ESA 6th Advanced Training Course on Radar Polarimetry

Lessons from campaign data

Stefano Tebaldini
Politecnico di Milano

Laurent Ferro-Famil
Université de Rennes 1, Centre **d'Etudes** Spatiales de la Biosphère

ESA UNCLASSIFIED – For ESA Official Use Only

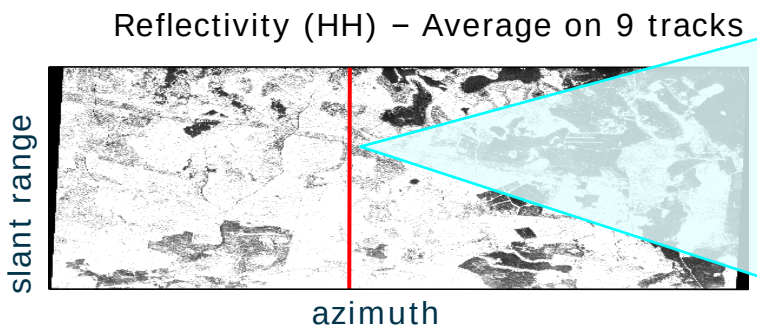
Forested areas

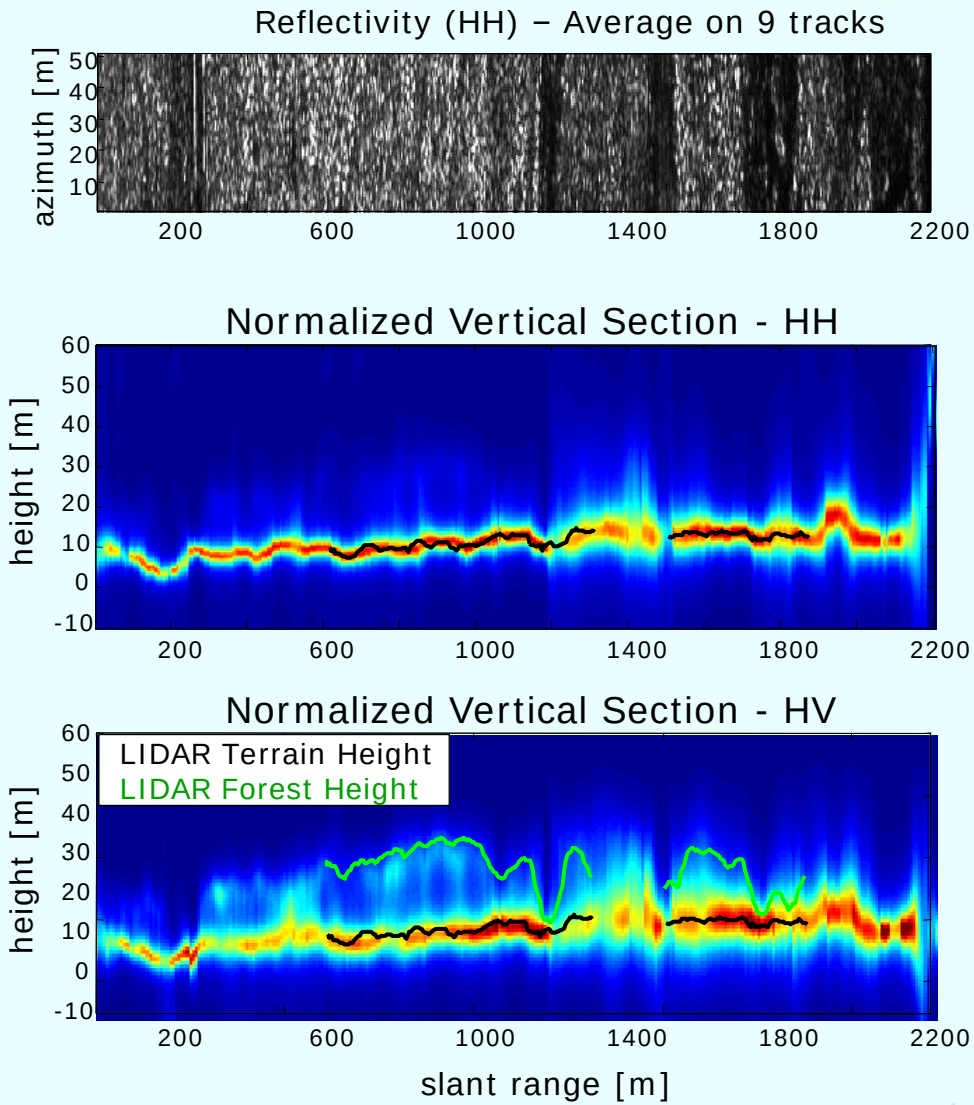
BioSAR 2007

Campaign	BioSAR 2007 - ESA
System	E-SAR - DLR
Period	Spring 2007
Site	Remningstorp, South Sweden
Scene	Semi-boreal forest
Topography	Flat
Tomographic tracks	9 – Fully Polarimetric
Carrier frequency	350 MHz
Slant range resolution	2 m
Azimuth resolution	1.6 m
Vertical resolution	10 m (near range) to 40 m (far range)

BioSAR 2007

Tomographic reconstruction of an azimuth cut:





The analyzed profile is almost totally forested, except for the dark areas

HH:

- Dominant phase center is ground locked
- Vegetation is barely visible

Similar conclusions for VV

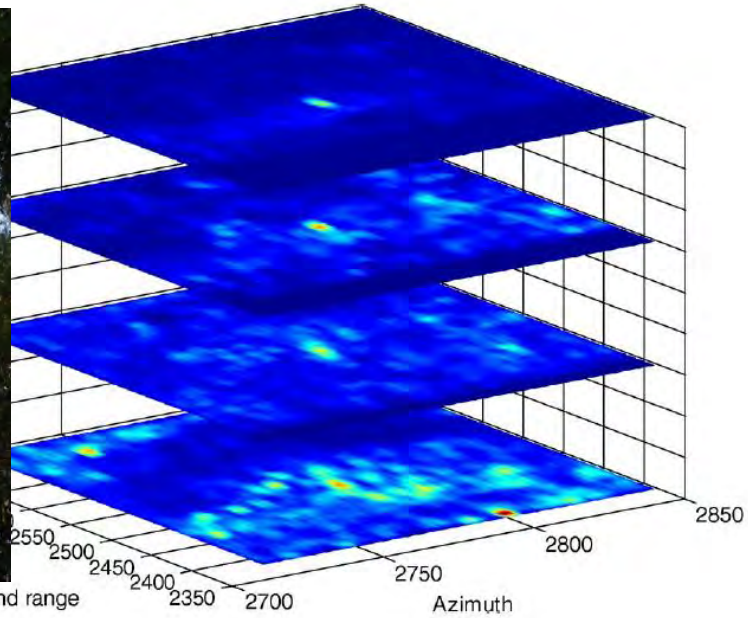
HV:

- Vegetation is much more visible
- Dominant phase center is ground locked

TropiSAR

Campaign	TropiSAR- ESA
System	Sethi- ONERA
Period	August 2009
Sites	Paracou & Nourages, French Guyana
Scene	Tropical forest estimated 150 species per hectare Dominant families: Lecythidaceae, Leguminoseae, Chrysobalanaceae, Euphorbiaceae.
Tomographic tracks	6 – Fully Polarimetric
Carrier frequency	P-Band
Slant range resolution	≈1 m
Azimuth resolution	≈1 m
Vertical resolution	15 m

3D Imaging of the Guyaflux Tower



TropiSAR

Tomographic reconstruction of two azimuth cuts:

Method: coherent focusing

All panels have been re-interpolated such that the ground level corresponds to 0 m

HH

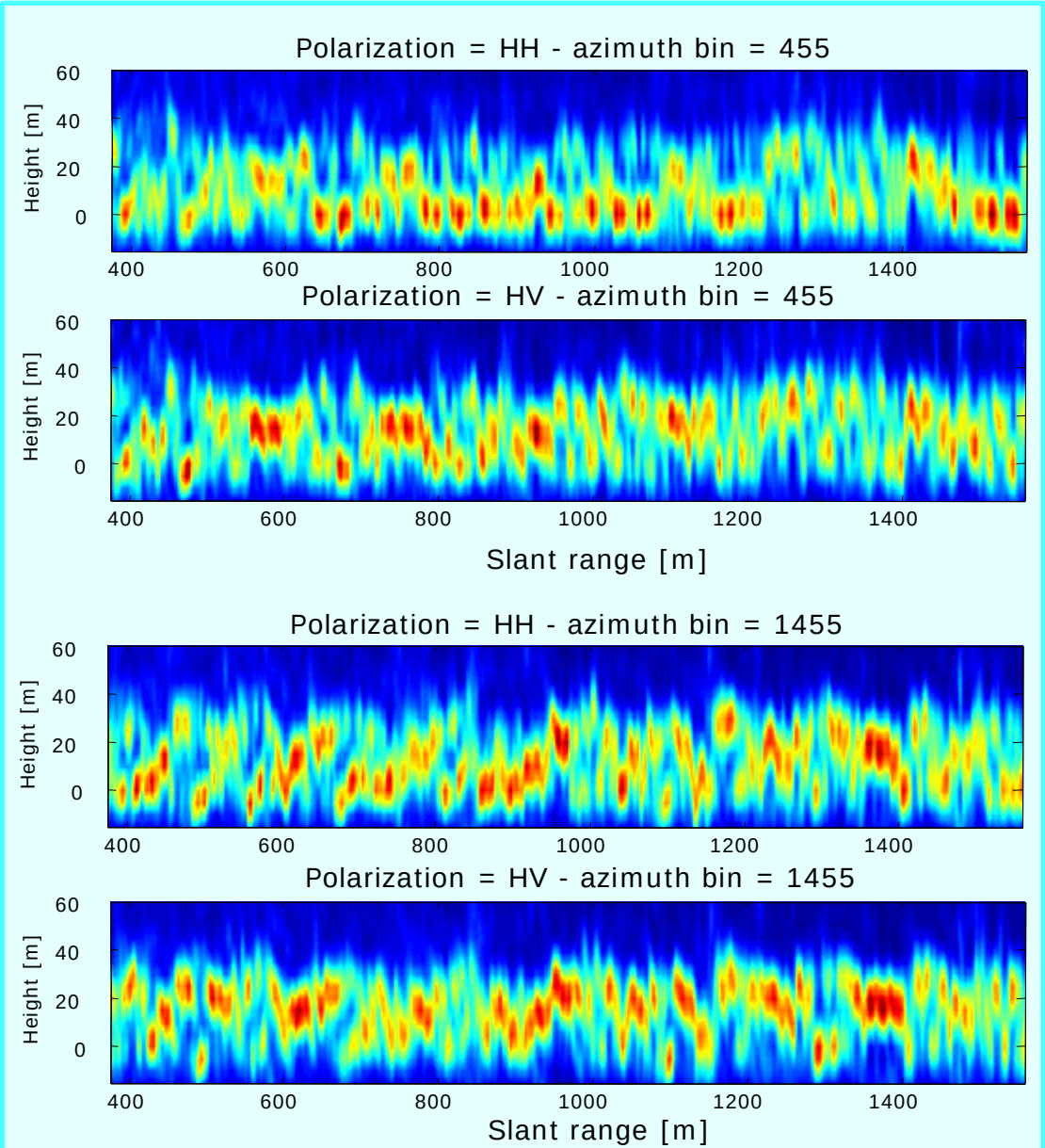
Visible contribution from the ground level beneath the forest

Vegetation is well visible

HV

Poor contributions from the ground level beneath the forest

Vegetation is well visible

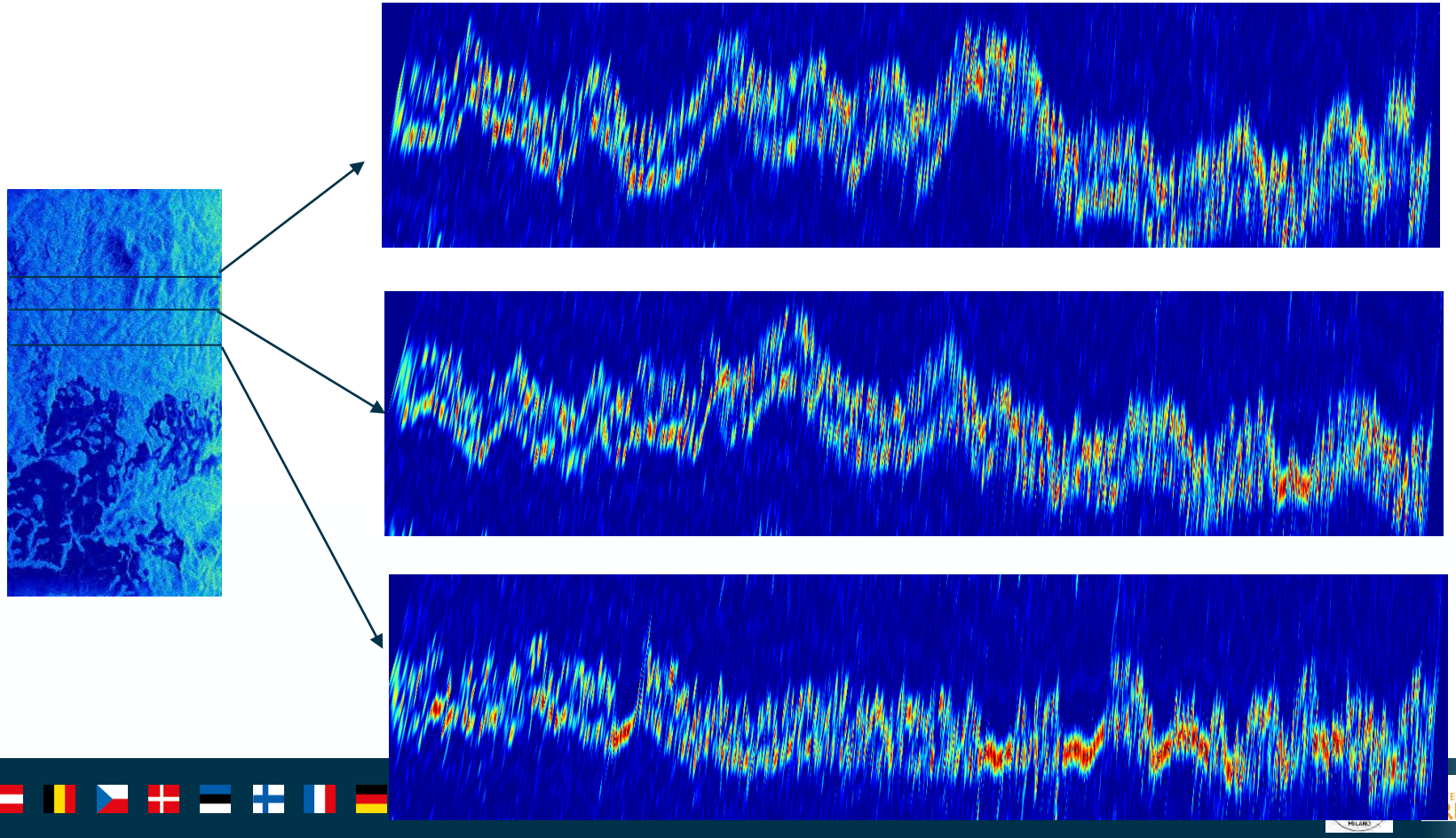


AFRISAR

Campaign	AfriSAR - ESA
System	Sethi- ONERA & F-SAR - DLR
Period	2015
Sites	La Lope, Mondah, Mabounie
Scene	Tropical forest
Tomographic tracks	7 to > 10, fully polarimetric

Processing algorithm:

Single-look 3D Time Domain BackProjection

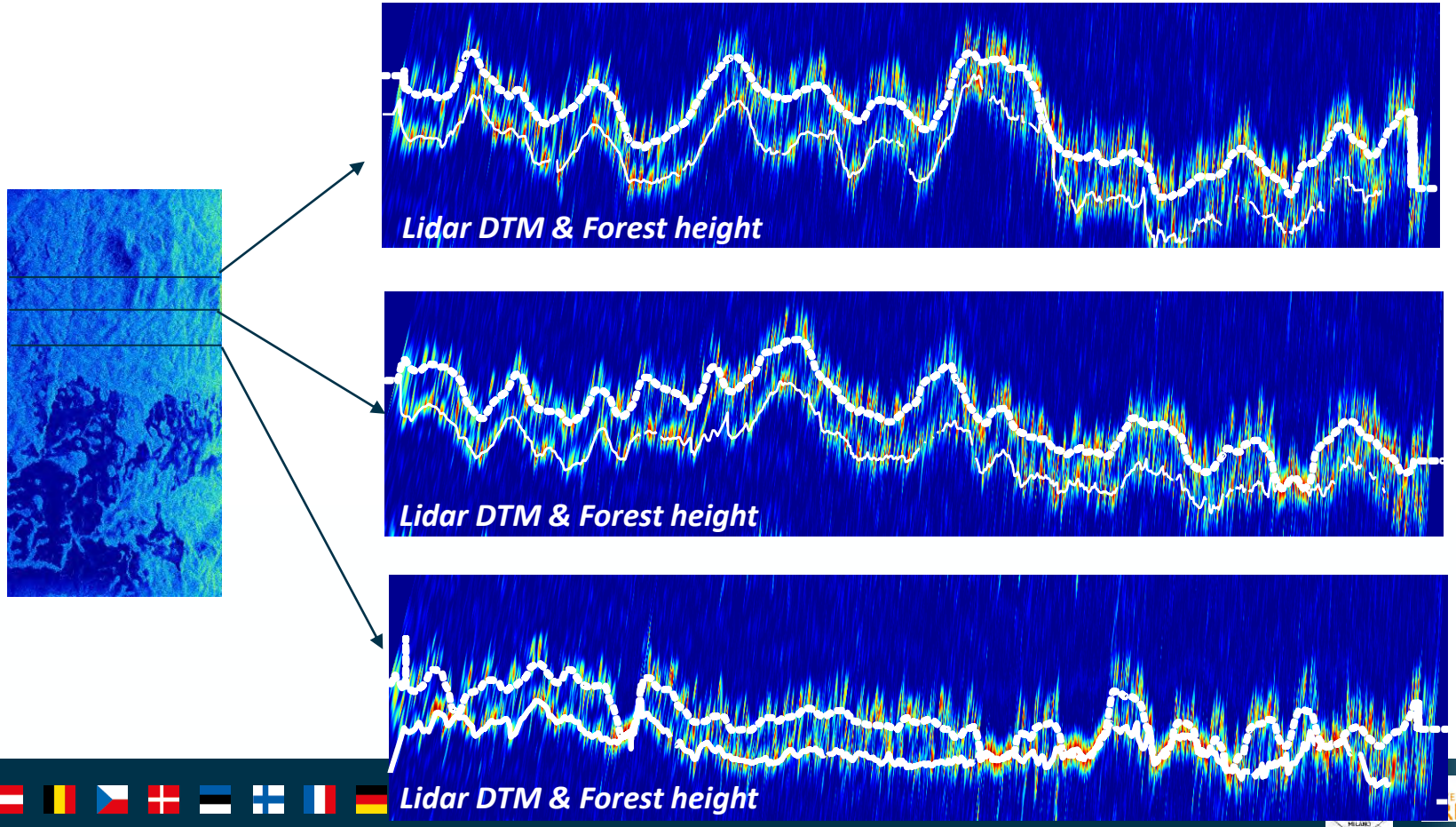


AFRISAR

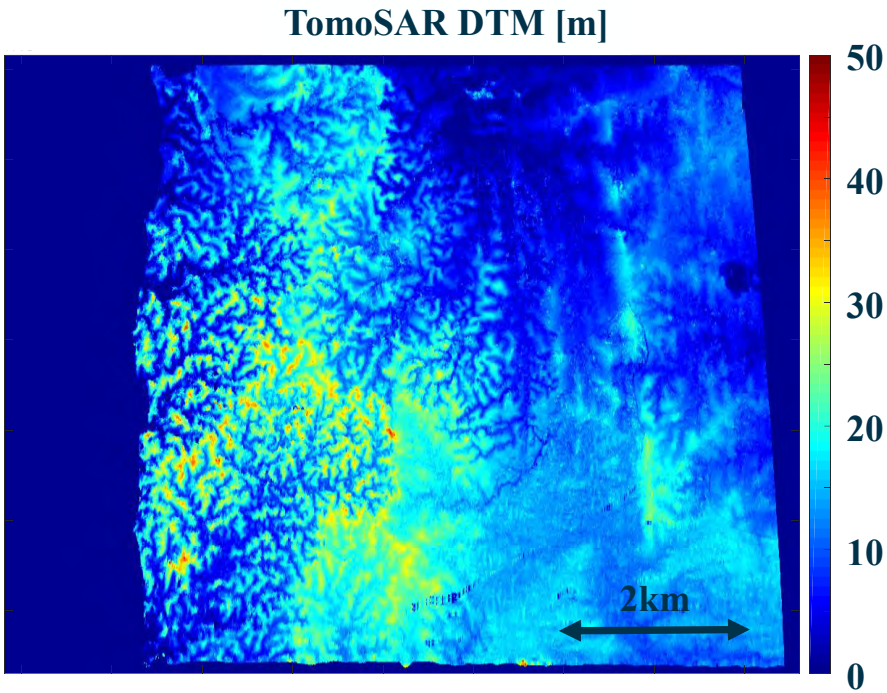
Campaign	AfriSAR - ESA
System	Sethi- ONERA & F-SAR - DLR
Period	2015
Sites	La Lope, Mondah, Mabounie
Scene	Tropical forest
Tomographic tracks	7 to > 10, fully polarimetric

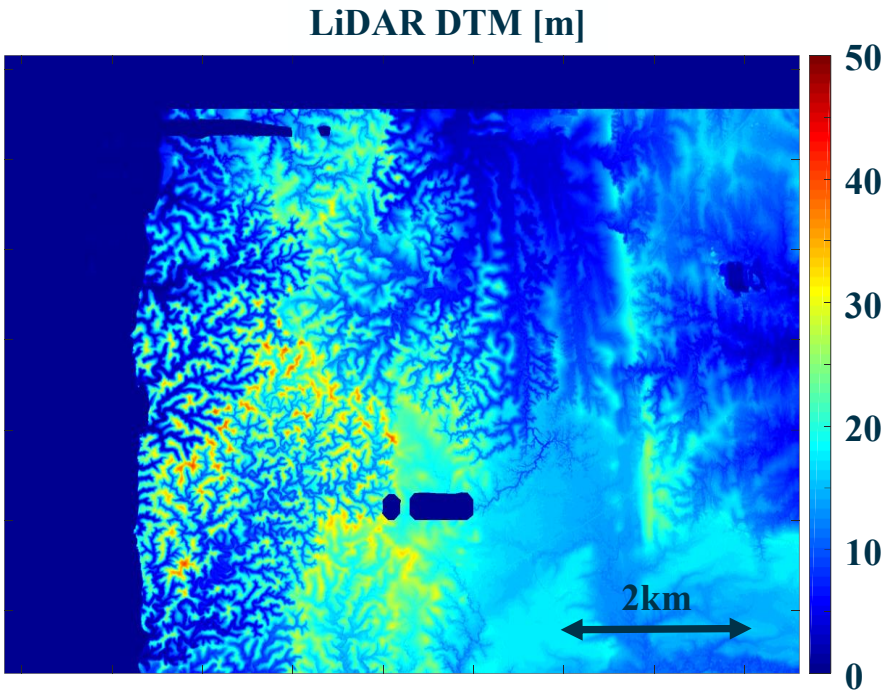
Processing algorithm:

Single-look 3D Time Domain BackProjection



AFRISAR – Digital Terrain Model by SAR Tomography





Site: Mondah, Gabon

Data-set: AfriSAR (ESA)

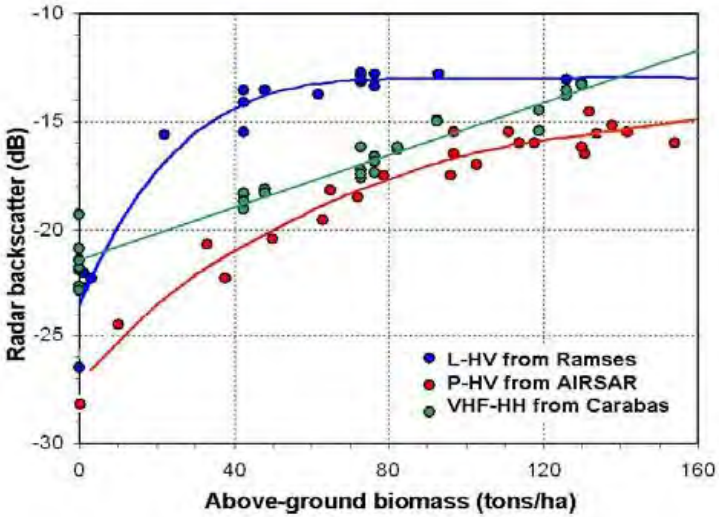
Frequency: P-Band

$\sigma_{SAR\text{-}LIDAR} \approx 2.8$ *m w.r.t. Lidar DTM*

TomoSAR & forest (above-ground) biomass

Longer wavelength SARs ⇔ precious tool for forestry remote sensing

- Under foliage penetration capabilities
- Mitigate saturation in backscatter vs forest biomass law



From Le Toan et al., 2004

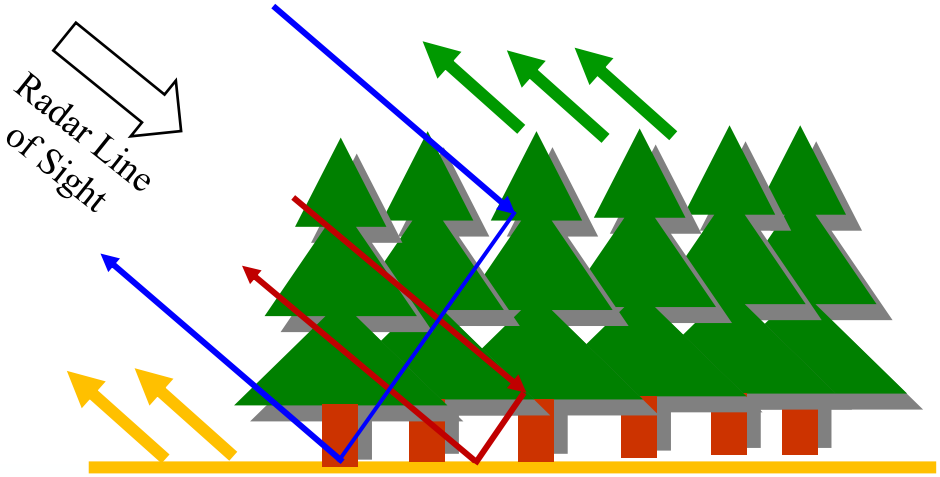
TomoSAR & forest (above-ground) biomass

Longer wavelength SARs ⇔ precious tool for forestry remote sensing

- Under foliage penetration capabilities
- Mitigate saturation in backscatter vs forest biomass law

Sensitivity to the whole forest structure ⇔ many different scattering mechanisms

- **Back scatter from the canopy**
- **Back scatter from the ground (Bragg)**
- **Trunk-Ground forward scatter**
- **Canopy-Ground forward scatter**



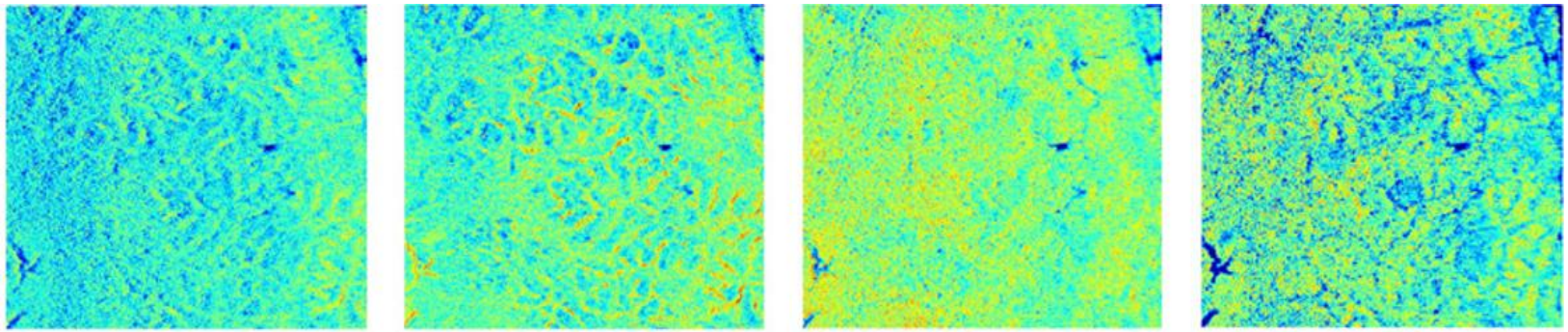
Can 3D Tomography help ?

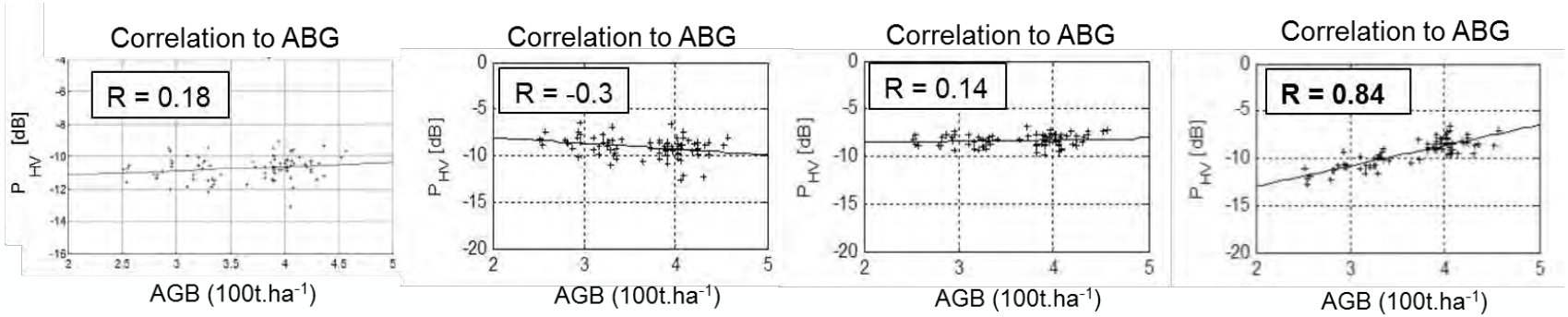
TropiSAR – *Paracou*

Correlation between Radar intensity and in-situ AGB

- 2D SAR intensity is poorly correlated to AGB
- TomoSAR intensity at 0 m is poorly and negatively correlated to AGB
- TomoSAR intensity at 30 m is highly correlated to AGB (≈ 50 Mg/ha per dB)

2D SAR | *TomoSAR: Ground level* | *TomoSAR: Ground level + 15 m* | *TomoSAR: Ground level + 30 m*





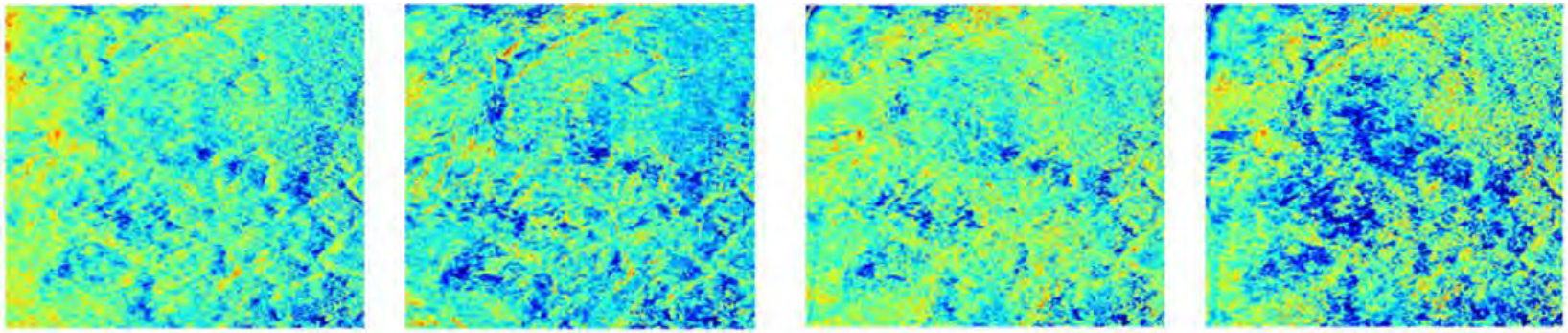
D. Ho Tong Minh et al., "Relating P-band SAR tomography to tropical forest biomass", TGRS, Feb. 2014.

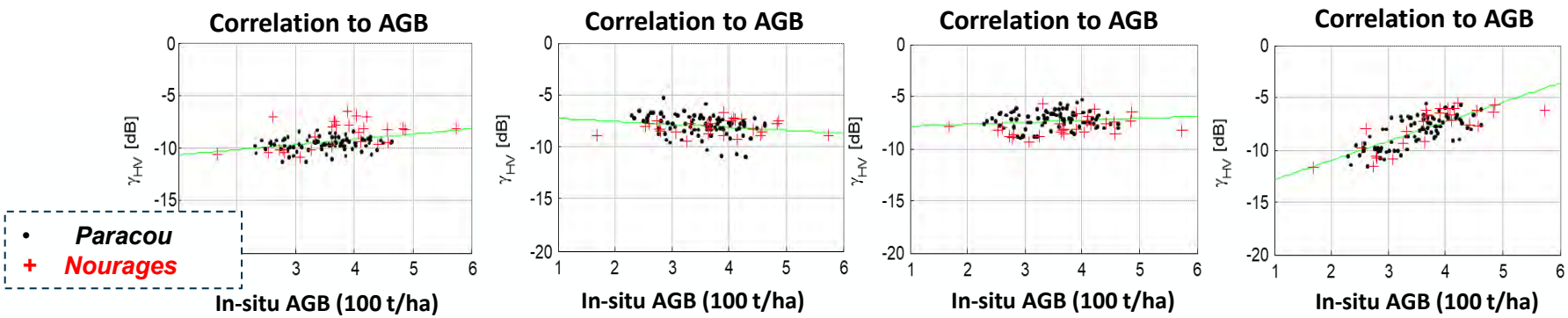
TropiSAR – *Nourages*

Correlation between Radar intensity and in-situ AGB

- 2D SAR intensity is poorly correlated to AGB
- TomoSAR intensity at 0 m is poorly and negatively correlated to AGB
- TomoSAR intensity at 30 m is highly correlated to AGB (≈ 50 Mg/ha per dB)

2D SAR | *TomoSAR: Ground level* | *TomoSAR: Ground level + 15 m* | *TomoSAR: Ground level + 30 m*



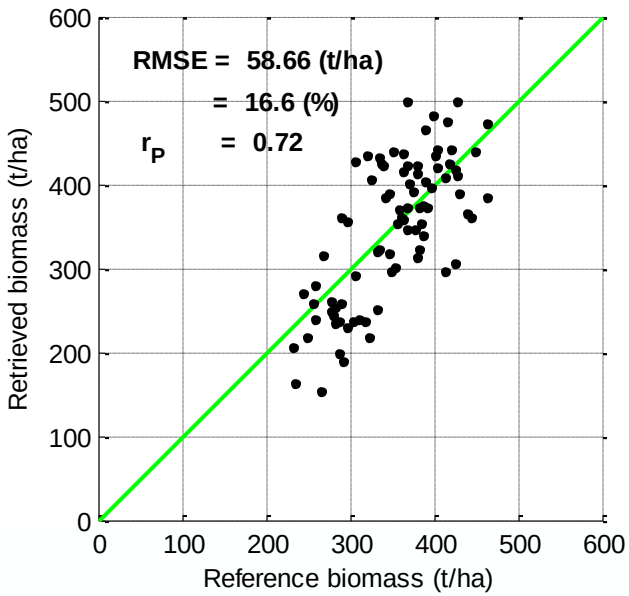


D. Ho Tong Minh et al., "SAR tomography for the retrieval of forest biomass and height : cross-validation at two tropical forest sites in French Guiana". Remote Sensing of Environment, vol. 175, pp. 138-147, Mar. 2016.

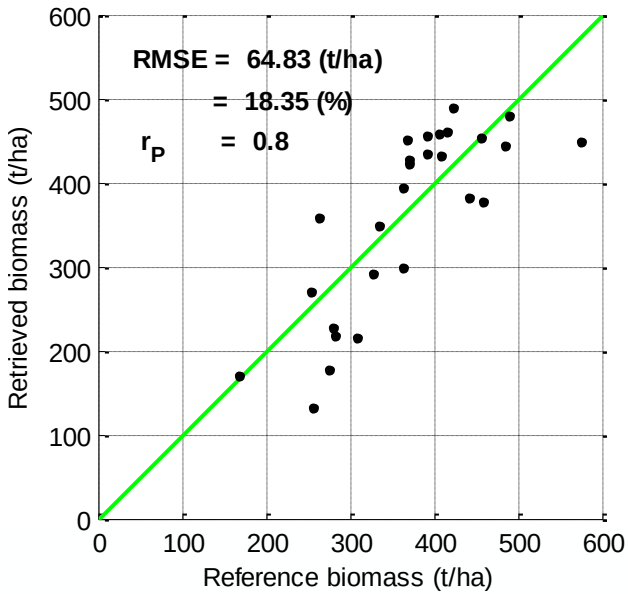
Cross-site transferability

Model: $AGB = a \cdot T_{30}^{HV} + b$

Training: Nouragues
Validation: Paracou



Training: Paracou
Validation: Nouragues



***D. Ho Tong Minh et al., "SAR tomography for the retrieval of forest biomass and height : cross**-validation at two tropical forest sites in French Guiana". Remote Sensing of Environment, vol. 175, pp. 138-147, Mar. 2016.*

TomoSAR & forest biomass

Results were confirmed for three African forest sites…..

Sites: Paracou, Nourages (French Guiana)

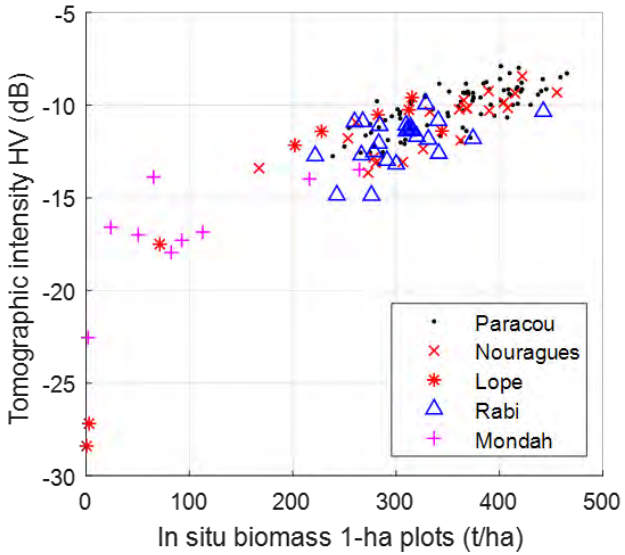
Lopé, Rabi, Mondah (Gabon)

Frequency: P-Band

Data-sets: TropiSAR and AfriSAR (ESA)

Data-set by ONERA

Tebaldini et al., Geophysical Surveys, 2019



…. and for a boreal site at L-Band

Site: Krycklan (Sweden)

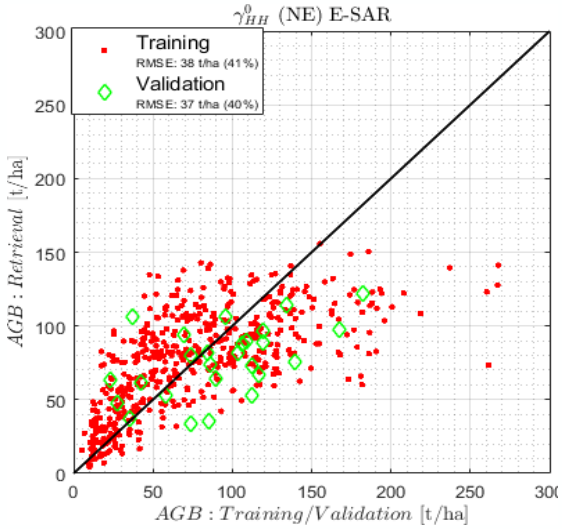
Frequency: L-Band

Data-set: BioSAR 2 (ESA)

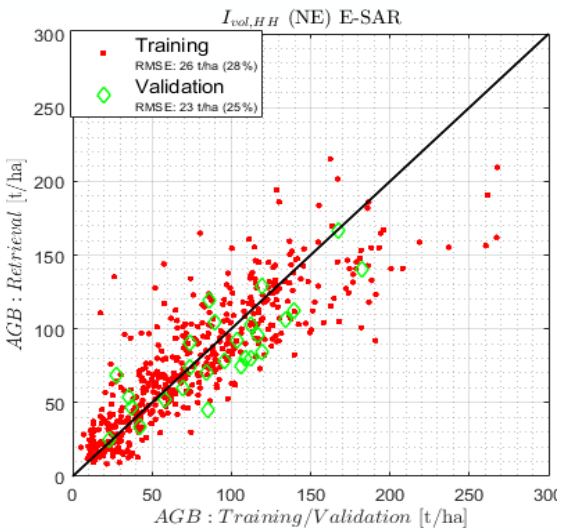
Data-set by DLR

Blomberg et al., GRSL, 2018

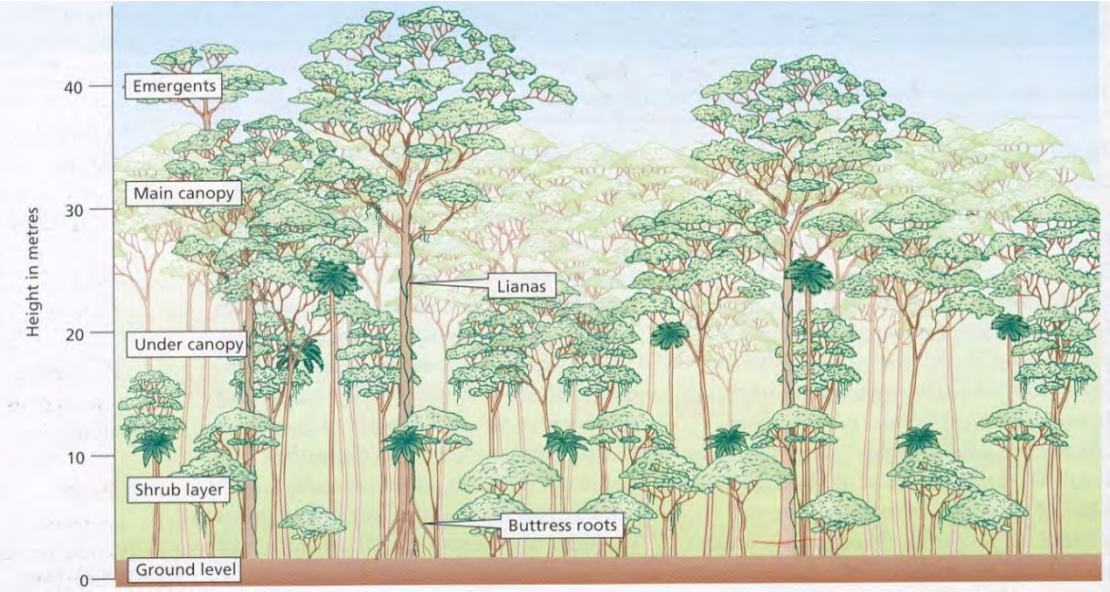
2D SAR



TomoSAR



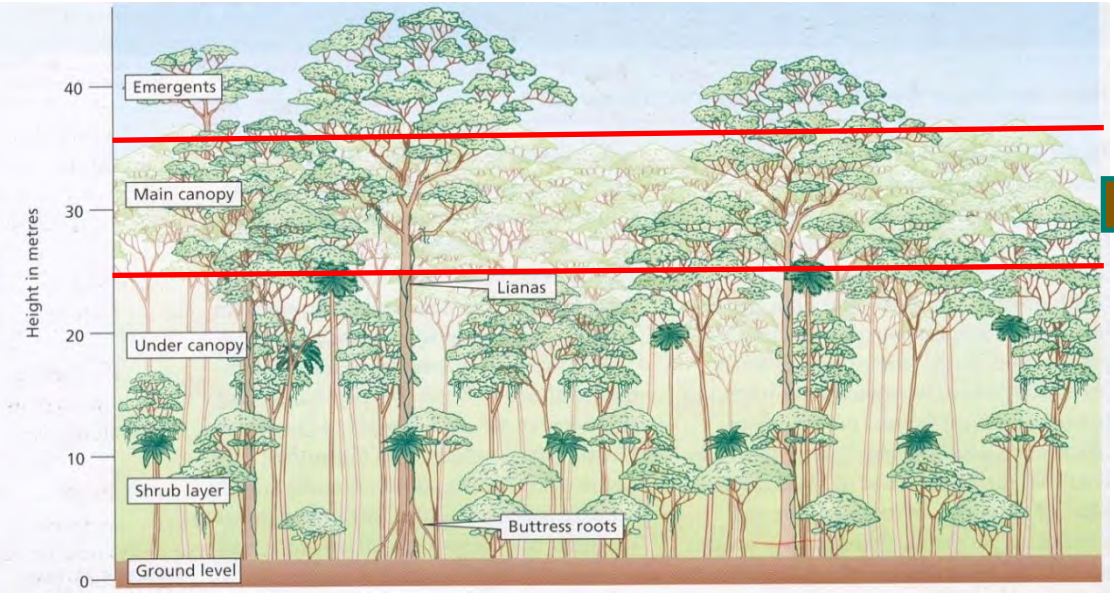
General structure of tropical forest



The tropical rainforest is vertically divided into at least four layers:

1. **The overstory** refers to the crowns of emergent trees which are above the rest of the canopy (40m in fig.)
2. **The main canopy** is the dense ceiling of closely spaced trees and their branches, centered at 30m,
3. **The undercanopy** is more widely spaced, smaller trees below the canopy (below 20m).
4. **The ground** layer containing the trubk bases, and shrubs and young trees that grow only 2-6 m

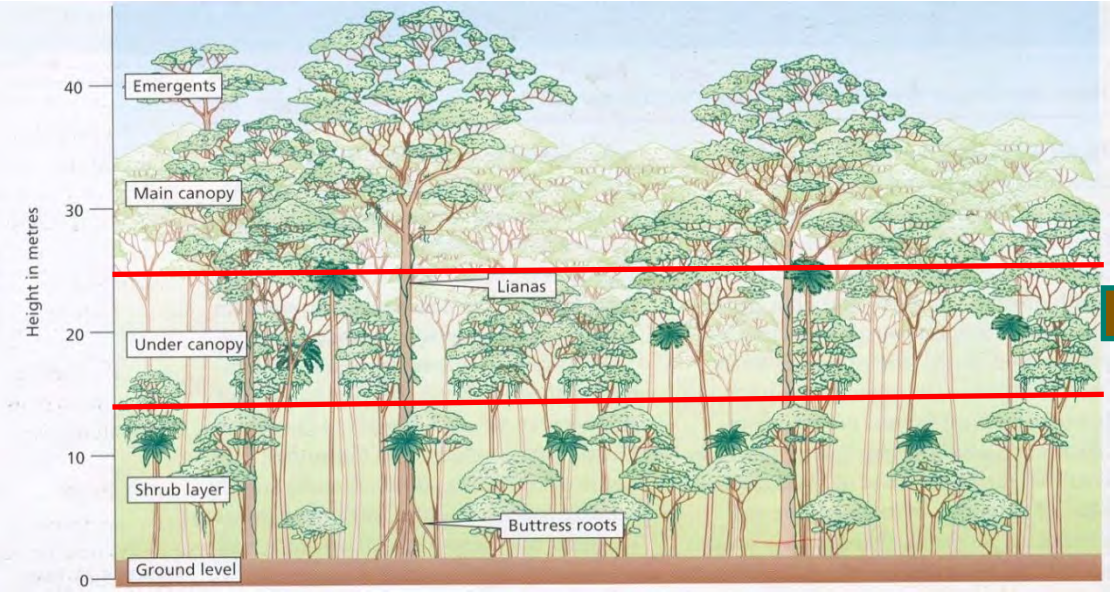
The main canopy layer



The canopy layer:

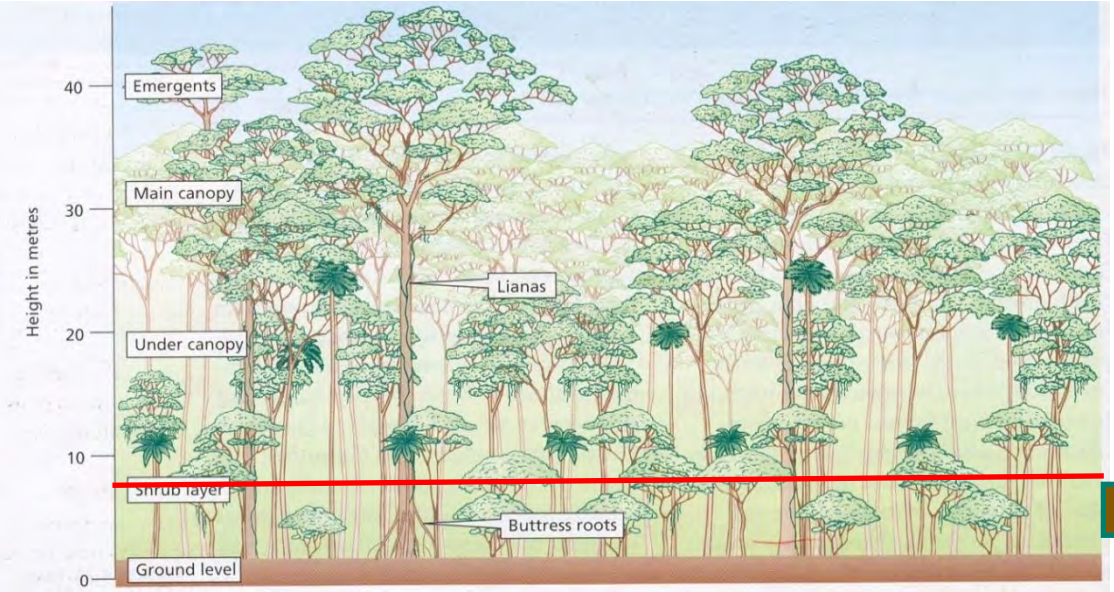
- o containing a major part of the leaves that convert sunlight to energy through photosynthesis,
- o being a principal site for the interchange of heat, water vapour, and atmospheric gases
- o contains a large proportion of the woody elements, including trunks and most of the branches (primary, secondary, and higher order) that contribute to the total AGB

The under canopy layer



Under the canopy,
there is little direct sunlight due to the extinction of the light through the canopy layer.
Contains part of trunk woody biomass

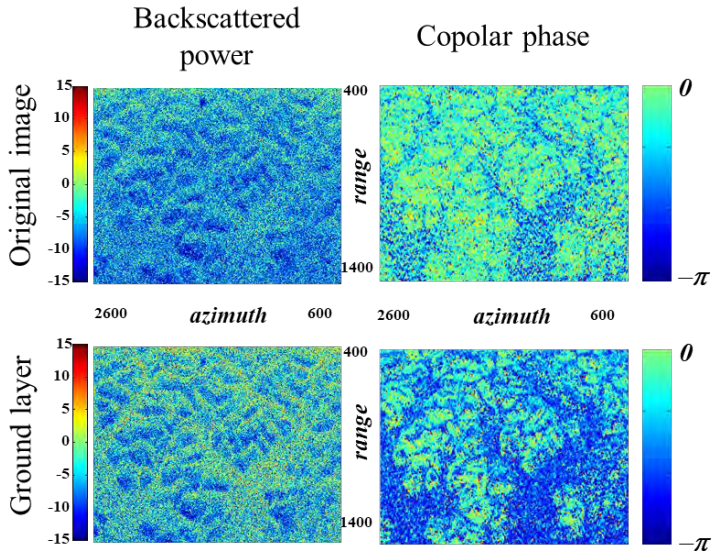
The ground layer

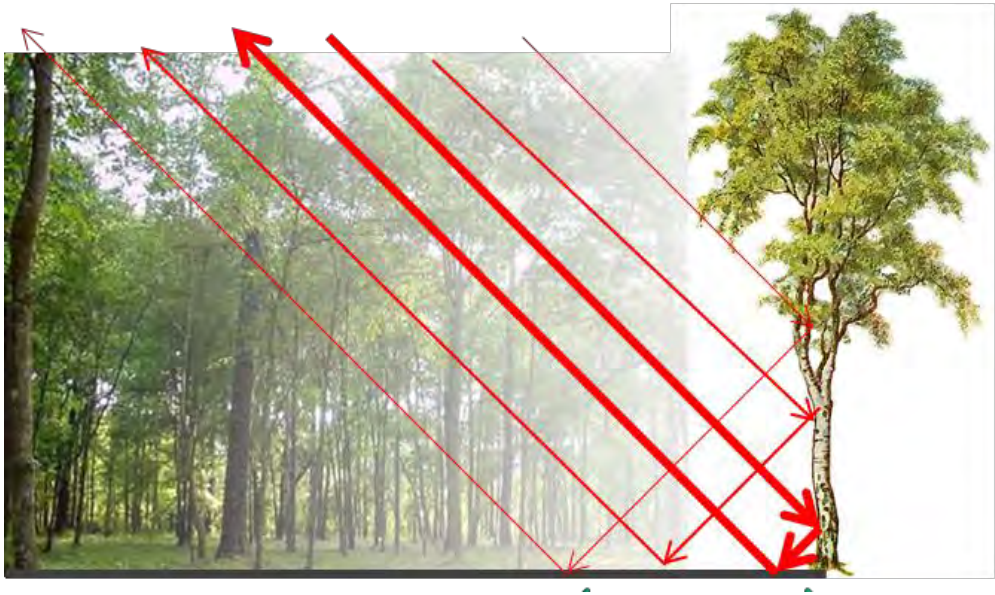


The ground layer contains the biggest part of the trunk biomass, and should have large proportion of total AGB

The ground layer as seen by Tomography

EM power returning from the ground layer is **strongly** determined by multiple scattering from vegetation-to-ground interactions





M. Mariotti ***d'Alessandro et al., "Phenomenology of Ground Scattering in a Tropical Forest Through*** *Polarimetric* ***Synthetic Aperture Radar Tomography", TGRS, 2013***

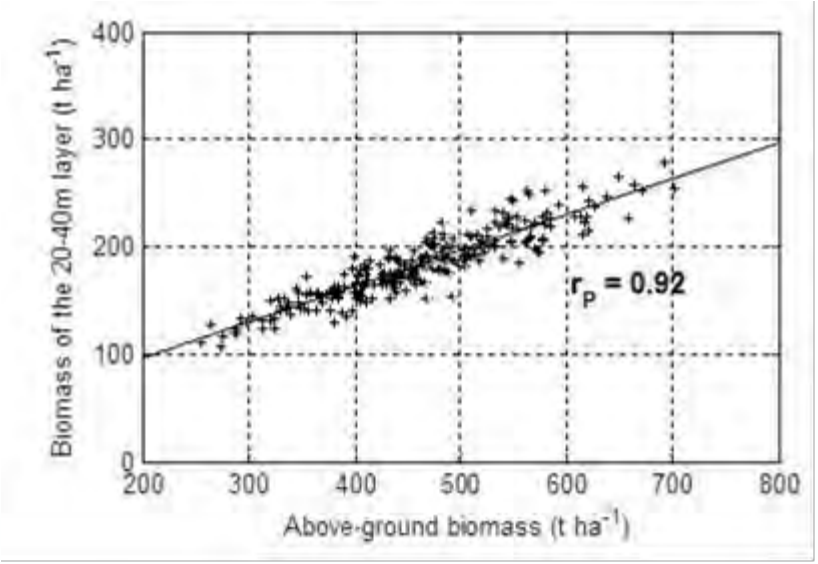
⇒ **Scattering from the ground layer is perturbed by a number of disturbance factors, including: local terrain slope, soil moisture, presence of nearby trees, understory**

The 30 m layer

Why is the best correlation observed at 30 m?

- How the biomass in this layer is related to AGB ?
- Is 30 m a general feature of tropical forests?

Assessment using the TROLL equations



- The biomass contained in the 20-40m layer vs the total AGB, both derived using the TROLL model.
- The biomass proportion is about 33%.
- A linear fit to the relationship gives a correlation coefficient of 0.92.
- An interesting feature is that it implies that this relation holds independent of biomass, from 250 to 700 t/ha, including the highest AGB plots with emergent trees

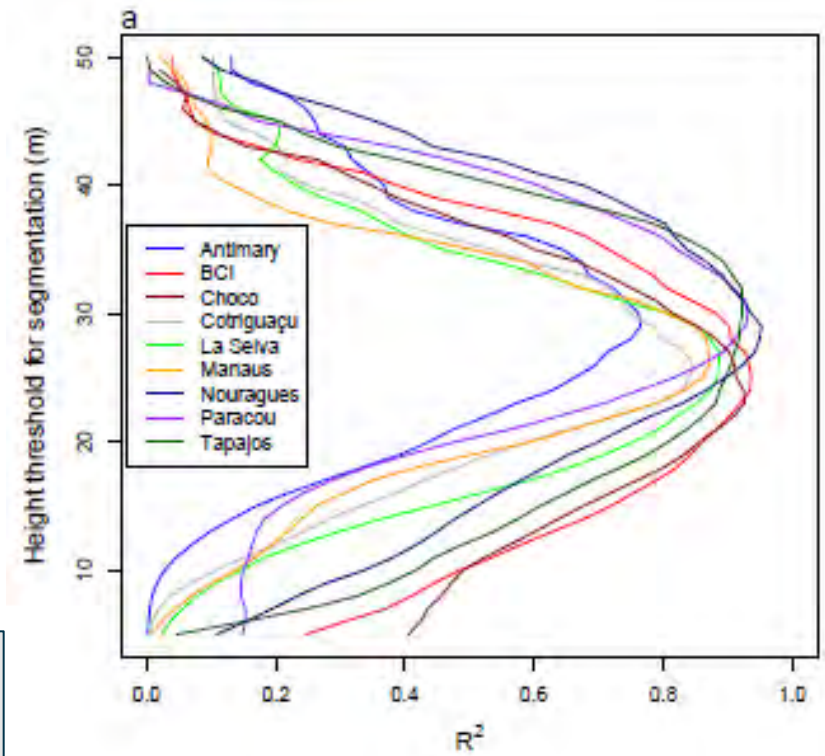
D. Ho Tong Minh et al., "Relating P-band SAR tomography to tropical forest biomass", TGRS, Feb. 2014.

Chave, Jérôme. "Study of structural, successional and spatial patterns in tropical rain forests using TROLL, a spatially explicit forest model." *Ecological modelling* 124.2 (1999): 233-254.

Assessment by LIDAR metrics

- The specific feature of the 30 m layer in tropical rainforests has also been noticed in a recent study of 9 tropical rainforest in South America by *Meyer et al.*

- Correlation between AGB and the area occupied at different heights by large trees (as derived from Lidar)
- Correlation (R^2) has been found to be maximum at height of 27-30 m, irrespectively of the 9 study sites.

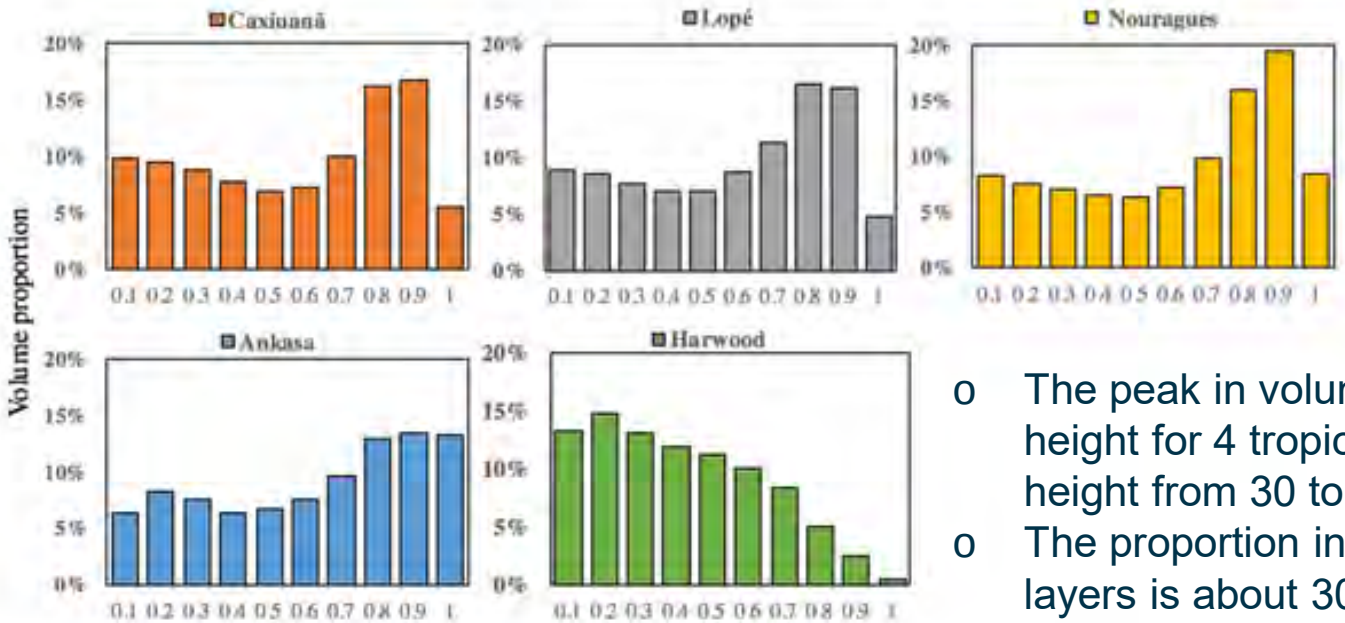


Meyer V. Saatchi S. . et al., 'Large canopy area explains landscape variation of Above Ground Biomass' Submitted to *Ecological Applications*, 2017.

Also in 'De la canopée à la biomasse' thèse de l'Université Paul Sabatier http://thesesups.ups-tlse.fr/3515/

Assessment by LIDAR metrics

- Study by UCL using Terrestrial Laser Scanning (TLS)
- Proportion of stand volume (*y axis*) as a function of normalized height (*x axis*) at 4 tropical forests and 1 temperate coniferous forest

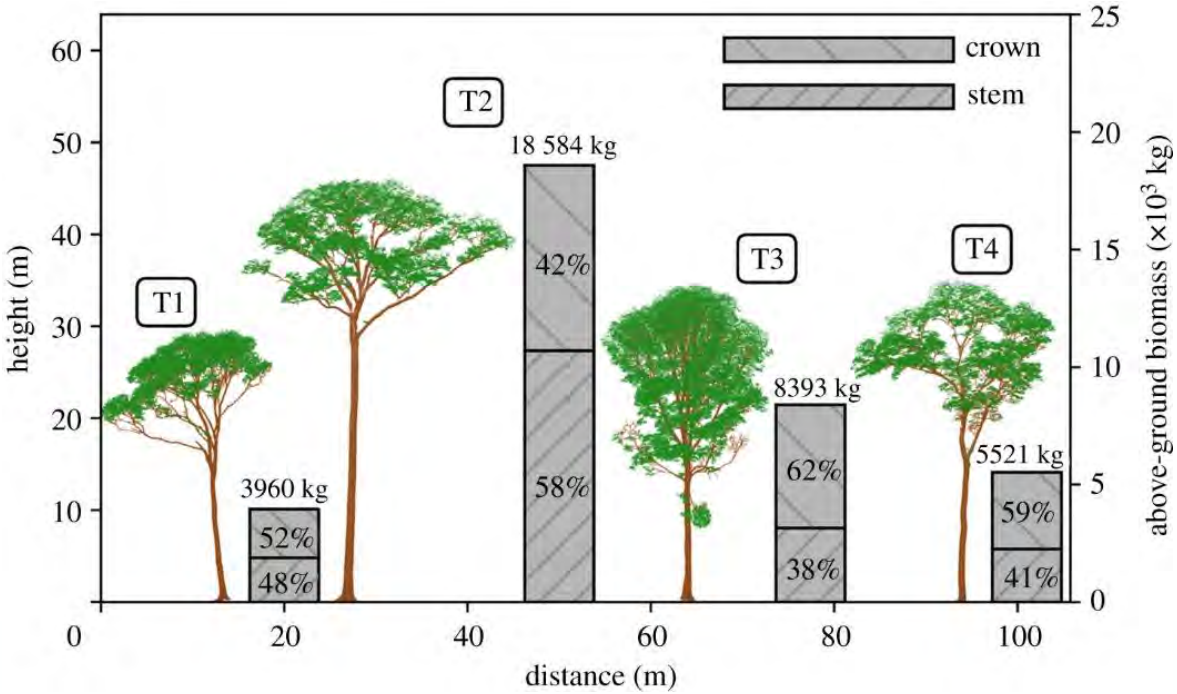


- The peak in volume occurs near the top height for 4 tropical forests (24-40 m for height from 30 to 45 m)
- The proportion in volume of the peak layers is about 30%

Image courtesy of Mathias Disney – Private communications
Sicong Tang - Quantifying Differences in Forest Structures with Quantitative Structure Models from TLS Data – M.Sc. Thesis - UCL

Assessment by LIDAR metrics

- Study by UCL using Terrestrial Laser Scanning (TLS)
- Terrestrial lidar point clouds collected from the four trees prior to harvest.



The bars on the secondary *y*-axis provide the harvest-derived reference values of above-ground biomass (AGB_{ref}).

Also shown in these bars are the distributions of AGB_{ref} between the stem and crown.

Burt et al., New insights into large tropical tree mass and structure from direct harvest and terrestrial lidar
The Royal Society, 2021, open sci.8201458201458

TomoSAR & forest (above-ground) biomass

The observations

- Correlation of Radar intensity to AGB in tropical forest improves dramatically by using Tomographic intensity at 30 m
- Observed in South American and African sites (Paracou, Nourages, Lope, Rabi, Mondah)
- Relation between AGB and TomoSAR intensity is consistent across all sites
- Also supported by experiments at L-Band in boreal forests

Interpretation

TomoSAR brings a two-fold beneficial effect on AGB retrieval, as it allows to:

1. Single out the most biophysically relevant layer in dense tropical forests
   - Consistent with ecological models of mature tropical forests, that predict that biomass contained in the 20-40m layer is about 33% of total biomass

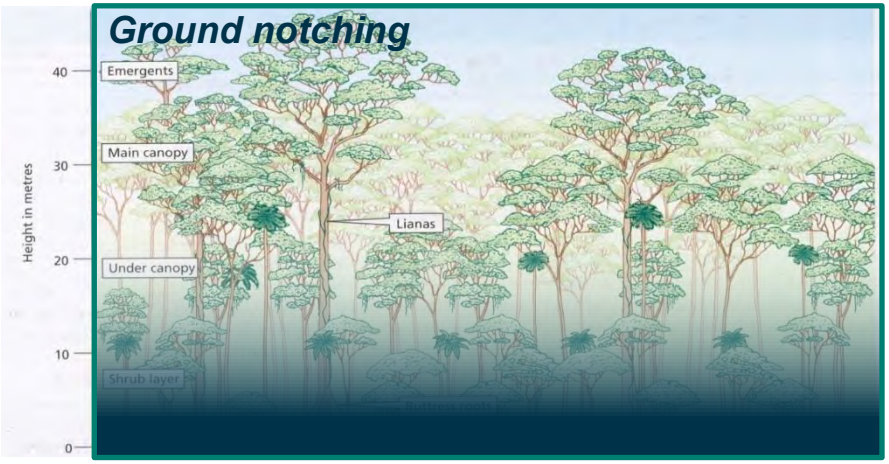
2. Cancel out ground scattering, which acts as a disturbing factor limiting sensitivity to AGB of conventional 2D SAR images

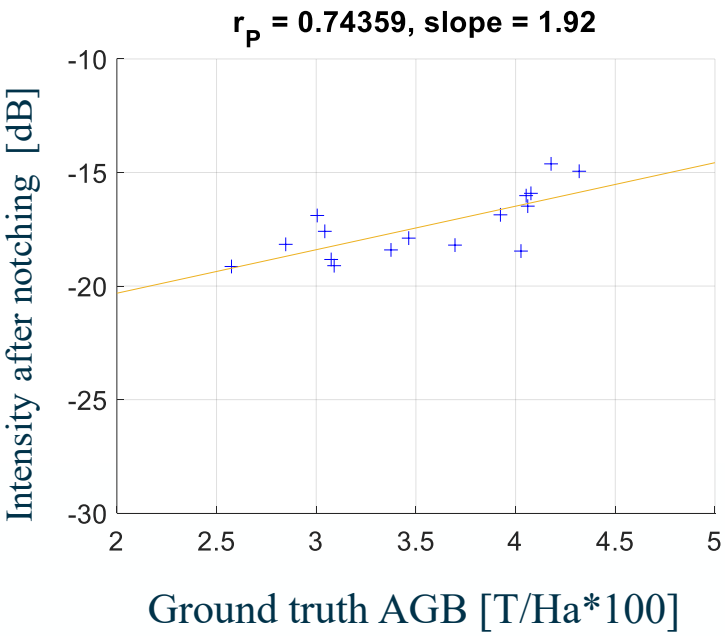
Ground cancellation

Idea: test the hypothesis that ground scattering is a disturbing factor by treating it as an *interfering signal*

⇒ **Notch filtering** to cancel the ground layer

- Old fashioned signal processing technique to cancel an interfering signal
- Can be implemented with just two passes



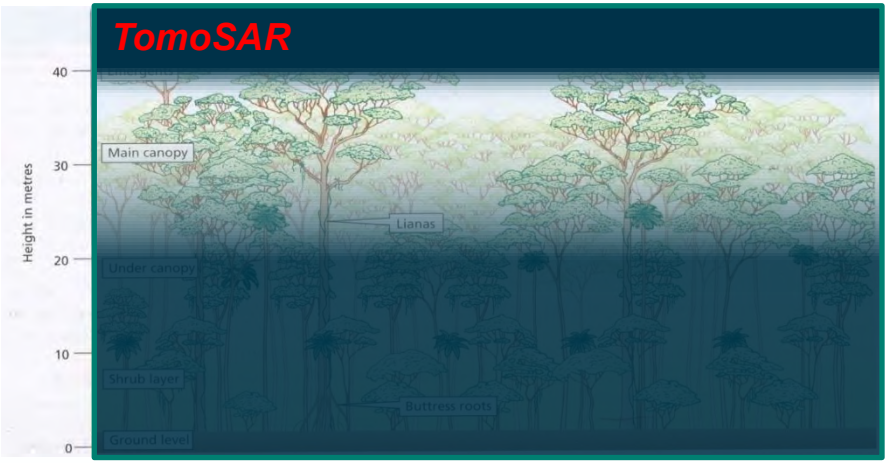


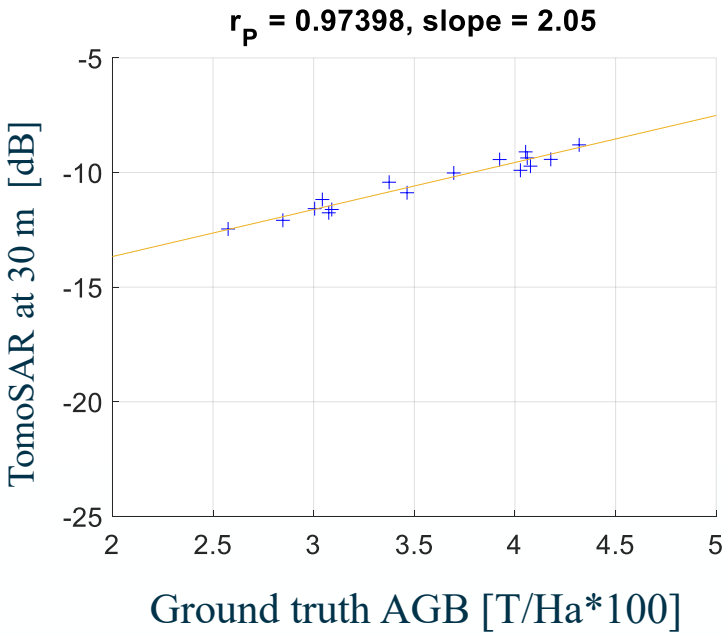
Ground cancellation

Idea: test the hypothesis that ground scattering is a disturbing factor by treating it as an *interfering signal*

⇒ **Notch filtering** to cancel the ground layer

- Old fashioned signal processing technique to cancel an interfering signal
- Can be implemented with just two passes





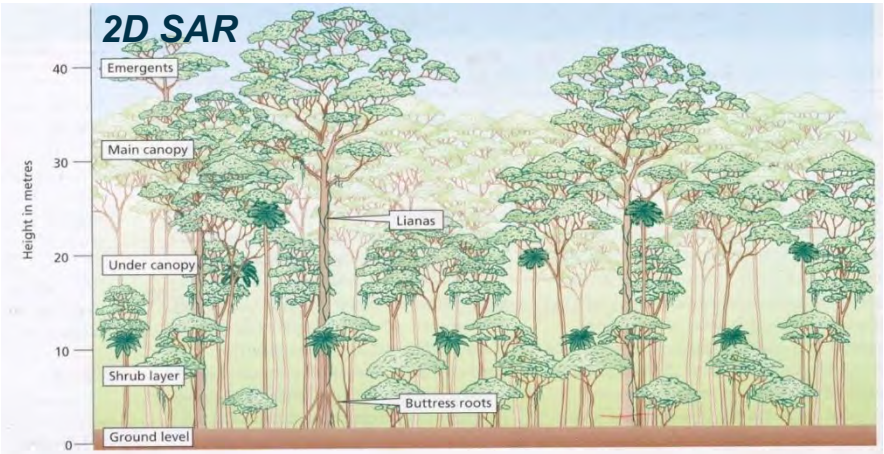
- **Not as good as Tomography**

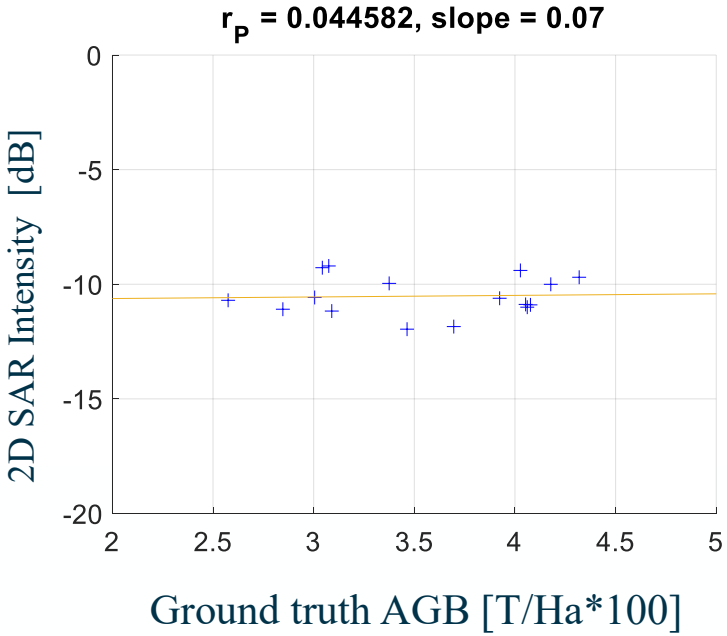
Ground cancellation

Idea: test the hypothesis that ground scattering is a disturbing factor by treating it as an *interfering signal*

⇒ **Notch filtering** to cancel the ground layer

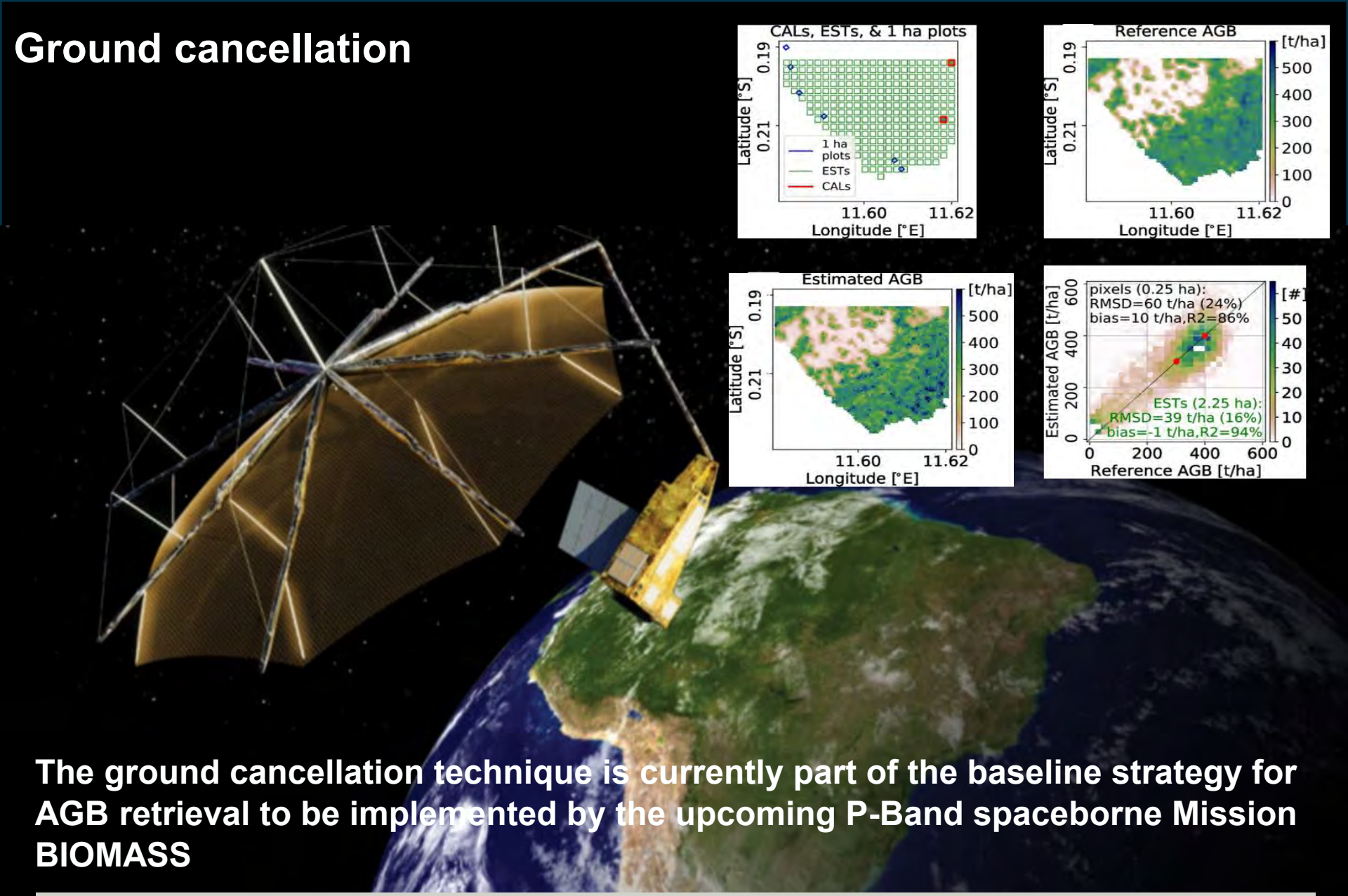
- Old fashioned signal processing technique to cancel an interfering signal
- Can be implemented with just two passes





- **Not as good as Tomography**
- **Dramatically better than using a single image**

Ground cancellation



The ground cancellation technique is currently part of the baseline strategy for AGB retrieval to be implemented by the upcoming P-Band spaceborne Mission BIOMASS

Soja, M., Quegan, S., Mariotti d'Alessandro, M. Banda, F. Scipal, K., Tebaldini, S. Ulander, L.M.H. "*Mapping above-ground biomass in tropical forests with ground-cancelled P-band SAR and limited reference data*", Remote Sens. Environ. Volume 253, February 2021

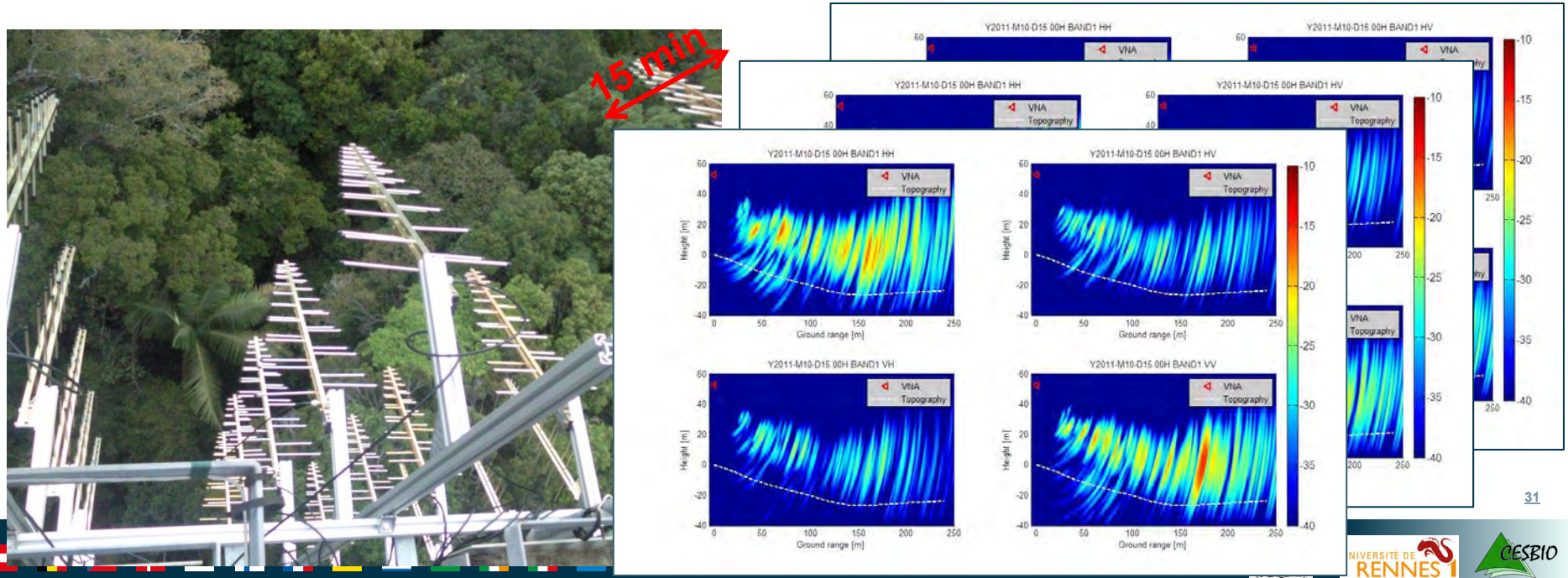
TropiSCAT

TropiSCAT – ESA – 2011

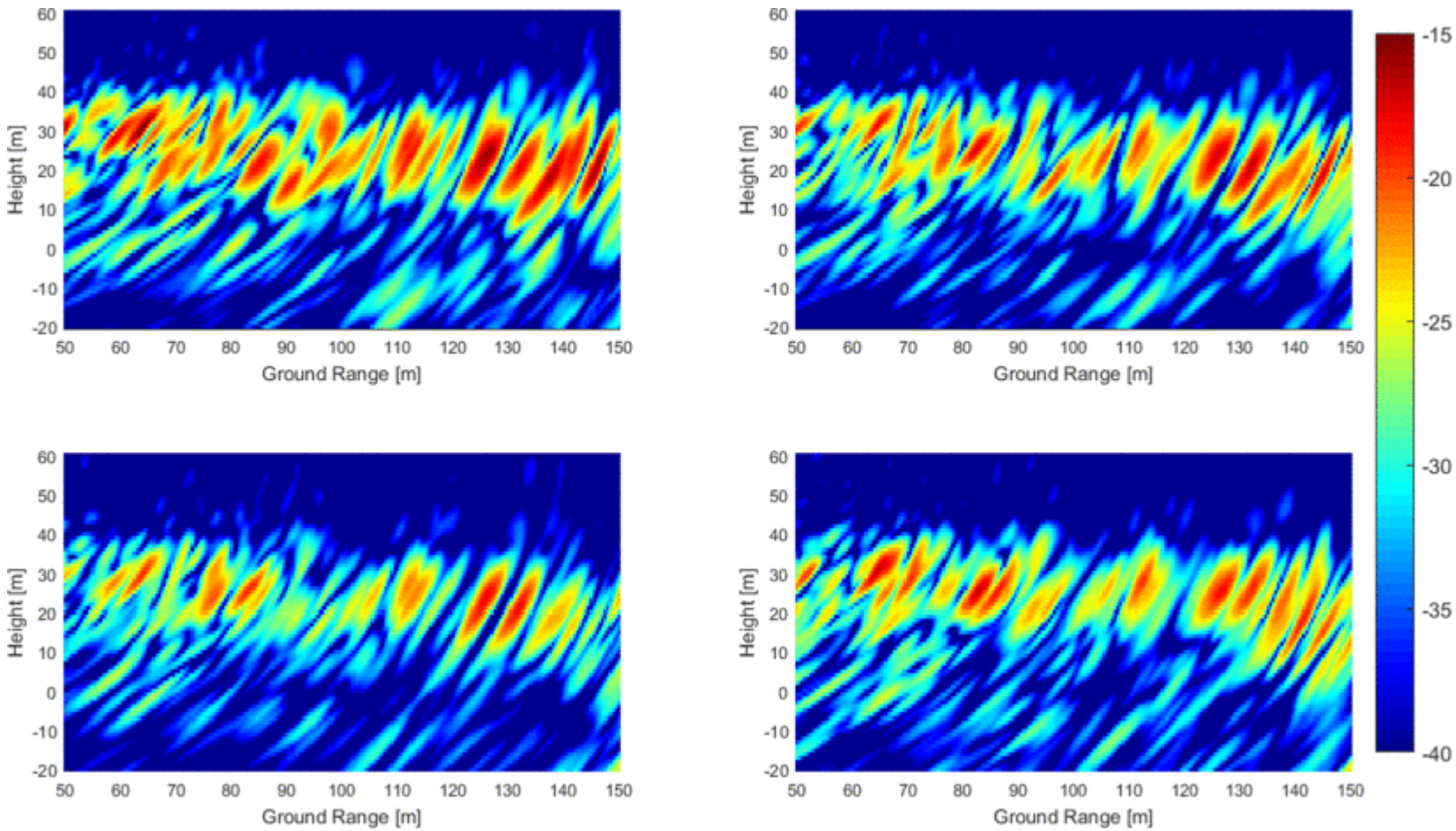
⇔ a static ground-based radar observing a tropical forest

- Located in French Guyana – same site as TropiSAR
- Team members from ONERA, CNES, CESBIO, POLIMI
- 20 antennas installed on top of the Guyaflux tower (55 m)
- Fully polarimetric (HH, HV, VH and VV)
- Vertical resolution capabilities
- One image every 15 minutes over a time span of one year

⇒ Access to the vertical structure of temporal decorrelation

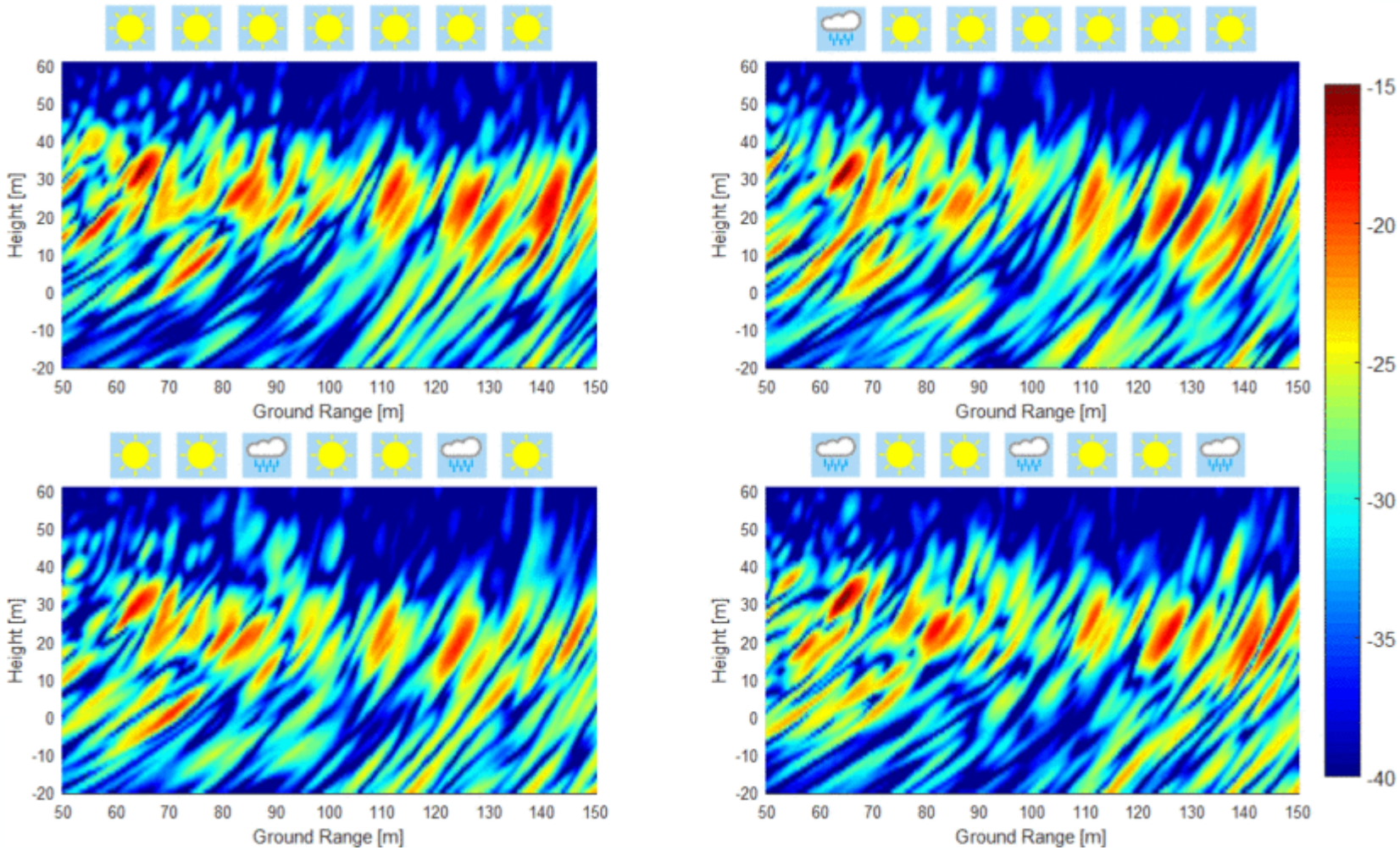


TropiSCAT

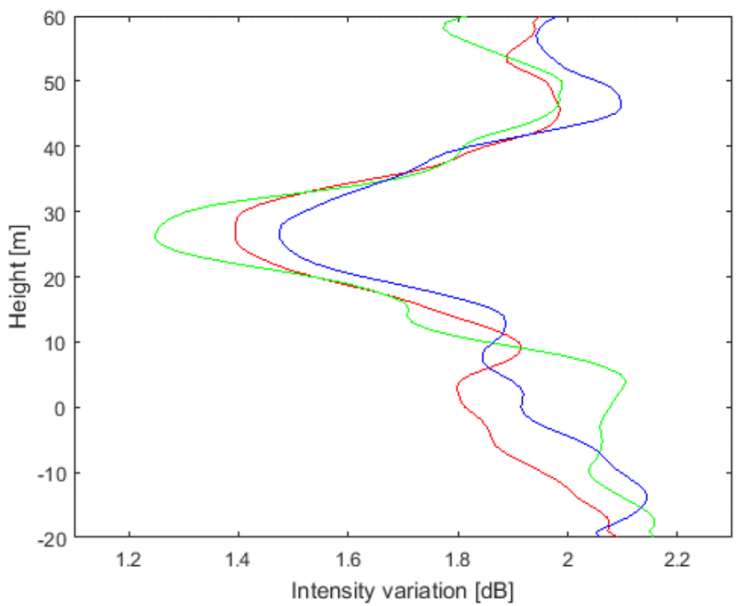


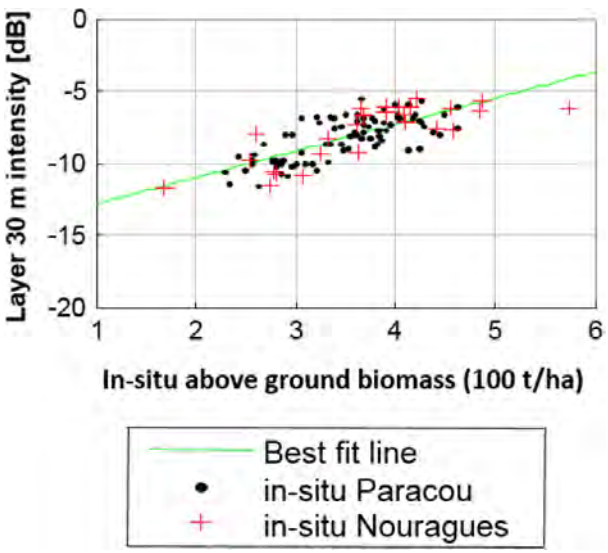
Instantaneous tomograms – all "baselines" acquired within 15 min in dry conditions

TropiSCAT



7-day tomograms – "baselines" gathered every 3th day in varying weather conditions





The variation of the tomographic signal at canopy level can be assessed in about 1−1.5 dB r.m.s. (1 sigma) in cross polarization.

This figure can be transposed into a biomass estimation error by considering that, at this forest site, tomographic intensity at 30 m was observed to increase about 4 dB as forest biomass passes from 250 to 450 t/ha.

Accordingly, the observed variation of 1−1.5 dB would entail a biomass retrieval error of around 50−80 t/ha at this test site using tomography, which is on the order about 20% or better.

Snow

The AlpSAR campaign

- Carried out in February 2013 in the Austrian Alps, in the frame of the ESA campaign AlpSAR, led by ENVEO
  - Snowpit data, GPR, Airborne SAR, **GBSAR**

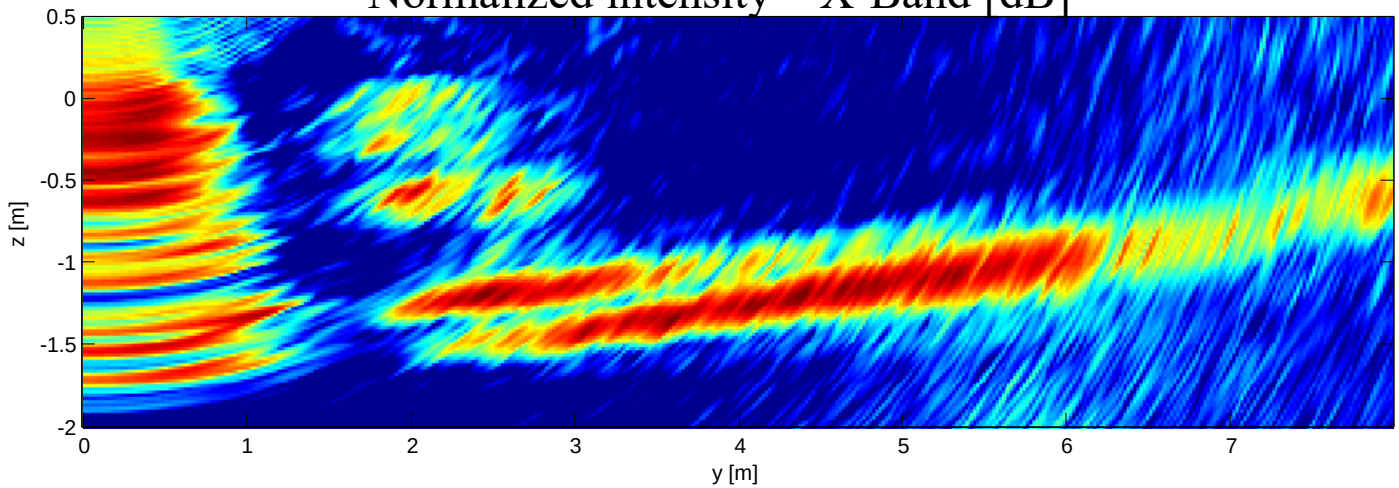
- X-Band: 4 GHz @ 10 GHz
- Ku-Band: 4 GHz @ 14 GHz
- VV Polarization
- Vertical resolution ≈ 10 cm (Ku-band), 15 cm (X-Band)
- Range resolution ≈ 4 cm
- Azimuth resolution ≈ 4 cm
- ⇔ **effective de-speckling via azimuth multi-looking**

Rotmoos – X-Band

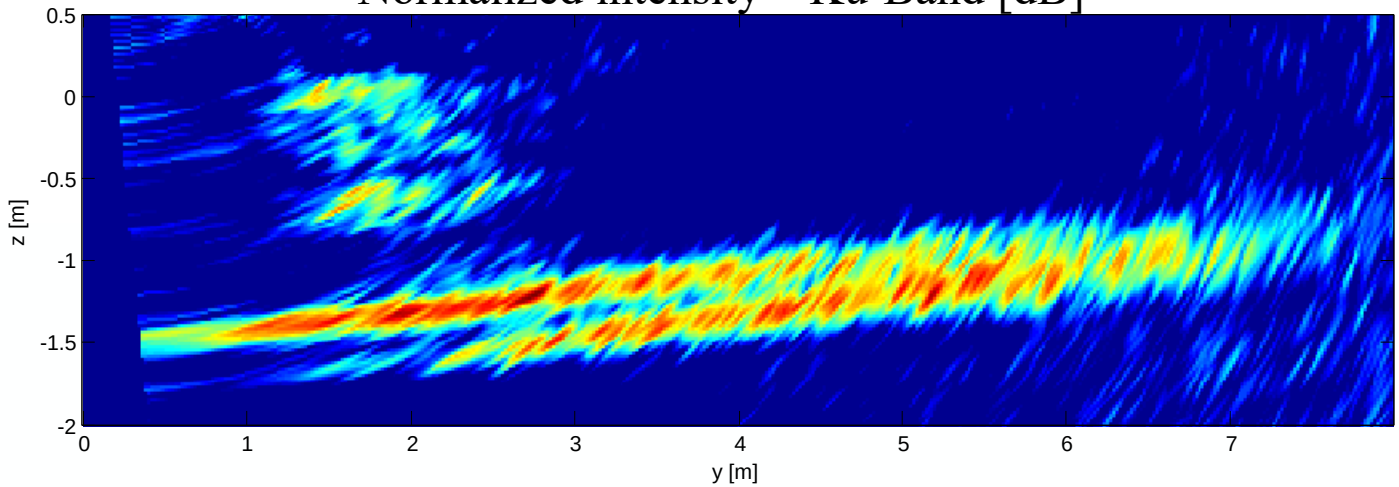
Remarks

- Neat imaging
- 5 surfaces
- Strongest returns are associated with the two bottom layers

Normalized intensity – X-Band [dB]



Normalized intensity – Ku-Band [dB]



Snowpit data:
snowpack thickness = 140 cm

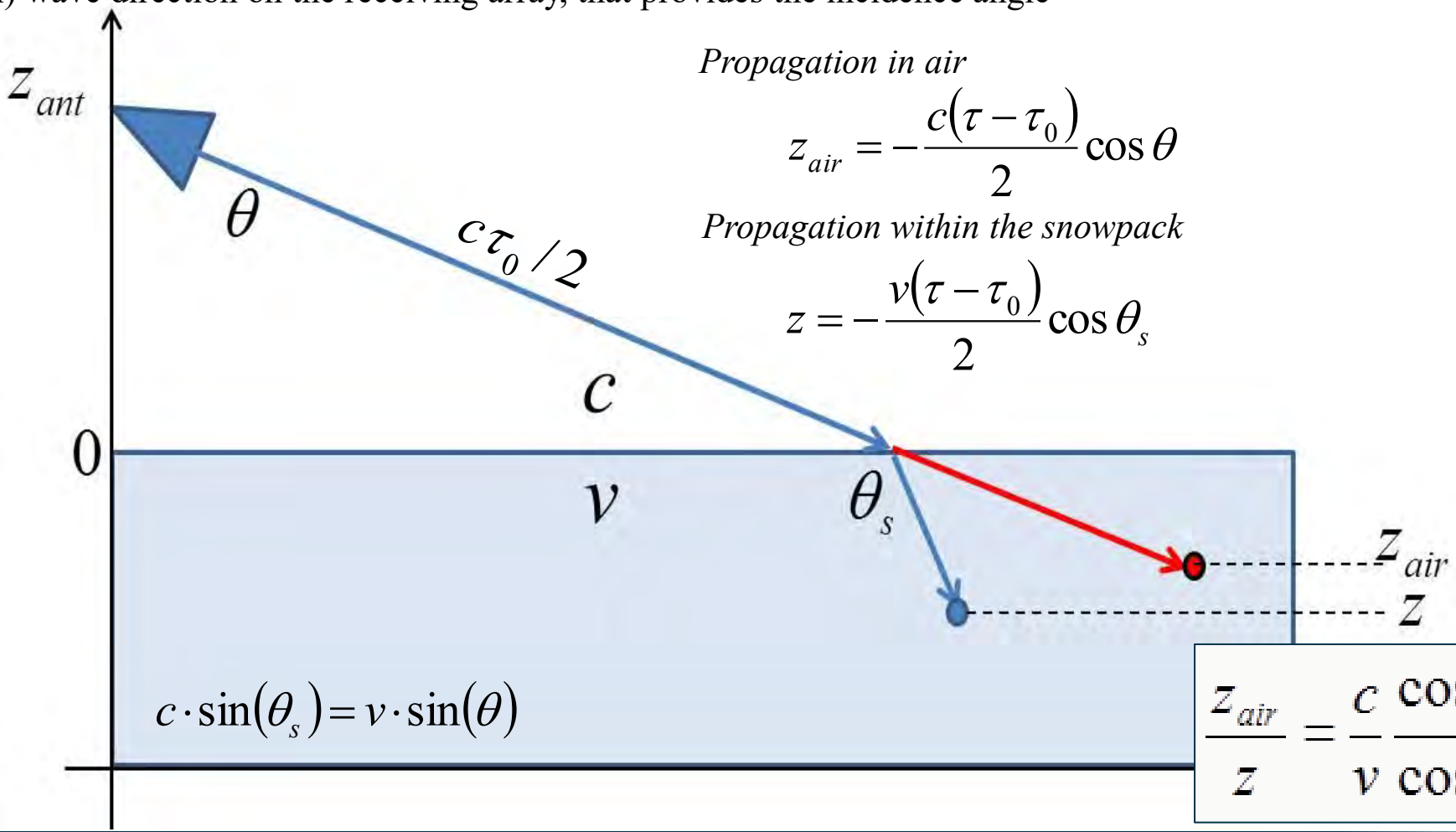
Normalized intensity is presented to highlight contrasts

Effect of propagation velocity

Localization in the **(y,z)** plane:

i) delay (τ), converted into a distance based on the knowledge of propagation velocity

ii) wave direction on the receiving array, that provides the incidence angle



Propagation in air

$$z_{air} = -\frac{c(\tau - \tau_0)}{2}\cos\theta$$

Propagation within the snowpack

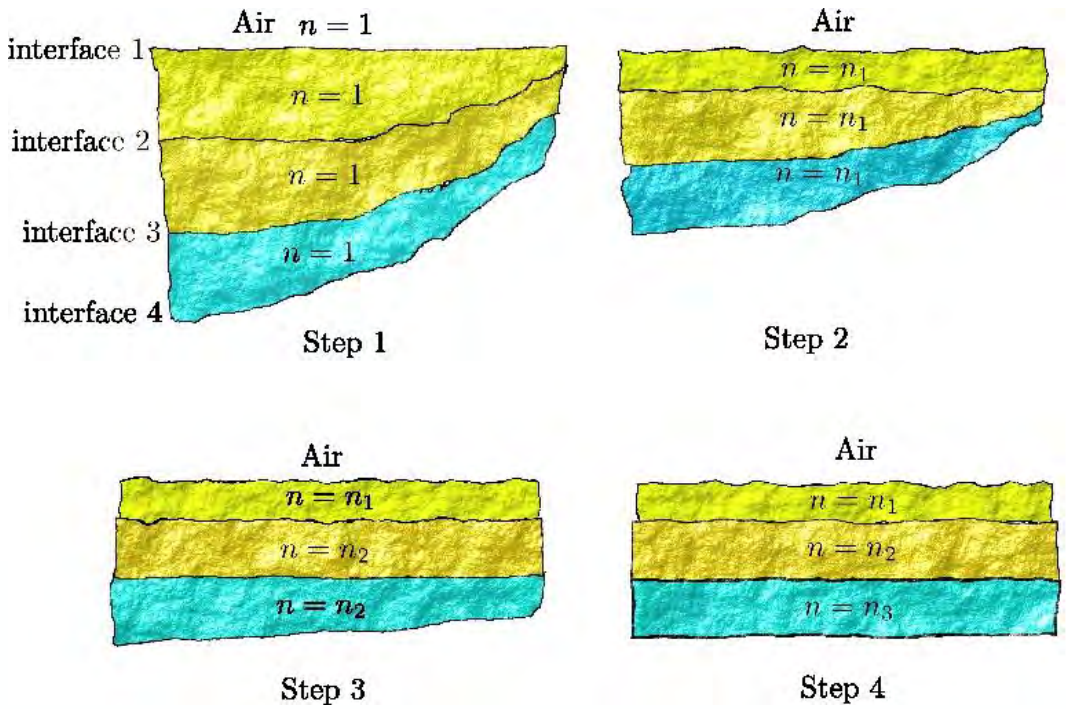
$$z = -\frac{v(\tau - \tau_0)}{2}\cos\theta_s$$

$$\frac{z_{air}}{z} = \frac{c}{v}\frac{\cos\theta}{\cos\theta_s}$$

Refractive index estimation

Iterative procedure for estimation of refractive indices:

- Assumption : horizontal snow layers with horizontal snow slabs;
- Main idea : choose refractive indices for the identified layers to make the appearance of the detected interfaces horizontal on the final tomogram;
- Iterative procedure :



Comparison against snow stratigraphy

- Refractive index is observed to increase with snow wetness and density
- The detected interfaces correspond to changes in the physical parameters of some layers reported on the snow stratigraphy.

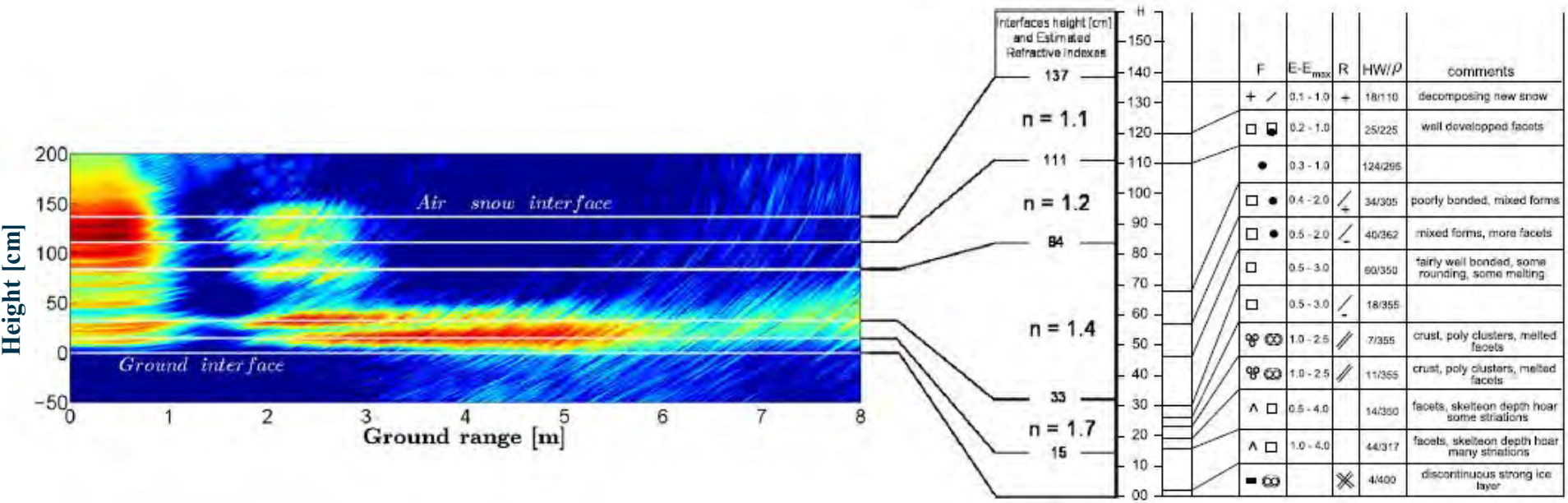
  Interface 1: air/snow

  Interface 2: transition from low density and decomposing new-fallen snow into a denser layer with spherical particles.

  Interface 3: separation between two layers with different particle shapes. The upper one contains mixed forms, while the lower one contains fairly well bonded particles with some melting.

  Interface 4: separates an upper snow layer, with fairly bonded melting forms from lower layer with higher wetness, larger grain sizes and more particles aggregates.

  Interface 5: layer with increasing wetness, grain sizes up to 4 mm and depth hoar.

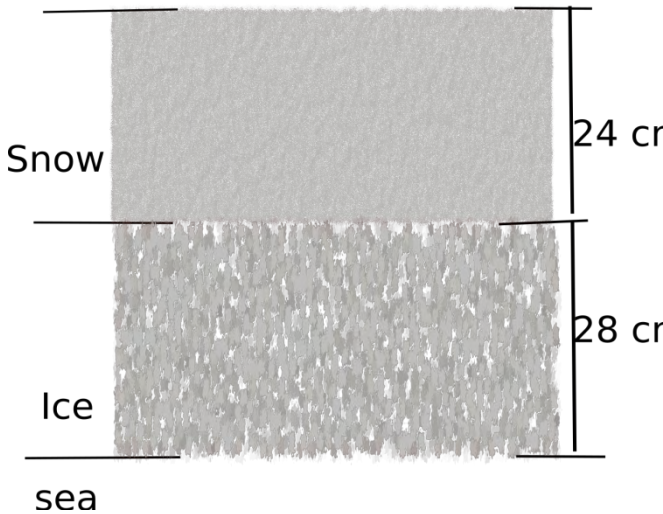


Fjord Ice

SAR Tomography over fjord ice

Data acquisition carried out in March 2013 at the Kattfjord, Tromsø, Norway

- In collaboration with the Arctic University of Norway

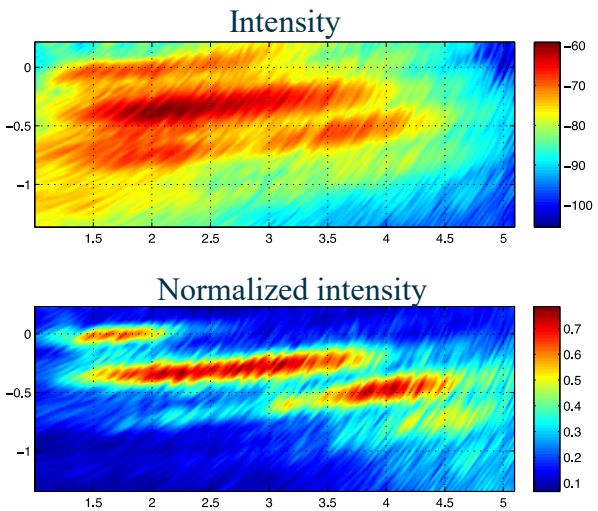


- Seasonal ice – life of 3-4 months
- Tomographic X-band measurements at VV and HV
- Temperature from -8° to -2°
- The fjord ice can be representative of low salinity sea ice (fresh water from surrounding mountains)
- Dry snow cover on top
- Significant amount air bubbles within the ice layer
  - 0.5 mm to 7 mm diameter
  - Irregularly shaped
  - Randomly oriented

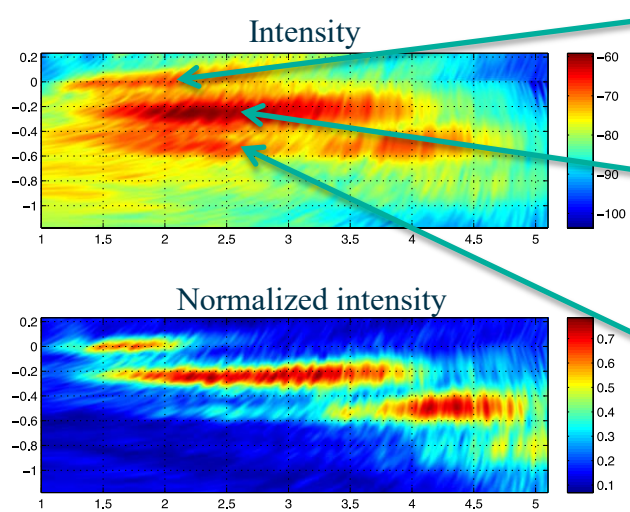
SAR Tomography over fjord ice

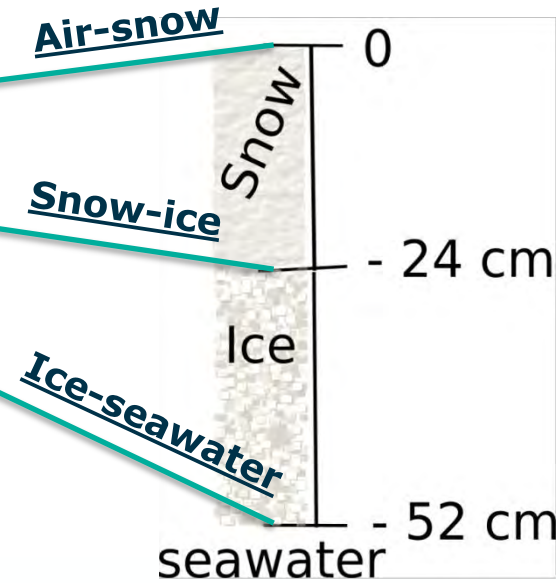
- Same tilt effect as snow-pack tomography
- Corrected assuming
  - refractive index of snow = 1.4
  - refractive index of fjord ice = 1.7
- Normalized intensity is presented to highlight contrasts (interfaces)

Uncorrected



Corrected

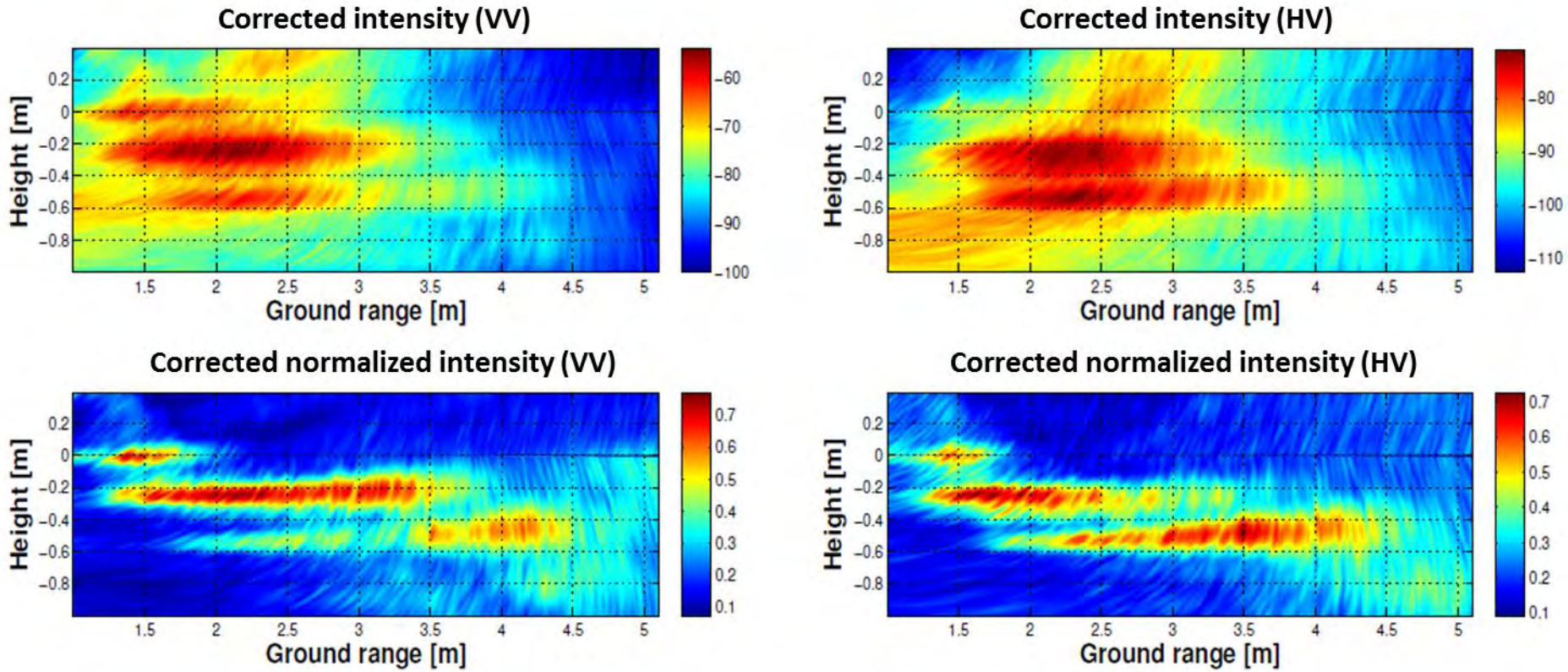




- Three clearly visible interfaces
  - Air/snow
  - Snow/ice
  - Ice/seawater

SAR Tomography over fjord ice

- VV & HV tomography



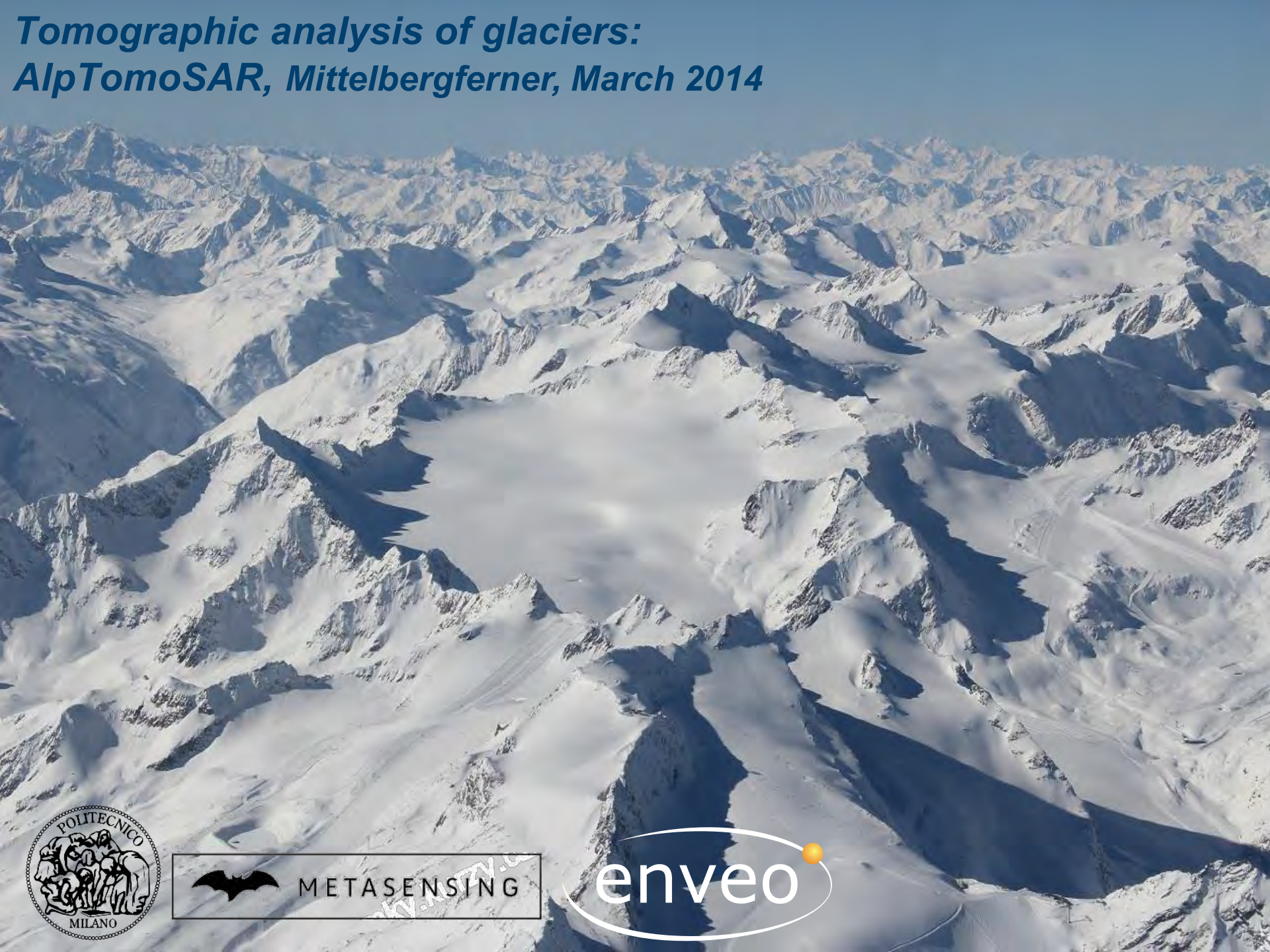
- Weaker air/snow and stronger snow/ice and ice/seawater scattering at HV than at VV

⇒ Mostly polarized contributions from regular spherical snow grains

⇒ Depolarized contributions from irregular air bubbles in the ice layer

Alpine Glaciers

Tomographic analysis of glaciers: AlpTomoSAR, Mittelbergferner, March 2014



Test site

***Test site*:** Mittelbergferner, Austrian Alps

- temperate glacier at the main ridge of the Alps in Tyrol
- main test area is a flat plateau in the upper part of the glacier between 3000 and 3200 m

Field Works

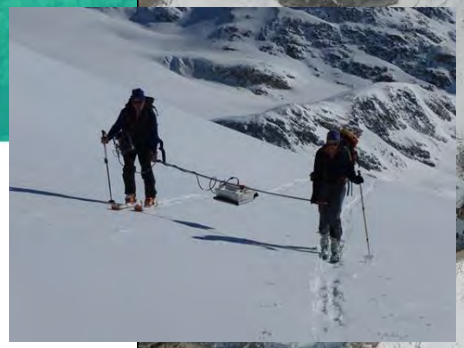
Field activities

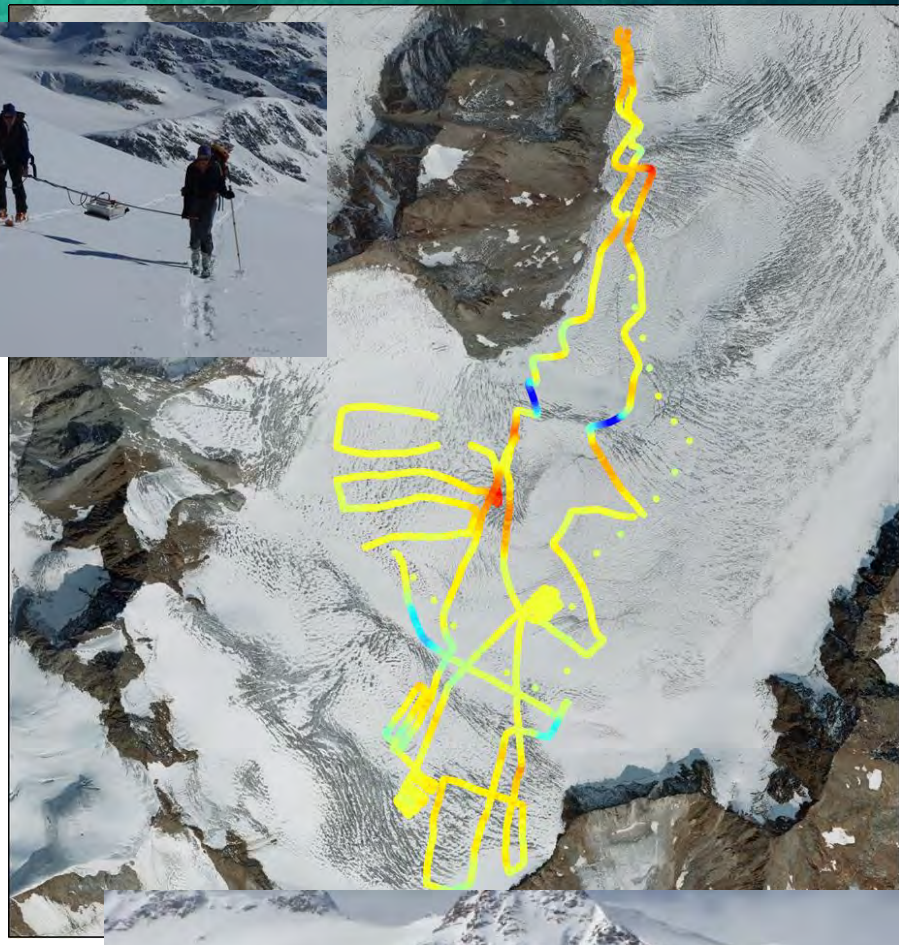
- Setting up Corner Reflectors
- Stratigraphy of winter snow pack

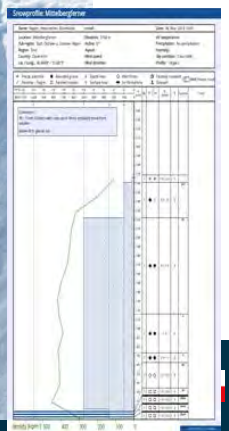
  Density / Hardness, ice layers, grain size
- Transects of snow depth
- GPR Measurements

GPR Equipment:

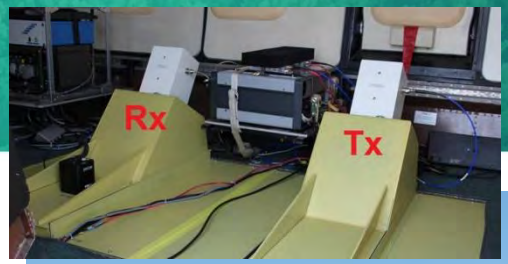
- IDS dual-frequency 200/600 MHz
- Total length of GPR profile: 18 km

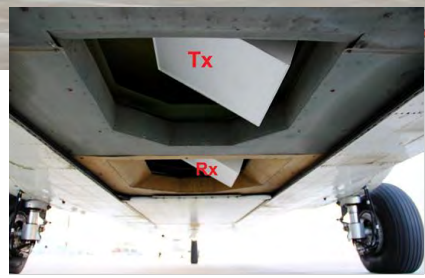






SAR Acquisitions





SAR Equipment:

- FMCW SAR by MetaSensing
- Transmitted bandwidth: 150 MHz
- Central frequency: 1275 MHz
- Fully polarimetric
- Spatial resolution ≤ 2 x 2 m (ground range, azimuth)

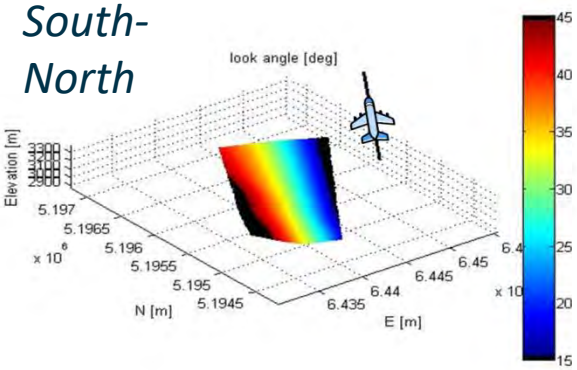
Aircraft

- CASA C-212 operated by CGR

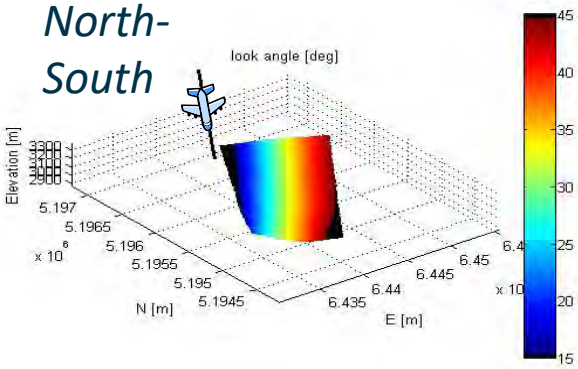
Flights:

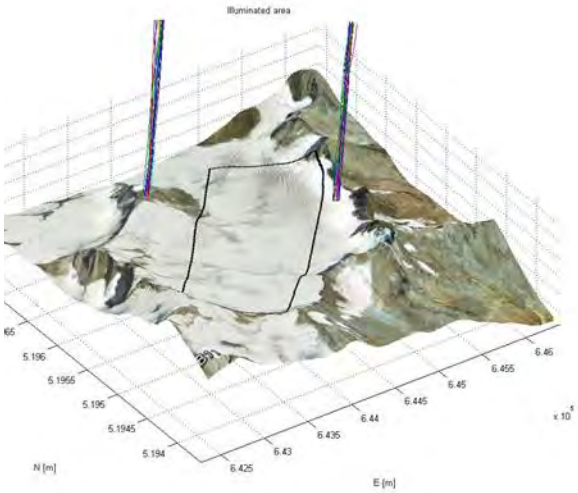
- Two flight directions
- 20+20 passes

South-North



North-South

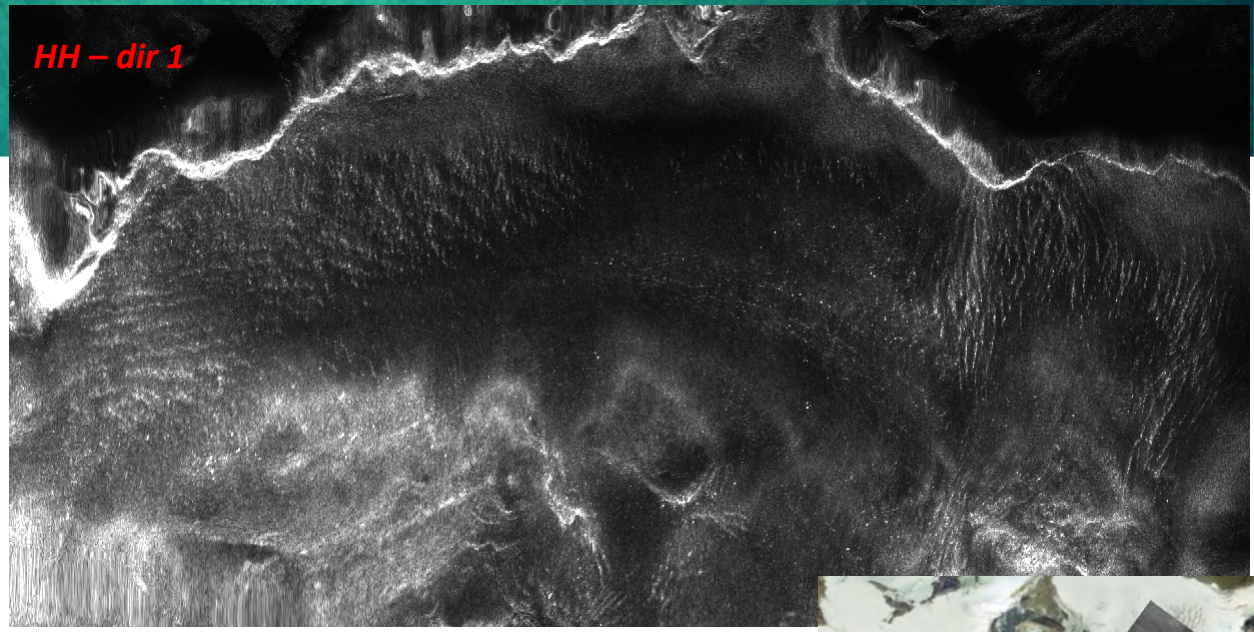


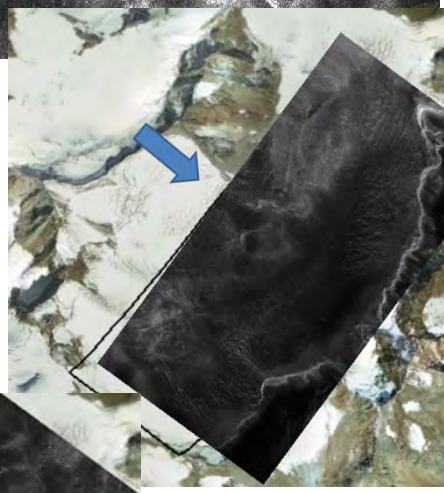


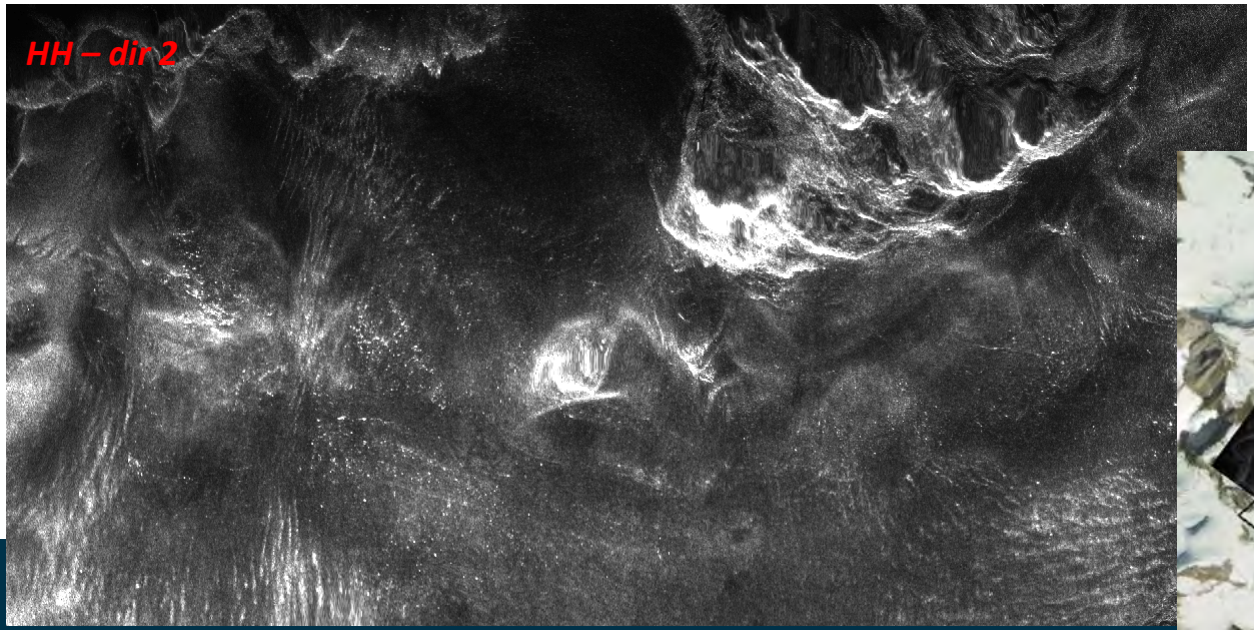
2D Focusing

2D Focusing via Time Domain Back Projection on a reference DEM

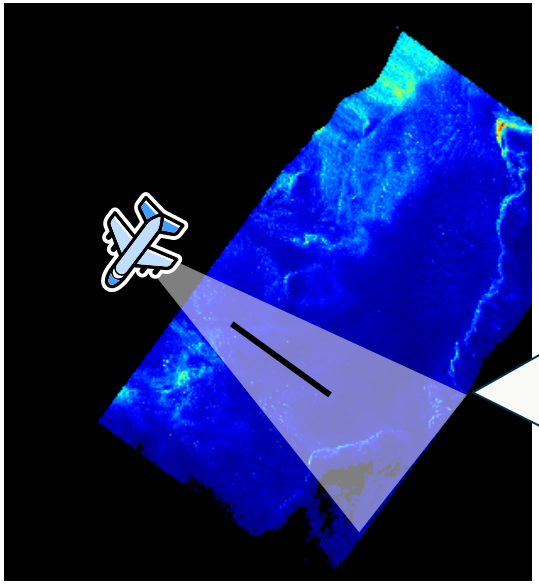
- Optimal motion compensation
- Common target wavenumbers in all passes
- Automatic coregistration at the reference elevation

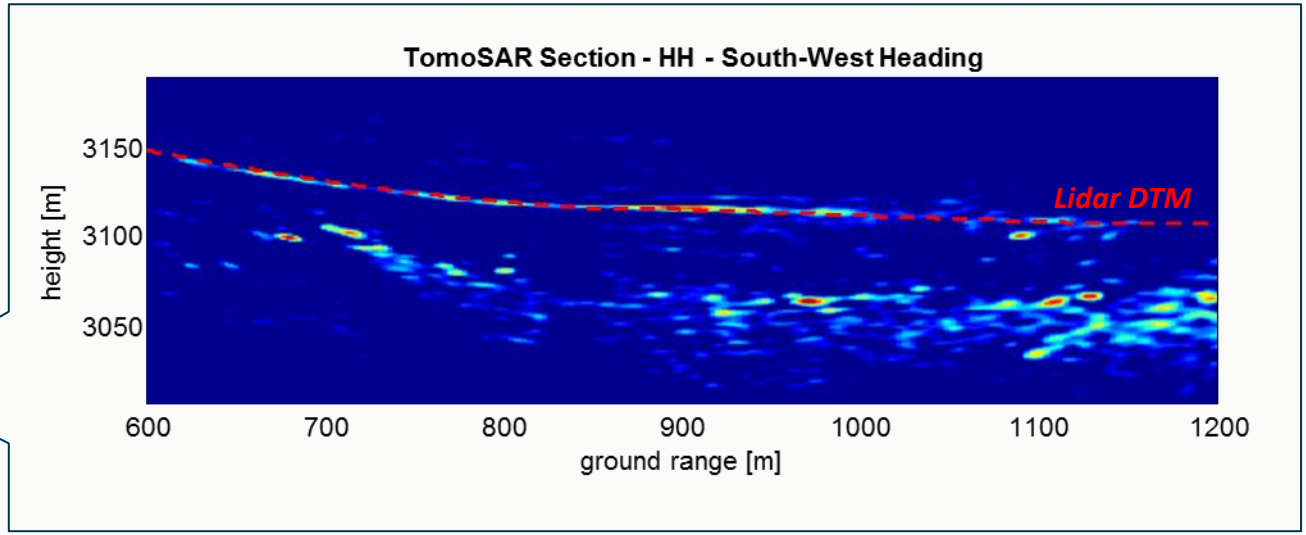


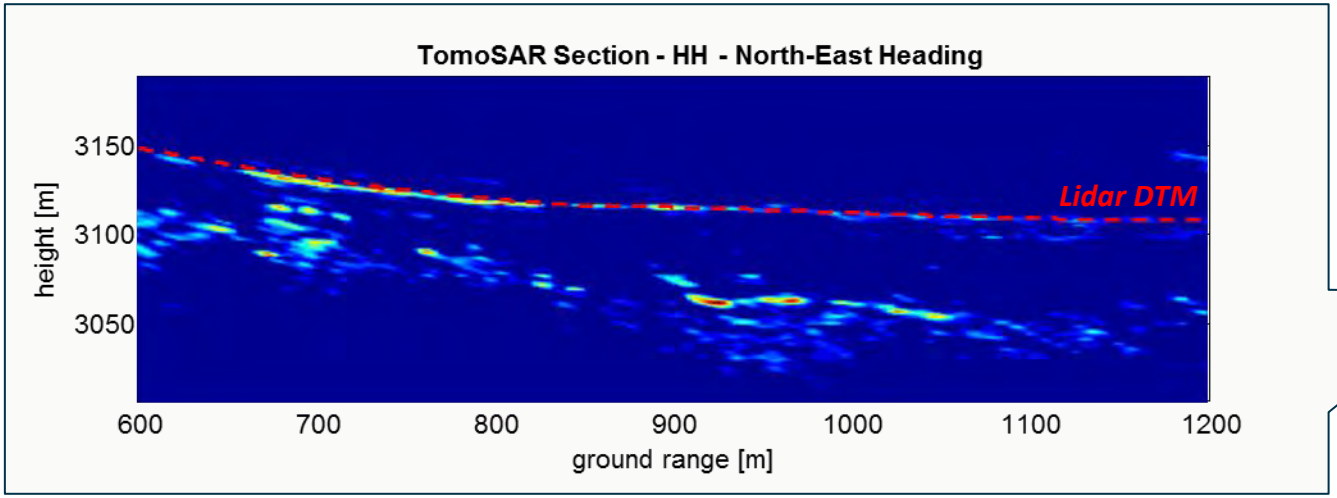


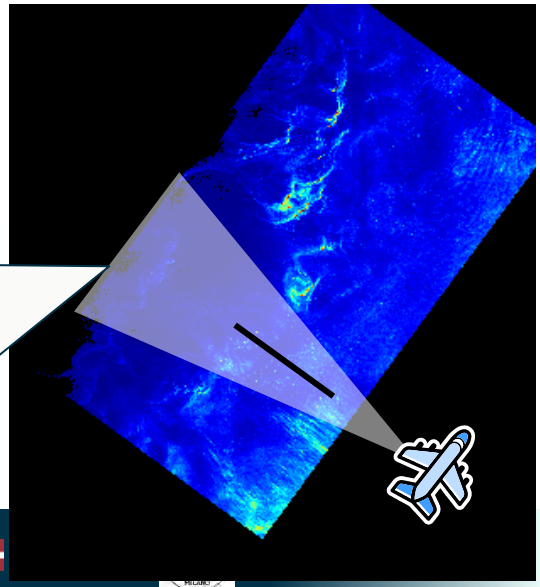


3D Focusing




TomoSAR Section - HH - South-West Heading
height [m]
3150
3100
3050
Lidar DTM
600
700
800
900
1000
1100
1200
ground range [m]


TomoSAR Section - HH - North-East Heading
height [m]
3150
3100
3050
Lidar DTM
600
700
800
900
1000
1100
1200
ground range [m]

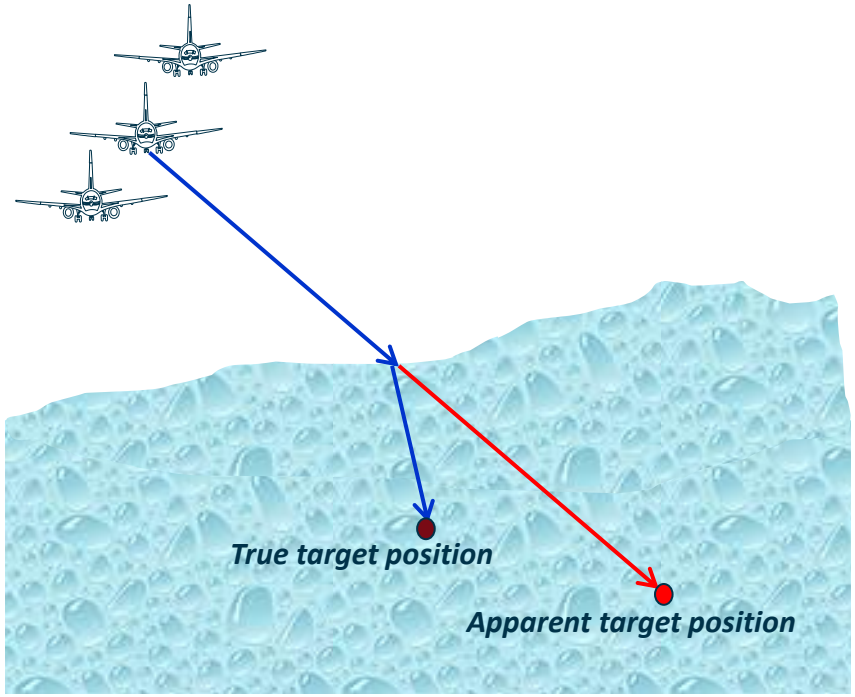


Ice Velocity Correction

Wave propagation through ice

- o Wave refraction
- o Changing delay-to-distance conversion law

⇒ **Targets are not focused at their geometrical position**

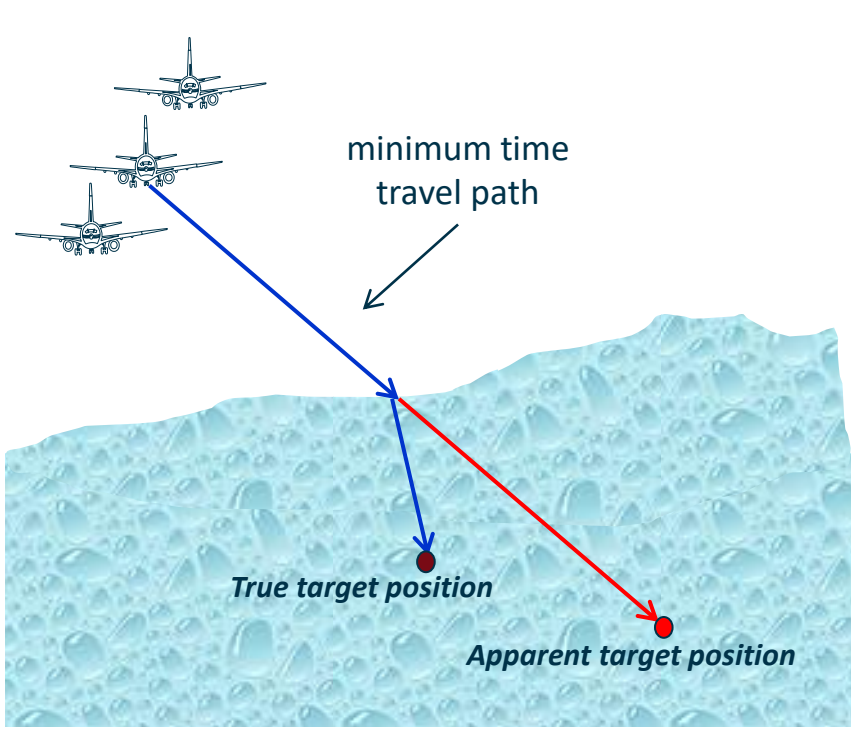


Ice Velocity Correction

Wave propagation through ice

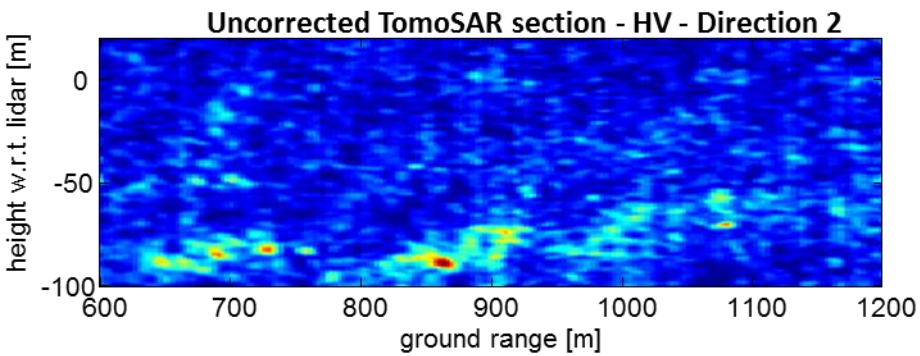
- o Wave refraction
- o Changing delay-to-distance conversion law

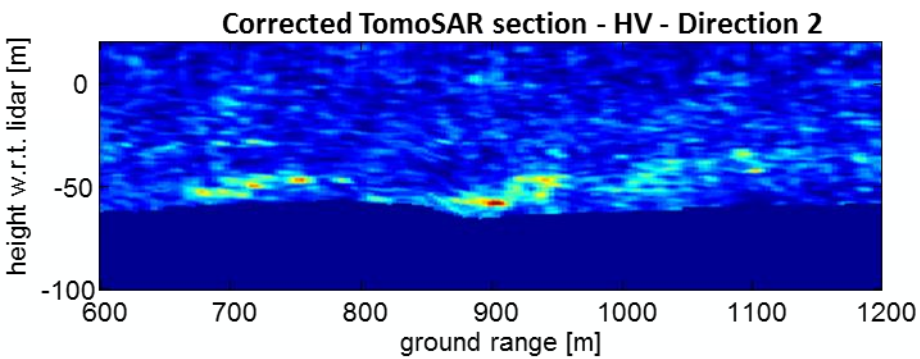
⇒ **Targets are not focused at their geometrical position**



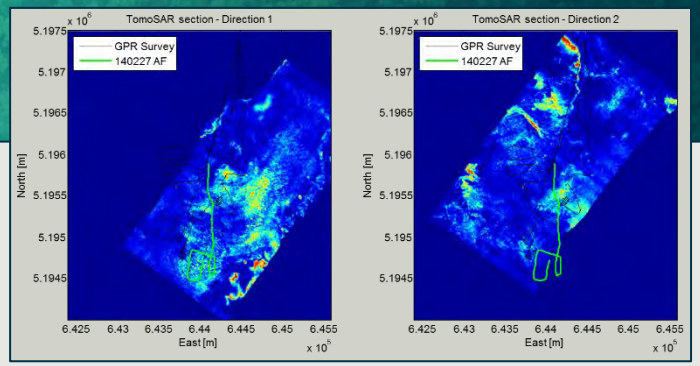
TomoSAR correction

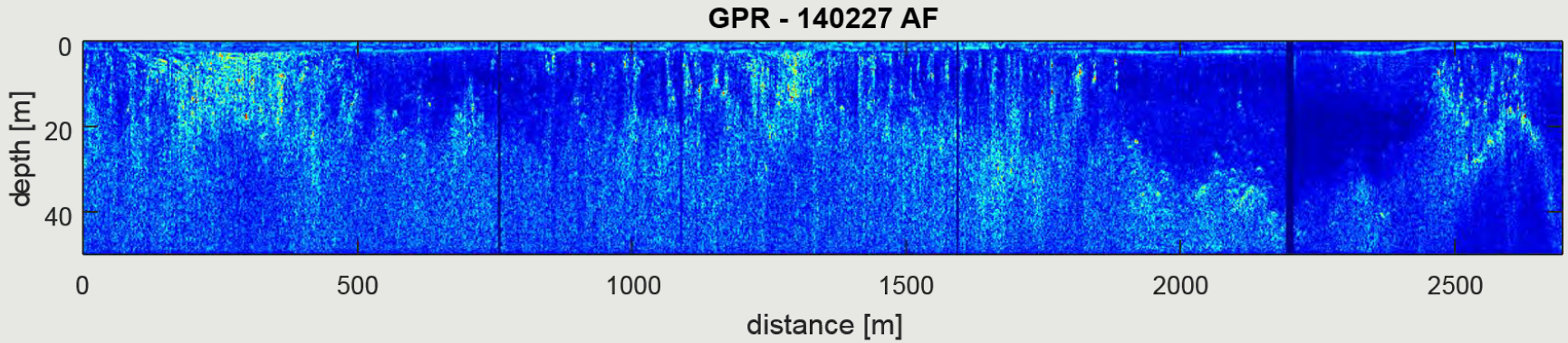
1. Mapping between true and apparent position based on Fermat's minimum time principle
2. Subsequent Tomogram interpolation

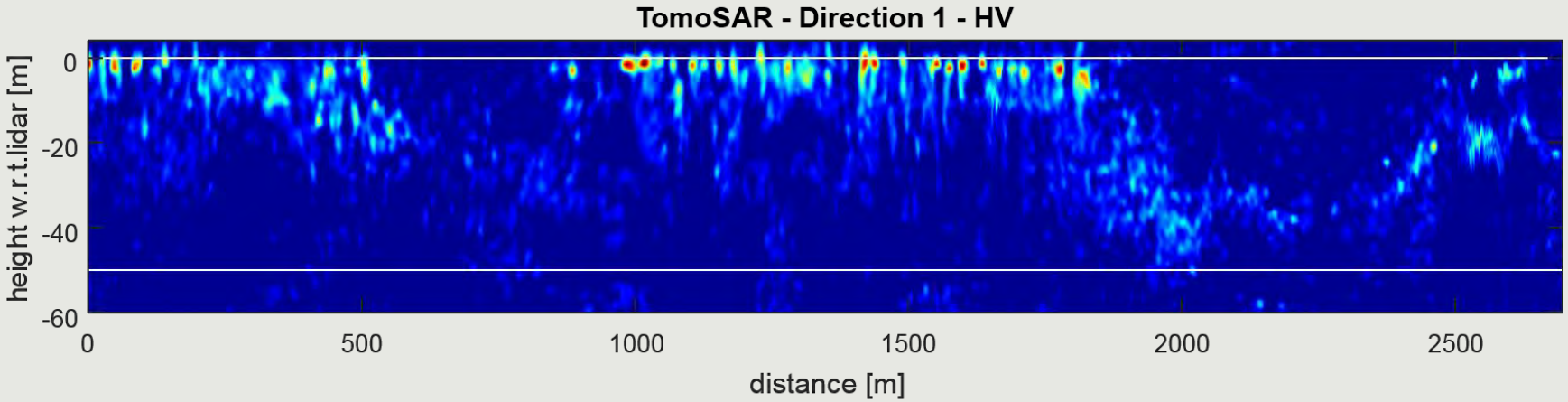




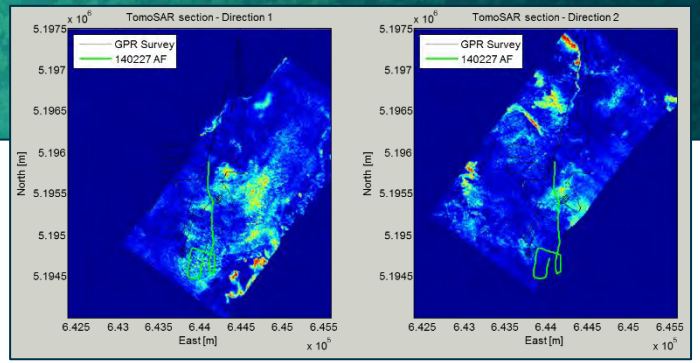
Comparison to 200 MHz GPR Transects

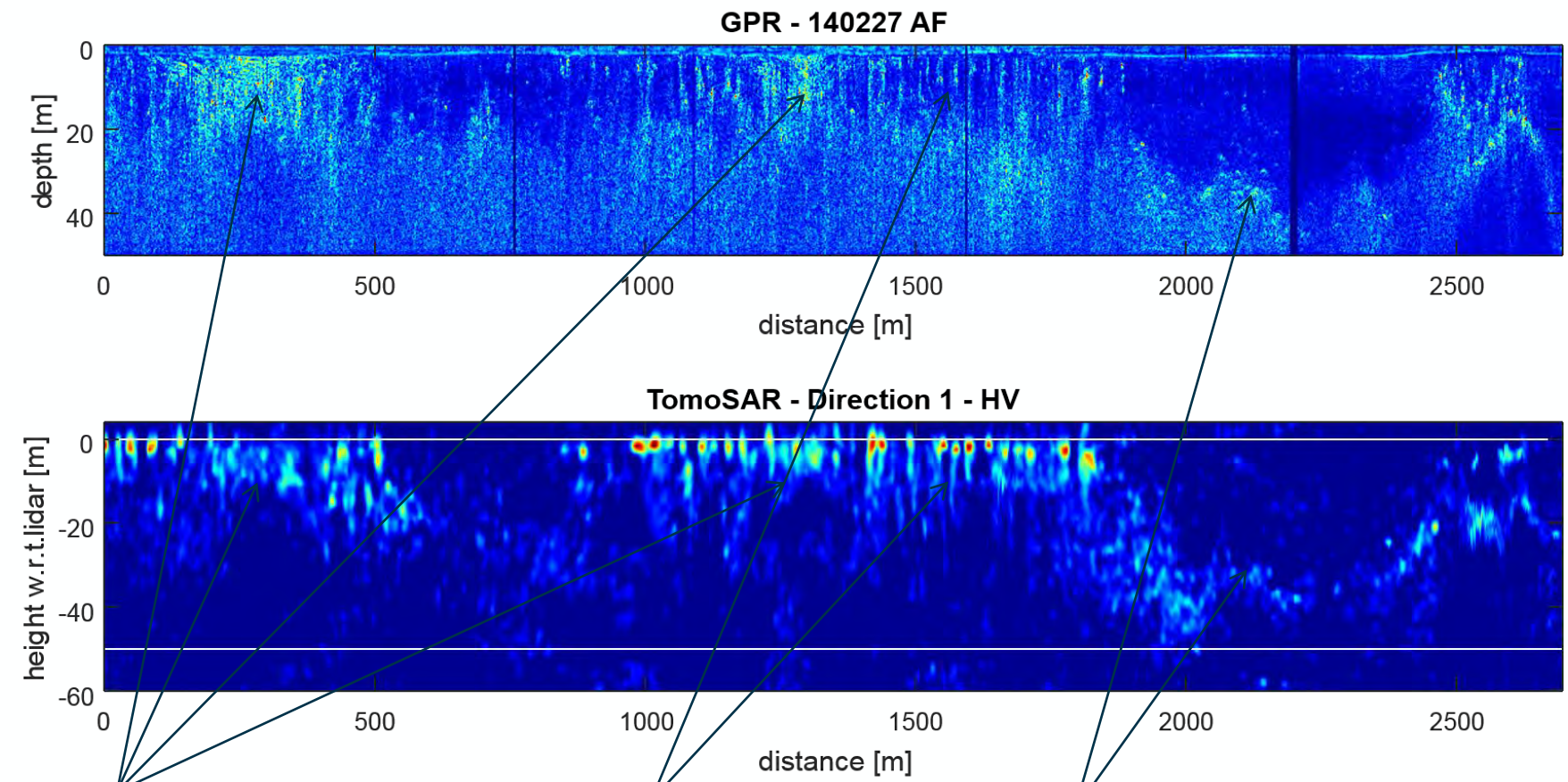






Comparison to 200 MHz GPR Transects



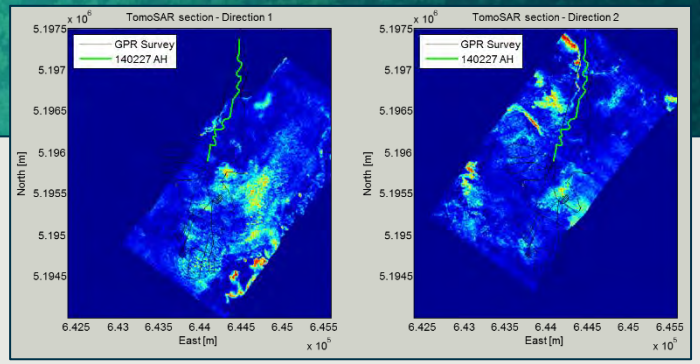


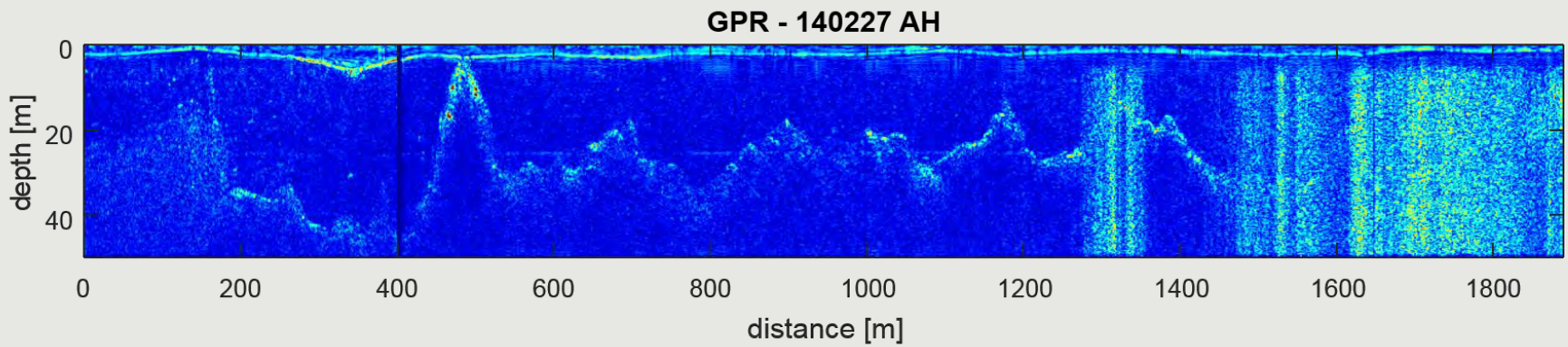
Firn areas

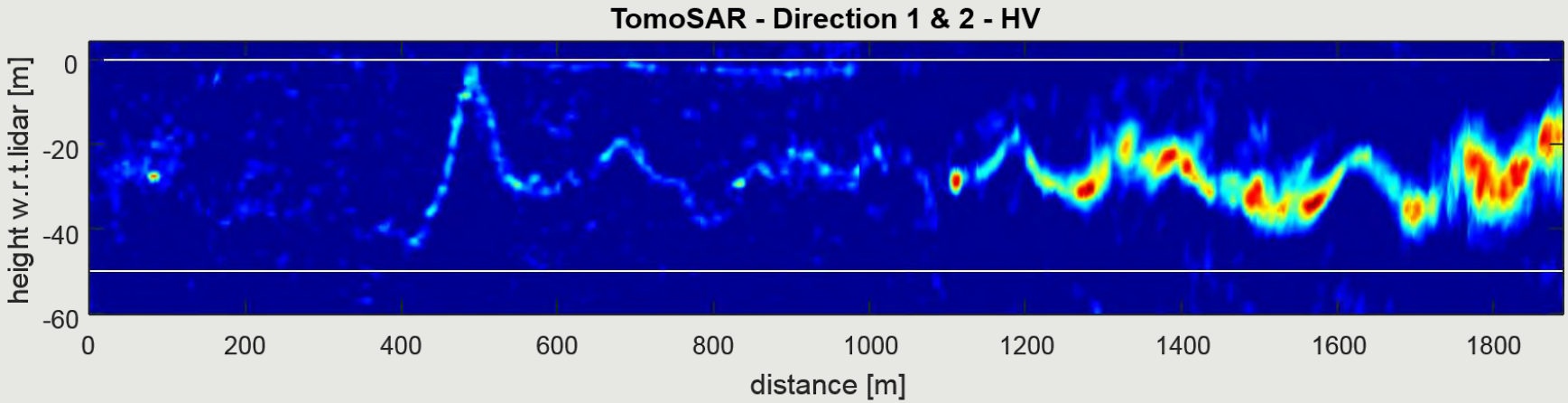
Crevasses

Bedrock/ground reflection

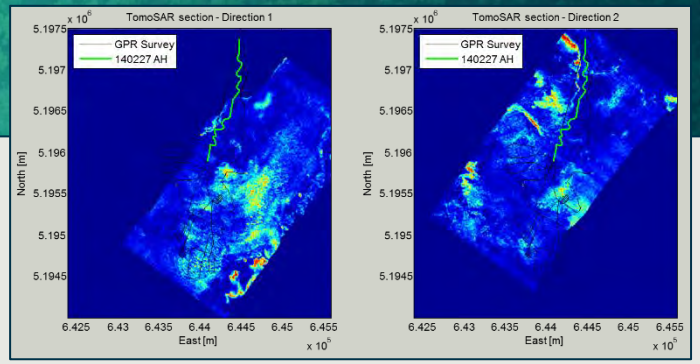
Comparison to 200 MHz GPR Transects

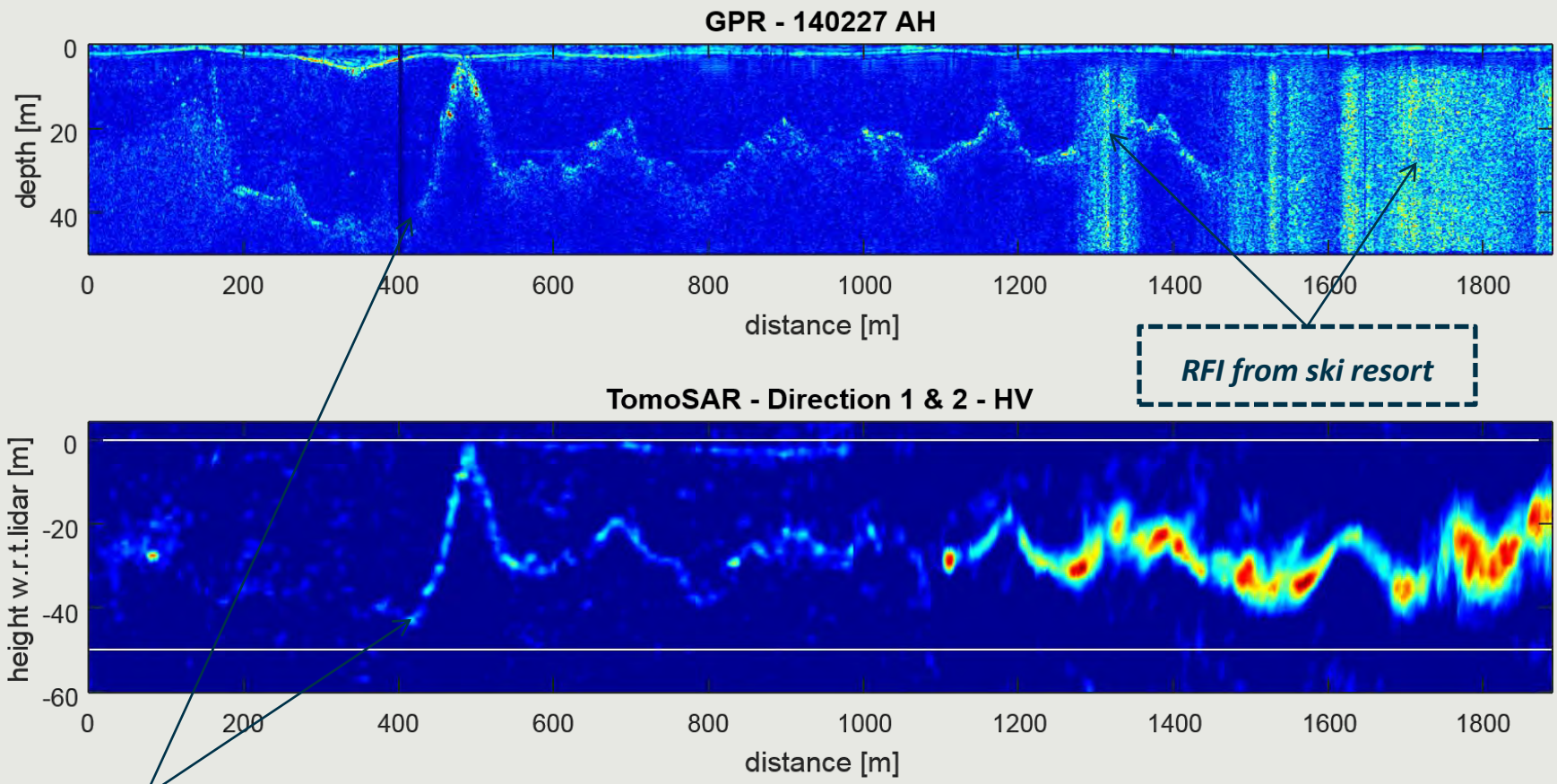




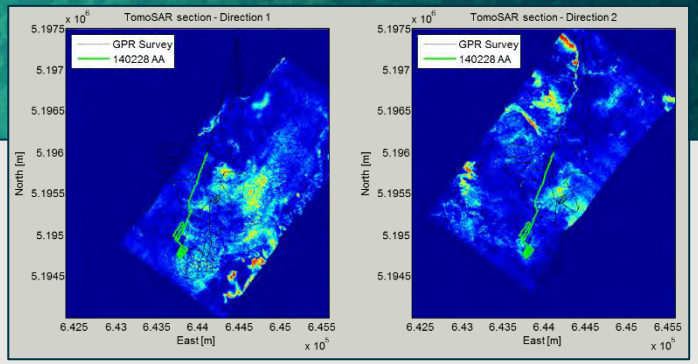


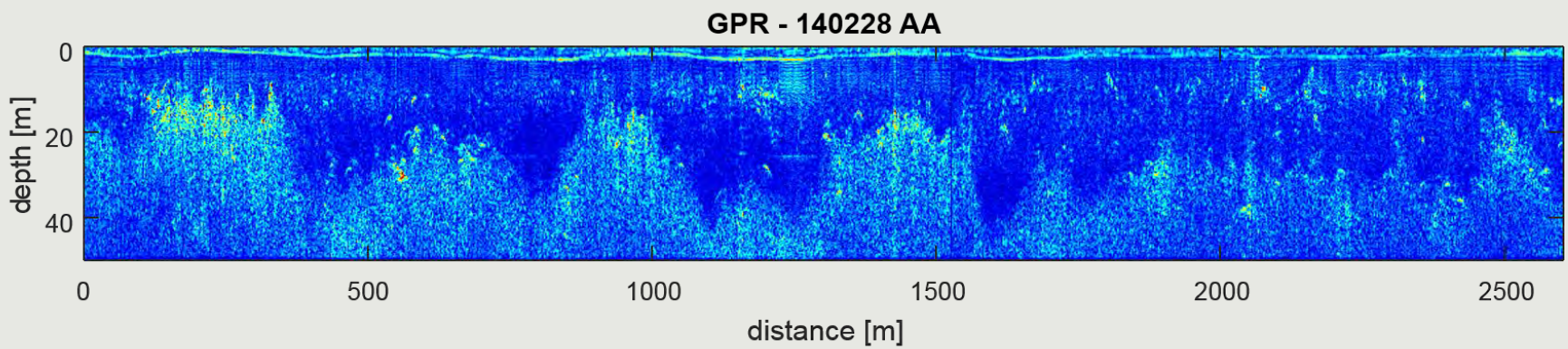
Comparison to 200 MHz GPR Transects

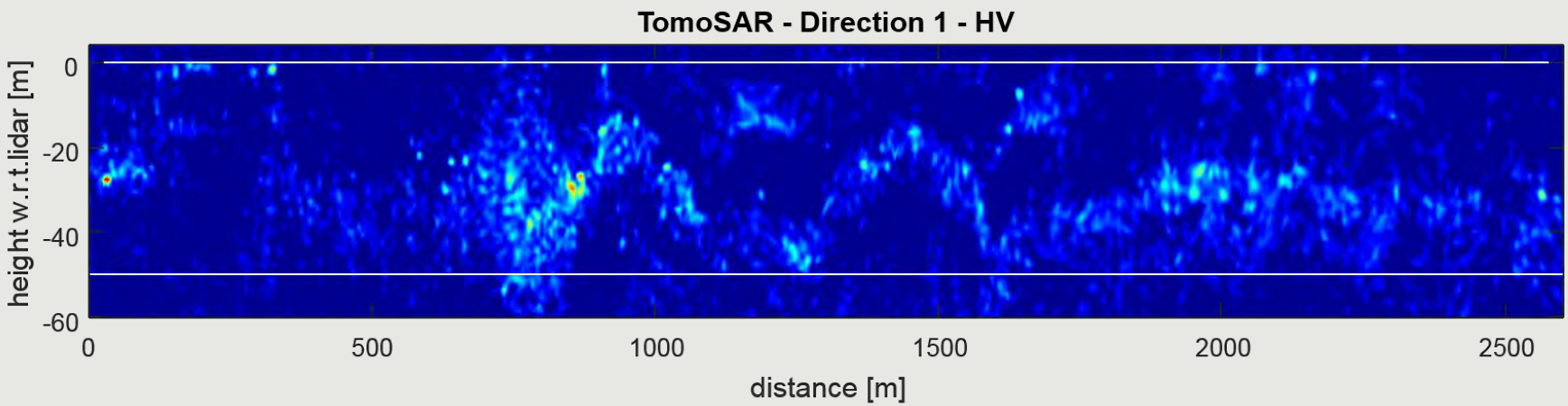




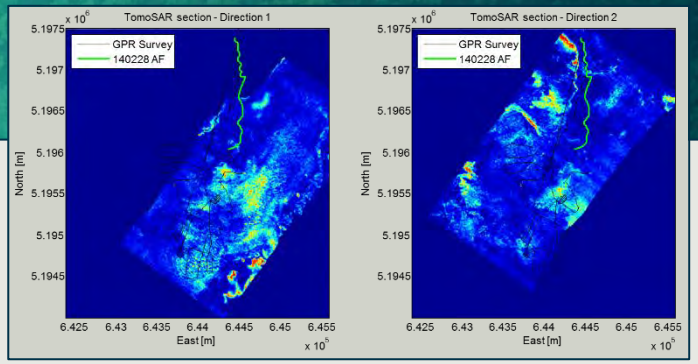
Comparison to 200 MHz GPR Transects

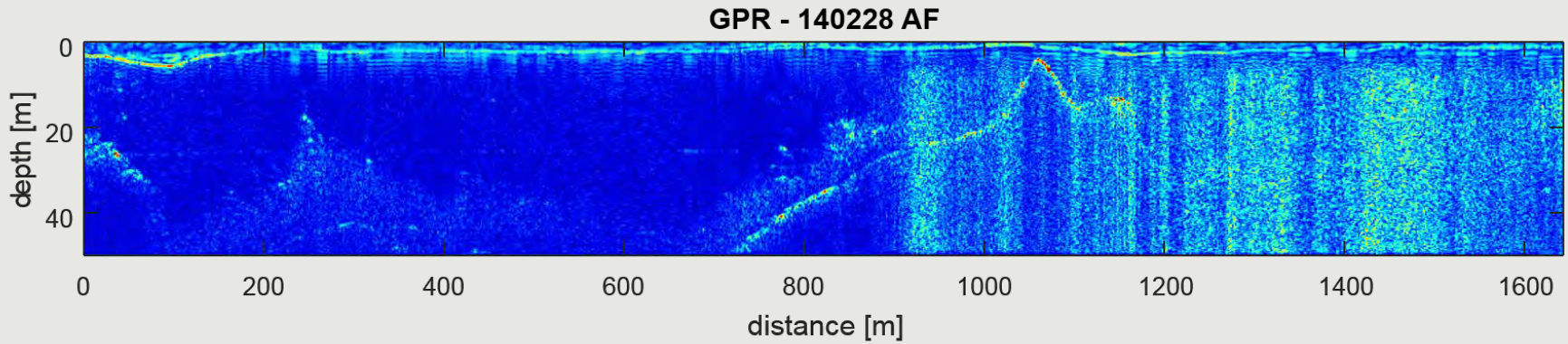


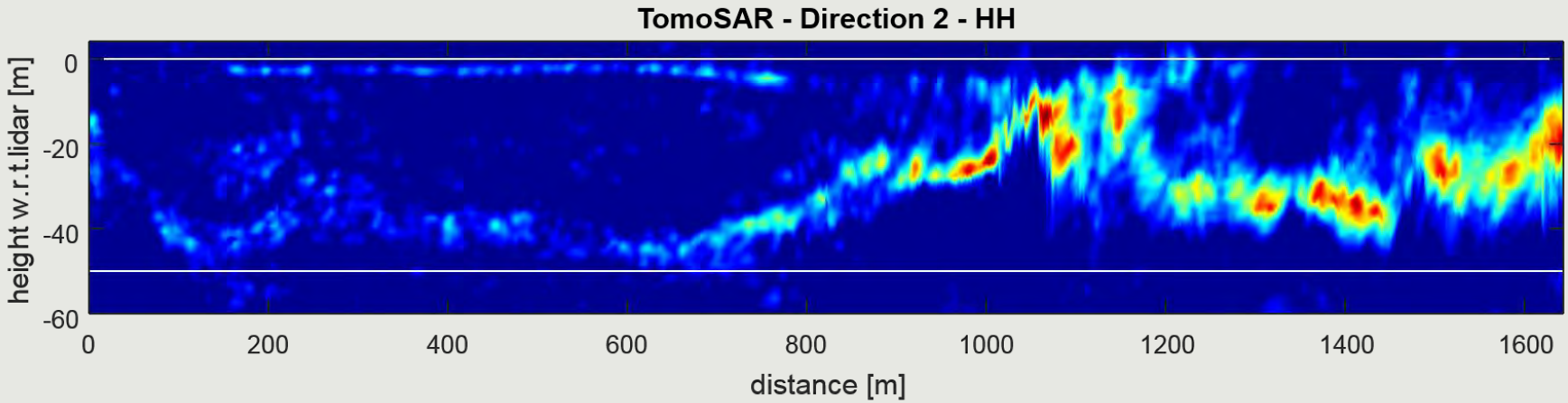




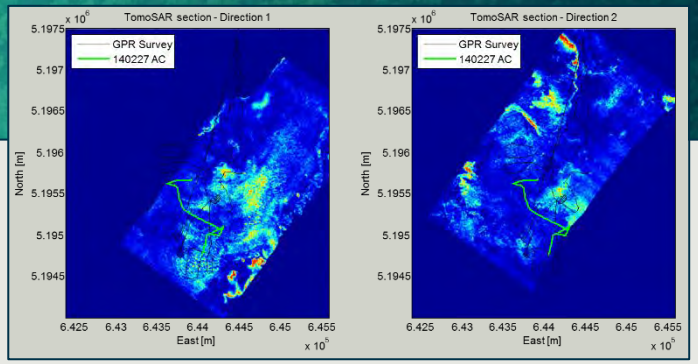
Comparison to 200 MHz GPR Transects



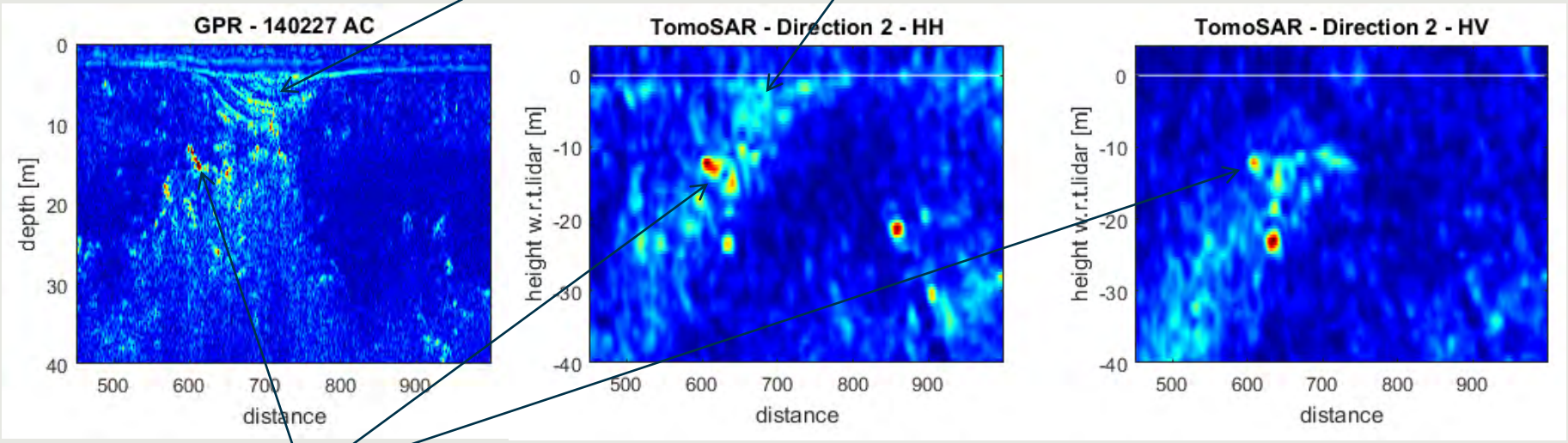




Comparison to 200 MHz GPR Transects



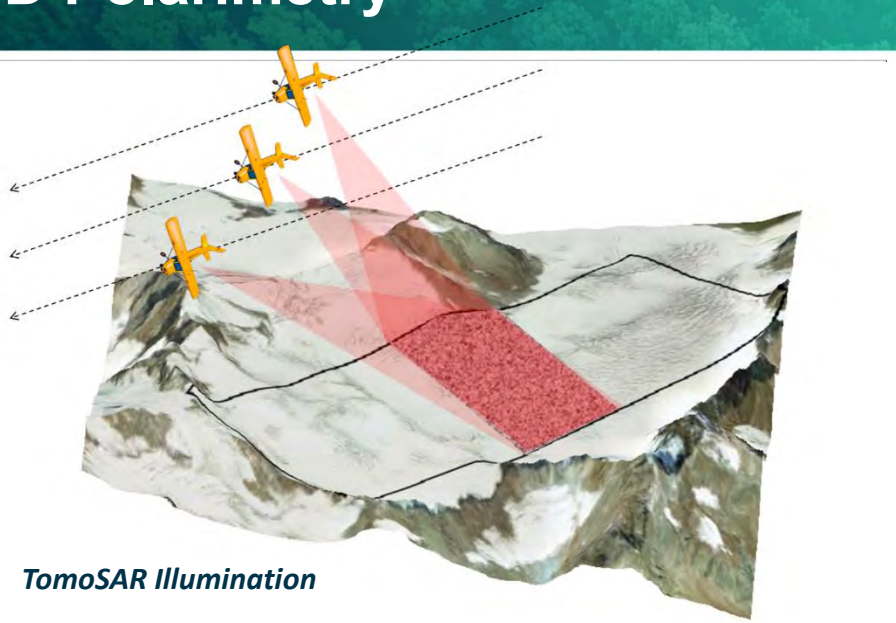
Firn layering



Dominant reflectors

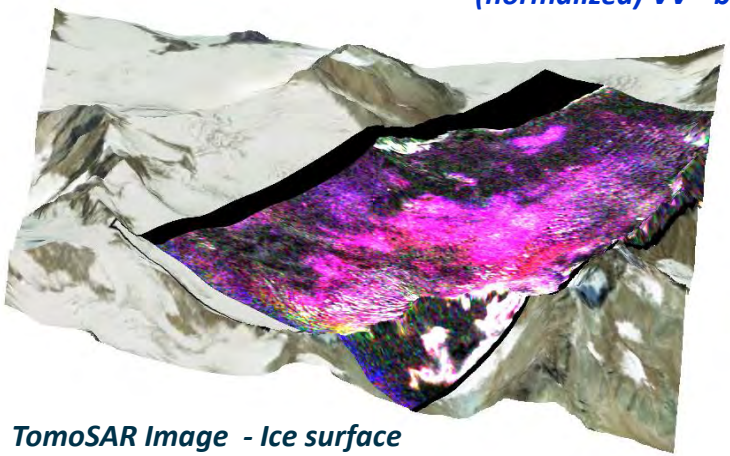
(Water pockets ?)

3D Polarimetry

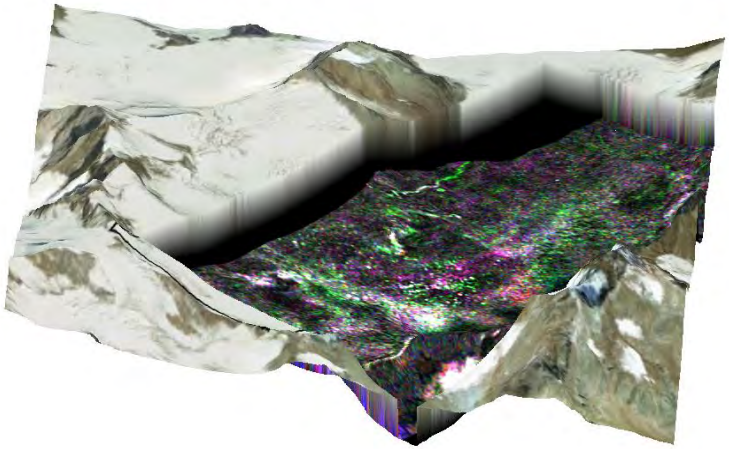


TomoSAR Illumination

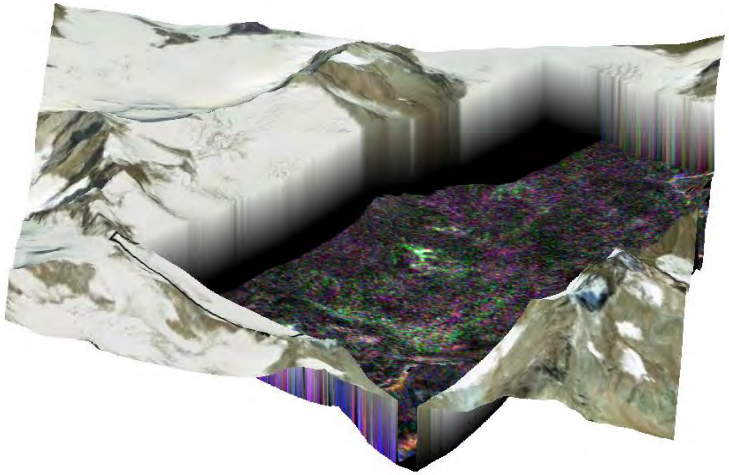
(normalized) HH - red
(normalized) HV – green
(normalized) VV - blue



TomoSAR Image - Ice surface

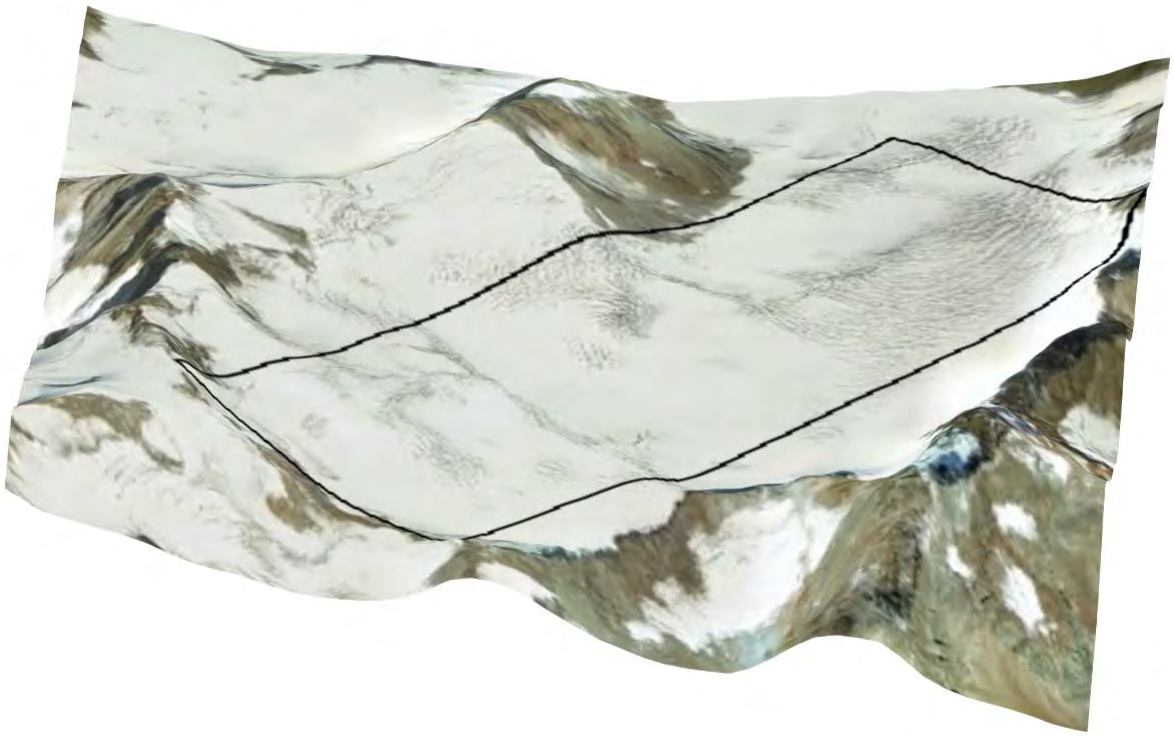


TomoSAR Image - 25 m below the Ice surface



TomoSAR Image - 50 m below the Ice surface

The Mittelbergferner @ L-Band



Data from AlpTomoSAR 2014 (MetaSensing, ESA)

Processing by PoliMi

Spaceborne Tomography

BIOMASS (ESA)

P-Band SAR

Selected as next ESA Earth Explorer Core Mission

Currently in Phase-B

Launch expected in 2020

Mission Objectives

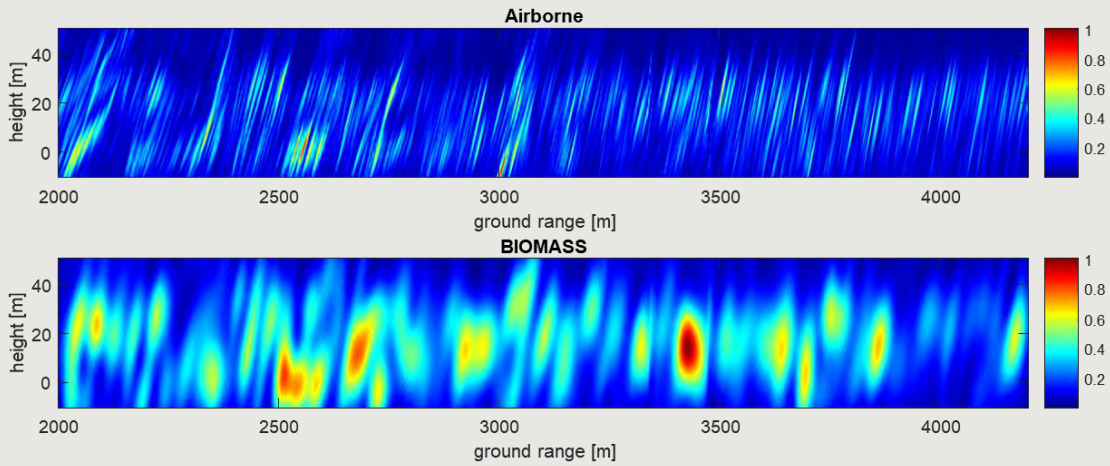
- to determine the distribution of aboveground biomass in the world's forests
- to measure annual changes in this stock over the period of the mission.

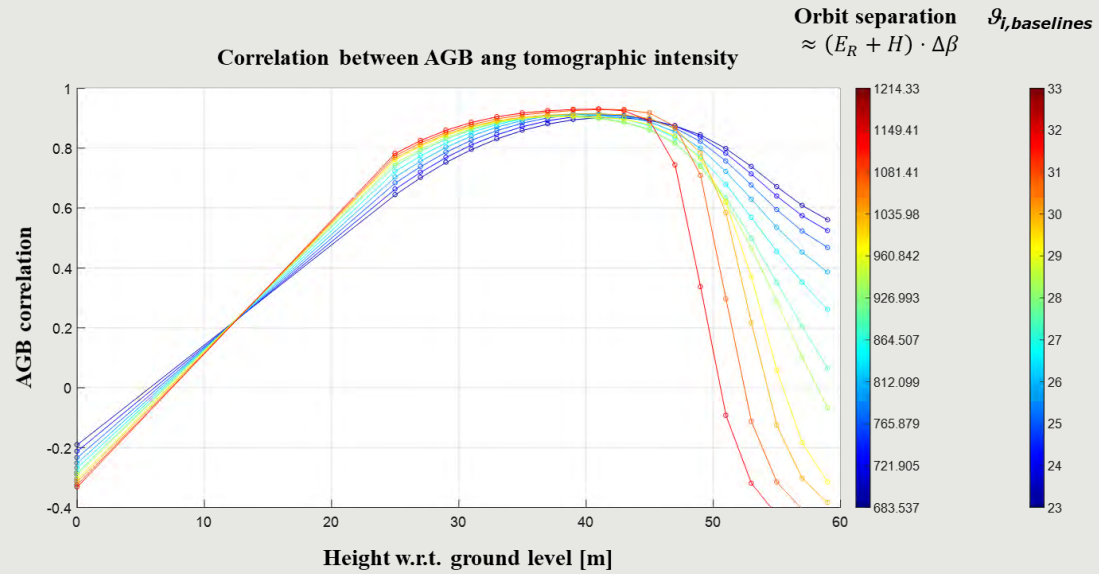
BIOMASS Tomography

The BIOMASS Tomographic phase

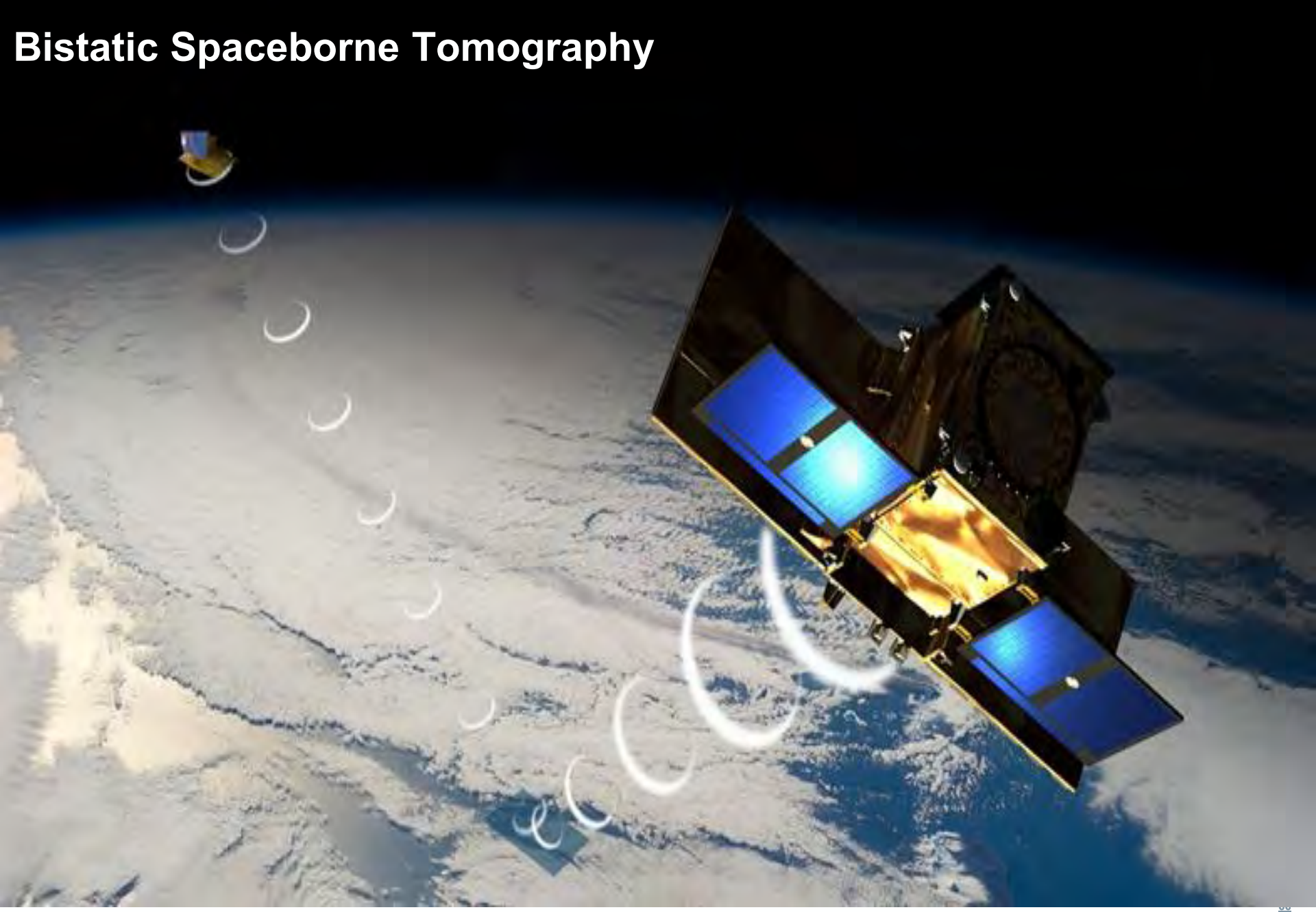
- 14 months duration
- Global coverage
- 7 passes per illuminated sites
- 3 day repeat pass time
- About 23 m vertical resolution
- Performance assessment based on simulated BIOMASS data derived from airborne campaign data

Forest tomography in tropical areas



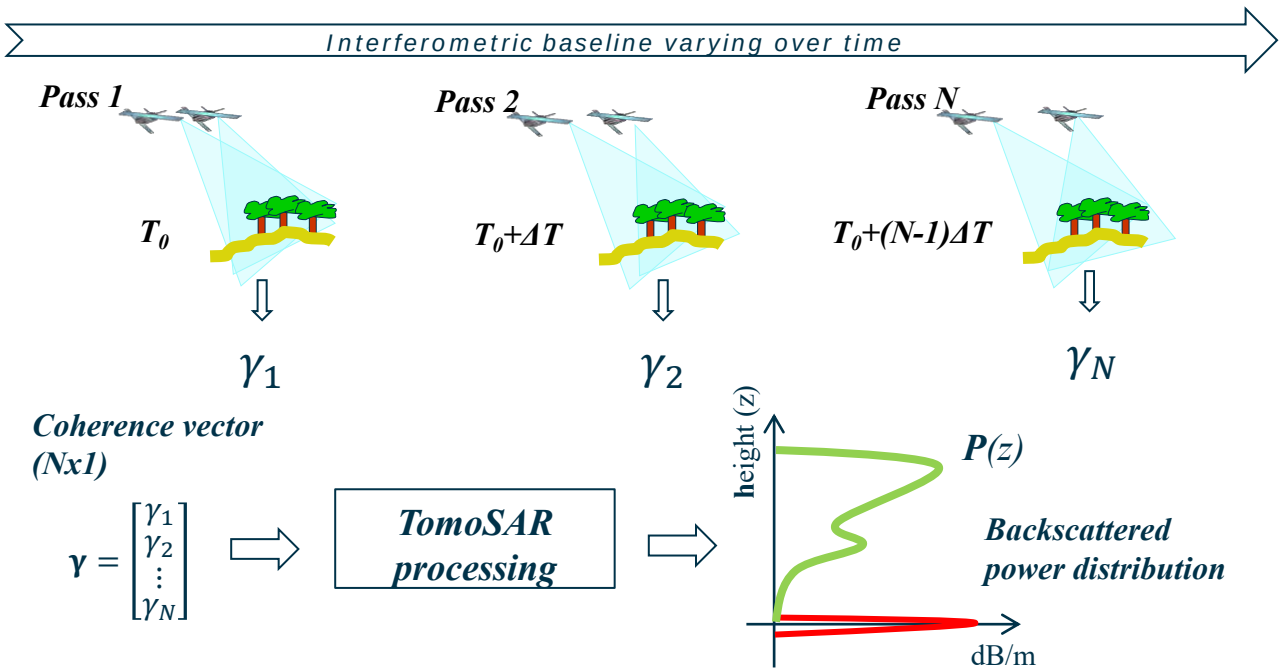


Bistatic Spaceborne Tomography



Bistatic Tomography: a way out of temporal decorrelation

Concept: collection of multiple single-pass InSAR baselines by varying the Rx position



Features:

- ✓ ***Robust***: largely immune to temporal decorrelation => possibility to use higher frequencies !
- ✓ ***Mature***:
  - o Strong heritage from several proposed missions (*Cartwheel, Tandem-L, SAOCOM-CS, SESAME, PARSIFAL*)
  - o Partly demonstrated by Tandem-X single-pass Interferometry

Simulated forest tomography

Prototype SAOCOM-CS (PARSIFAL) mission product derived from airborne measurements

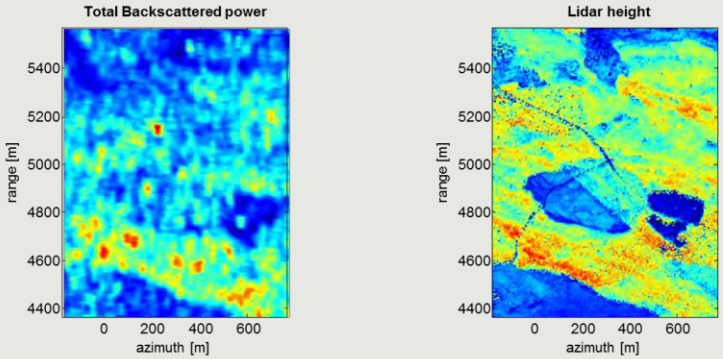
- Geometrical simulation of SAOCOM-CS (PARSIFAL) SLC data based high-resolution 3D Coherent Tomography from airborne data
- Correlation Tomography is implemented based on simulated data

Input data: BIOSAR 2

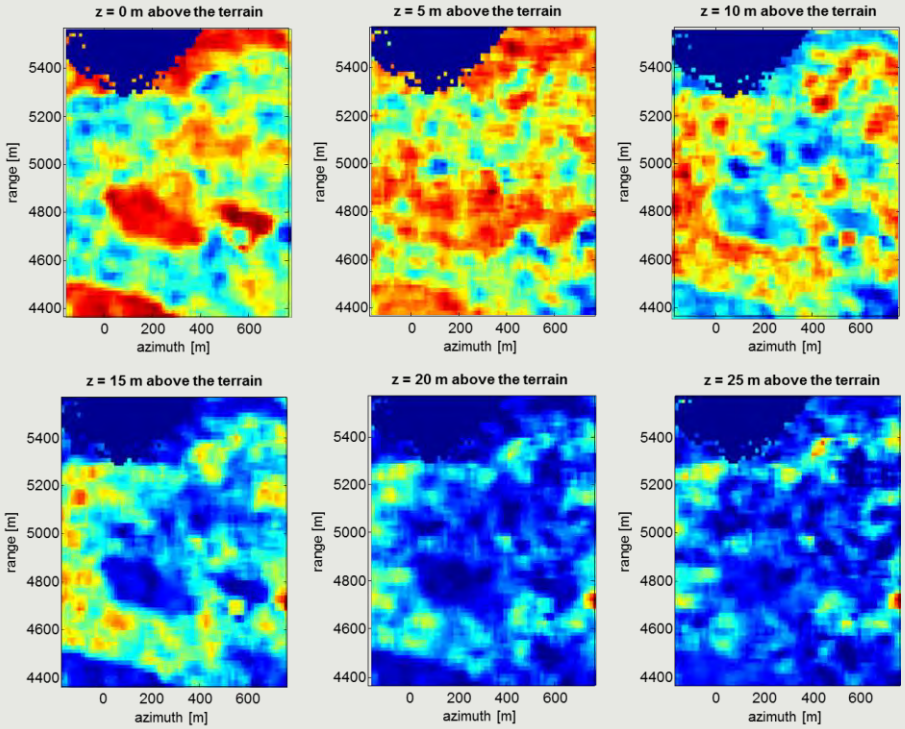
- Krycklan River catchment, Northern Sweden
- 6 L-Band passes acquired by DLR
- The dominating forest type is mixed coniferous.
- Hilly topography
- Forest height is typically 20 m,

Forest tomography in boreal areas

SAOCOM: 2D Imaging



SAOCOM-CS TomoSAR: 3D Imaging



Simulated forest tomography

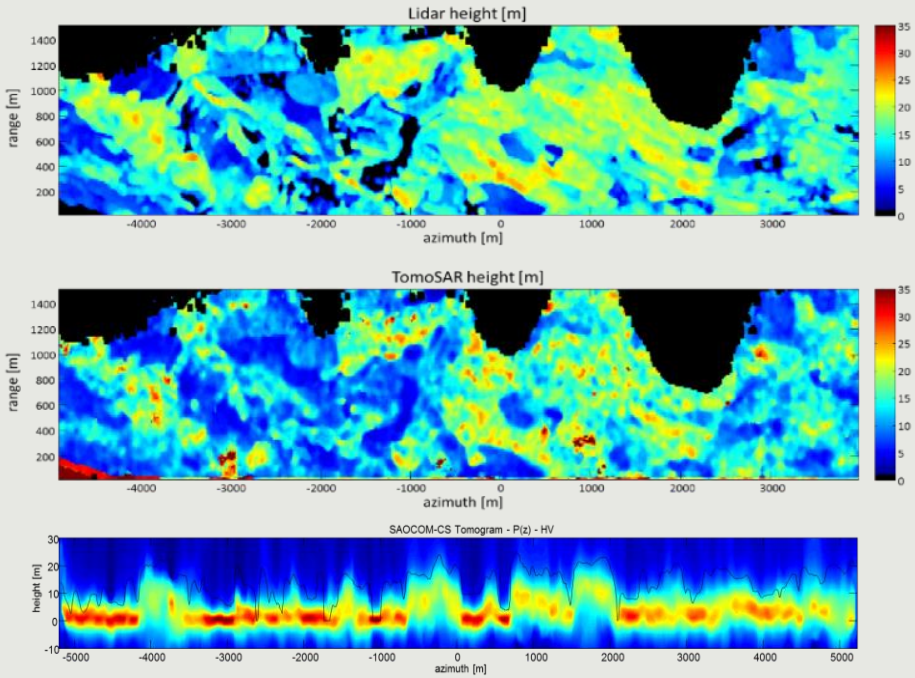
Prototype SAOCOM-CS (PARSIFAL) mission product derived from airborne measurements

- Geometrical simulation of SAOCOM-CS (PARSIFAL) SLC data based high-resolution 3D Coherent Tomography from airborne data
- Correlation Tomography is implemented based on simulated data

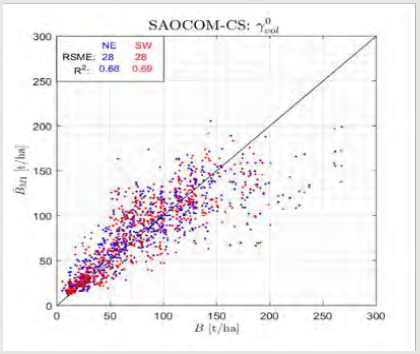
Input data: BIOSAR 2

- Krycklan River catchment, Northern Sweden
- 6 L-Band passes acquired by DLR
- The dominating forest type is mixed coniferous.
- Hilly topography
- Forest height is typically 20 m,

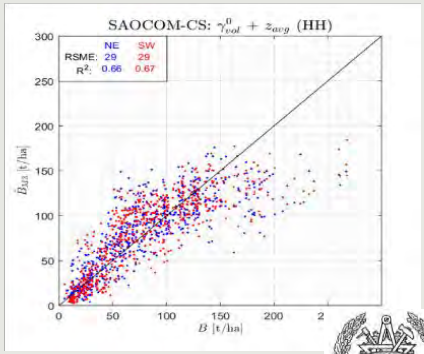
Forest height and biomass retrieval in boreal areas



SAOCOM-CS tomography (full pol)



SAOCOM-CS tomography (single pol)



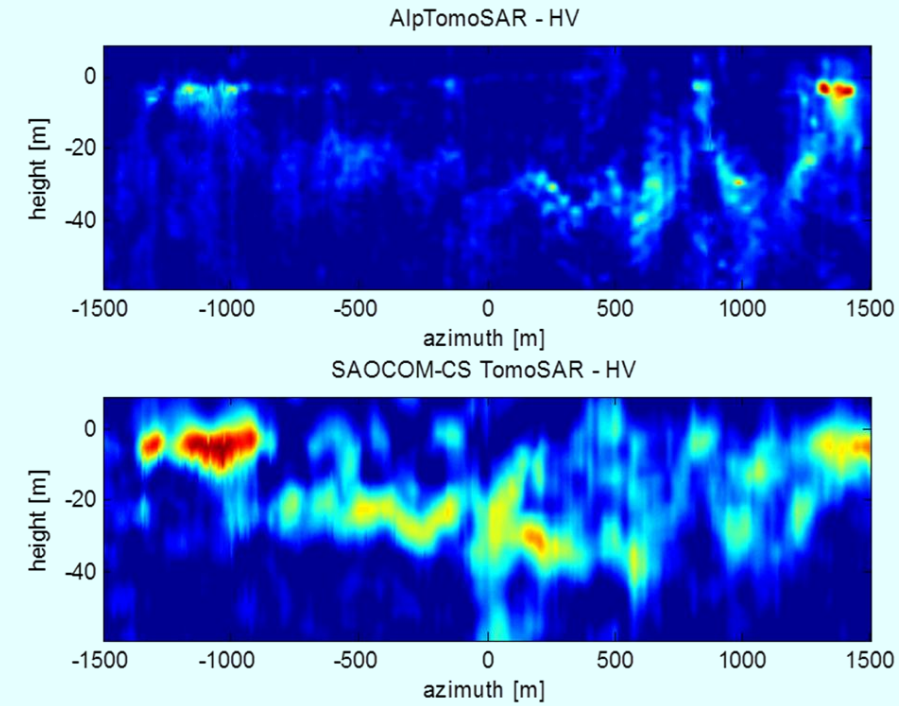
Simulated ice tomography

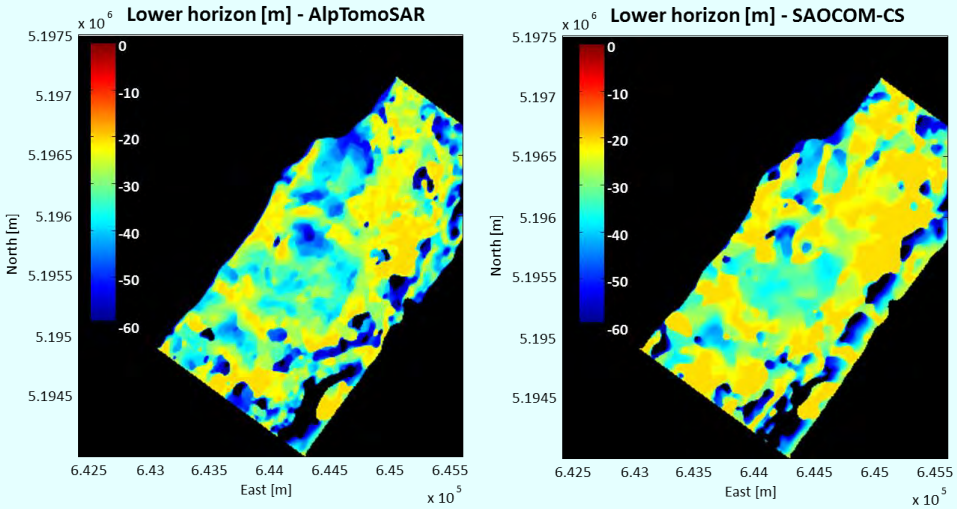
Prototype SAOCOM-CS (PARSIFAL) mission product derived from airborne measurements

- Geometrical simulation of SAOCOM-CS (PARSIFAL) SLC data based high-resolution 3D Coherent Tomography from airborne data
- Correlation Tomography is implemented based on simulated data

Input data: AlpTomoSAR

- Mittelbergferner, Austrian Alps
- 15 L-Band passes acquired by MetaSensing
- Alpine glacier
- Penetration depth down to the bedrock (ca. 50 – 60 m)





Conclusions

SAR Tomography ⇔ 3D structure of distributed media at high resolution

- Forests
- Snow
- Ice sheets/glacier

Rapidly evolving

- Mid 90's: principle formulated (Knaell and Cardillo) & first experiment (Pasquali et al)
- 2000: First airborne demonstration (Reigber & Moreira)
- 2007: TomoSAR is considered in the frame of BIOMASS phase-A activities
- 2013-today: Intensively being studied for SAOCOM-CS and Tandem-L
- 2023: expected launch date for BIOMASS – **first global tomographic coverage of tropical forests**
- 2023-(?): L-Band Tomography systems to provide high-resolution tomographic products

Current researches on geophysical product retrieval

- Quantitative investigation of forest parameters (biomass, structure) and agriculture
- Assessment of potential for snow, ice sheets, glaciers
- Arid terrains ?

Current researches on signal processing

- Treatment of high-resolution 3D data (cell migration, sidelobe rejection)
- Focusing with changing wave propagation velocity (known/unknown)
- Robustness to disturbance factors (seasonality/rain/moisture) for incoherent tomography