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Republic of Poland

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EUROPEAN SPACE AGENCY

15 - 19 June 2026 | Auditorium Maximum of the Jagiellonian University, Kraków, Poland

FRINGE 2026

BIOMASS Digital Terrain Model Retrieval

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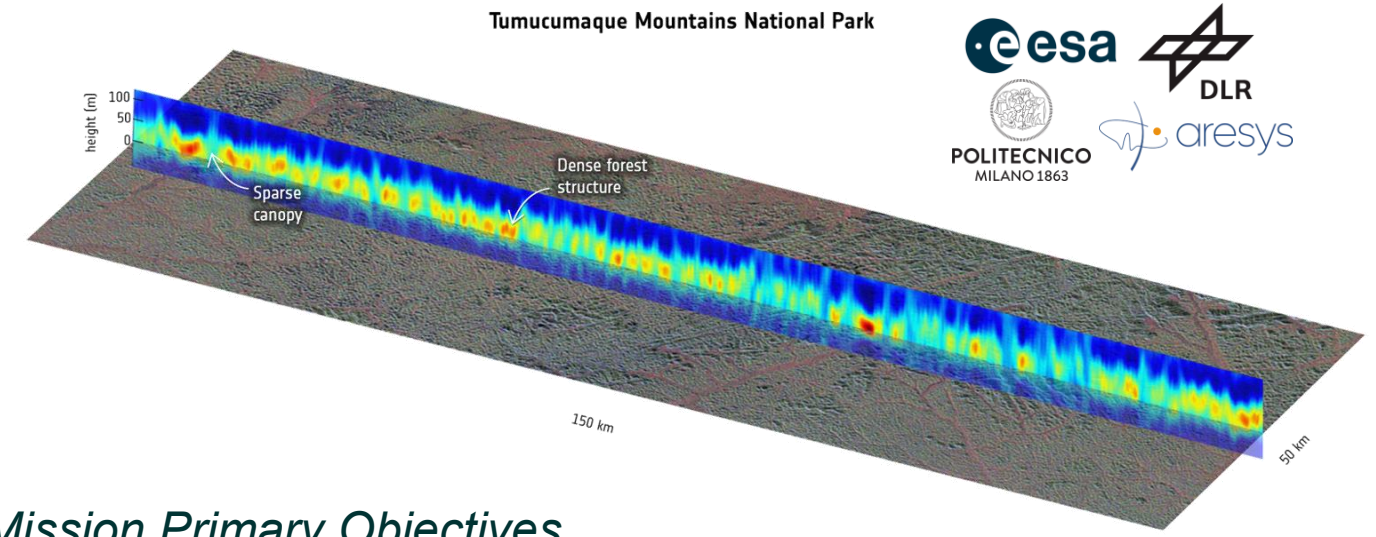
BIOMASS

Launched April 29, 2025, ESA's seventh Earth Explorer Mission, *BIOMASS*, carries the **first P-band SAR ever flown in space**, to gather fully polarimetric acquisitions over forested areas worldwide in interferometric and tomographic modes

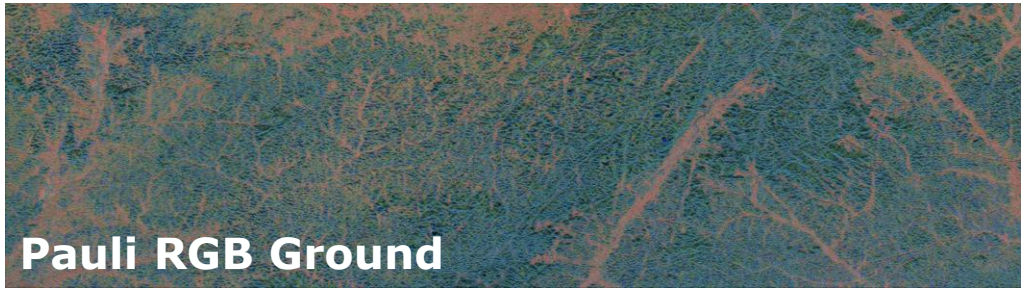


Mission Primary Objectives

- to determine the distribution of aboveground biomass in the world's forests
- to measure annual changes in this stock over the period of the mission

P-Band waves ($\lambda = 70\,cm$) penetrate the vegetation layer down to the underlying terrain, while giving rise to backscattering from trunks and branches

⇒ *P-Band provides sensitivity to the whole forest vertical structure*, as demonstrated by 3D tomographic analyses



BIOMASS Interferometry

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Retrieval of forest products and experimental processing (ice, desert) largely relies on ***interferometry***:

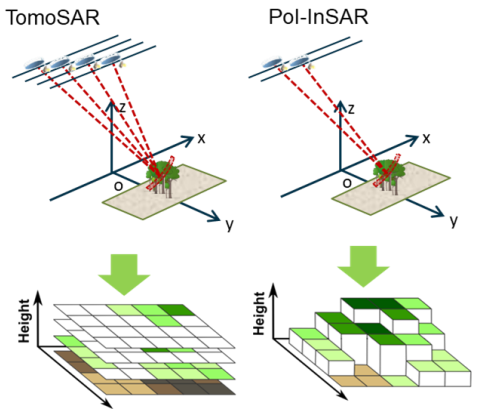
- *stacks of 7 acquisitions in TOM phase*
  - *15% of critical baseline spacing*
  - *vertical resolution of about 23 m (at the equator)*
- *stacks of 3 acquisitions in INT phase*
  - *30% of critical baseline spacing*
- *revisit of 3 days*

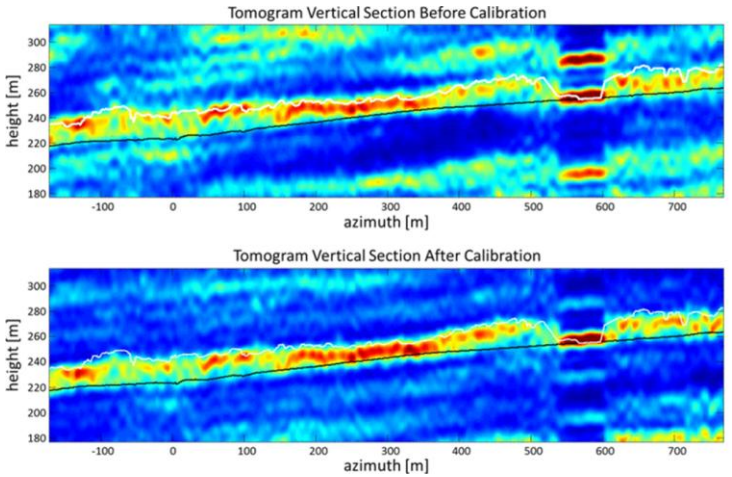
Polarimetric diversity helps in characterization/calibration:

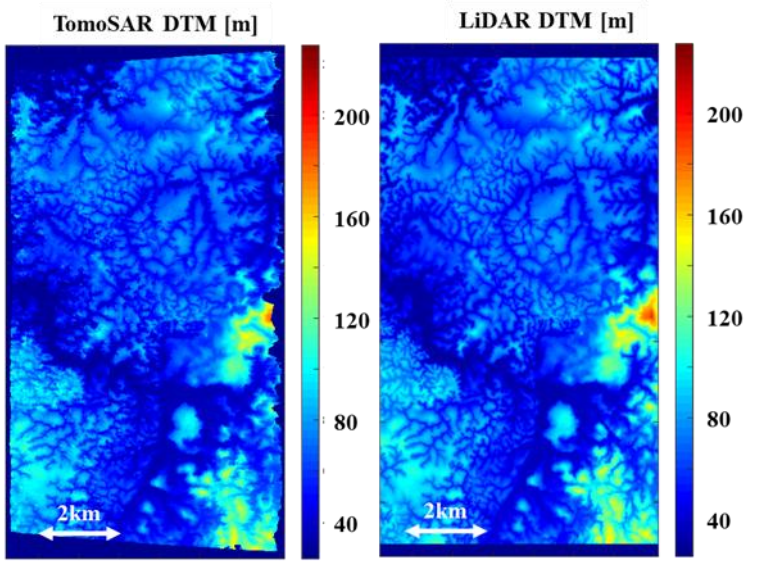
- *ground phase locking*
- *forest/scenario properties*

Level-1 stacks are coregistered and ***phase calibrated***:

- *correction of ionosphere, baseline errors, troposphere*



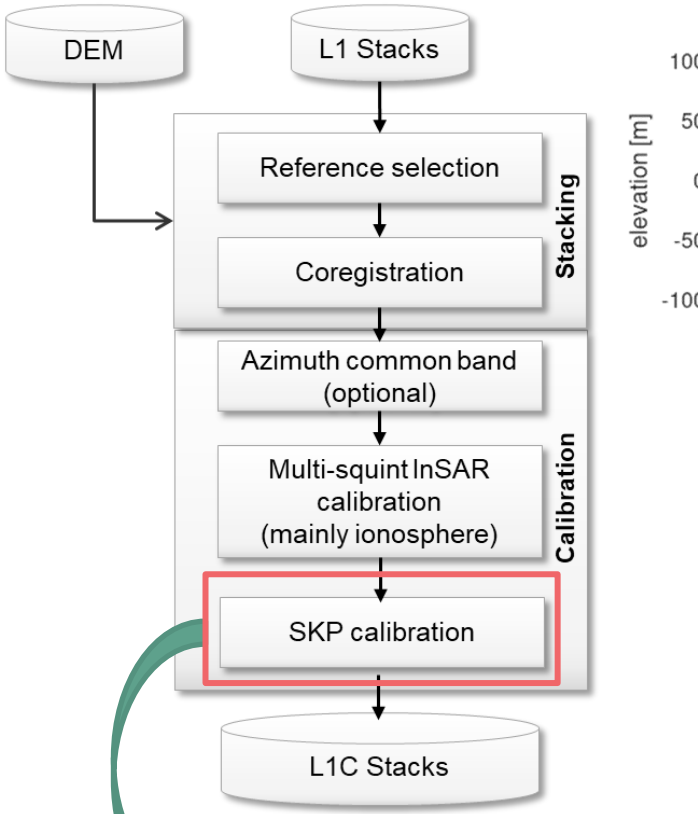




DTM from AfriSAR (Gabon)

Unprecedented opportunity for **under-canopy DTM estimation**!

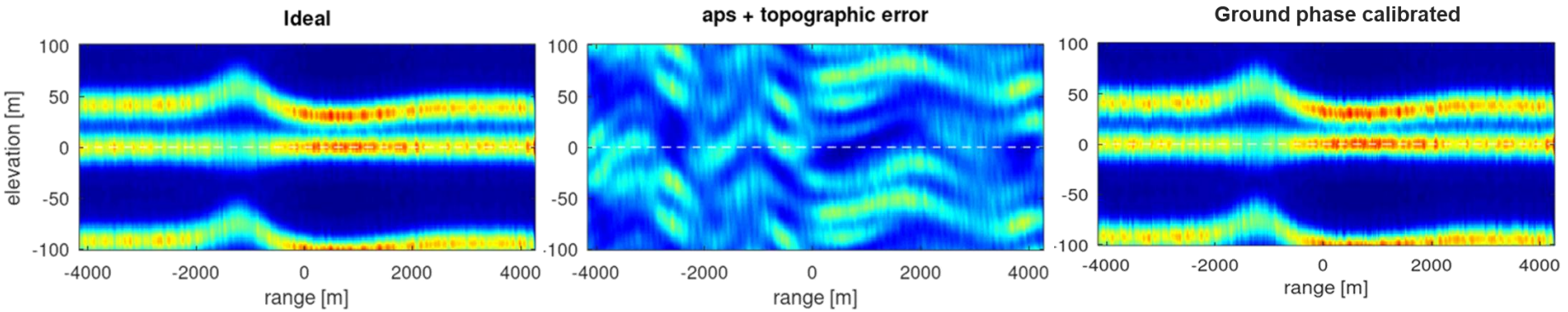
BIOMASS ground phases



$$\widehat{\varphi}_i^{GR} = k_z^i z_{GR} + \alpha_i$$

Terrain — Phase screen

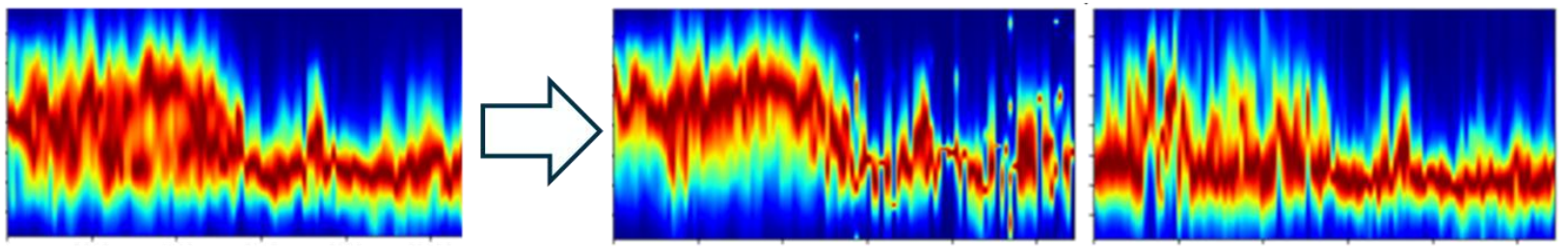
InSAR wavenumber

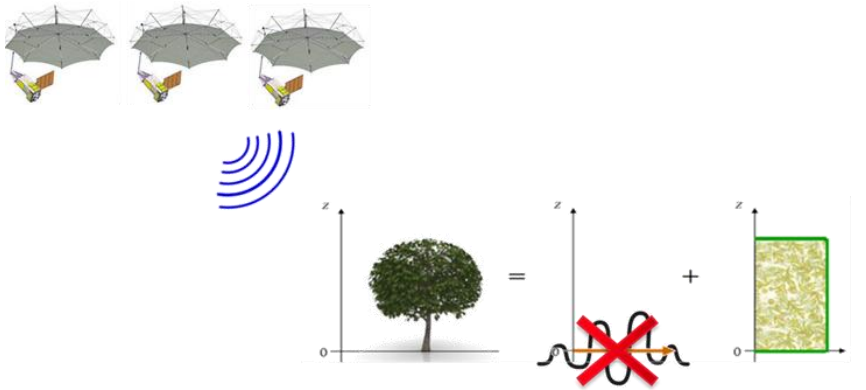


- Ground phases contain *residual low-pass screens* and *terrain phase*
  - estimated from BIOMASS InSAR processor (after ionospheric calibration)
  - residual low-pass screens are mostly due to troposphere
- Ground phase calibrated stacks are Level-2 and *Tomography ready*
  - **phase calibration and ground steering to zero**
- **Ground phase is a proxy for DTM estimation**
- Estimation is currently based on SKP decomposition

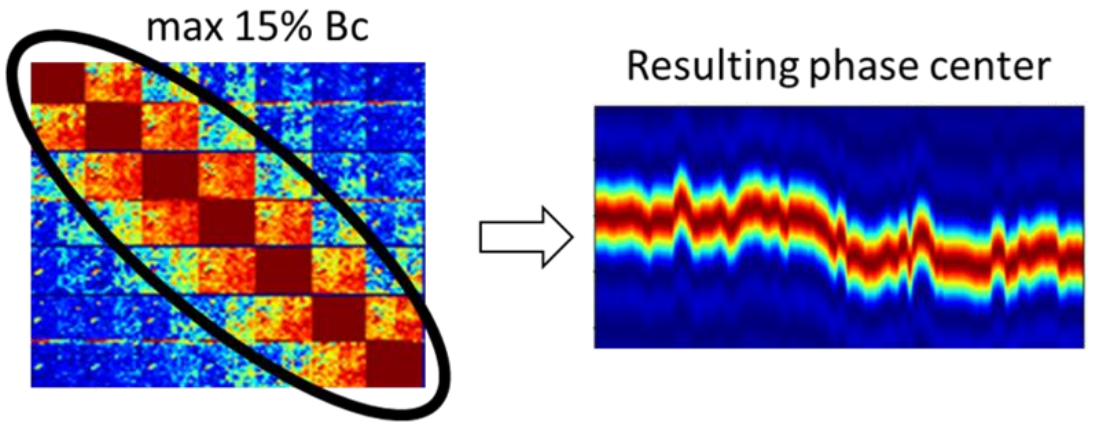
Ground phase estimation

- **SKP decomposition** provides *ground/volume separation* from **multibaseline PolInSAR** coherence
- *Triangular* ground phase is estimated from NxN **ground InSAR coherence**
- **Phase center should correspond to terrain**, except for statistical errors





- **Phase Linking** is an **InSAR** estimator of triangular phases from NxN InSAR coherence
- BIOMASS coherence impacted by wavenumber shift
  - *use small baselines*
- **Phase center ≠ terrain**
  - **lock terrain by tomography/model inversion**

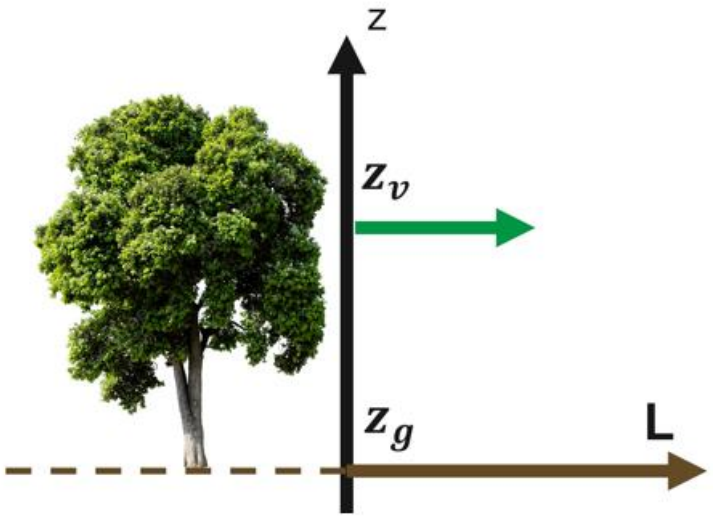


Precision vs resolution

Both SKPD and PL require consistent N. of looks

- **windows on the order of 100s meters**
  - ✓ this is ok for low-pass atmospheric screens (APS)
  - ❑ *not optimal for DTM*

Solution: steer the stack, reprocess and lock terrain with hi-res spectral estimation



$$\gamma_{FT}\left(Le^{jk_z z_g} + (1-L)e^{jk_z(z_g+z_v)}\right)$$

Wavenumber shift decorrelation

2 delta decorrelation model

Minimum number of parameters:

- L: relative contribution of ground backscatter to total coherence
- z_g: Ground height
- z_v: Volume height

Advantages:

- Easy to treat computationally and analytically
- Accurate for tropical forests at P-band*

P. -A. Bou, L. Ferro-Famil, F. Brigui and Y. Huang, "Tropical Forest characterisation using parametric SAR tomography at P band and low-dimensional models,"

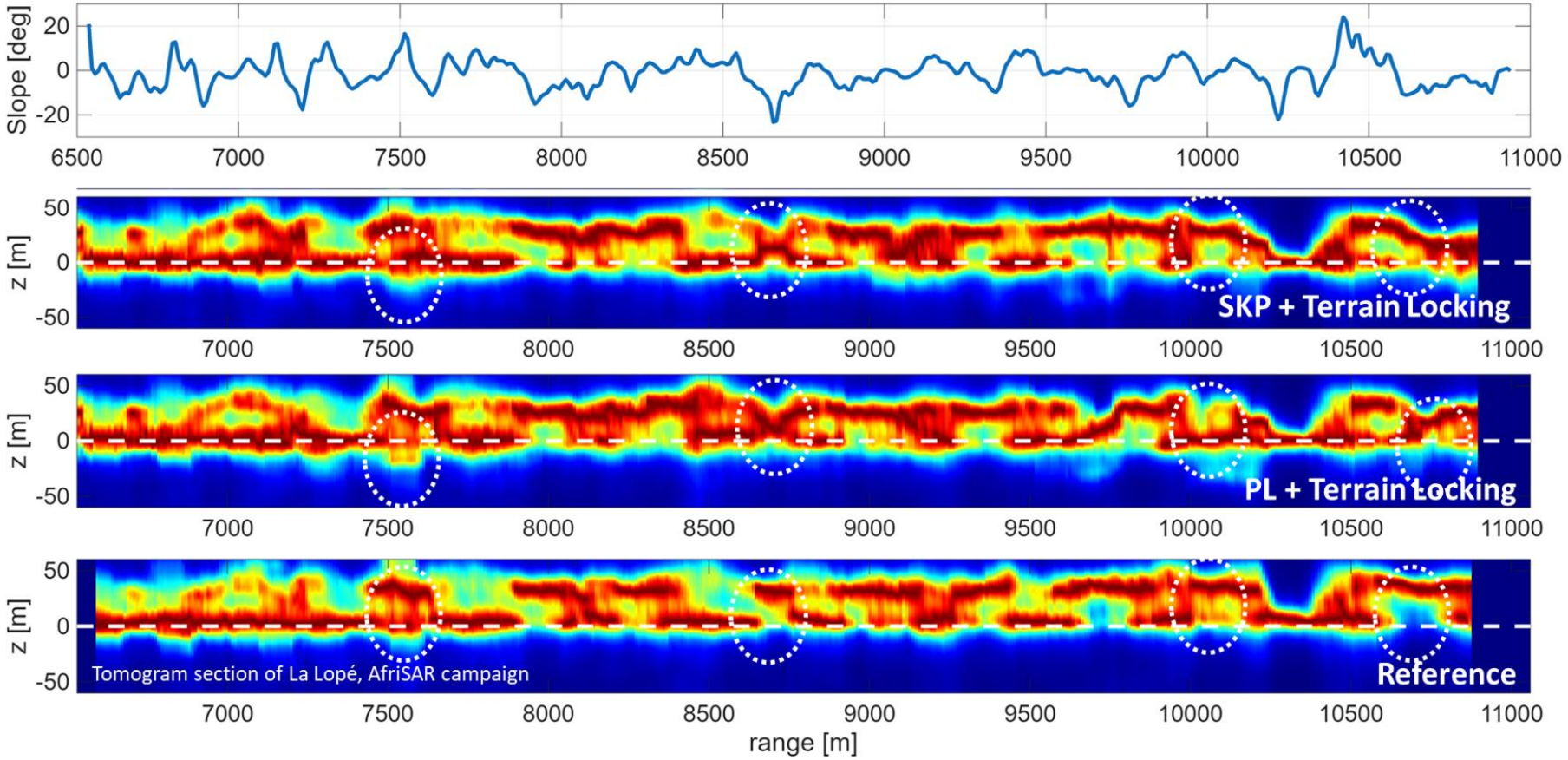
AfriSAR reprocessed

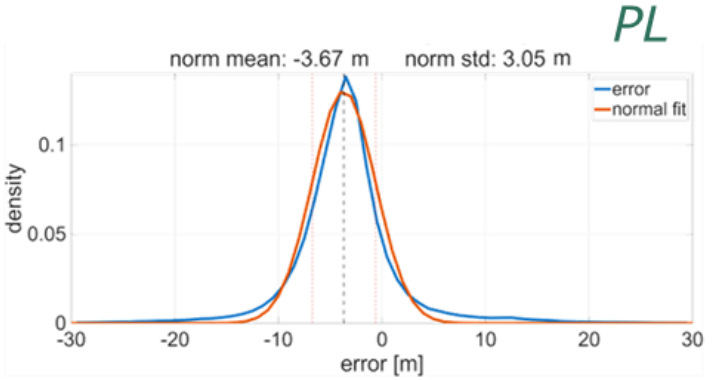
No APS, validation is possible

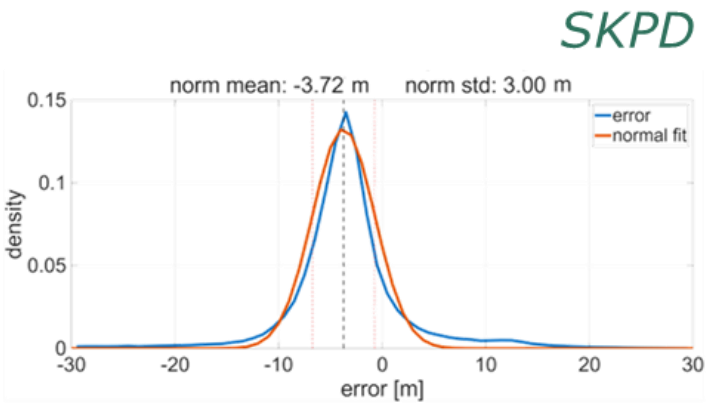
Comparable performance

Some error in points where **slopes/two-layer model weaker**

Can be corrected in post-processing







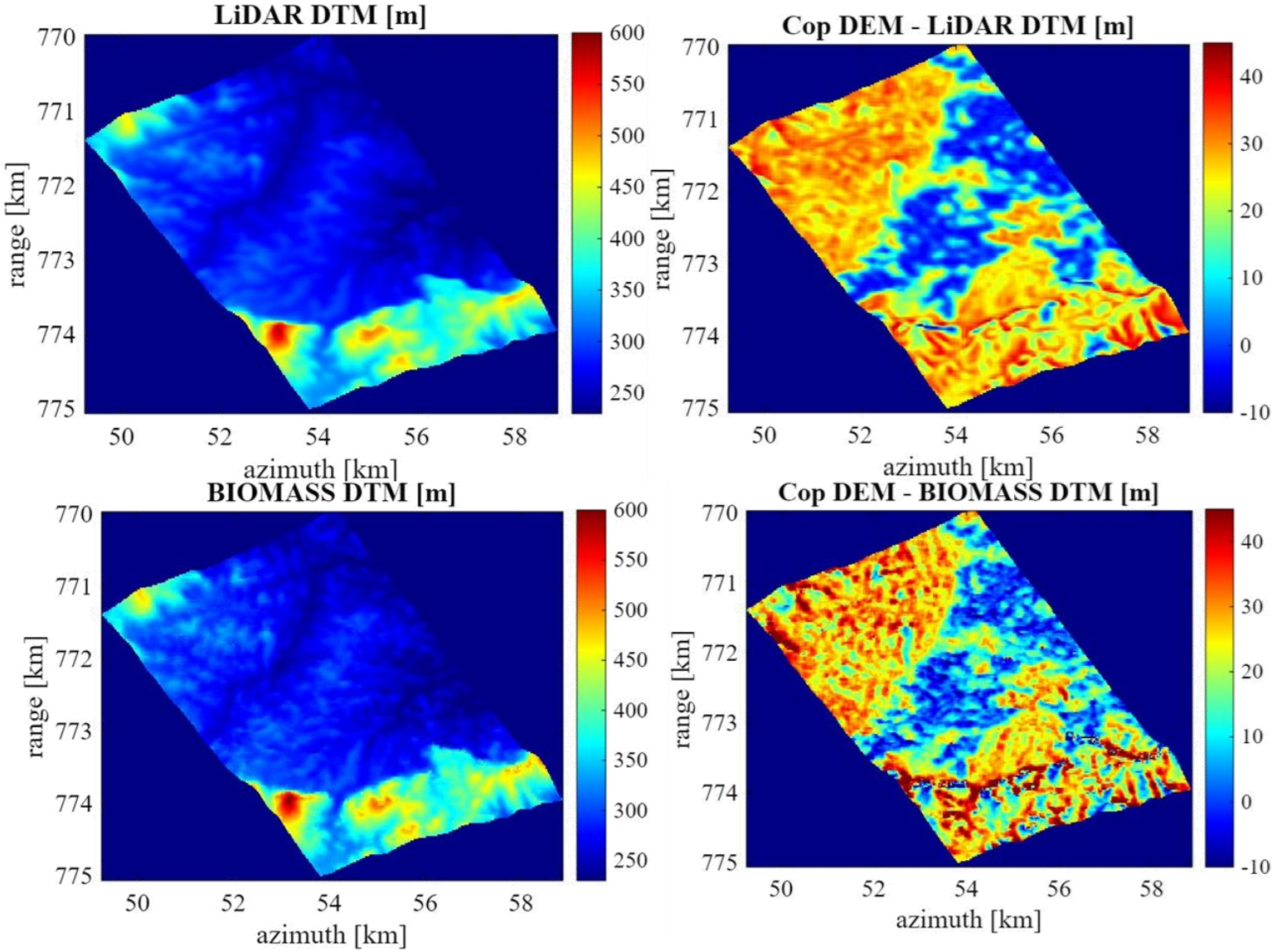
BIOMASS DTM validation

We produced a **preliminary** DTM to compare with LiDAR reference over the tropical forest of La Lopè National Park, Gabon

Demonstration performed over a **small area** (10 x 10 sqkm), **APS** is estimated and removed:

- considering it **constant** over the scene
- **locking on a single point in an open area**

Estimated DTM and DTM-DEM difference is accurate with respect to the reference



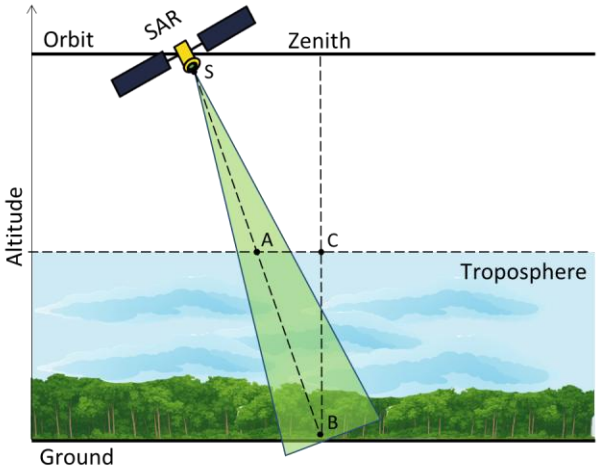
Atmospheric Phase Screen

Troposphere (surface to ~10–15 km) introduces excess path delays biasing InSAR phase

- small variations in refractivity due to changes in water vapour/temperature/pressure, varying with time of day/season/weather
- refractivity is usually decomposed into a **stratified part**, varying with altitude, and a **turbulent part**, capturing small-scale variability

Approaches for modelling/correction:

- space-time (PS-InSAR, SBAS) ⇒ APS correlated in space, information correlated in time, redundancy from many acquisitions
- model-based ⇒ stratification and turbulence
- weather model/GNSS integrated (GACOS, ERA5) ⇒ converted into compensation phase screen
- machine learning ⇒ learning APS patterns by training on stacks



Challenges for BIOMASS:

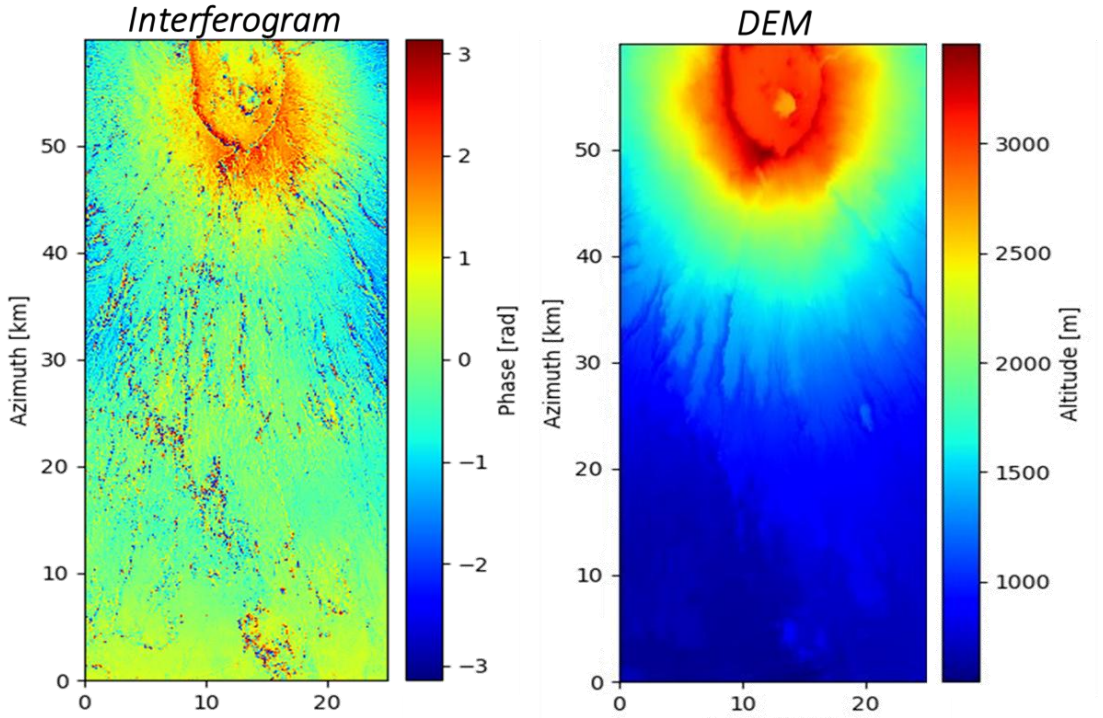
- dense humid canopies, volume scattering ⇒ **APS changing over short distance/time** ⇒ limited weather model applicability
- **limited number of acquisitions** ⇒ no PS-InSAR/SBAS

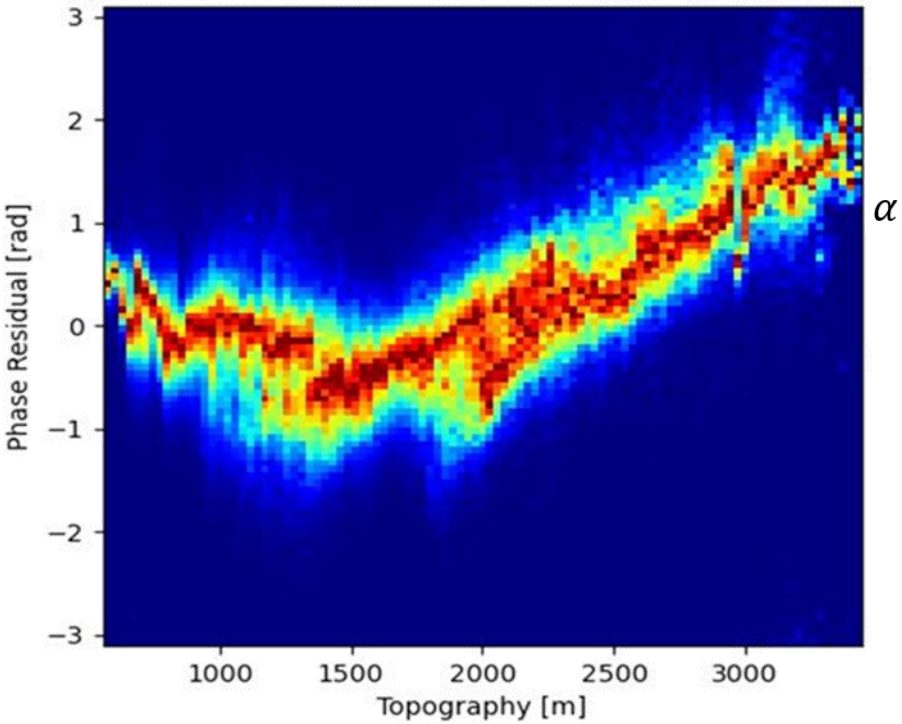
Objective: develop an operational correction focused on DTM retrieval, starting from estimated ground phases

Stratified APS removal

Main assumption: **stratified APS follows global phase-DEM trend** over the entire swath for each interferogram, differently from other residual phase terms

- linear phase-DEM trend estimation in the complex domain (avoid unwrapping)
- removal of a 2D residual orbital phase plane at each trial (after detrending)
- optionally: add linear-trend back to phase and fit low-order polynomial (estimate more complex stratification)





Linear APS model

$$\alpha(r,a) = \beta \cdot z(r,a) + \nu(r,a)$$

stratified *turbulence*

Example on SAOCOM in Chad Courtesy of CONAE

Plane removal

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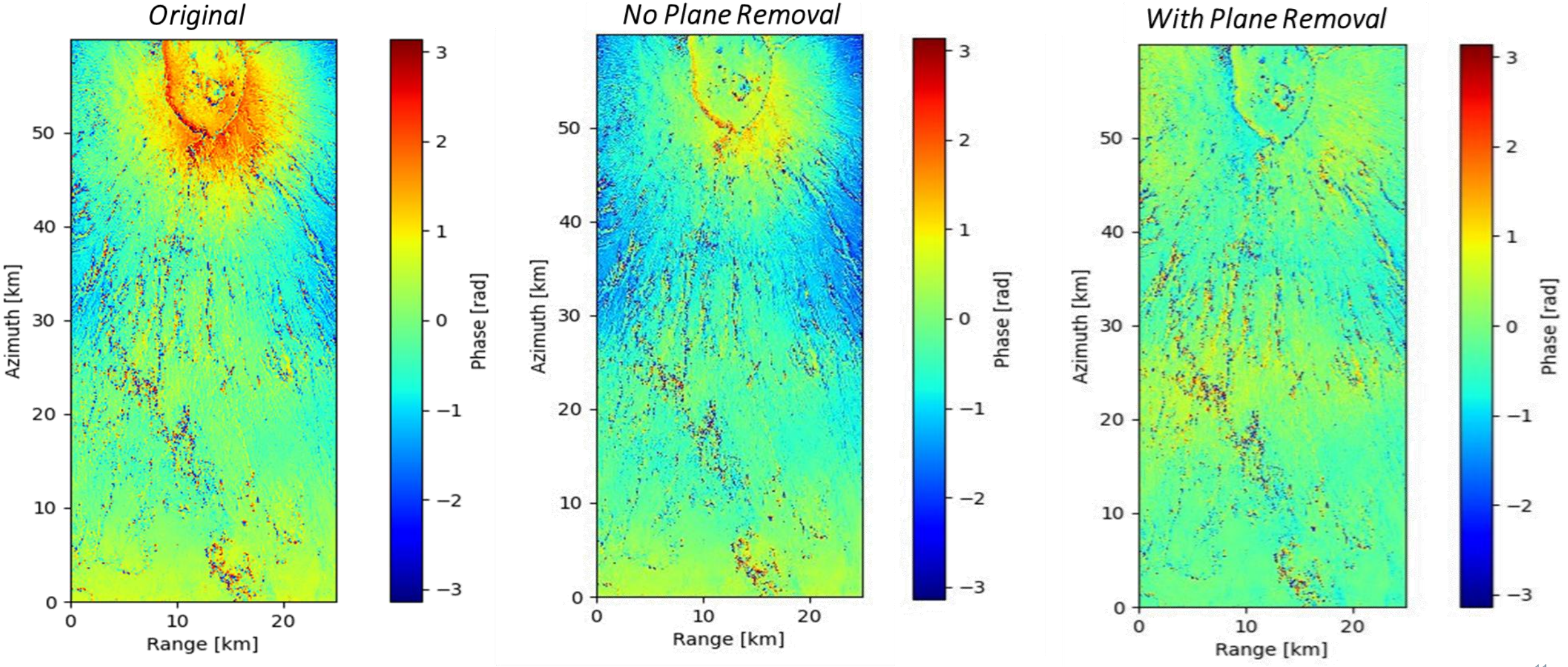

Benchmark with GACOS

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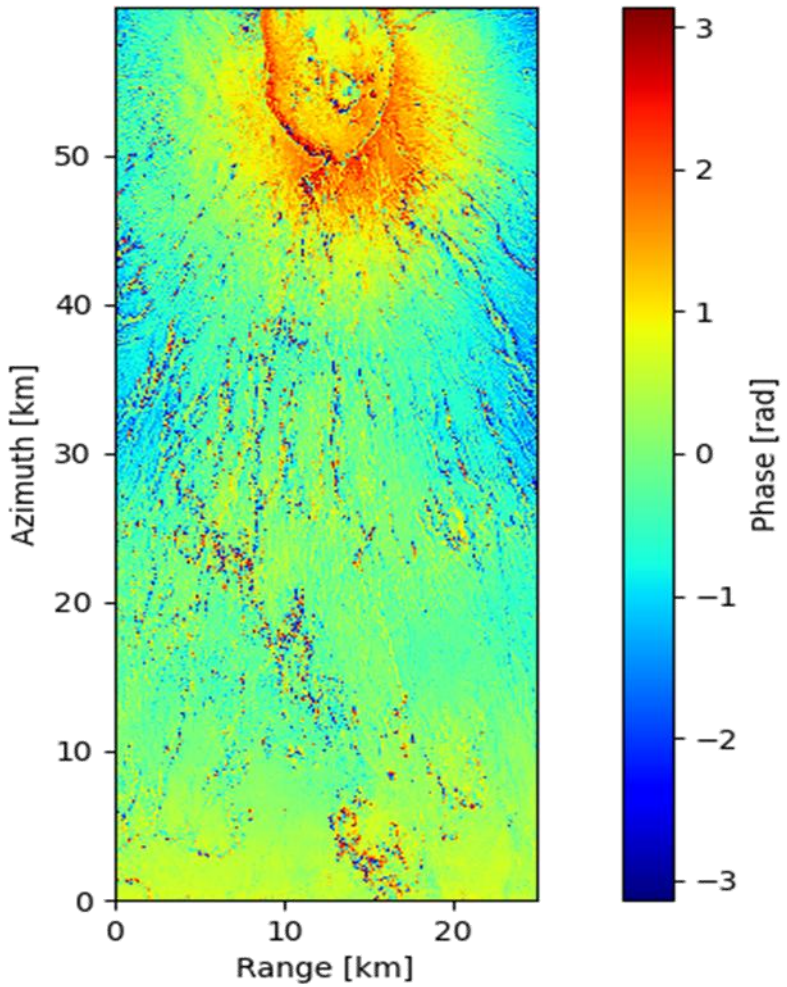
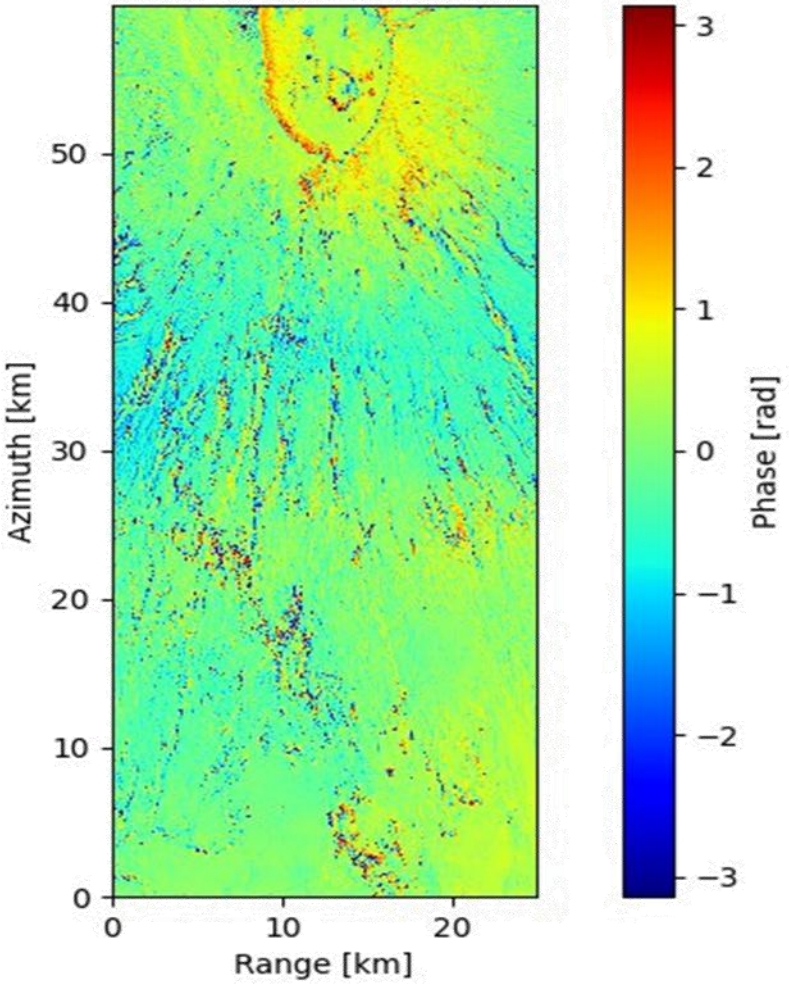
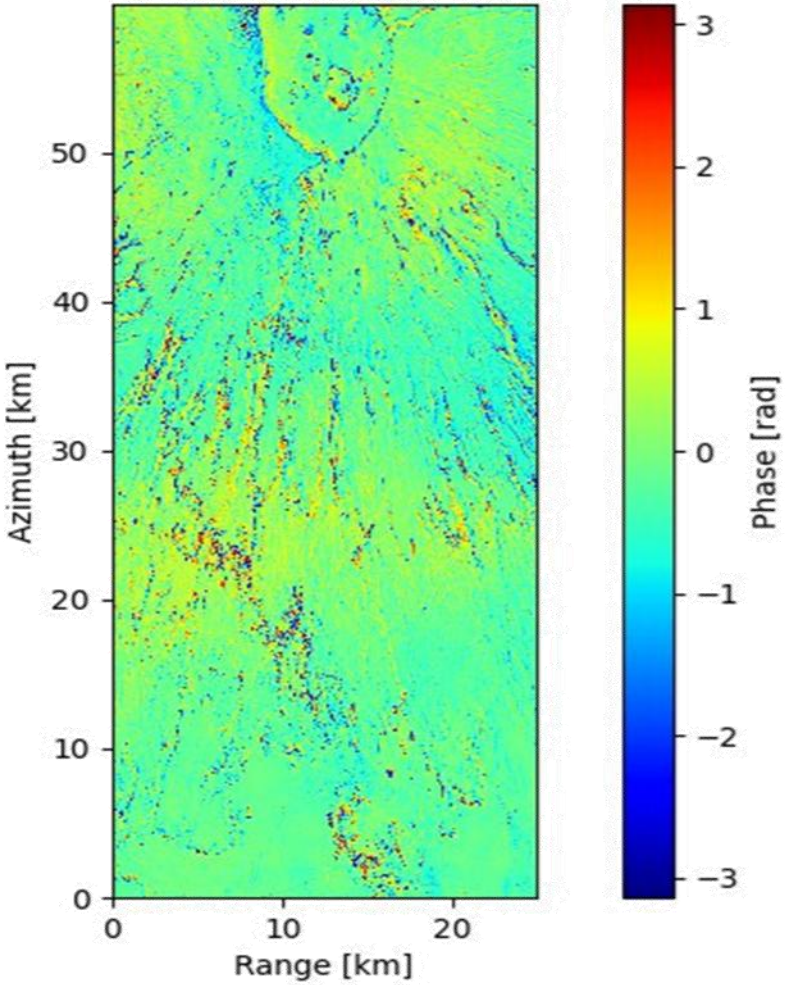
Original



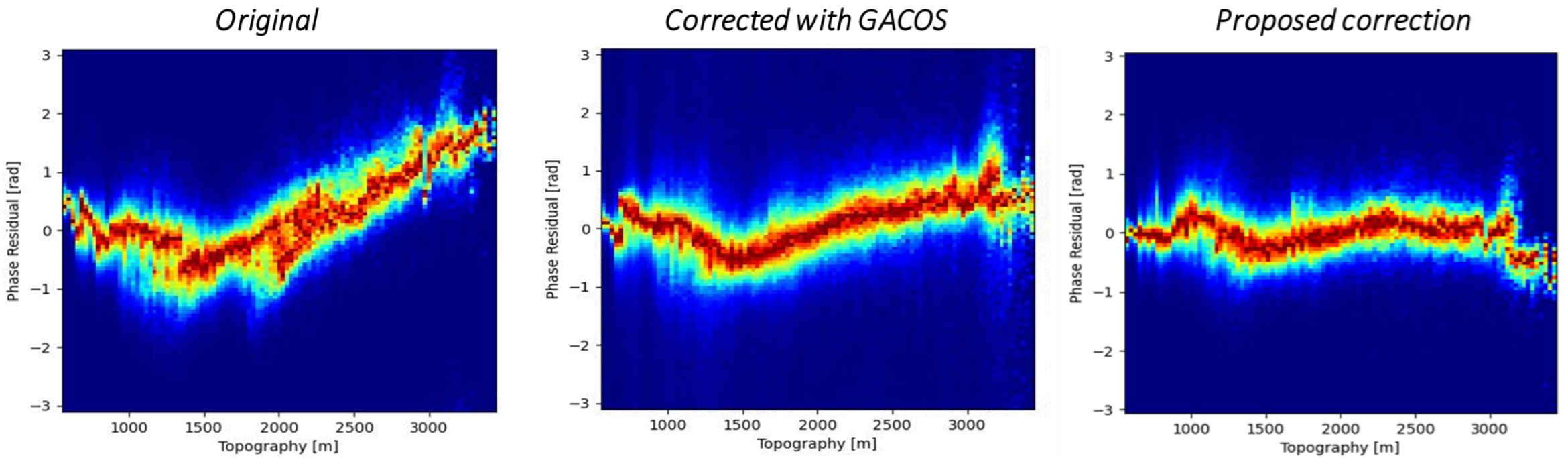
Corrected with GACOS



Proposed correction



Benchmark with GACOS



GACOS: external correction service based on GNSS and weather model

- spatial resolution 0.1° (roughly 11 km at equator) ⇒ no fine scale
- dependence on GNSS coverage ⇒ can be very sparse
- **temporal resolution 6 hours** ⇒ turbulence can change in less than one hour

Mount Fuji (SAOCOM)

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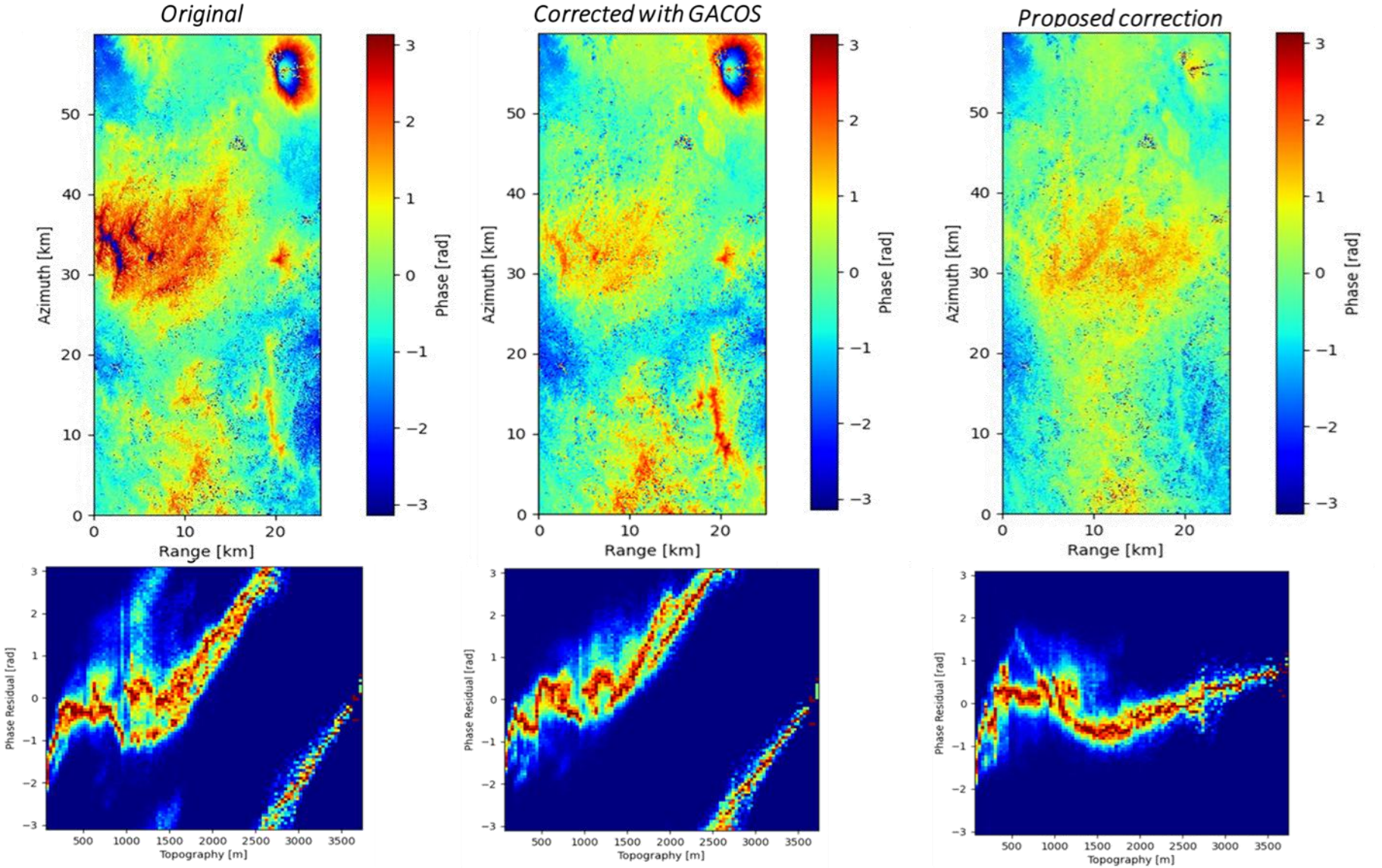
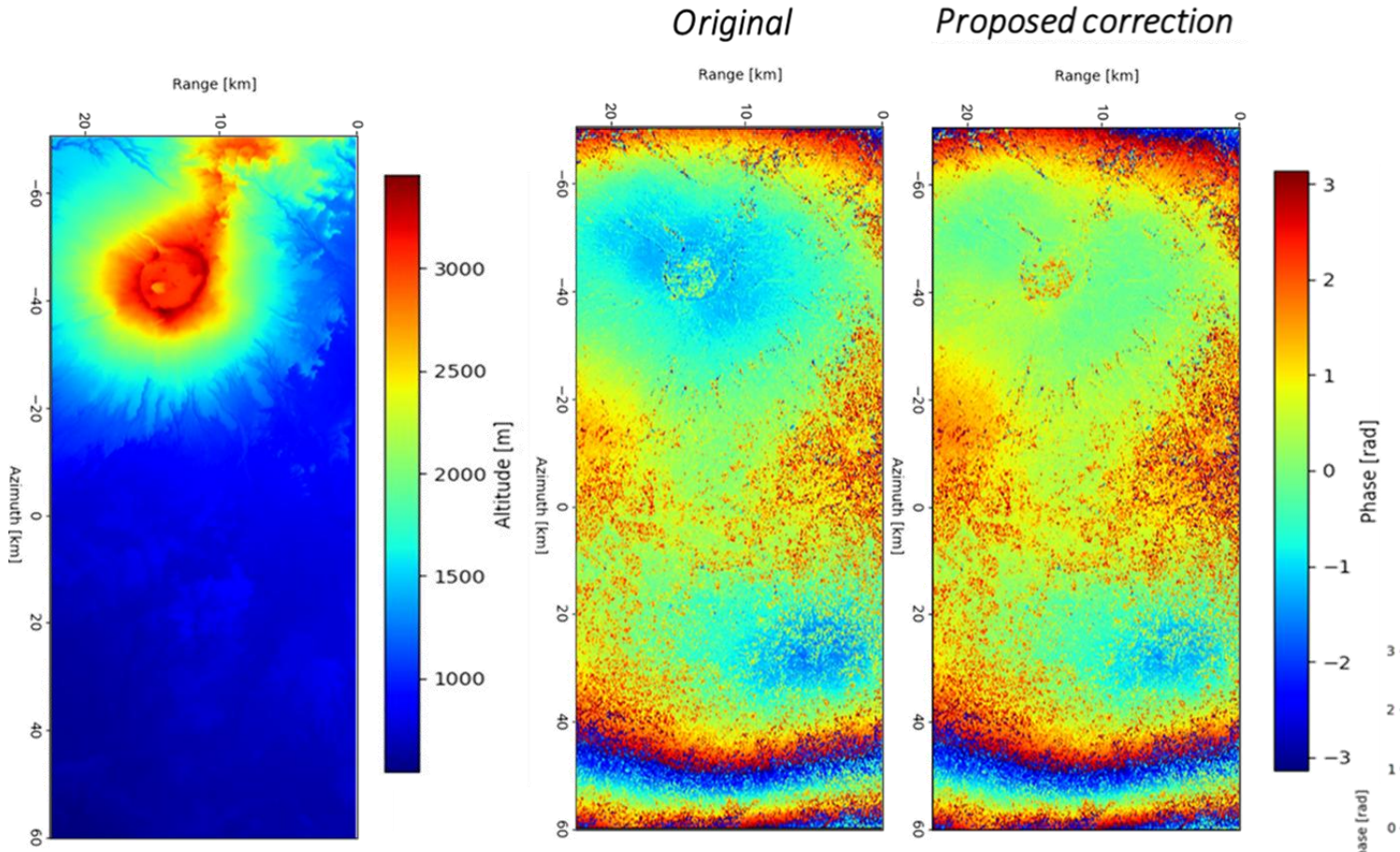
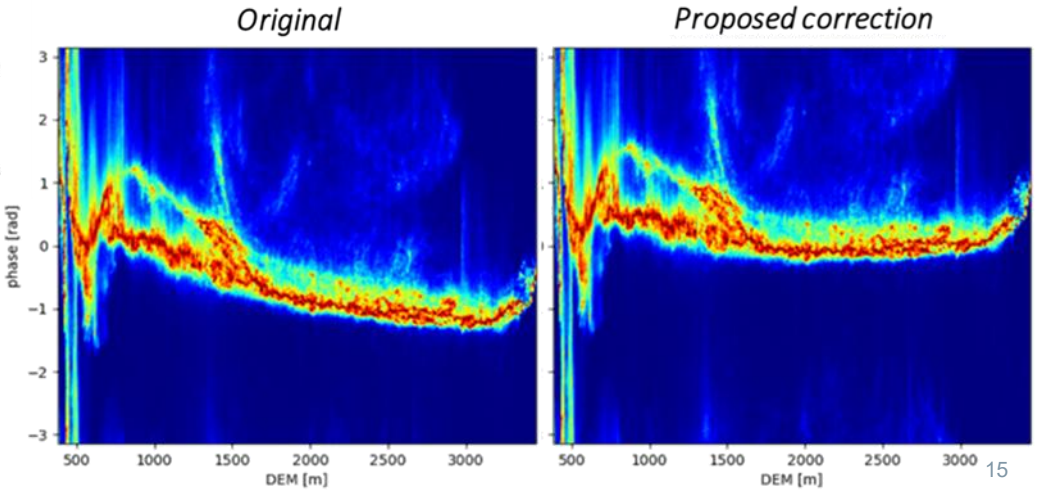


BIOMASS example



- Preliminary example, Chad
- Approximately same SAOCOM area

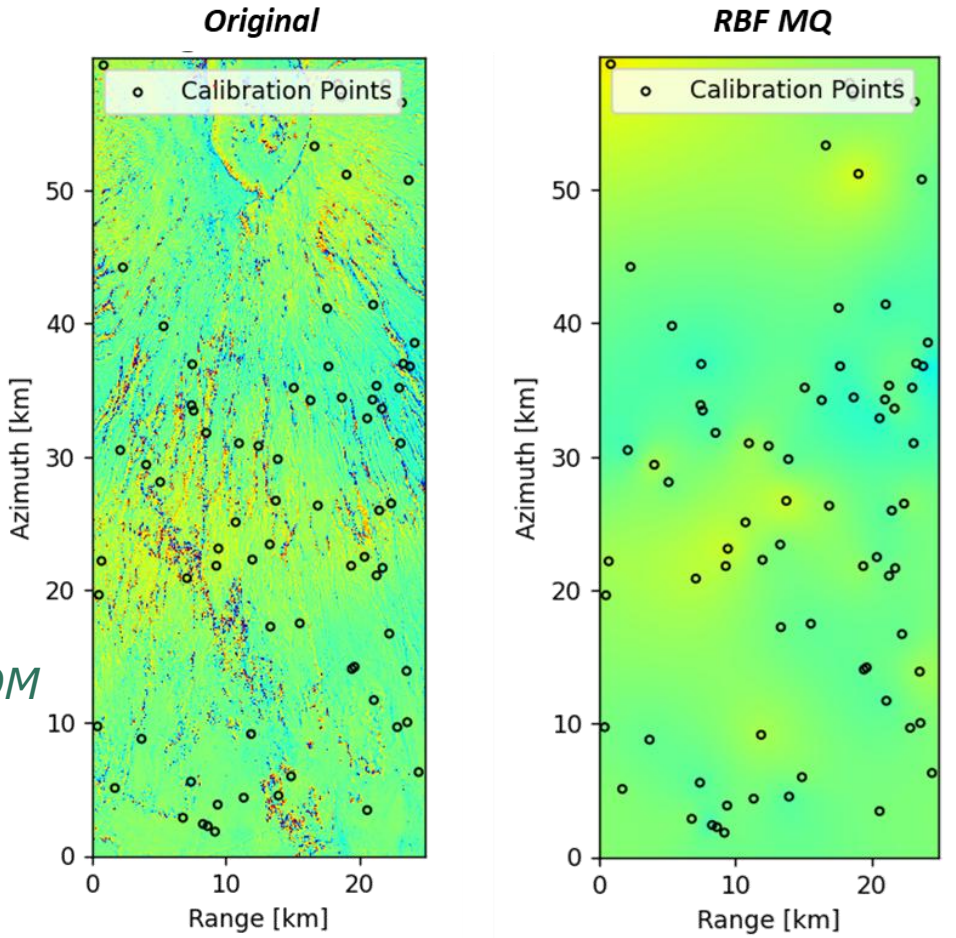
- Phase-DEM correlation still reduced
- More residual features in the interferogram (possibly due to residual low ionospheric frequencies)
- *To be investigated more*



Turbulent APS removal

- **After de-stratification, residual turbulence is "read" on open areas (DEM=DTM), interpolated wall-to-wall and removed**
- RBF Multi Quadric: good reconstruction/performance compromise
- DTM can be estimated fitting residual phases
- If bare areas are few, fitting can be tried directly
  - *more noisy*
  - *lack of absolute reference*
- *Still work in progress*

Simulated on SAOCOM



BIOMASS example (Brazil)

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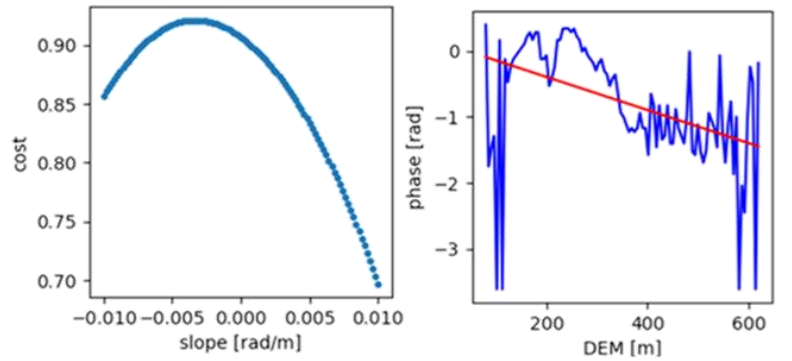
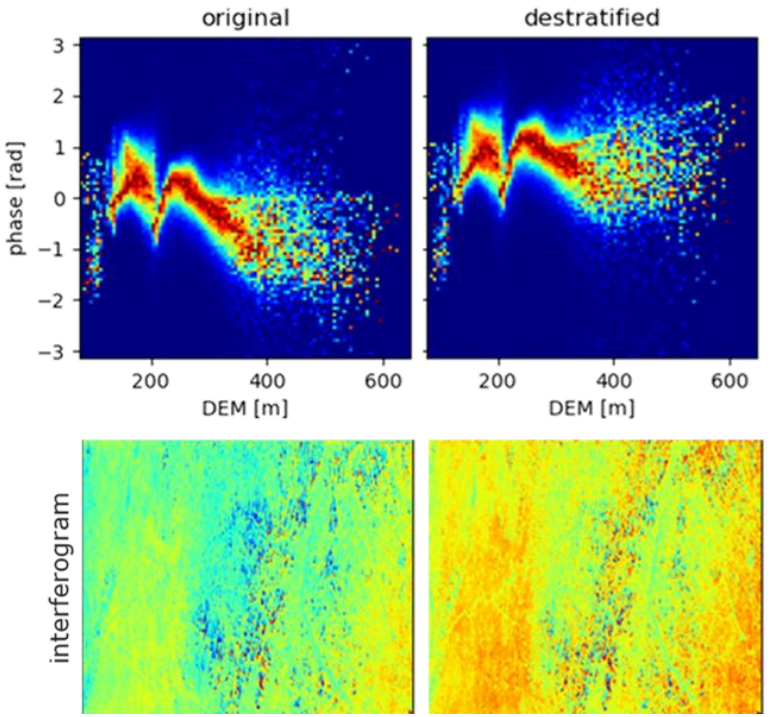
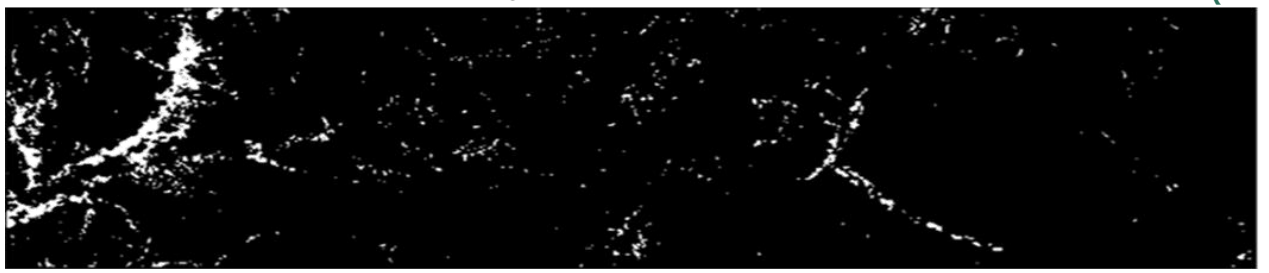
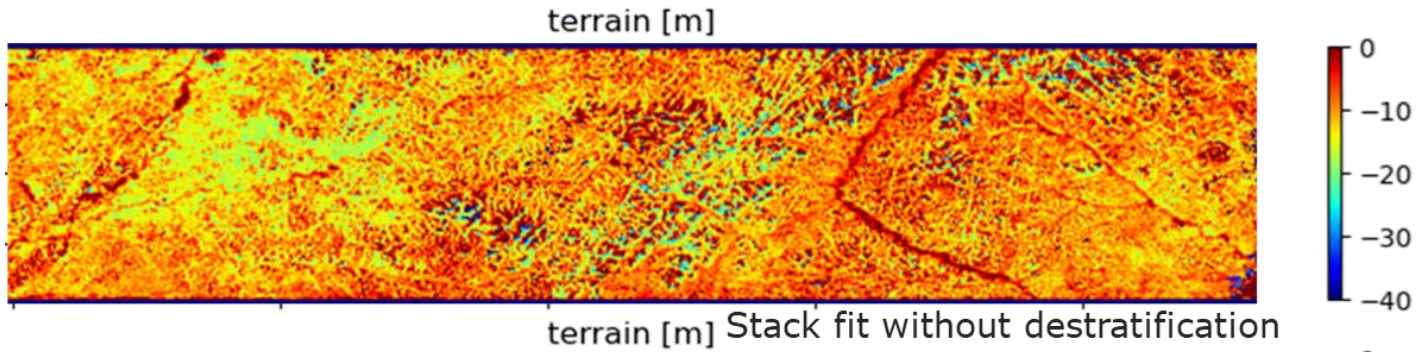
(example on one interferogram)





Open areas mask *(full stack)*





Disclaimer:

- **preliminary example**
- **still tuning and testing**

Discussion, future work

BIOMASS DTM retrieval starts from coregistered and ionosphere calibrated stacks, main steps:

- **ground phase estimation**
- **APS stratified component removal**
- **turbulence wall-to-wall interpolation and removal**

Supported by preliminary results (SAOCOM, AfriSAR, BIOMASS) and **independent from external APS corrections**

Some open points to address:

- correction of artifacts in ground phases (e.g., terrain level discontinuities)
- phase-DEM higher order correction in more complex environments
- turbulence reconstruction with sparse open areas coverage and absolute reference
- systematic testing/validation with *reference DTM (available in AF and SA from airborne campaigns)*
- interplay with (ionospheric) pre-processing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