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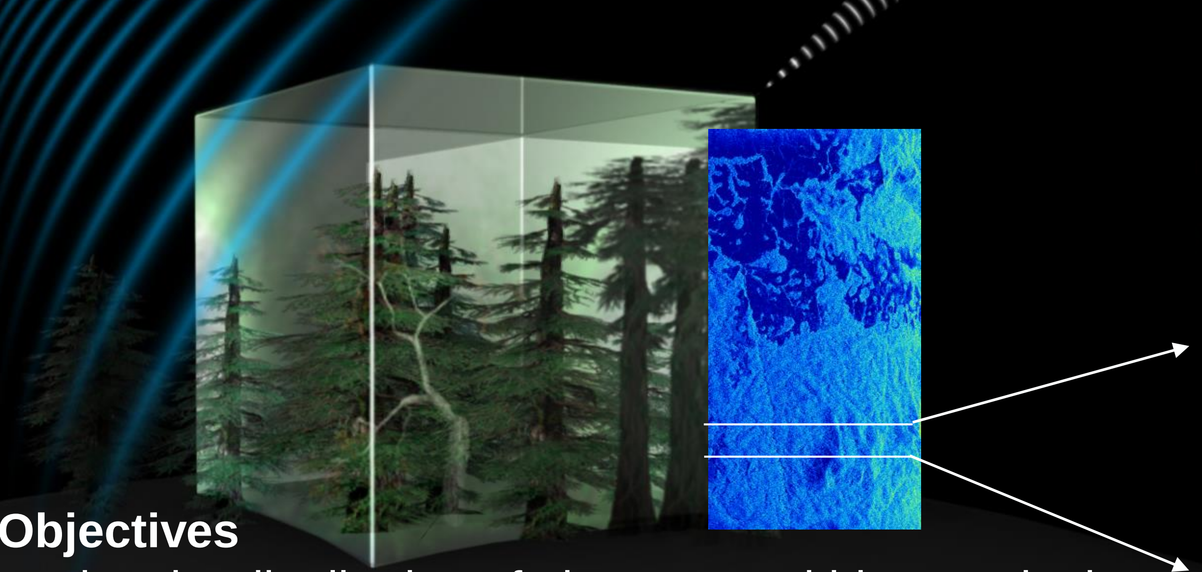
BIOMASS Interferometric Processor: Current Status

Banda, Francesco (1); Mancon, Simone (1); Mariotti D'Alessandro, Mauro (2); Tebaldini, Stefano (2); Giudici, Davide (1); Pinheiro, Muriel (3); Scipal, Klaus (3)
1: aresys, Italy; 2: Politecnico di Milano, Italy; 3: ESA/ESRIN, Italy

BIOMASS

Scheduled for launch in 2024, ESA's seventh Earth Explorer Mission, *BIOMASS*, will carry the first P-band SAR to be flown in space, to gather fully polarimetric acquisitions over forested areas worldwide in interferometric and tomographic modes

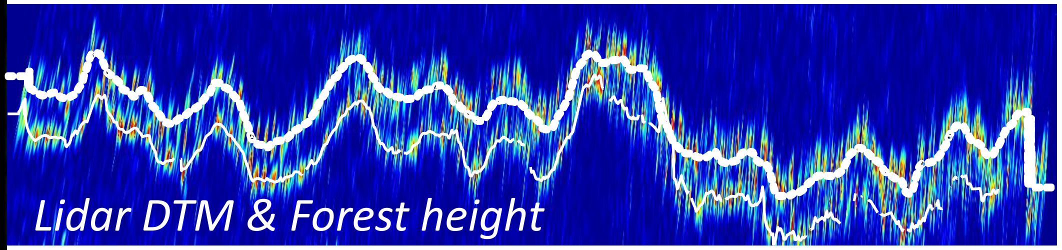


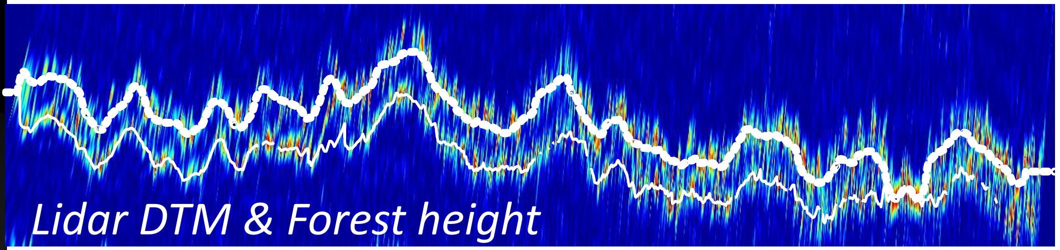
Mission Objectives

- 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

$\Rightarrow$ P-Band provides sensitivity to the whole forest vertical structure, as demonstrated by 3D tomographic analyses





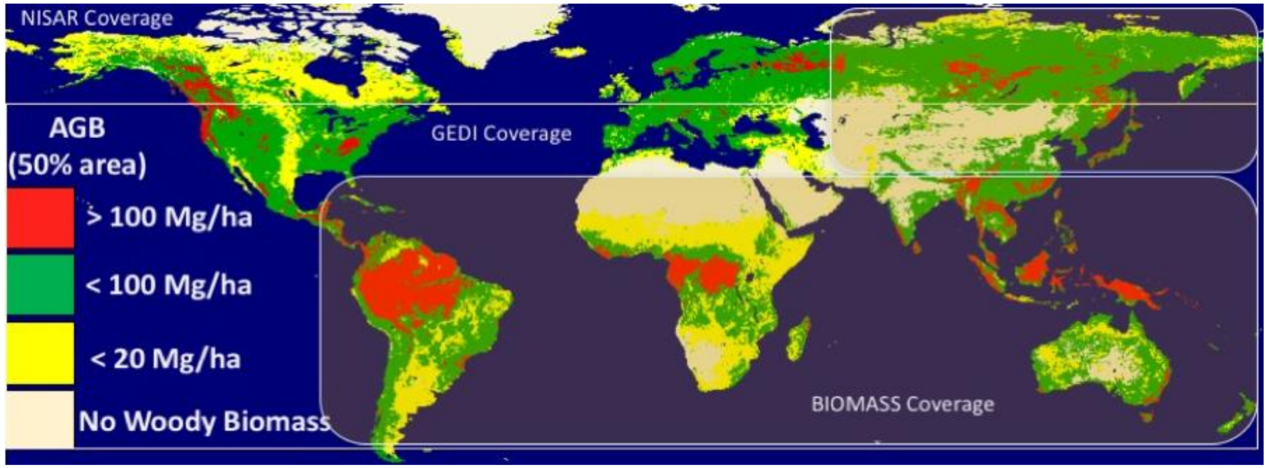
Vertical sections from AfriSAR (Gabon)

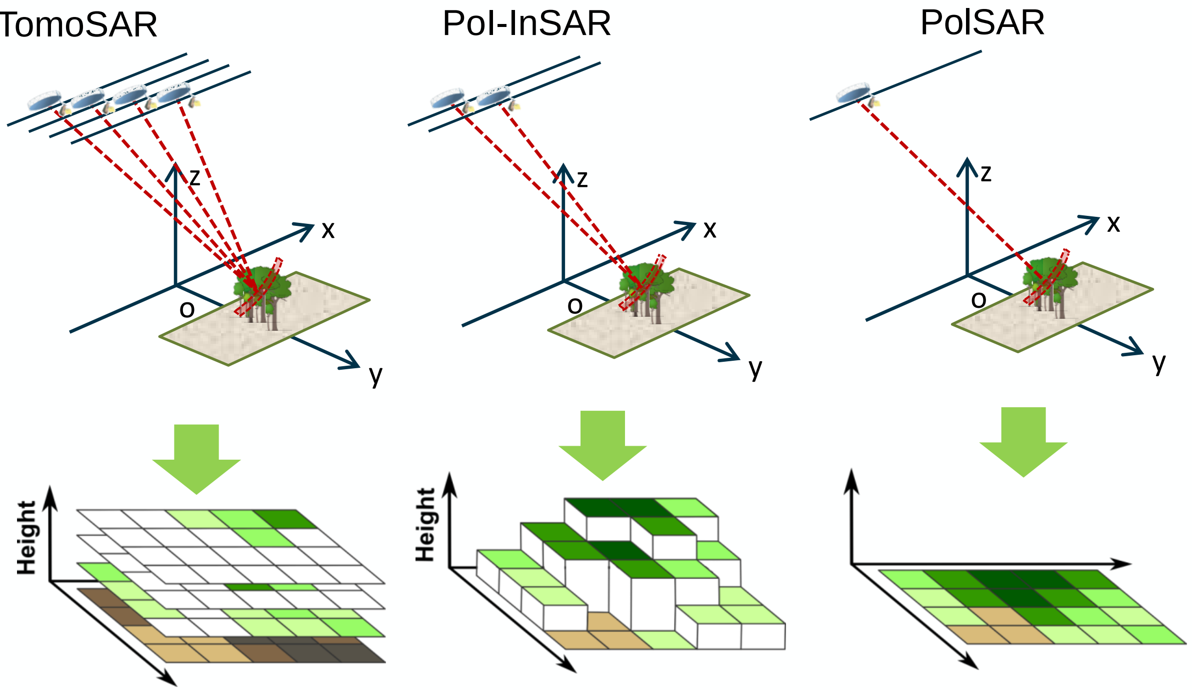
BIOMASS PHASES

BIOMASS will implement two acquisition phases:

- *Tomographic phase (first 14 – 16 months):* stacks of seven consecutive passes with a revisit time of 3 days, to provide 3D imaging capabilities with a vertical resolution of about 23 m at the equator
- *Interferometric phase* (rest of mission lifetime): stacks of three consecutive acquisitions (or triplets) with a revisit time of 3 days, ensuring interferometric global coverage every seven to nine months

all acquisitions are full-pol 😎





BIOMASS OBJECTIVES

Primary objectives

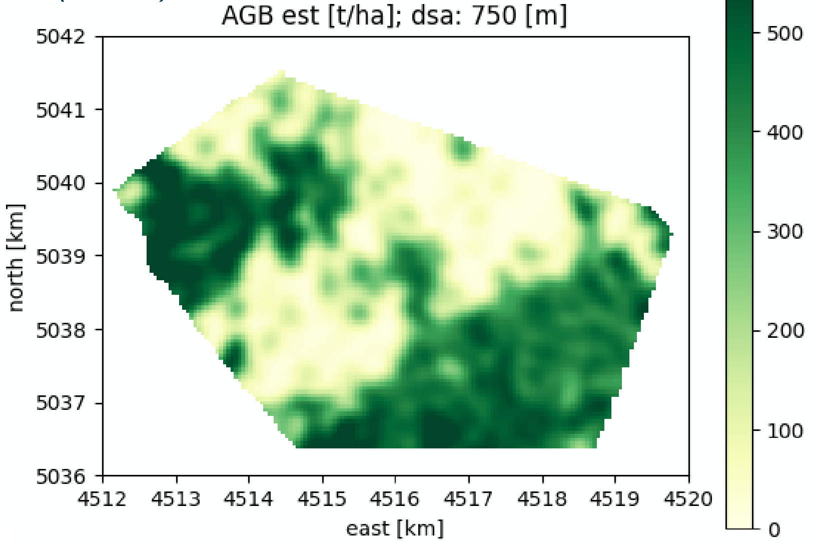
Above Ground Biomass (AGB): dry weight of woody matter per unit area above the soil

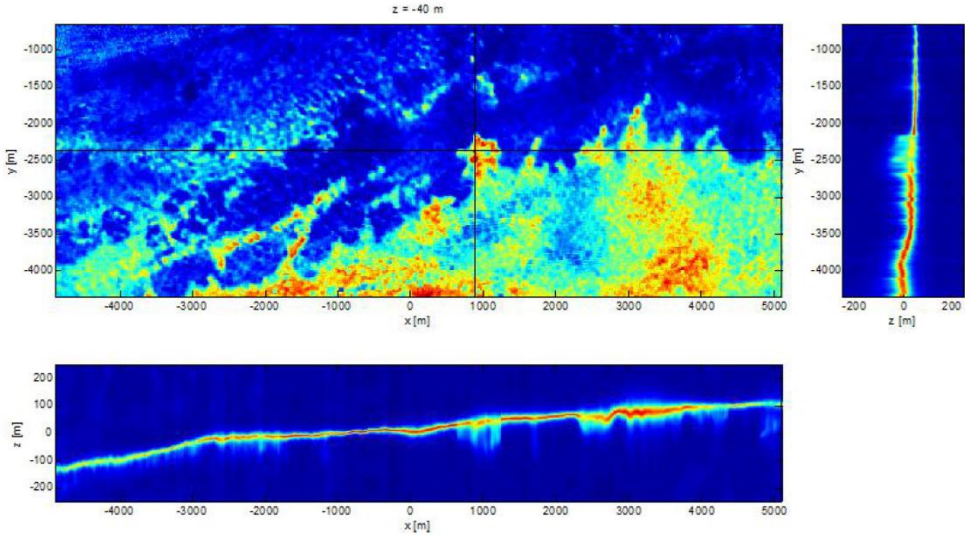
Forest Height (FH): upper canopy height according to H100 standard

Forest Disturbance (FD): area where an intact patch of forest has been cleared

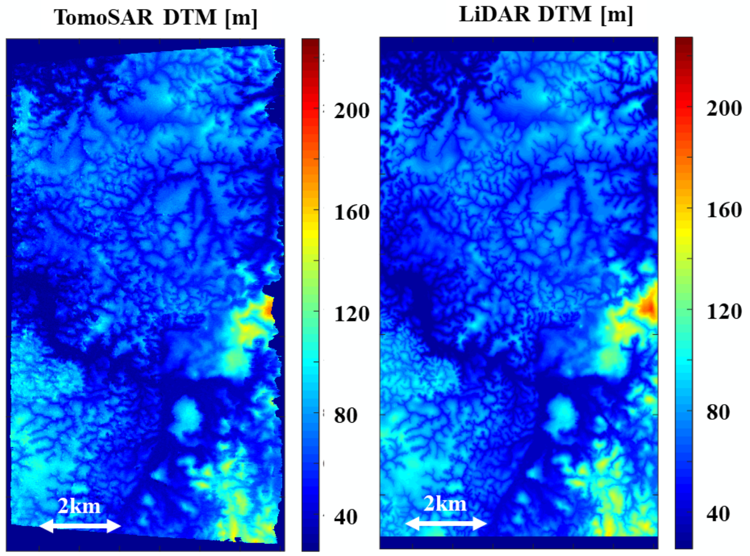
Tomography: 3D voxels representing forest reflectivity

AGB from AfriSAR (Gabon)





3D sections from IceSAR 2012 (Greenland)



Tomography sections from AfriSAR (Gabon)

Secondary objectives

Digital Terrain Model (DTM): sub-canopy terrain topography

Forest/Non-Forest mask (FNF): indication of forested areas as seen by P-band

Exploration of glacier dynamics

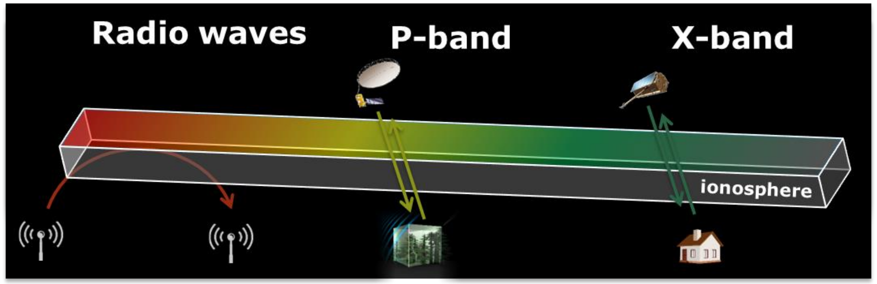
Subsurface geology

INTERFEROMETRIC CALIBRATION

Preliminary step to using Level-1 acquisitions: stack coregistration and phase calibration

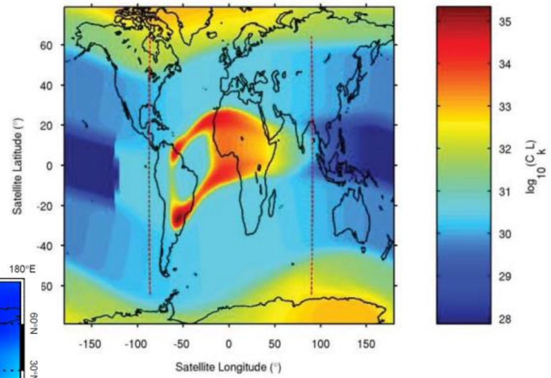
Main sources of disturbance, lowering coherence:

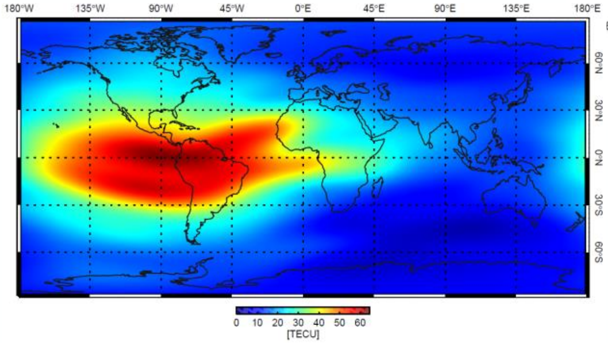
- ionosphere → **additional shifts**, **phase disturbance** & **defocusing**, **Faraday rotation**
- baseline errors & troposphere → additional shifts, phase disturbance & defocusing



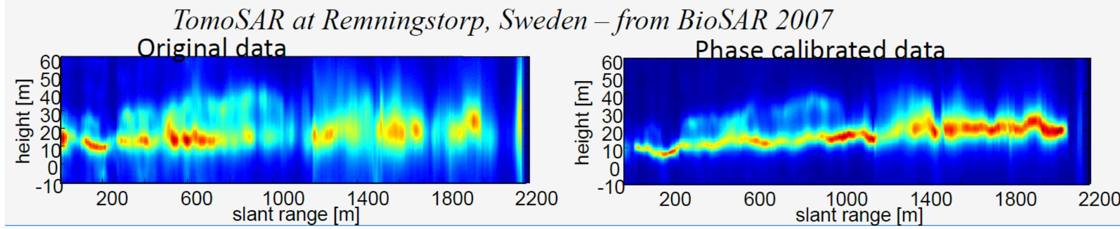
Disturbance	Area of occurence	Effects	Impact at L1	Impact at Tomo & InSAR level
Ionosphere	all latitudes (stronger around post-sunset equatorial zone)	additional phase advance & group delay	range shifts of about 4 m/TECU & phase variation of roughly 40 rad/TECU	differential shifts & phase
		range defocusing	negligible	negligible
		azimuth shifts (linear variations within the synthetic aperture)	about 8 m azimuth shift w gradient of 1 TECU/100 km (w iono height 350 km)	differential shifts
		Faraday rotation	phase variation of roughly 0.05 rad/TECU	errors in polarimetry
	higher latitudes (thanks to dawn-dusk orbit)	azimuth defocusing (non-linear variations within the synthetic aperture)	several dBs IRF degradation and resolution loss	moderate coherence loss
Baseline errors	all latitudes	about 1 m orbit accuracy w large baselines	shifts of some pixels	phase disturbance & defocusing
Troposphere	all latitudes	additional low-pass phase screens	negligible	phase disturbance & defocusing

ROGERS et al., 2014





GOMBA, 2015

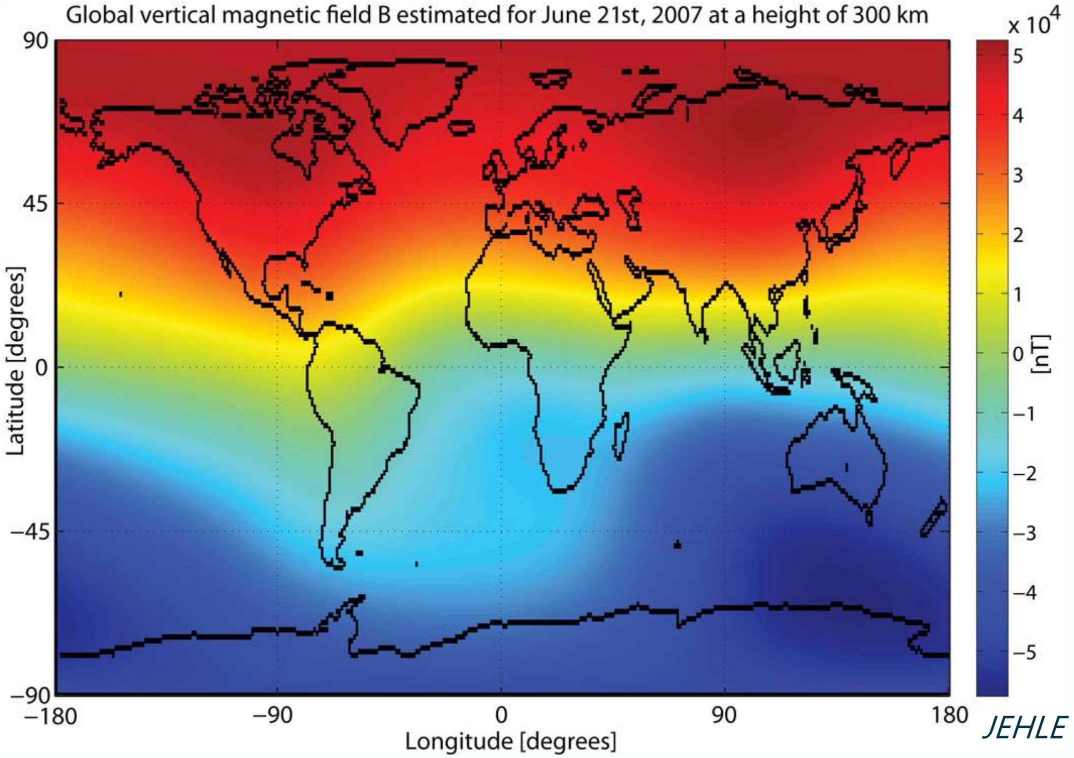


L1 IONOSPHERIC CORRECTION

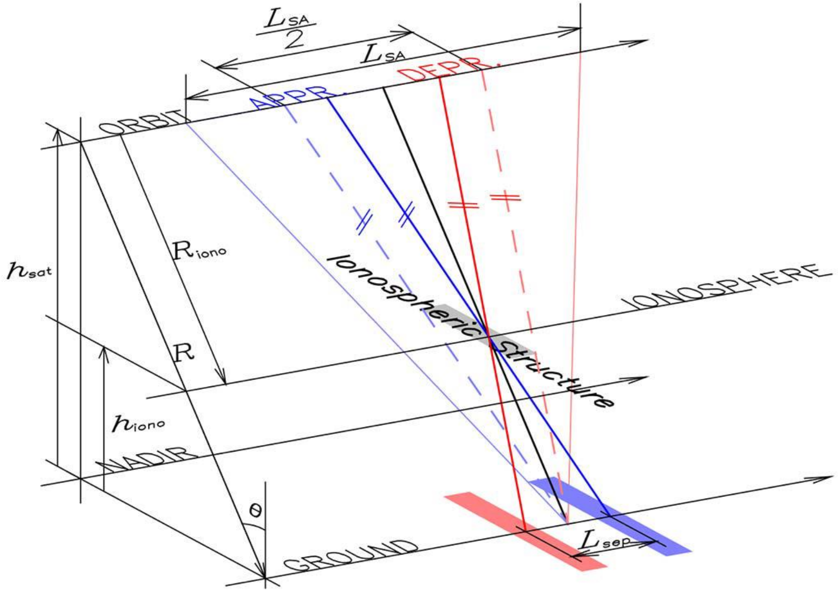
BIOMASS L1 processor compensates ionosphere on single images:

- estimation of ionosphere height from Faraday rotation variation in sub-apertures (needs relevant azimuth variations)
- conversion of Faraday rotation to ionospheric screen
- defocusing at ionosphere height and compensation
- group delay correction
- optional autofocus for scintillations

$$\Omega = \frac{\zeta(e\vec{B}\cdot\hat{\kappa})}{c_0 m_e f^2} TEC$$



JEHLE et al., 2009



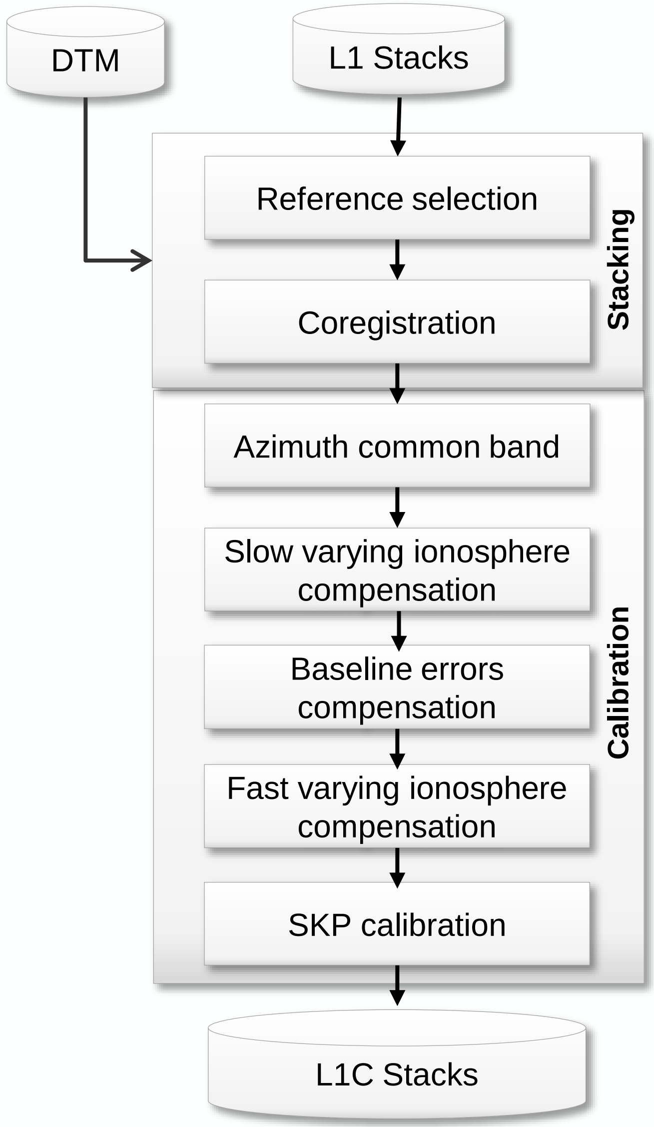
KIM et al., 2015

Caveats:

- low equatorial sensitivity
- requires wide averaging (tens of kilometers)
- wide averaging reduces ionospheric screen resolution
- autofocus requires scene contrast & is model-free

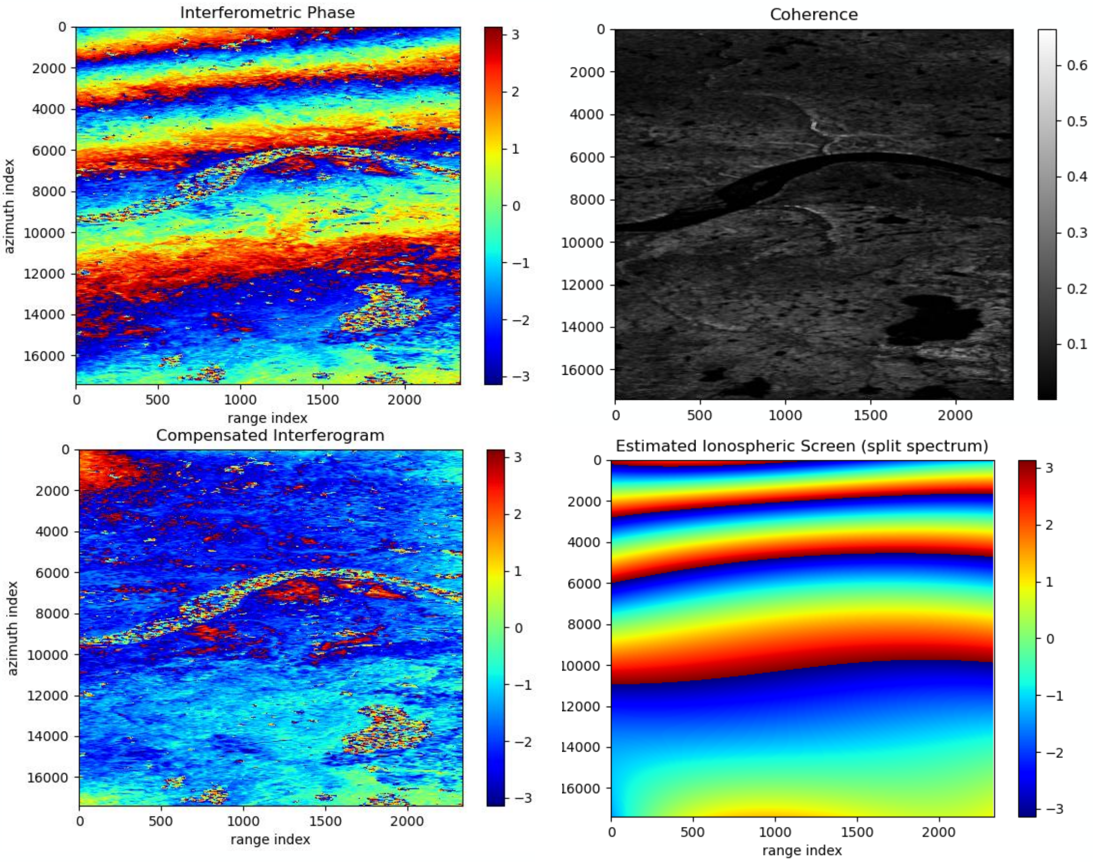
- ***the technique is being revised/integrated:*** *Kim, Papathanassiou "TEC and Ionospheric Height Estimation by Means of Azimuth Subaperture Analysis in Quad-Polarimetric Spaceborne SAR Data" IEEE JSTARS (2021)*
- ***further (interferometric) corrections in synergy are needed***

INTERFEROMETRIC PROCESSOR SCHEME



- **higher interferometric accuracy** wrt single acquisitions (differential errors)
- first target differential shifts & low-pass disturbances (background ionosphere, baselines), finally **faster ionosphere**
- *additional SKP calibration* (residual low-pass screens & phase offsets) *to meet L2 requirements*
- HH channel selected as more responsive to terrain (except for SKP, full-pol)
- reference image selection based on geometry & quality from L1 (ionosphere, RFI)
- all steps have multi-baseline refinement of single baseline estimates (except for SKP, multi-baseline)

SLOW VARYING IONOSPHERE



Strong Phase gradient in azimuth direction due variation in TEC along track

(acquisitions courtesy of CONAE)

- split-spectrum correction: exploits different frequency behaviour of ionosphere-dispersive and non-dispersive phase
- preliminarily tested on L-band SAOCOM pair (normal baseline: 128m, bandwidth 50 MHz, on North Canada)
- for BIOMASS (6MHz) large area averaging is required to obtain 5° phase accuracy
  - phase ramps are estimated
- *work in progress* to account for bias due to large BIOMASS baselines

can amount to fraction of cycles/some cycles with high TEC and large baselines

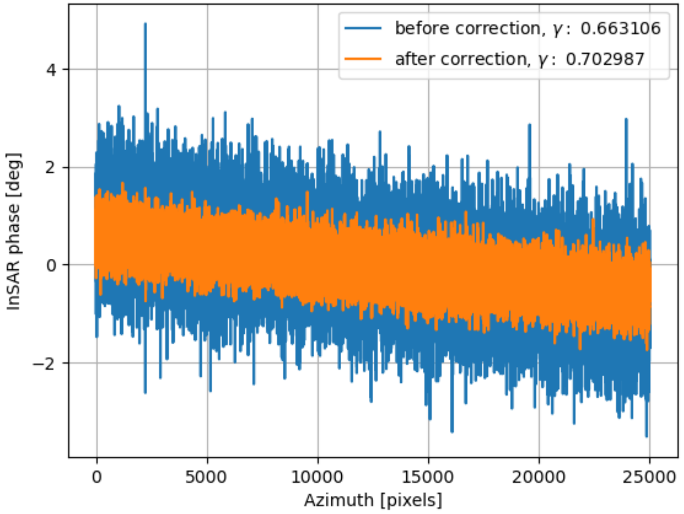
$$\Delta\hat{\phi}_{\mathrm{iono}} \approx \Delta\phi_{\Delta\mathrm{iono}} + \frac{\Delta f}{f_0}\Delta\phi_{\Sigma\mathrm{iono}}$$

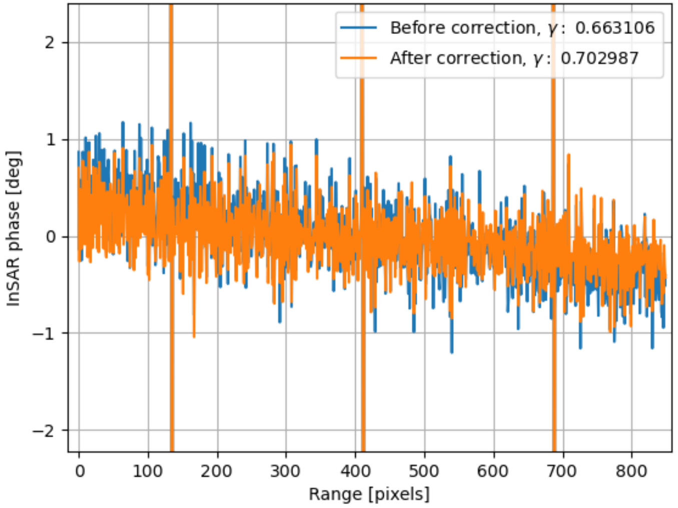
BASELINE ERRORS

- model-based inversion of dual-squint InSAR phase
- dual-squint phase mostly insensitive to troposphere, targets displacement and topography (low squint systems)
- lower-rank parametrization of the model chosen for BIOMASS geometry:

$$\frac{\Delta\phi_{ds}(\theta)}{\Delta\psi} = \frac{4\pi}{\lambda}\cos\psi_0\left[\bar{B}_{az} - \sin(\theta-\theta_{ref})R_0\Delta B_\perp\right]$$

- residual azimuth coregistration is also compensated



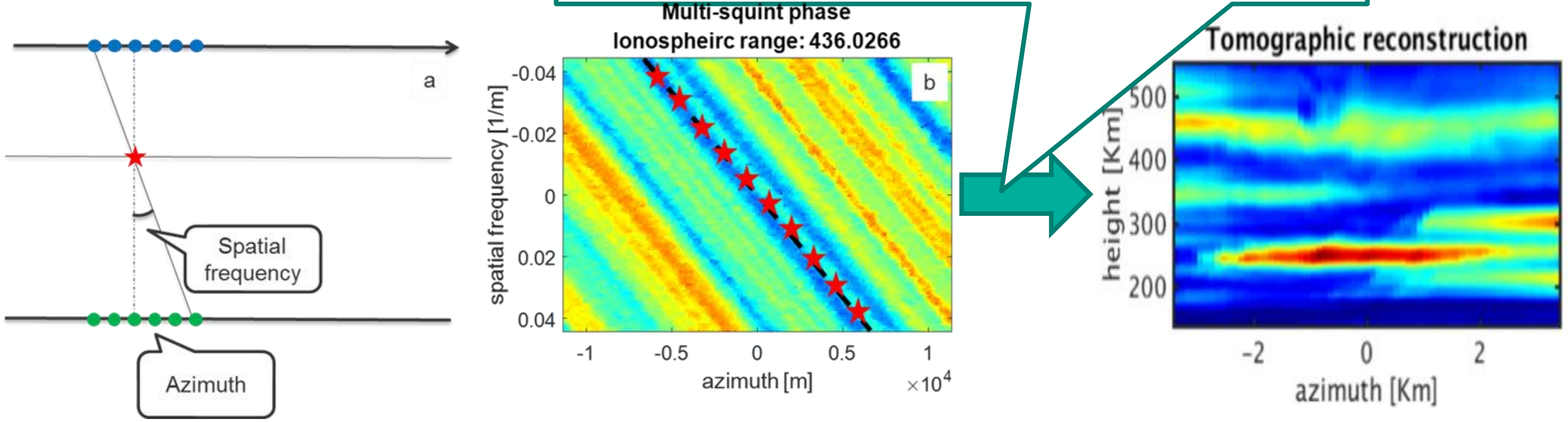


- simulated interferometric pair over distributed scene (30% of critical baseline)
- errors added to the orbit of secondary image:
  - Baz = 1.41 m
  - ΔB⊥ = 1.37 mm/km
  - $\Delta B\|$ = 0.01 mm/km
- coregistration from geometry applied before correction
- Baz & ΔB⊥ are correctly estimated
- some residual remains due to uncorrected $\Delta B\|$ baseline

FAST VARYING IONOSPHERE

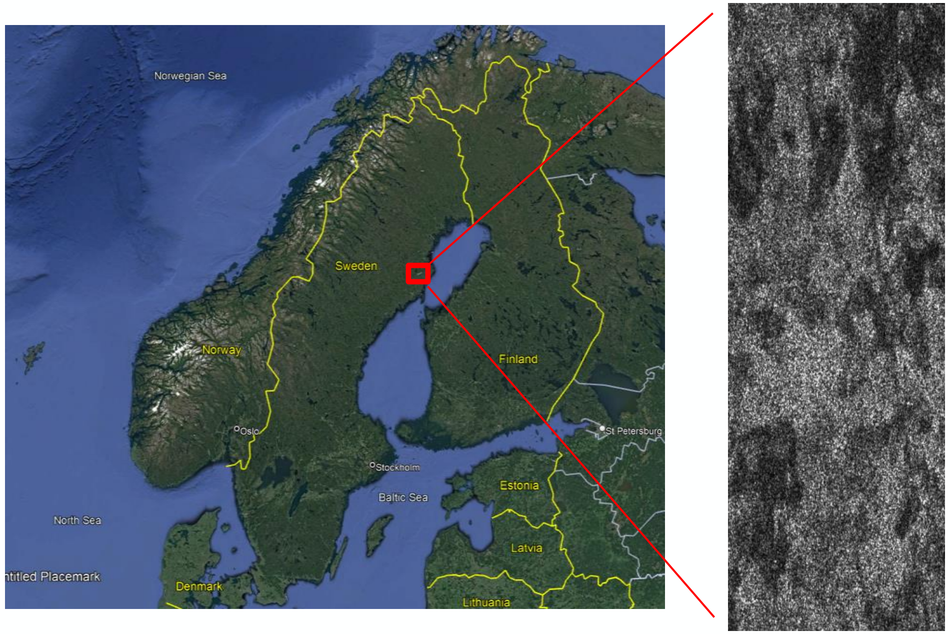
- applied at high latitudes
- azimuth sub-apertures are generated for each slant range and image
- spatial bandwidth chosen based on a-priori ionosphere information
- azimuth-squint ionospheric phase screen is a blade-like function with slope depending on ionospheric height (thin single layer ionosphere model is assumed)
- model is inverted by backprojection, applied to complex coherence to avoid phase unwrapping:

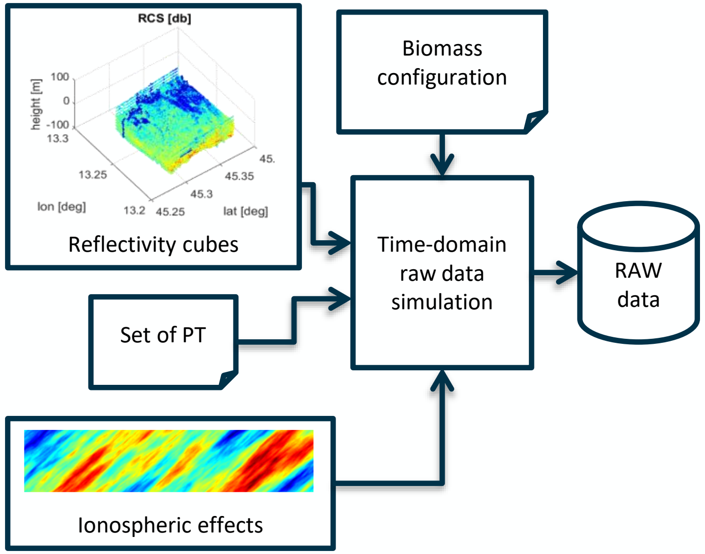
$$\hat{\phi}_i(x,h) = \angle \langle \gamma_i \left(x + \psi h / \cos\theta, \psi \right) \rangle_\psi$$

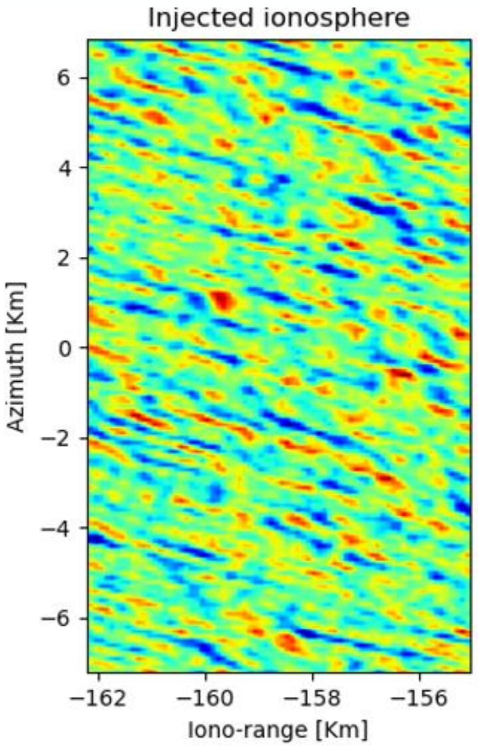


- ionosphere height is estimated as the tomographic peak (average for all ranges)
- stack is refocused compensating the screen retrieved at estimated height
- if no ionospheric height is detected, the module applies no correction

FAST VARYING IONOSPHERE

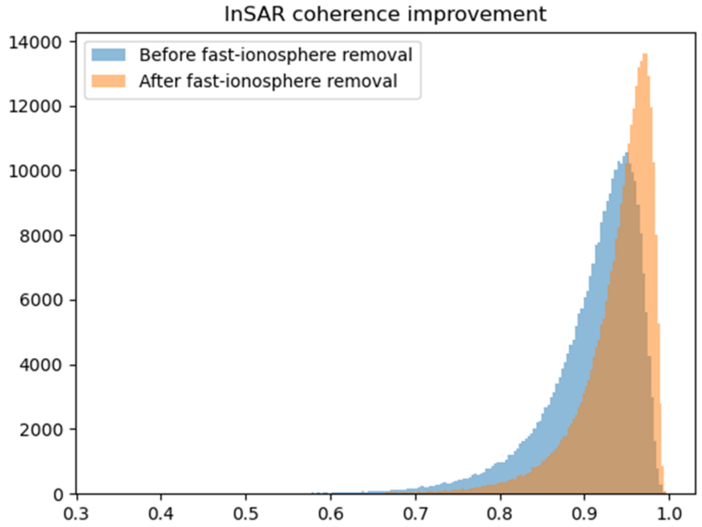


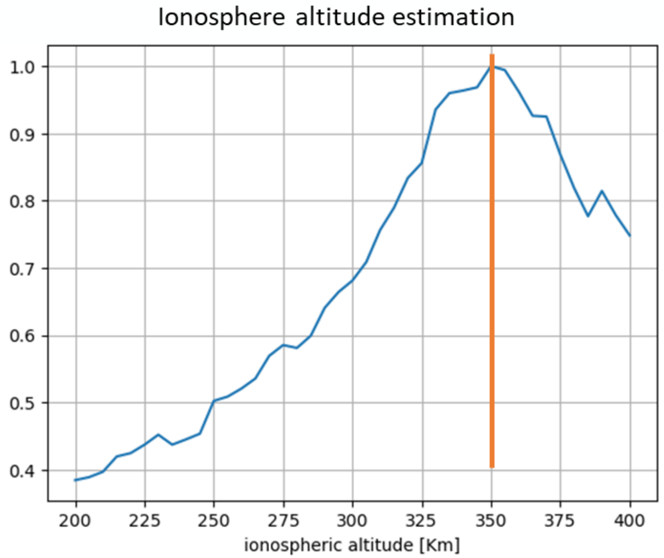


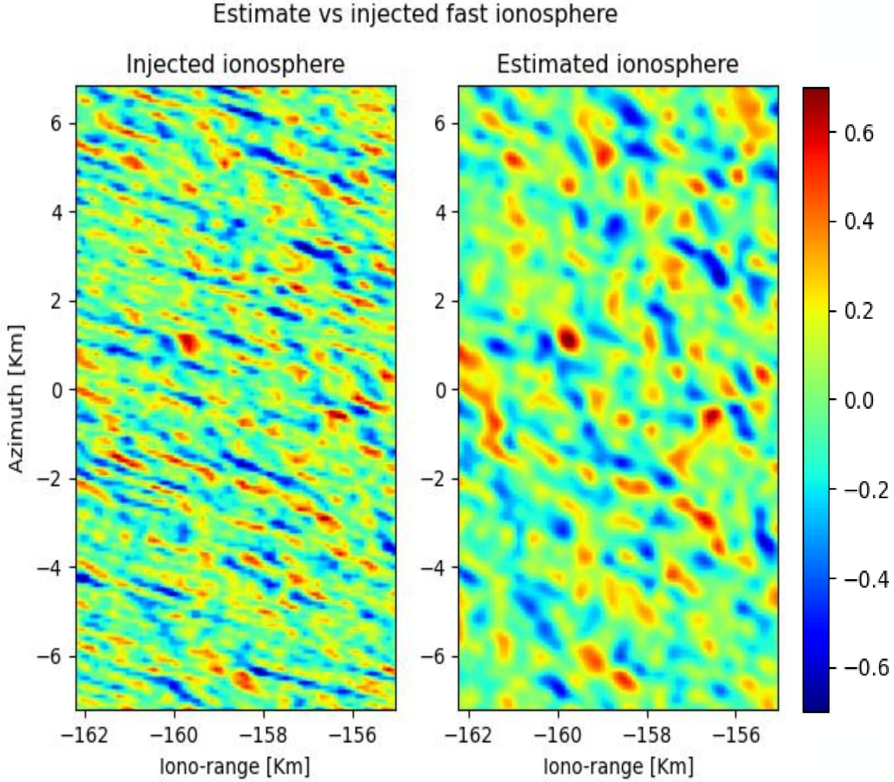


- boreal scenario simulated modeling the scene from TomoSAR (BioSAR 1)
- time-domain approach to compute raw acquisitions
- focusing to obtain a BIOMASS interferometric pair
- strong fast ionosphere is simulated (CkL = 10^{34}, ionospheric height 350 km)
- low pass screen component is removed to emulate preliminary L1 correction
- screen is injected to the secondary acquisition within time-domain simulation

FAST VARYING IONOSPHERE

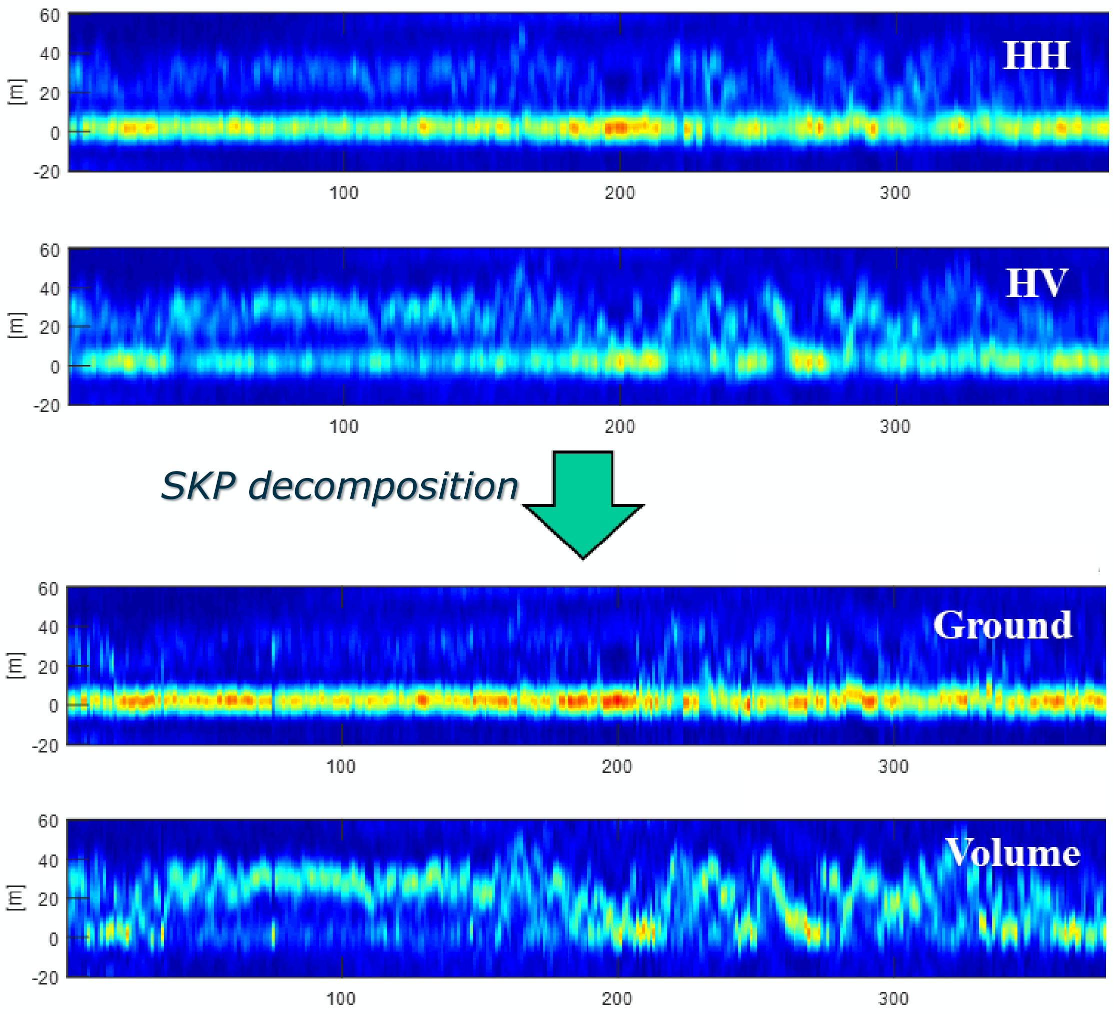




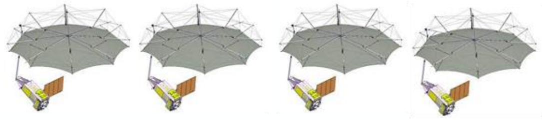


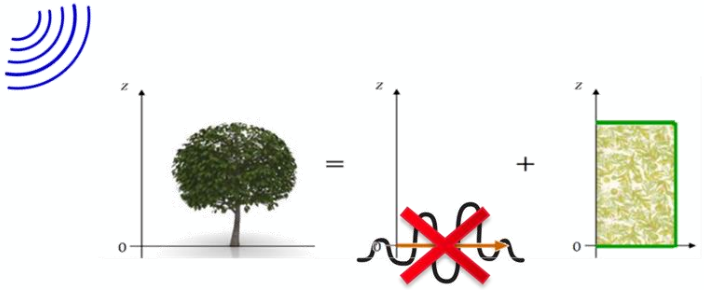
- injected and estimated ionosphere agree well
- estimated screen is low-pass because of the finite synthetic aperture
- ionospheric height is correctly estimated
- InSAR coherence over the scene after screen compensation improves

SKP CALIBRATION



- L2 processing requires fine level of calibration and topography correction
- SKP calibration compensates phase due to both ground and residual disturbance
- SKP decomposition provides structure matrices of ground and volume
- phase screens correspond to ground structure phases
- afterwards the stack is ideally fully phase calibrated and terrain compensated (terrain at zero level in tomography)

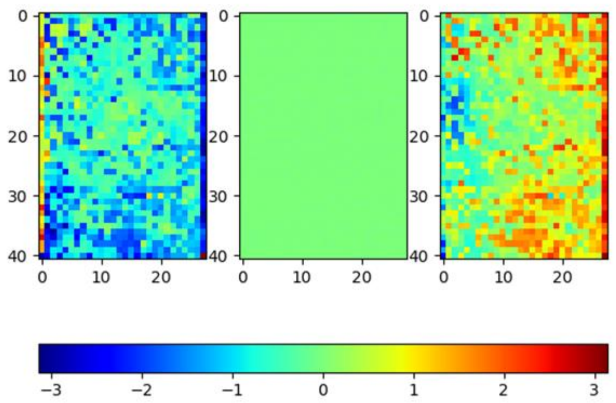




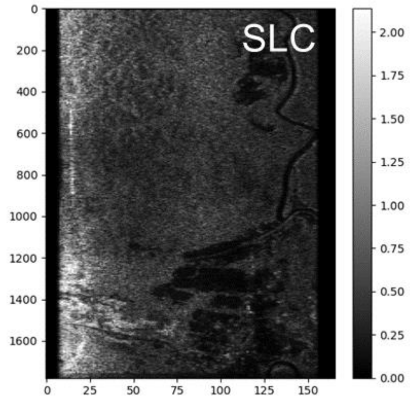
SKP CALIBRATION

- TropiSAR acquisitions reprocessed to emulate BIOMASS
- the only residual phase term is topography

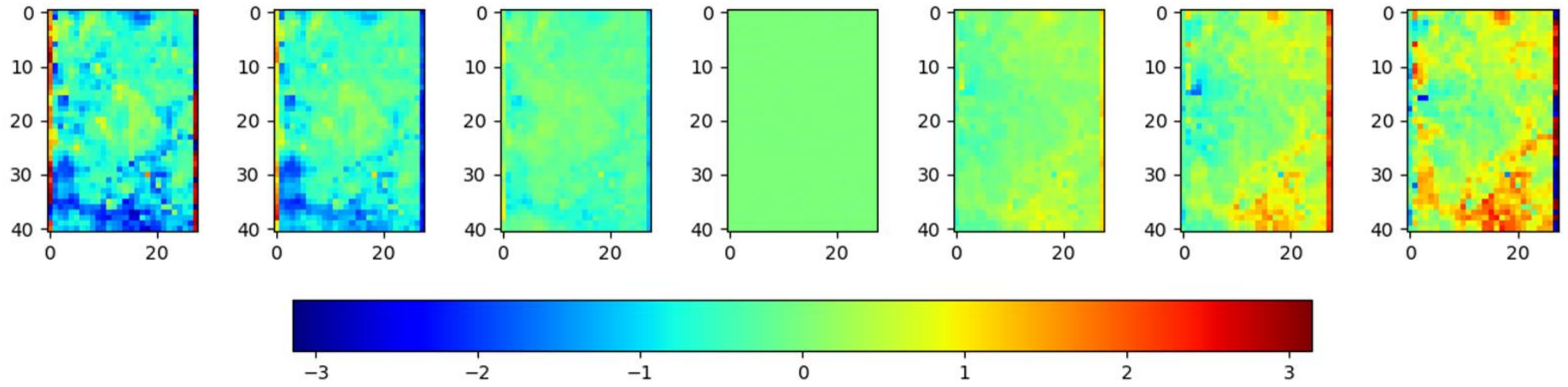
INT

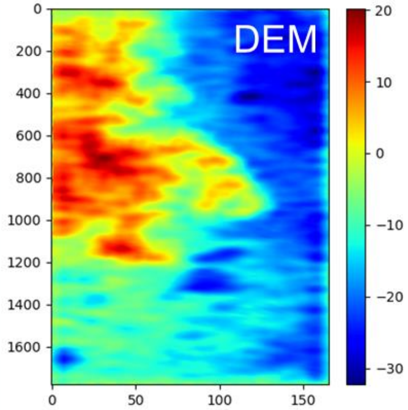


- SKP screens resemble topography scaled by different baselines
- INT screens are noisier (less acquisitions to perform SKP)



TOM





SUMMARY AND CONCLUSIONS

BIOMASS interferometric processor implements state-of-the art calibration techniques

Some preliminary results support the proposed design

Further work is devoted to better assess performance and review the design

Applying fast ionosphere correction to maximise coherence before low-pass corrections is to be investigated

L1 corrections effects on interferometry are to be precisely assessed, to harmonize the calibration steps

Eventually, end-to-end testing is to be carried out