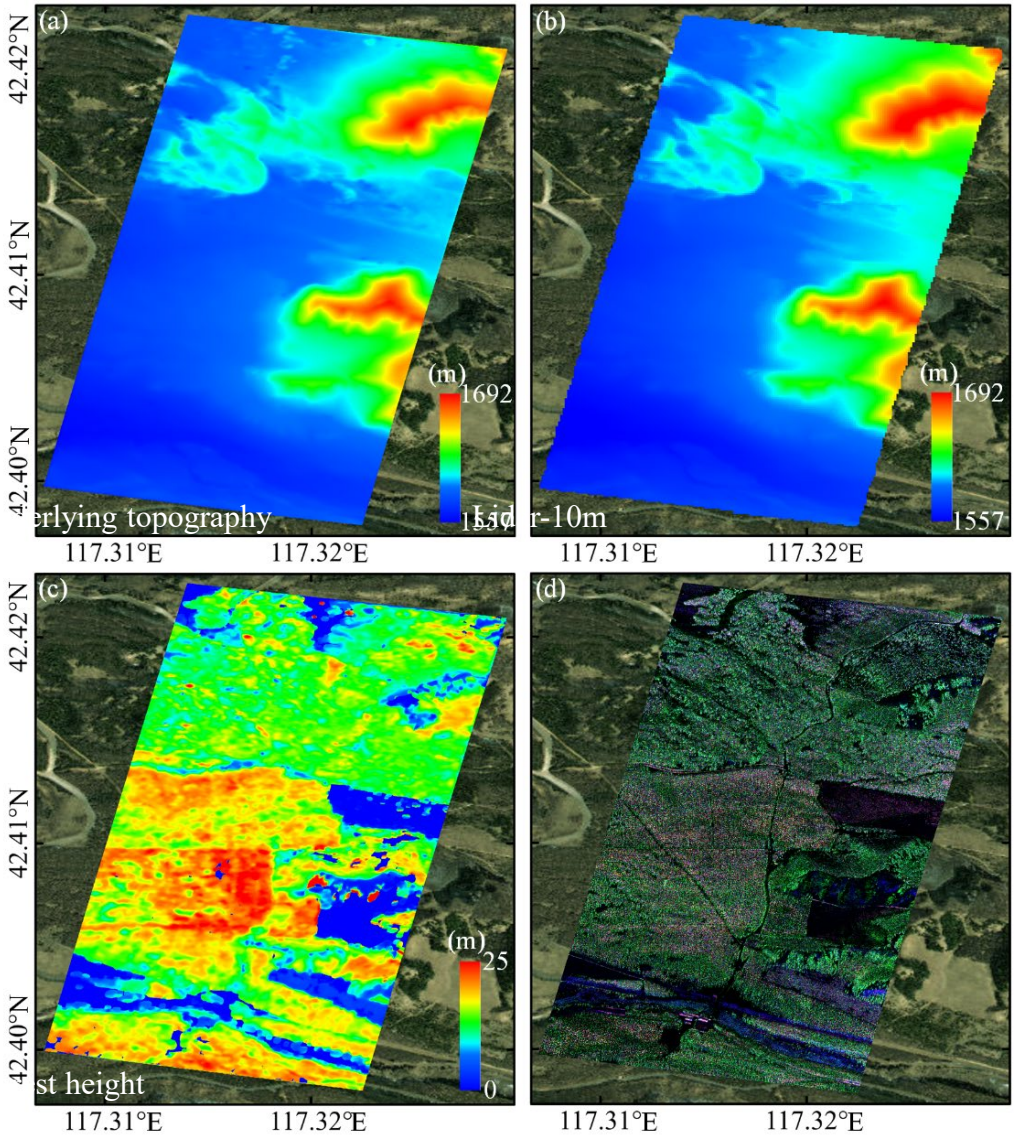
Phase calibration and TomoSAR imaging

Preliminary results - *YSs research*

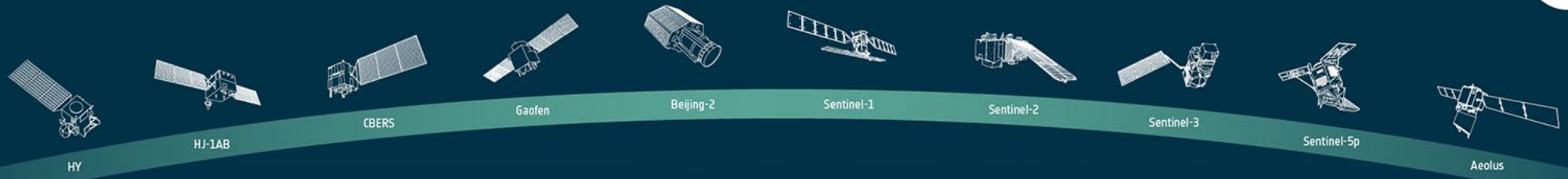
Imaging algorithms comparison and parameters inversion



Comparison of TomoSAR 3D imaging algorithms



Retrieved underlying topography and forest height by TomoSAR



THANK YOU FOR YOUR ATTENTION !

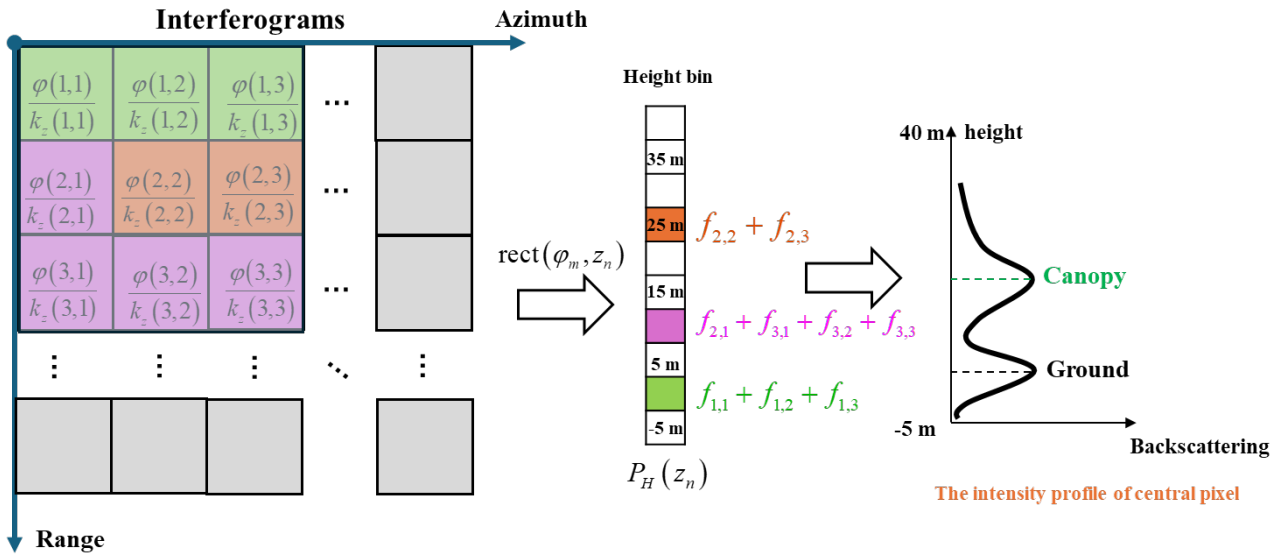
PROJECT ID. 95358

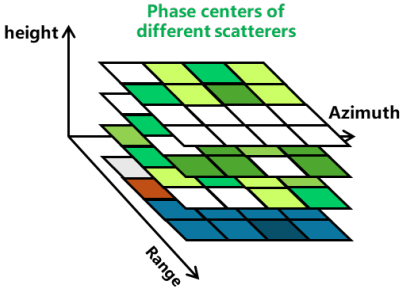
GEOPHYSICAL AND GEODETICS RETRIEVAL FROM SAR DATA STACKS OVER NATURAL SCENARIOS

Preliminary results - *YSs research*

For Single-baseline and Single-polarization InSAR data:

Can phase histogram technique detect forest vertical structure and invert biophysical parameters?





3D vertical structure



Forest height



AGB

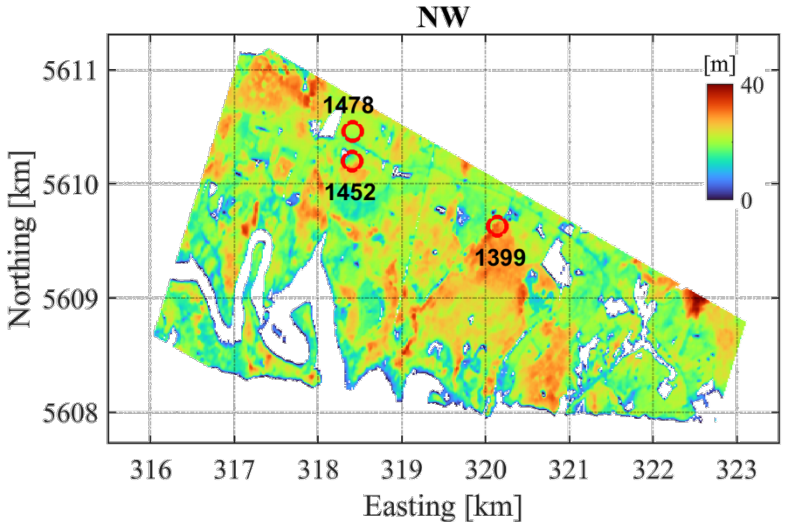
$$P_H(z_n) = \sum_{m=1}^{M} f_m \cdot \mathrm{rect}(\varphi_m,\ z_n)$$

$$\mathrm{rect}(\varphi_m, z_n) = \begin{cases} 1, & \text{if } z_n - \dfrac{\Delta z}{2} < \dfrac{\boldsymbol{\varphi_m}}{\boldsymbol{k_z}} \le z_n + \dfrac{\Delta z}{2} \\ 0, & otherwise \end{cases}$$

Preliminary results - *YSs research*

1.Evaluating Phase Histograms for Remote Sensing of Forested Areas Using L-Band SAR: Theoretical Modeling and Experimental Results

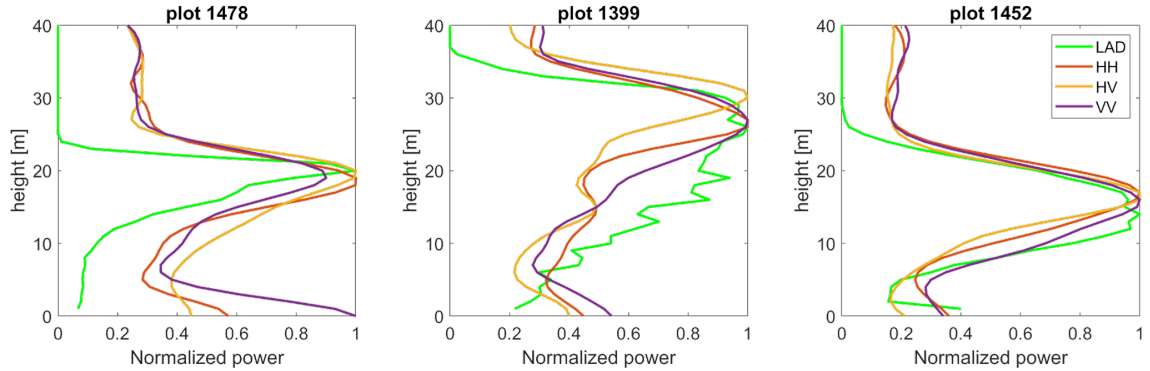
Both algorithms are validated based on L-Band tomographic data acquired by MetaSensing in 2020 at the Eifel Park, North-West Germany, in the context of the ESA campaign TomoSense.



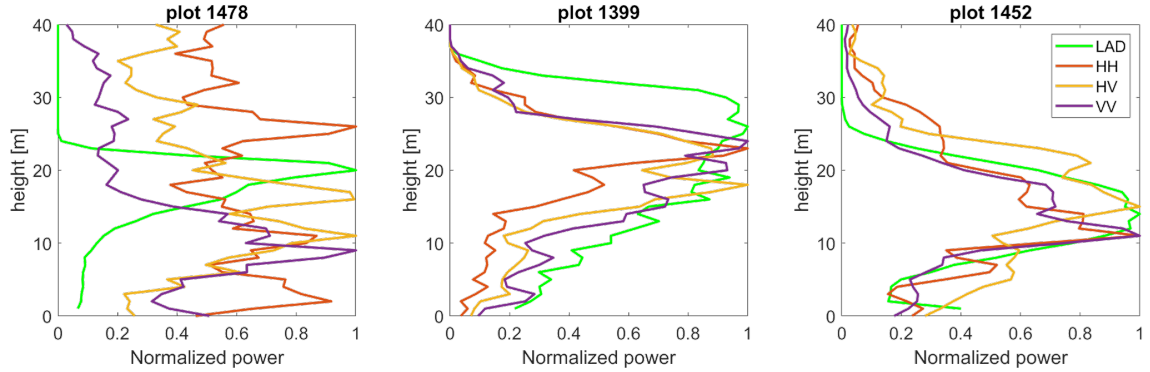
Red circle: TLS plot (25 m radius)

Evaluating Phase Histograms for Remote Sensing of Forested Areas Using L-Band SAR: Theoretical Modeling and Experimental Results,

TLS vs TomoSAR



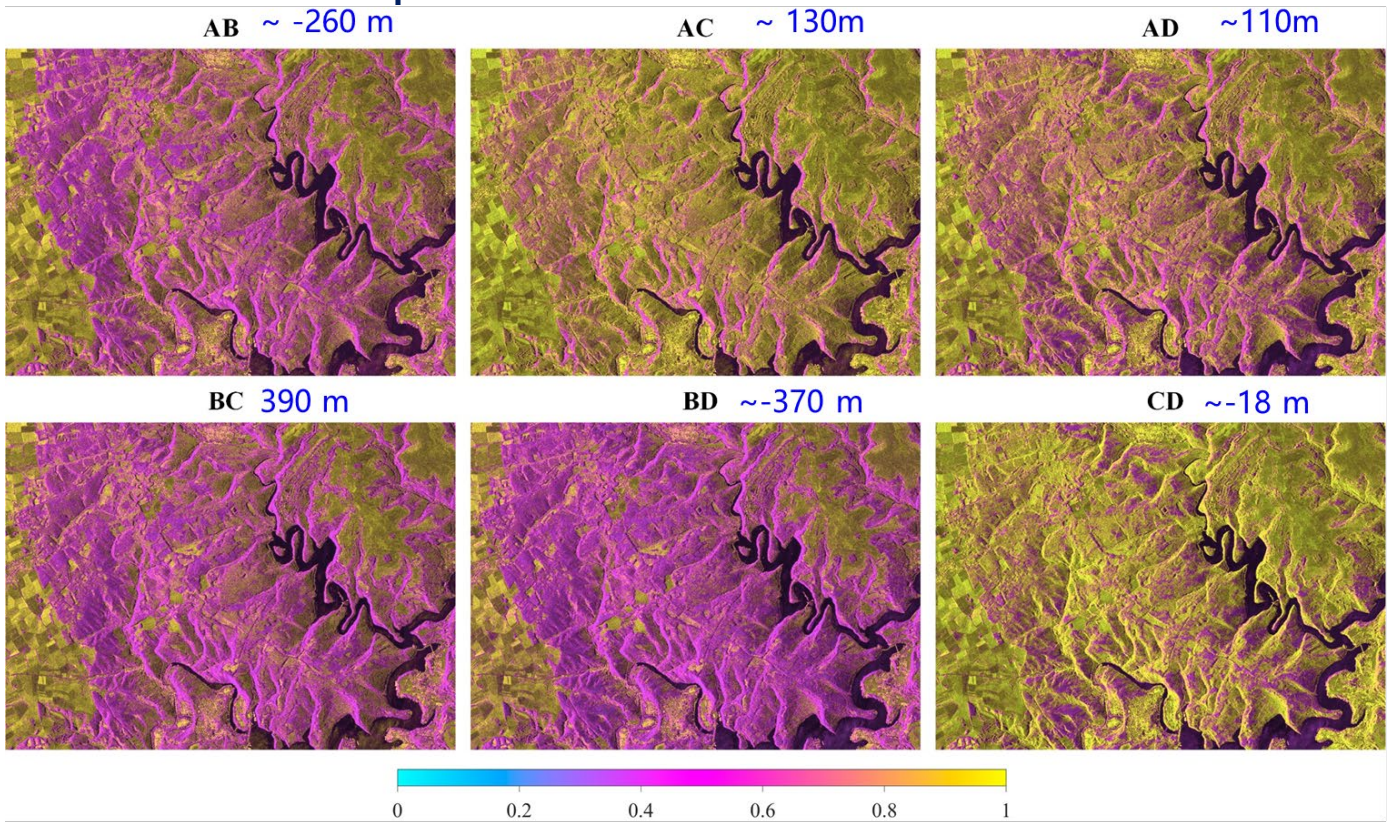
TLS vs Phase Histograms



3. Verification and Evaluation of Spaceborne SAR Phase Histogram Technique

The basic parameters of HT-1 SAR images		
PARAMETERS	**Value**	
Sensor	HT1-A/B/C/D	
Acquisitions date	2024, 07, 16	
Bandwidth	**9.6 GHz(X-band)**	
Polarization	HH	
Pixel spacing (range)	0.75 m	
Pixel spacing (azimuth)	1.33 m	
Resolution (azimuth)	**3 m**	
Resolution(range)	**<3 m**	
Baseline (m)	AB: ~ -260 AC: ~ 130 AD: ~ 110	BC: ~ 390 BD: ~ 370 CD: ~ -18
Kz (rad/m)	AB: ~ -0.175 AC: ~ 0.087 AD: ~ 0.074	BC: ~ 0.262 BD: ~ 0.248 CD: ~ -0.012
Platform altitude	~ 528 km	
Incidence angle	29.5°	

Comparison of coherence under different baselines

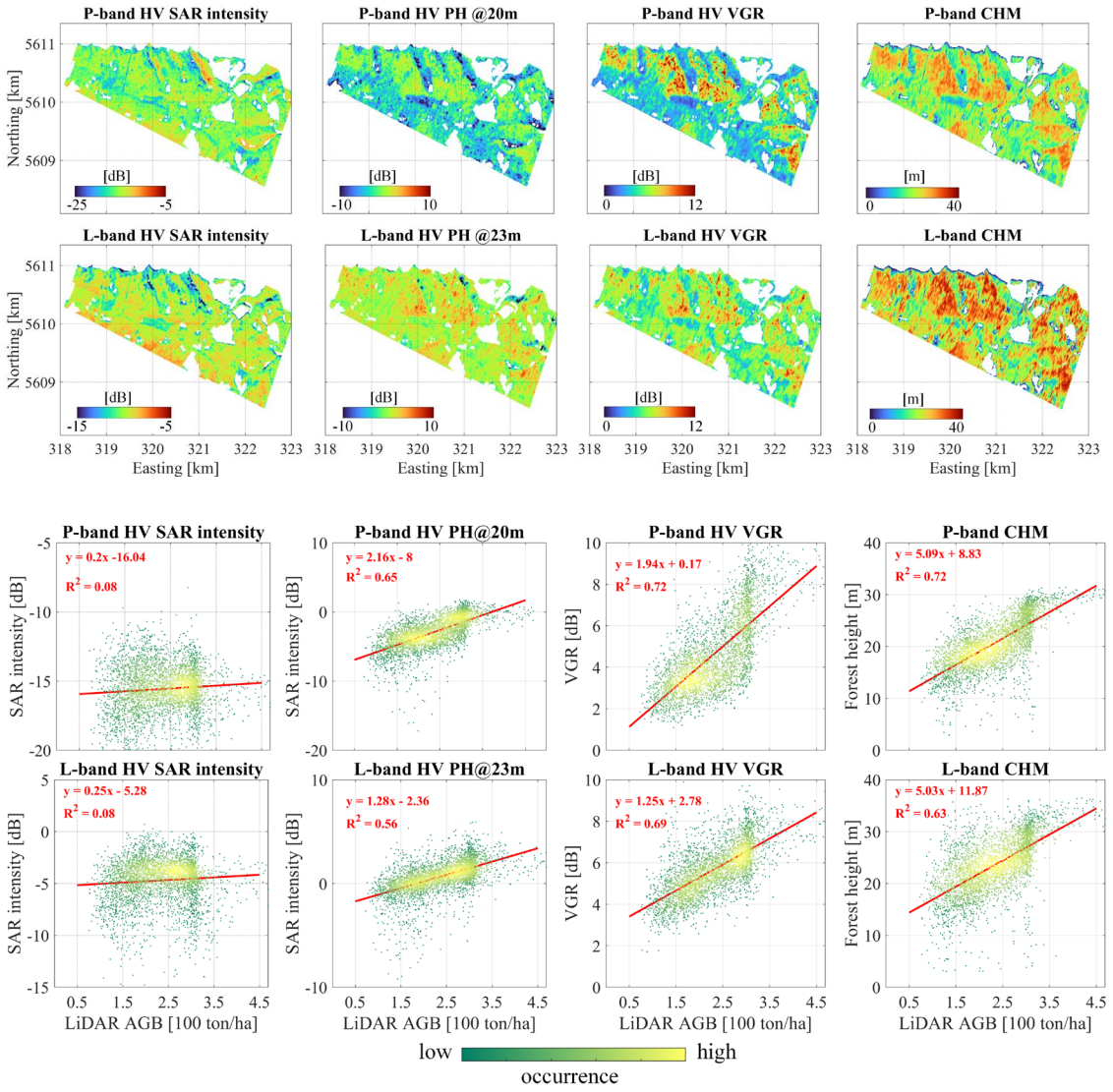


- Longer baselines → lower coherence.
- Decorrelation occurs in areas with rough terrain, vegetation, or shadow.
- **AC** is the best-suited baseline for PH-based forest parameters retrieval, based on **baseline length** and **coherence**.

Preliminary results - *YSs research*

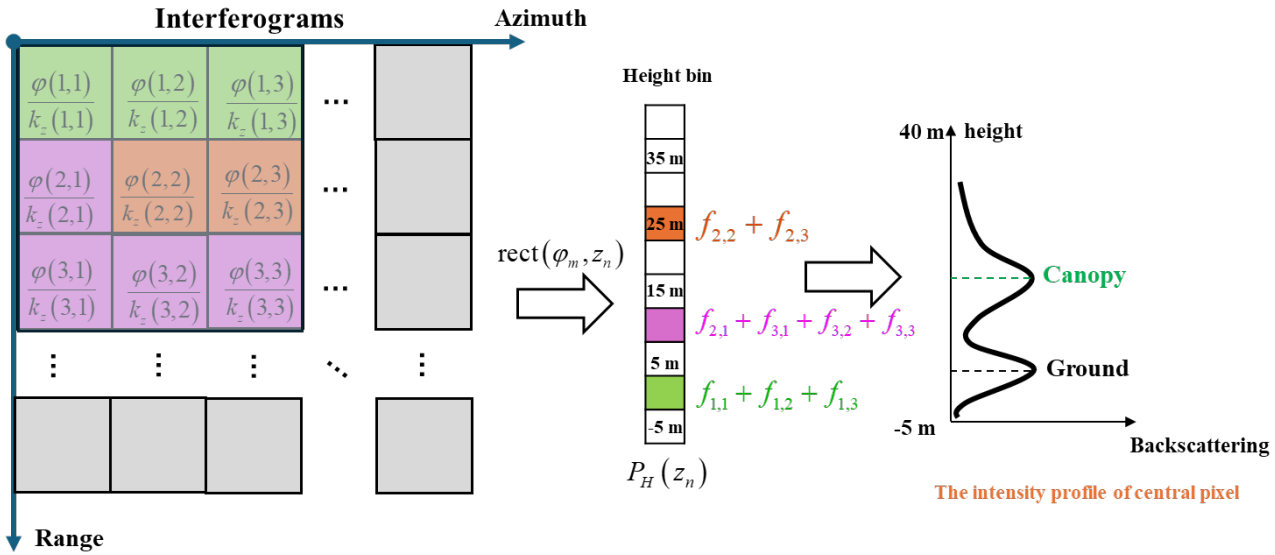
2. PH Based Estimates of Above-Ground Biomass

- A clear saturation problem is observed in the relationship between SAR intensity and AGB.
- The 3D parameters derived from PH technique show a strong positive correlation with AGB.
- PH-derived vertical structural features support improved accuracy in forest AGB estimation.



Preliminary results - *Chinese YSs research*

Can phase histogram technique detect forest vertical structure and invert physical parameters (√)



Conclusion

1. The PH technique can effectively reconstruct low-resolution forest vertical structure and generate reliable forest height products under condition **where a dominant scatterer exists within the SAR resolution cell.**
2. The PH technique effectively improves **the estimation accuracy of forest AGB** and provides reliable parameters reflecting vertical forest structure.
3. **With accurate sub-canopy terrain**, the PH technique enables effective retrieval of forest canopy structure and height from **high-resolution, high-frequency spaceborne SAR data**.

Preliminary results - *YSs research*

2. InSAR-Based Estimation of Forest Above-Ground Biomass Using Phase Histogram Technique

- **Higher accuracy is achieved by combining multi-frequency bands with 2D and 3D parameters for AGB regression.**

