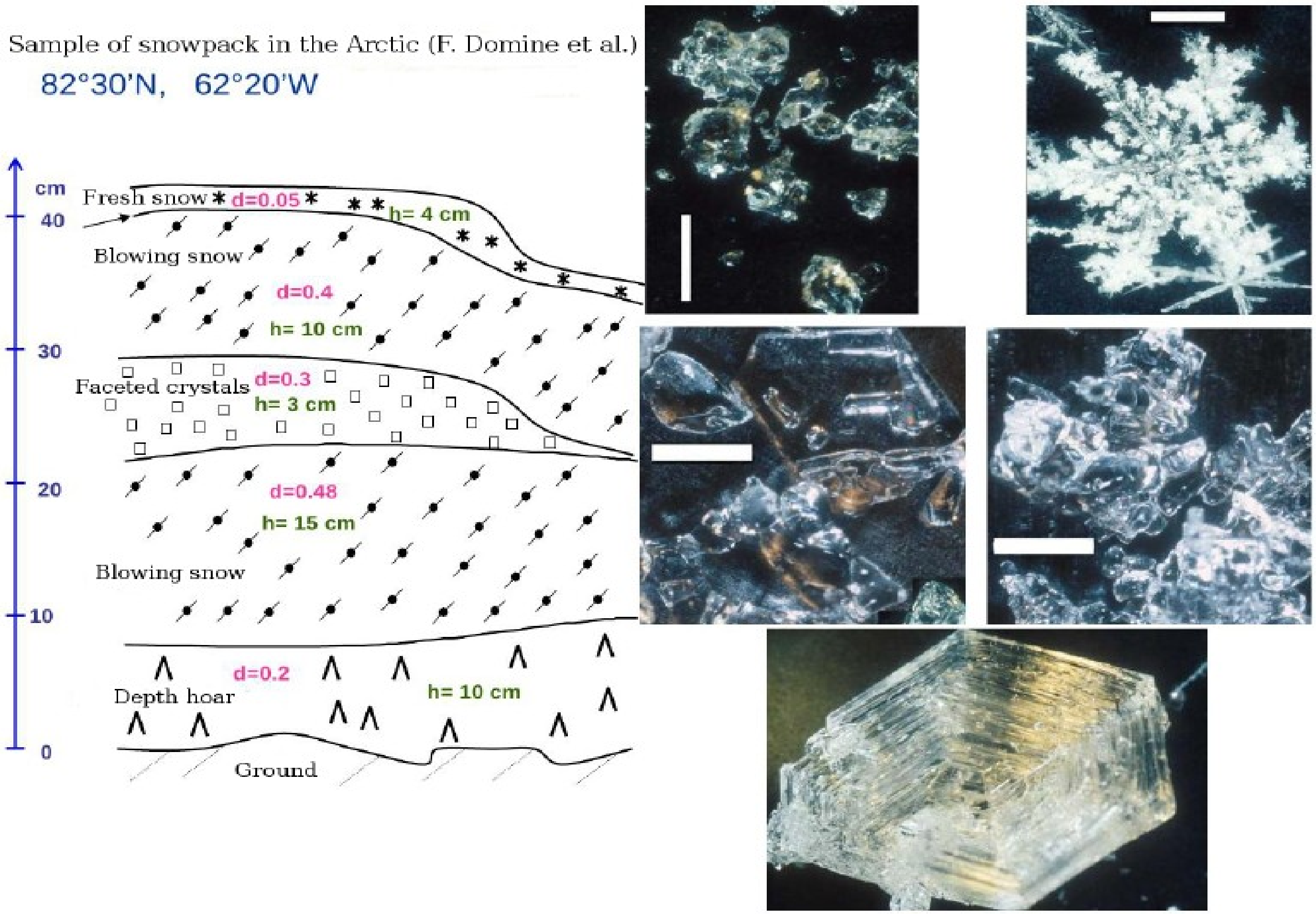
Characterization of the internal structure snow and ice packs using 3-D SAR imaging at various scales

Laurent Ferro-Famil [(1)] & Stefano Tebaldini [(2)]

(1) IETR, University of Rennes 1, France
(2) DEIB, Poitecnico di Milano, Italy

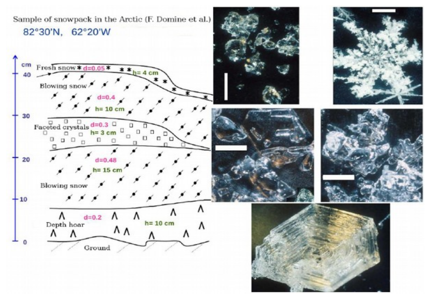
Laurent.Ferro-Famil@univ-rennes1.fr

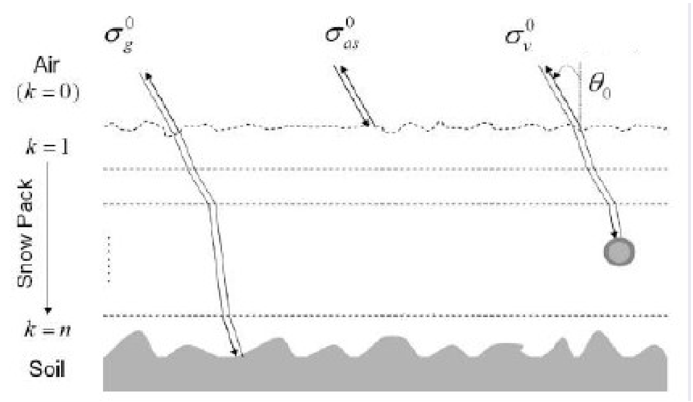
SNOWPACK PHYSICAL DESCRIPTION



Snowpack:

- dense and complex medium, made of several layers
- 1 layer ≡ several parameters: thickness, grain size, density, liquid water content …
- Spatial and temporal variations





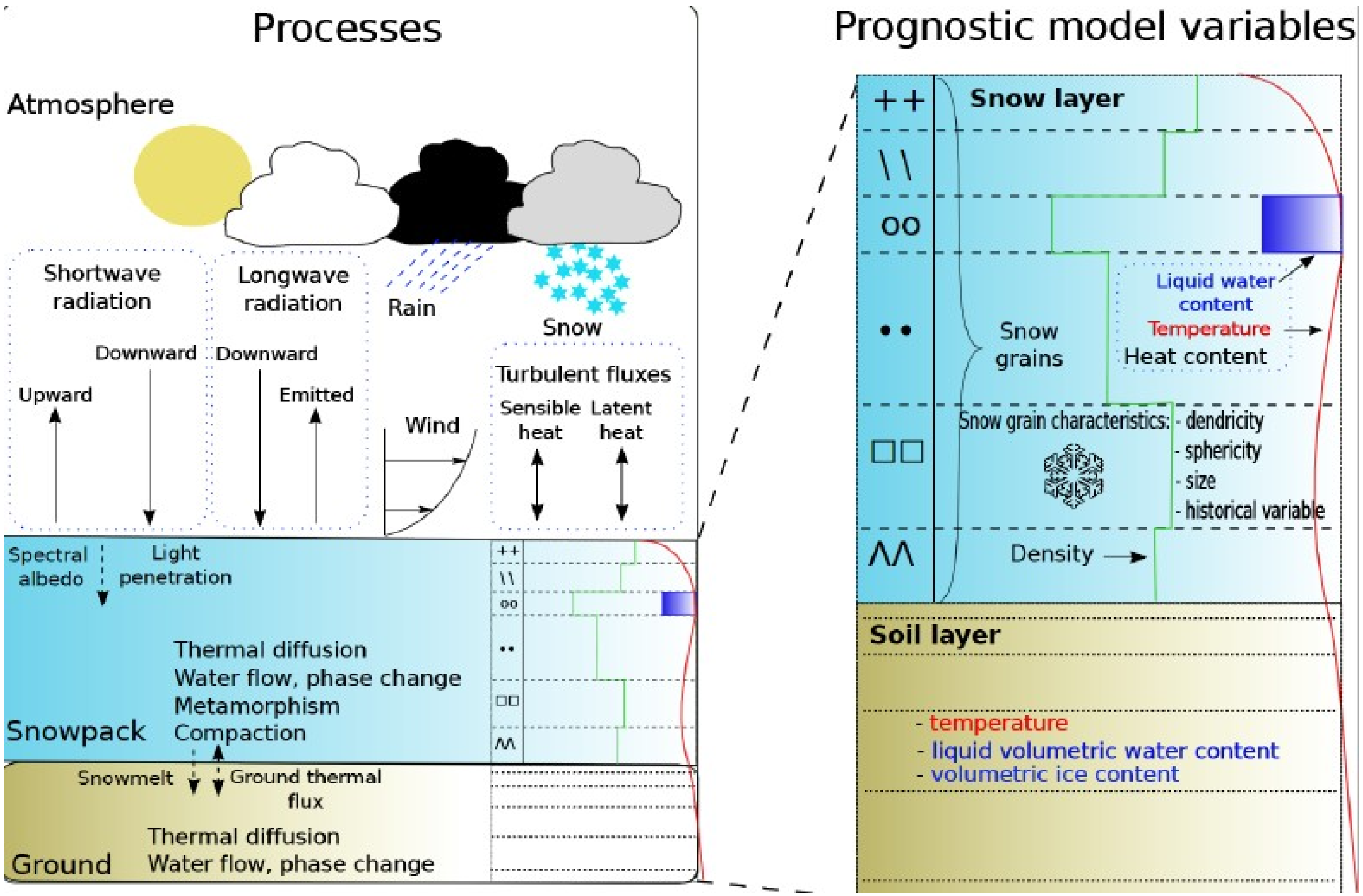
Physical parameters
(tens: N x 10) → **EM scattering model** → **Modeled** scattering coefficients **(<< 10)**

Estimated physical parameters
(tens: N x 10) ← **Inverse model** ← **Measured** scattering coefficients **(<<10)** ← SAPHIR

Snowpack structure estimation from SAR data
≡
Guess tens of parameters from a few measurements
⇒ Highly badly conditioned inverse problem

Need for additional information !

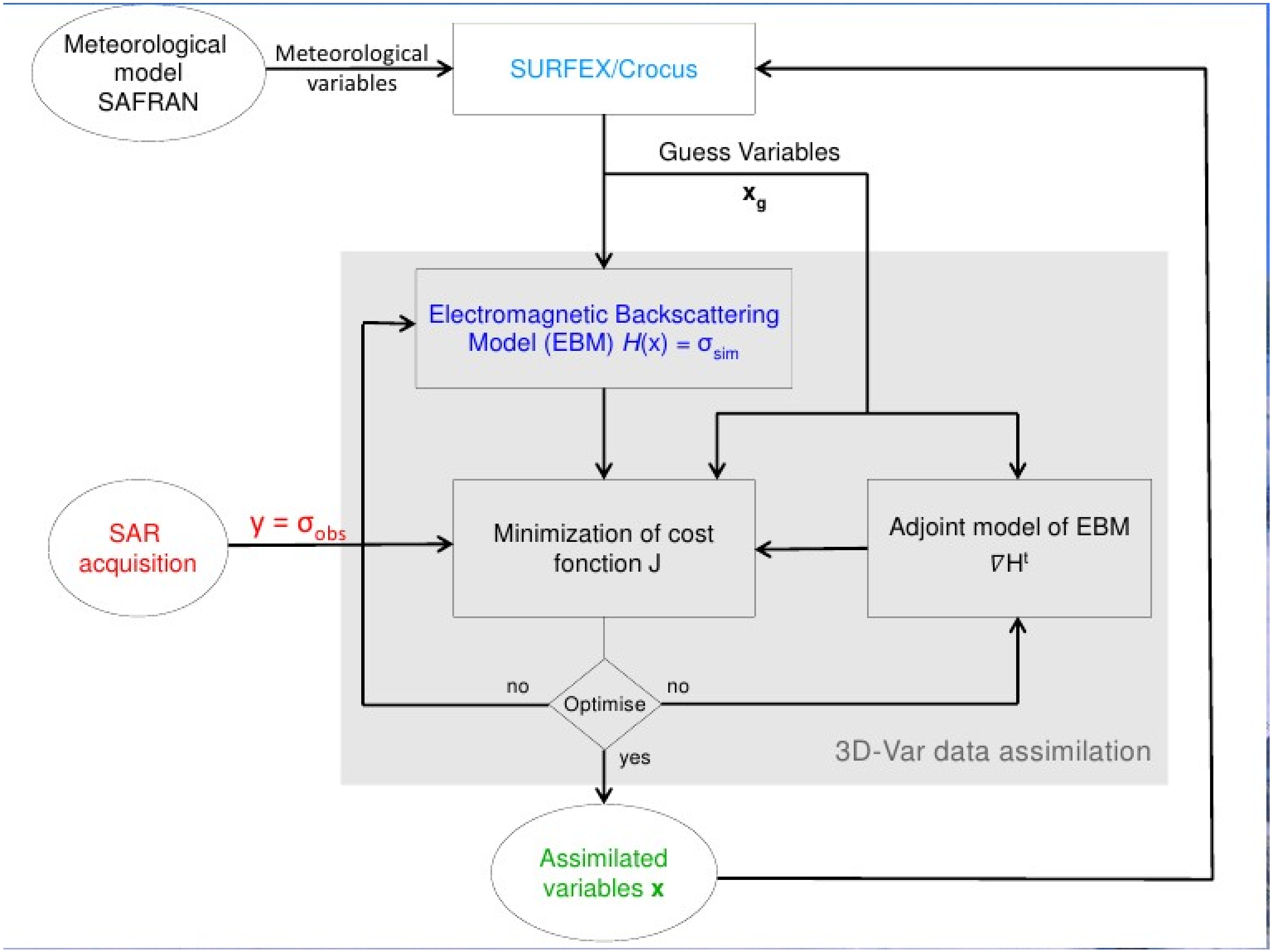
SURFEX/CROCUS METEOROLOGICAL MODEL



- MeteoFrance meteorological model simulating the structure of snowpacks
- 1D snowpack temporal evolution model
- Operates without in-situ measurements (open loop), no in-situ measurements
- Very low spatial resolution

Provides a stable initial guess of the snowpack structure
⇒ inverse problem conditioning improvement

ASSIMILATION SCHEME



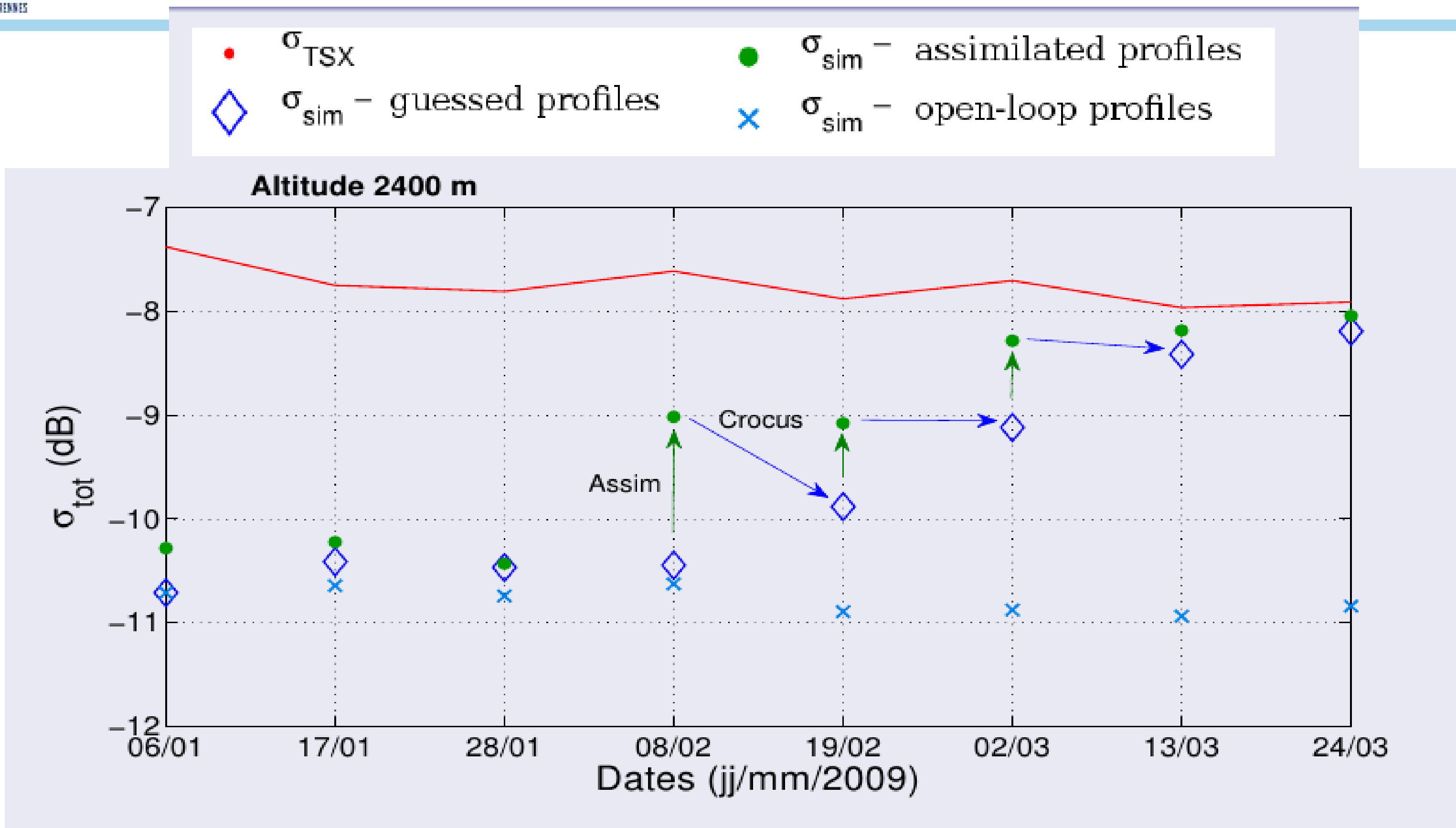
Snowpack structure estimation:

- resolution of an under-determined inverse problem (variational approach)

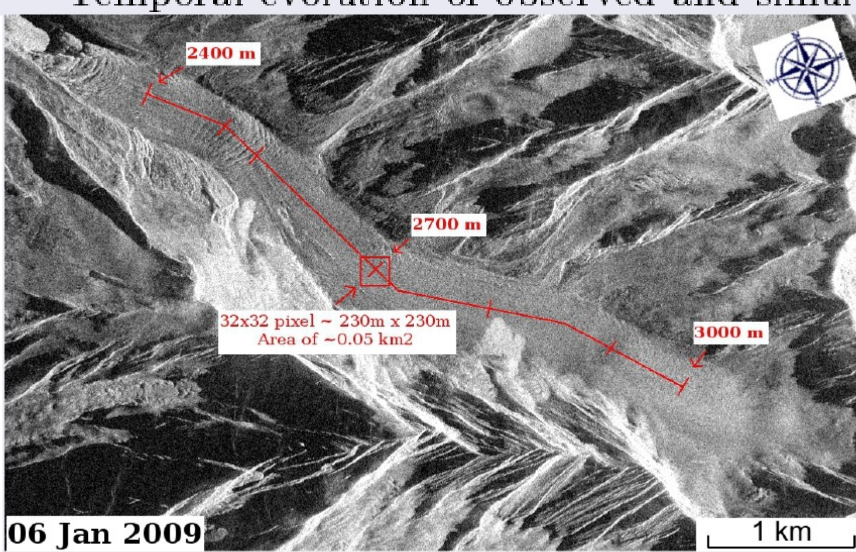
- solutions lie in the vicinity of SURFEX/Crocus predictions

- use of multi-temporal measurements: convergence of the estimation

ILLUSTRATION OF THE ASSIMILATION PROCESS

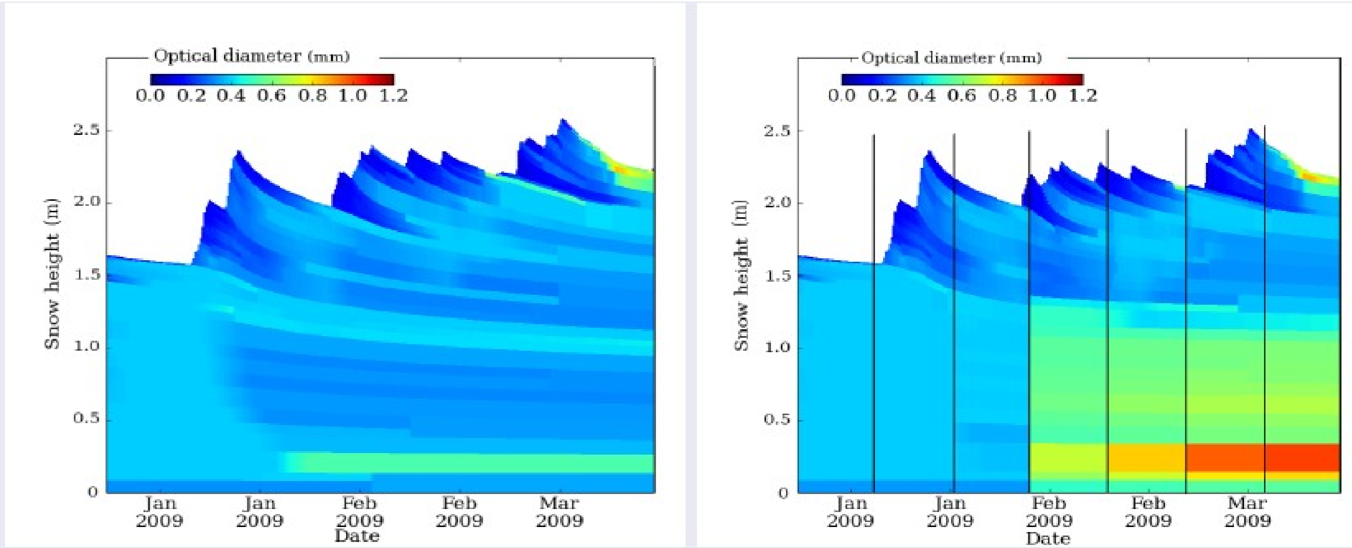


Temporal evolution of observed and simulated backscattering coefficients.

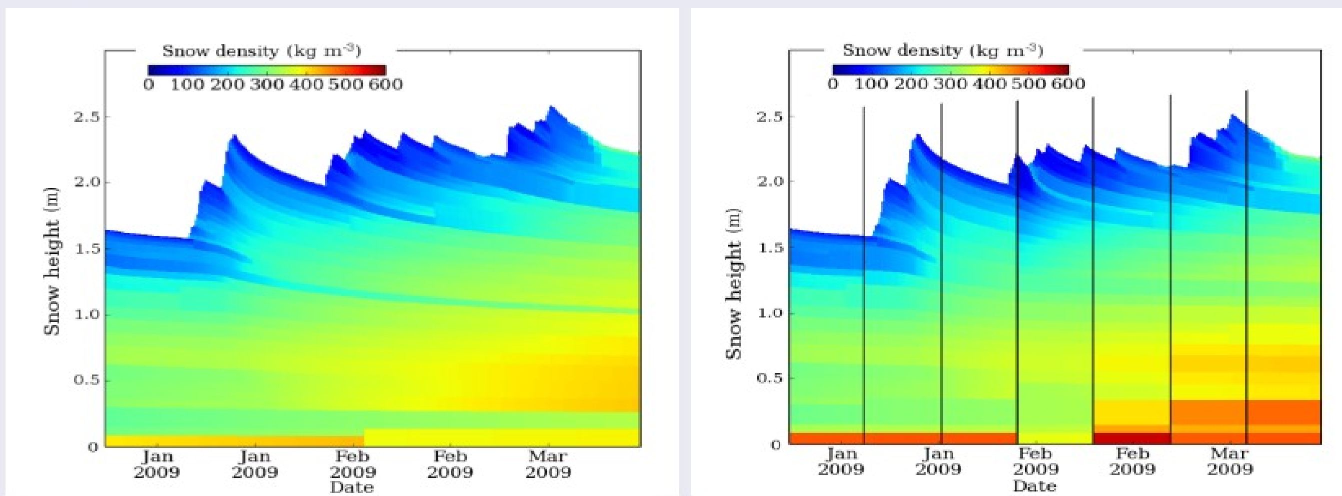


Application to TSX time series over the Argentière glacier

ASSIMILATION RESULTS



Temporal evolution of grain optical diameter, open loop (left) and assimilated (right).

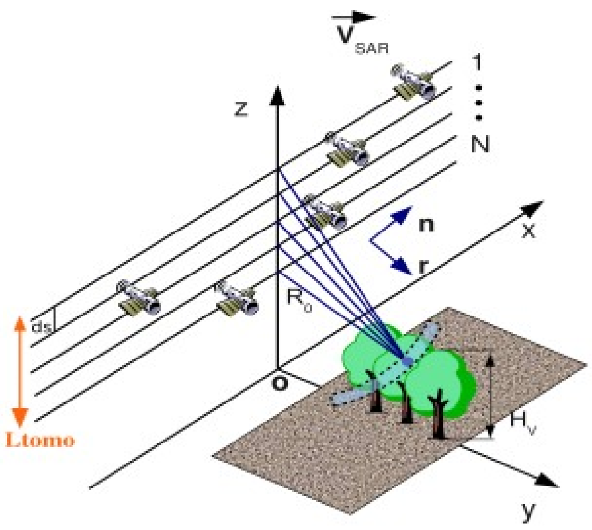


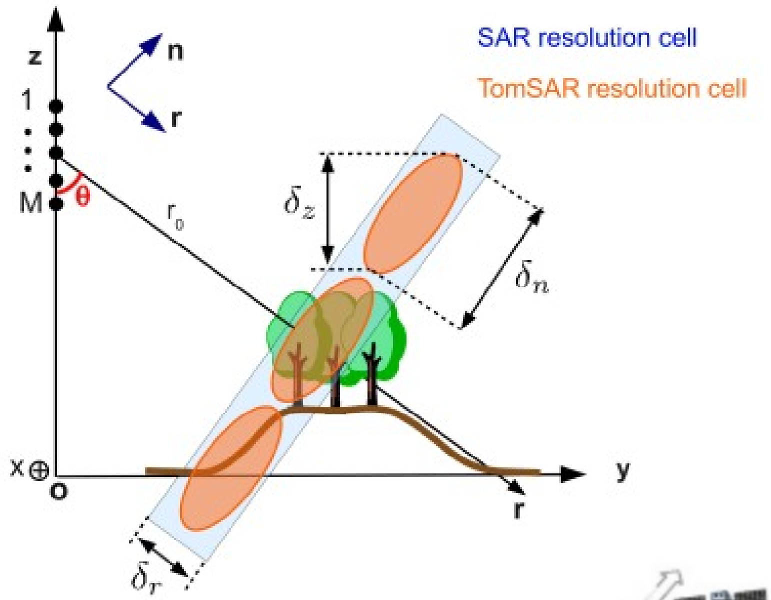
Temporal evolution of snow density, open loop (left) and assimilated (right).

Multibaseline InSAR (MB-InSAR) tomography

Several mixed scatterers → many across-track positions

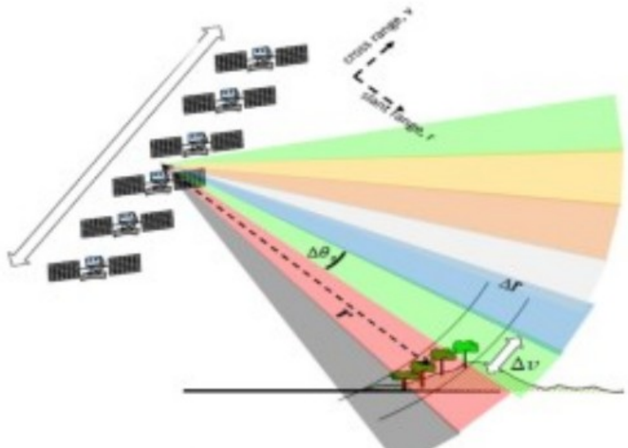
Acquisition geometry





Vertical focusing

- Vertical aperture : L_{tomo}
- Resolution : $\delta_z = \delta_n \sin\theta$ with $\delta_n = \frac{\lambda R_0}{2L_{tomo}}$



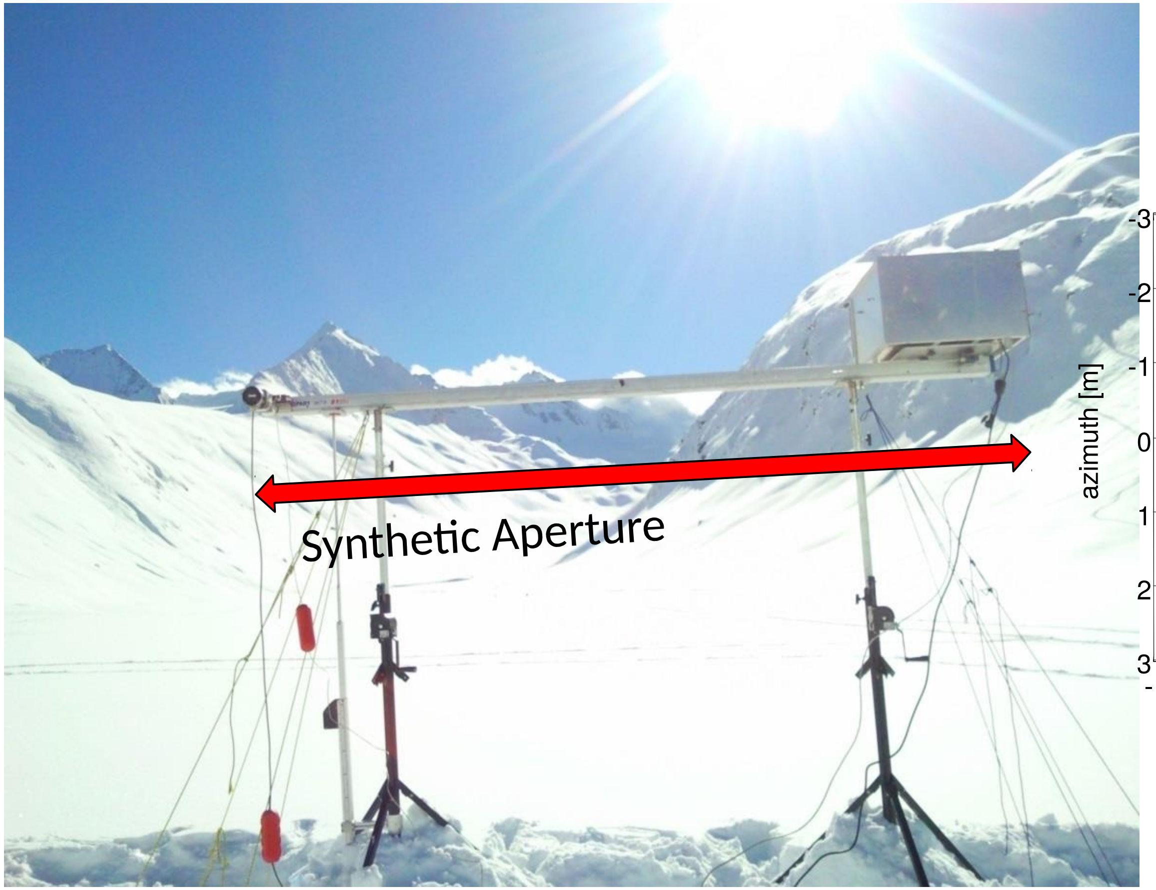
Antenna array formation at each (x,r) position

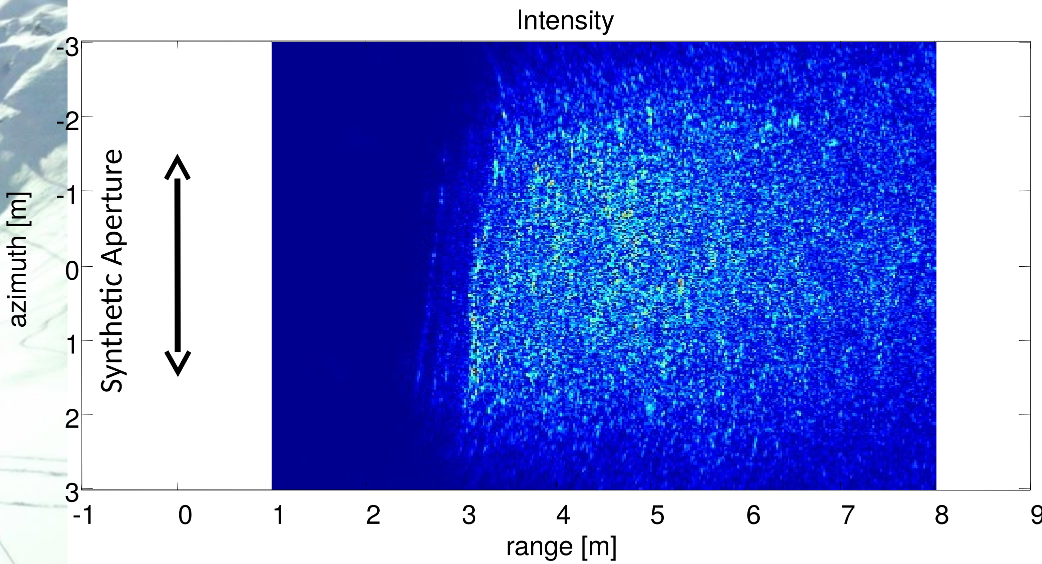
Measurements by a Ground based Synthetic Aperture Radar system, developed and implemented by the SAPHIR team at the University of Rennes 1

- Signal Tx and Rx: VNA
- Available frequency bands: 3 GHz to 20 GHz (C,X,Ku bands)
- Dynamic range ≈ 90 dB
- Sealed in a metallic box when operating 🔔 works under a snow fall
- Box + VNA = 40 Kg

Ground Based SAR

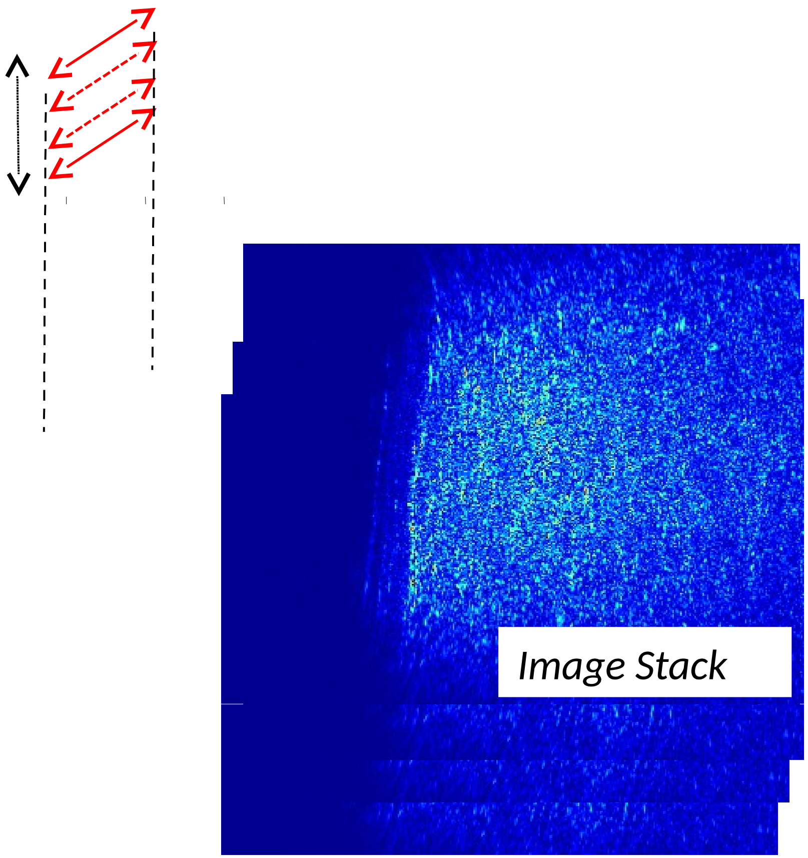
- Accurate sensor motion along a 3 m rail
- Fully automated
- Resolutions: Az < 5cm, Rg = 3.75 cm, El=10 cm centimeters at X- and Ku bands
- Max swath ≈ 8 m

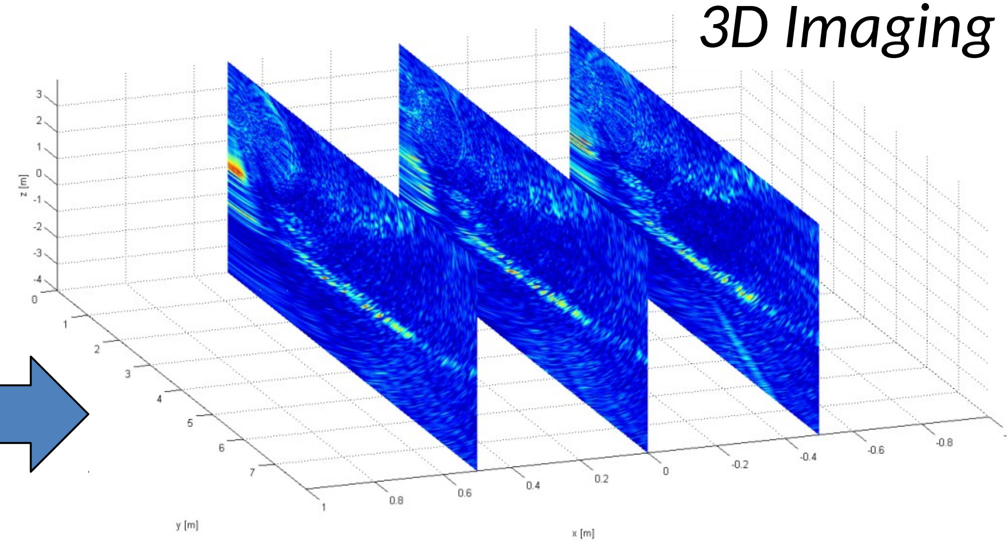


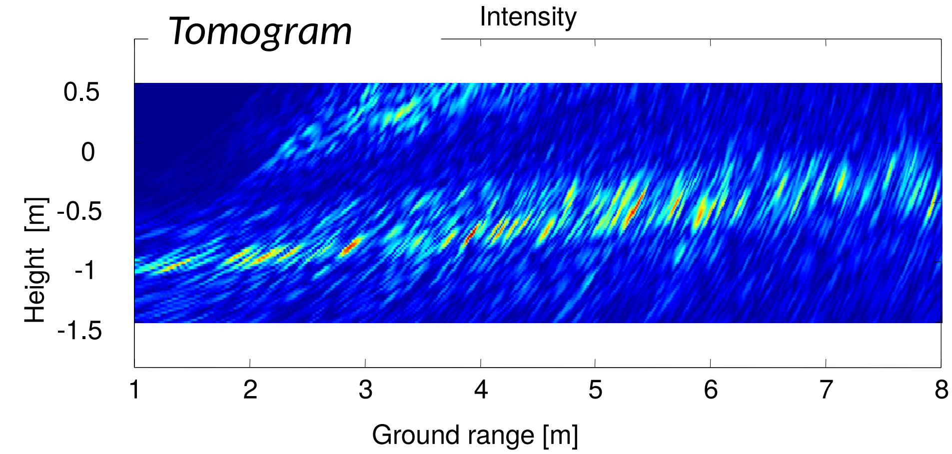


Ground Based SAR

- 2D synthetic antenna: parallel vertical passes
  - ⇒ 3D resolution capabilities



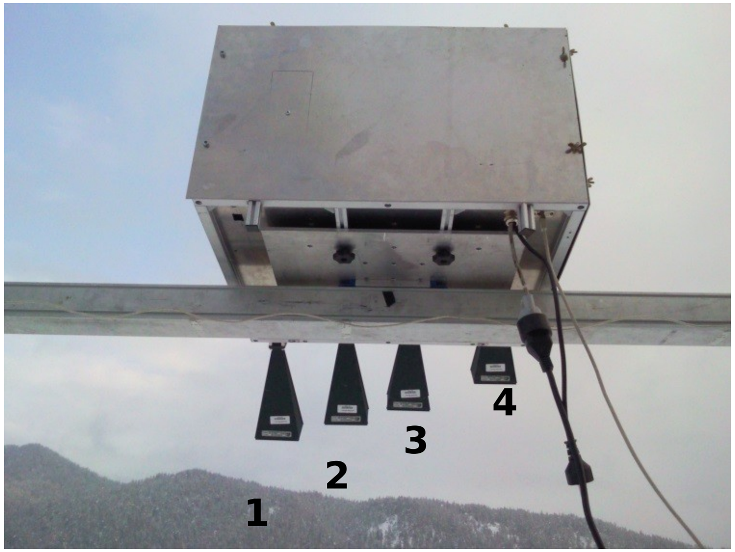




IETR GBSAR: 3 Multi-Baseline acquisition modes

1. Combining different Tx and Rx antennas (multistatic Radar)

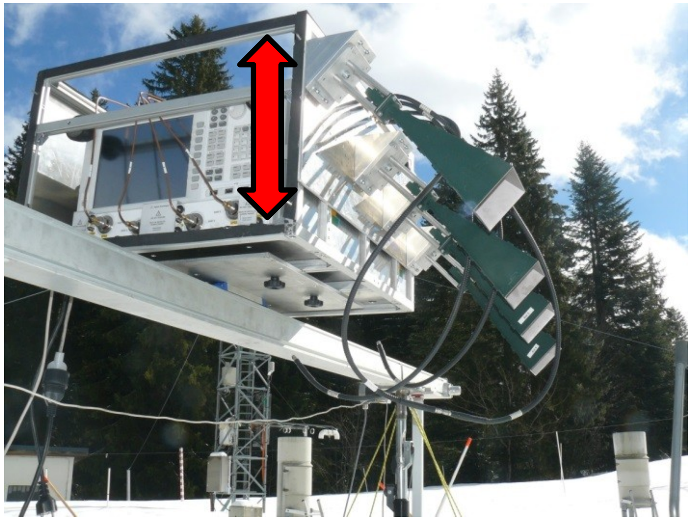
Equivalent to 6 virtual passes



Rx	Tx
1	2
1	3
1	4
2	3
2	4
3	4

IETR GBSAR: 3 Multi-Baseline acquisition modes

2. Varying the position w.r.t. the rail along the the VNA box



3. Varying rail height

Campaign at Col de Porte

- Carried out in December 2010 over a Meteo-France snowfield at Col de Porte (French Alps)

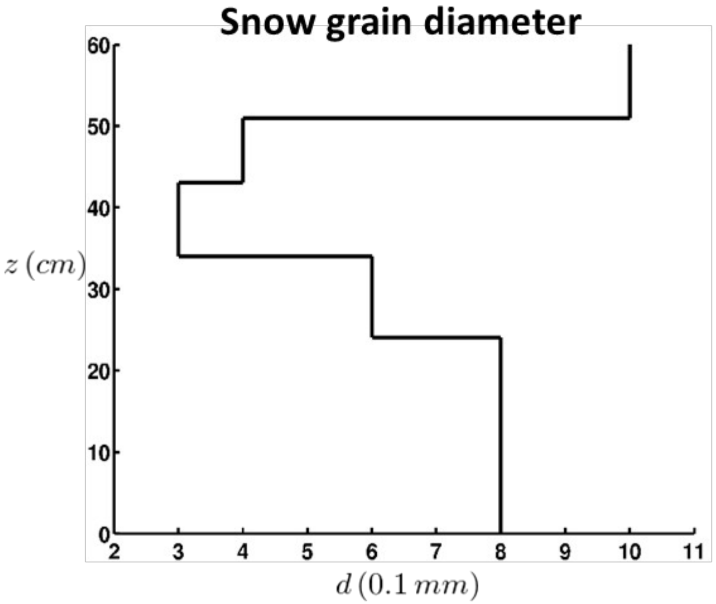
- Availability of in-situ data (Meteo-France/CEN)
  - Snow grain diameter
  - Liquid water content
  - Density

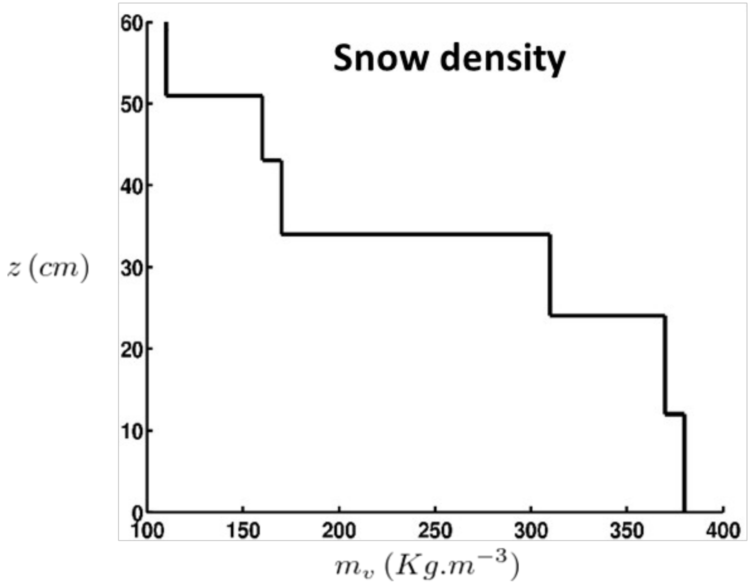
- Operated at X and Ku-Band
  - Total transmitted bandwidth = 8 GHz
  - Range resolution ≈ 2 cm
  - Azimuth resolution ≈ 2 cm

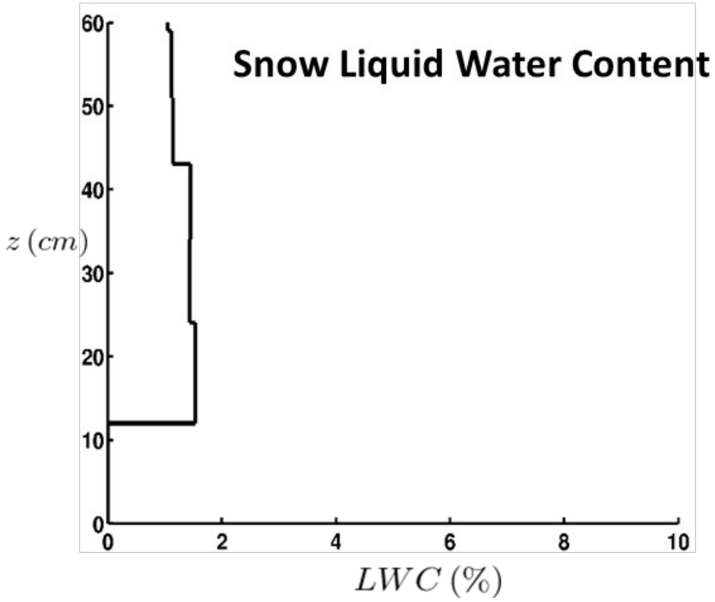
- 10 acquisitions: varying rail height
  - Cross range resolution ≈ 8 cm
  - Revisit time ≈ 20 minutes

Campaign at Col de Porte – In-situ data

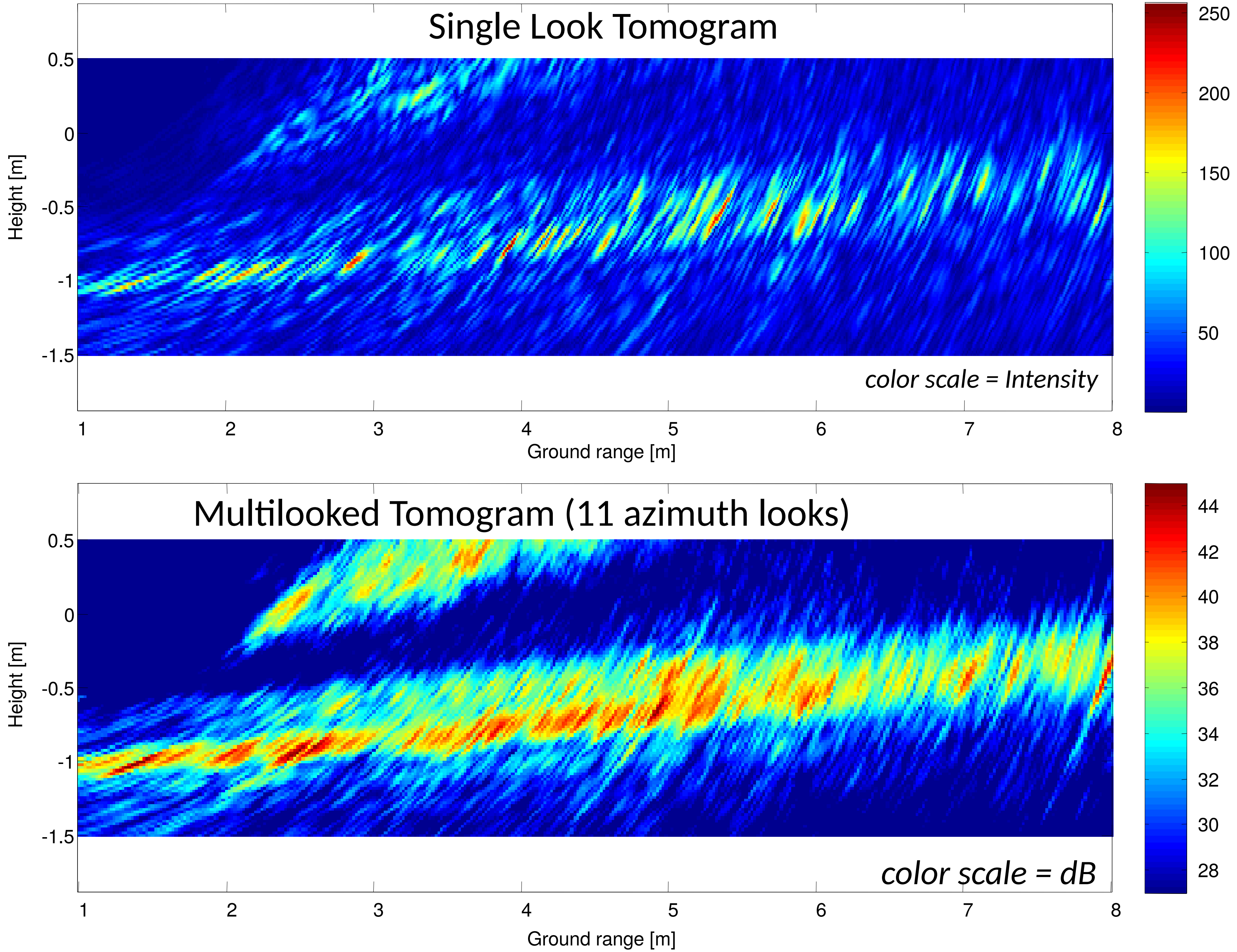
- Snow layer depth: approx. 60 cm
- Vertical snow profile probing (Meteo-France)
- Snow pack structure:
  - *Upper layer: low density of fresh snow*
  - *Middle layer : intermediate density, smaller grains*
  - *Lower layer: high density and size, very compact snow/ice*







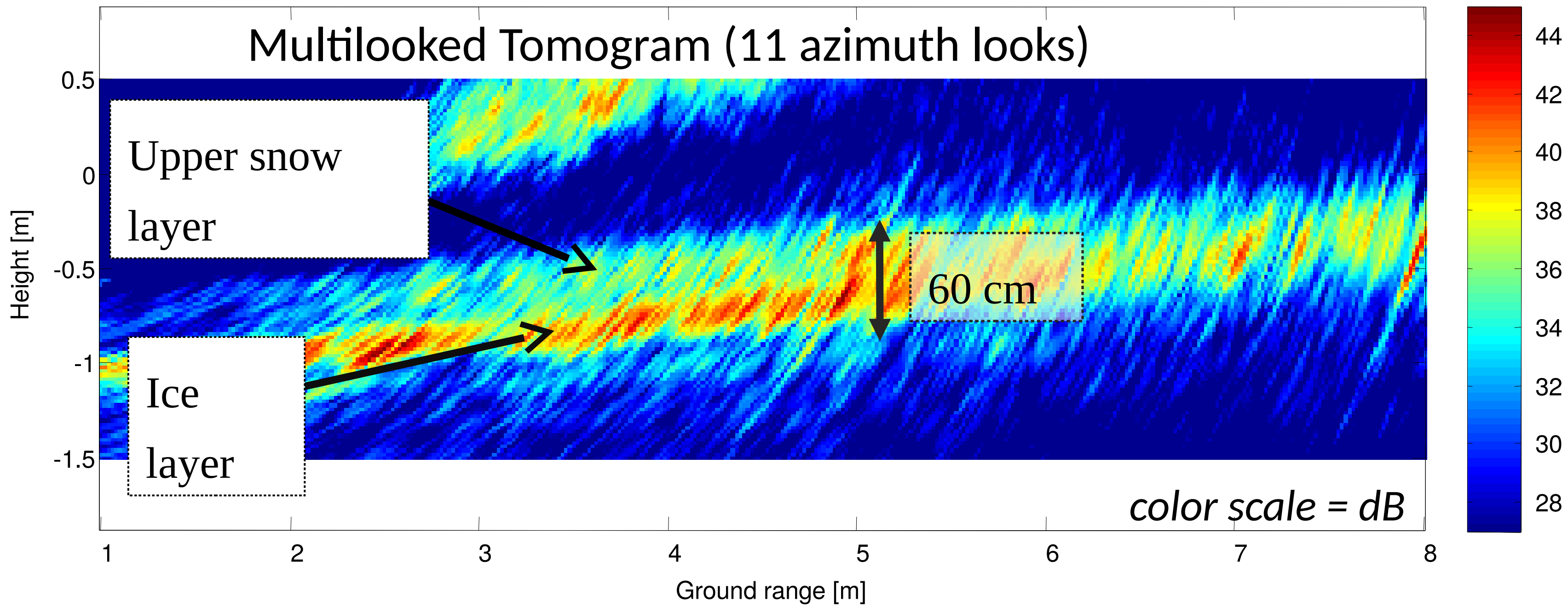
Wide band imaging (8.2 GHz – 16.2 GHz)



Wide band imaging (8.2 GHz – 16.2 GHz)

Physical Interpretation

- **Observed thickness ≈ 60 cm; Observed slope ≈ 7 cm/m (rising)**
  - **Strongest contribution from the bottom layer (buried ice/very dense snow)**
  - **Upper snow layer: intermediate intensity**

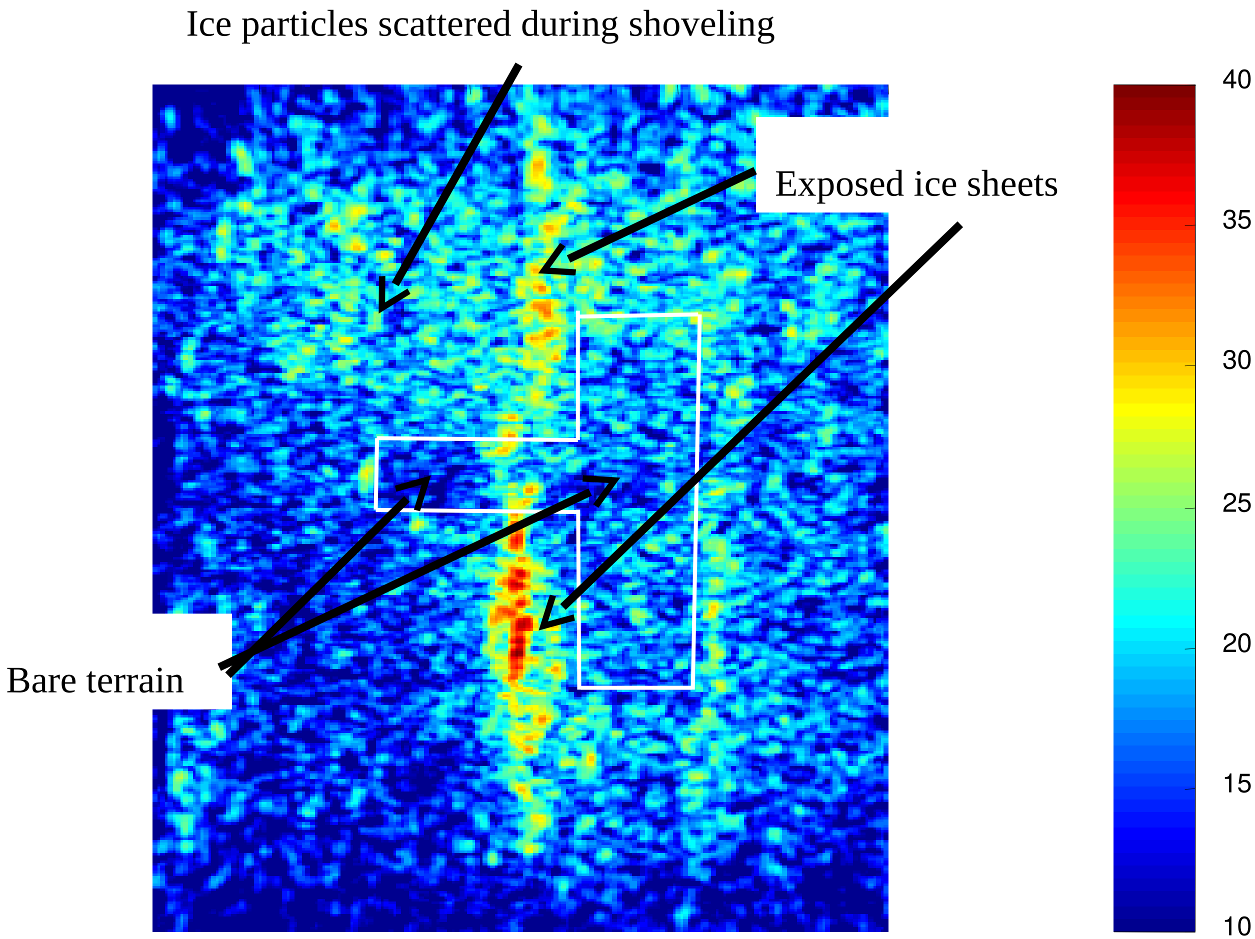


Terrain or ice ?

Digging of a T-shaped hole: terrain backscattering contribution

During digging the burried was deployed aside on the snow layer

contributions from exposed ice sheets **dominate those from the terrain by over 30 dB**



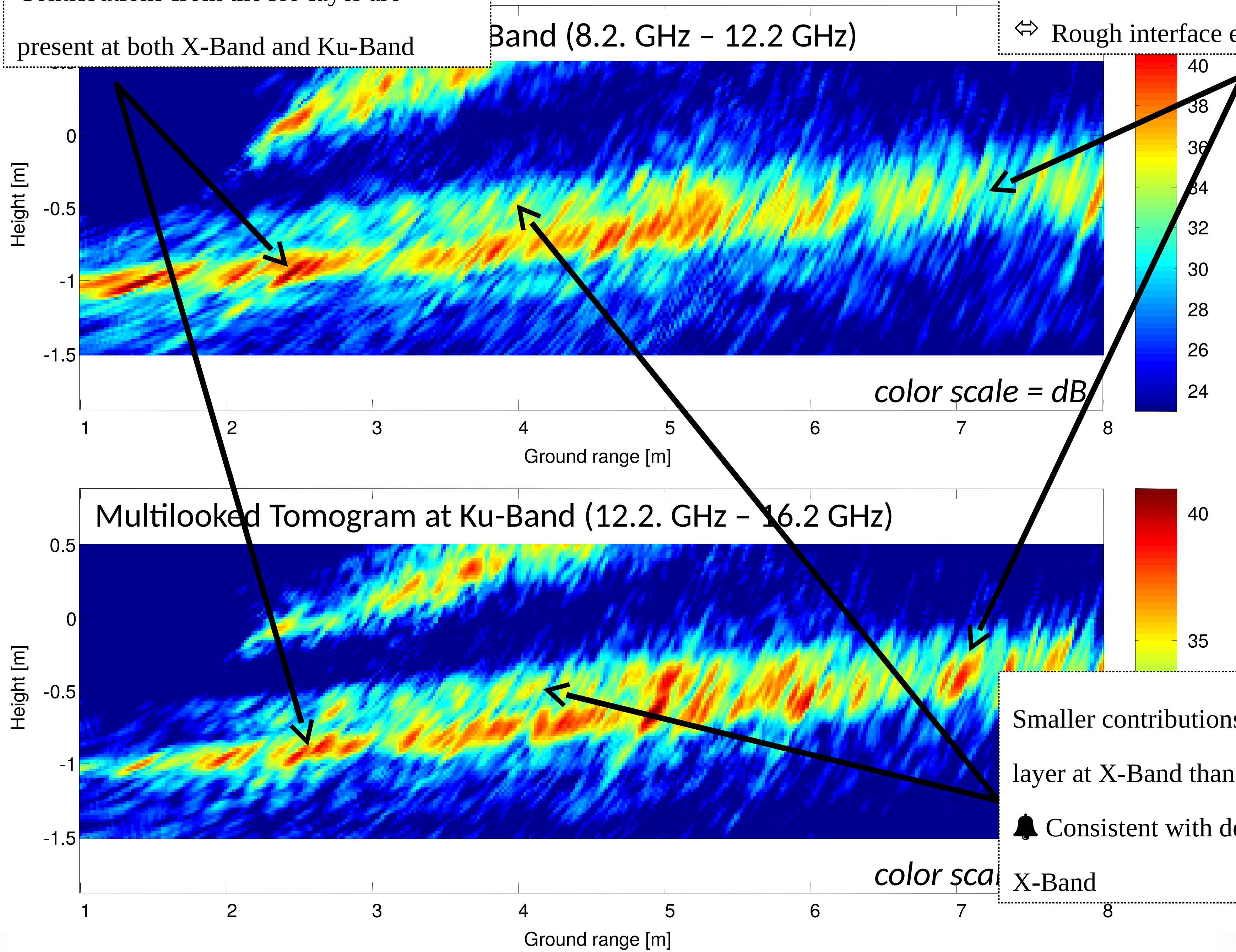
color scale = dB

Imaging at X – and Ku-Band

Contributions from the ice-layer are present at both X-Band and Ku-Band

Grazing angles show higher returns at Ku-Band than at X-Band

⇔ Rough interface effects ?



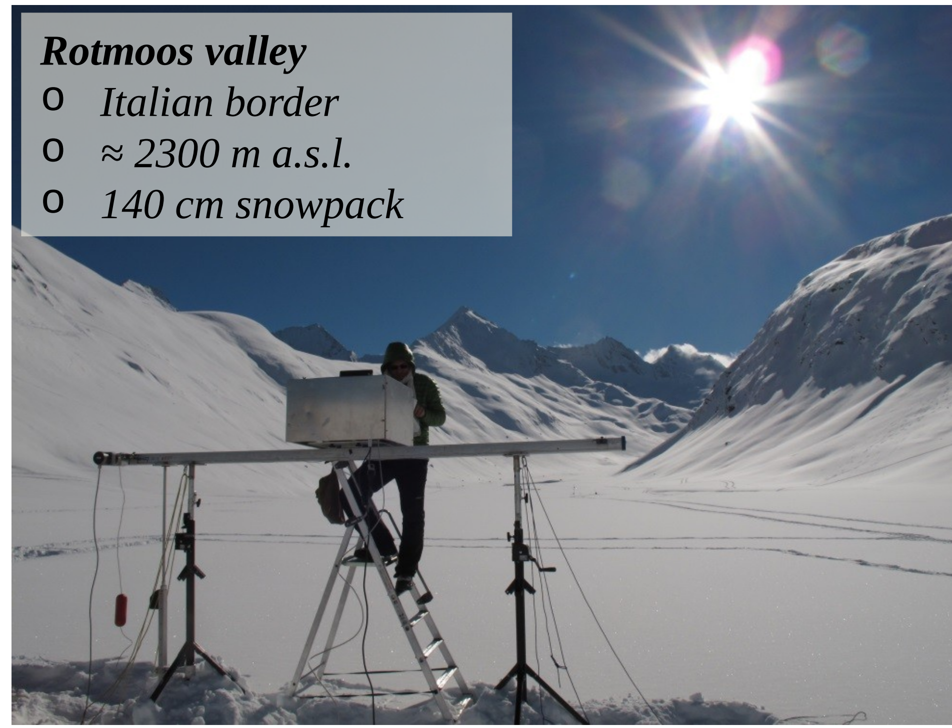
Smaller contributions from the upper snow layer at X-Band than at Ku-Band

🔔 Consistent with deeper penetration at X-Band

The AlpSAR campaign

- AlpSAR ESA campaign, led by ENVEO, Austrian Alps, Feb. 2013
  - Snowpit data, GPR, Airborne SAR, **GBSAR**

- Two sites:

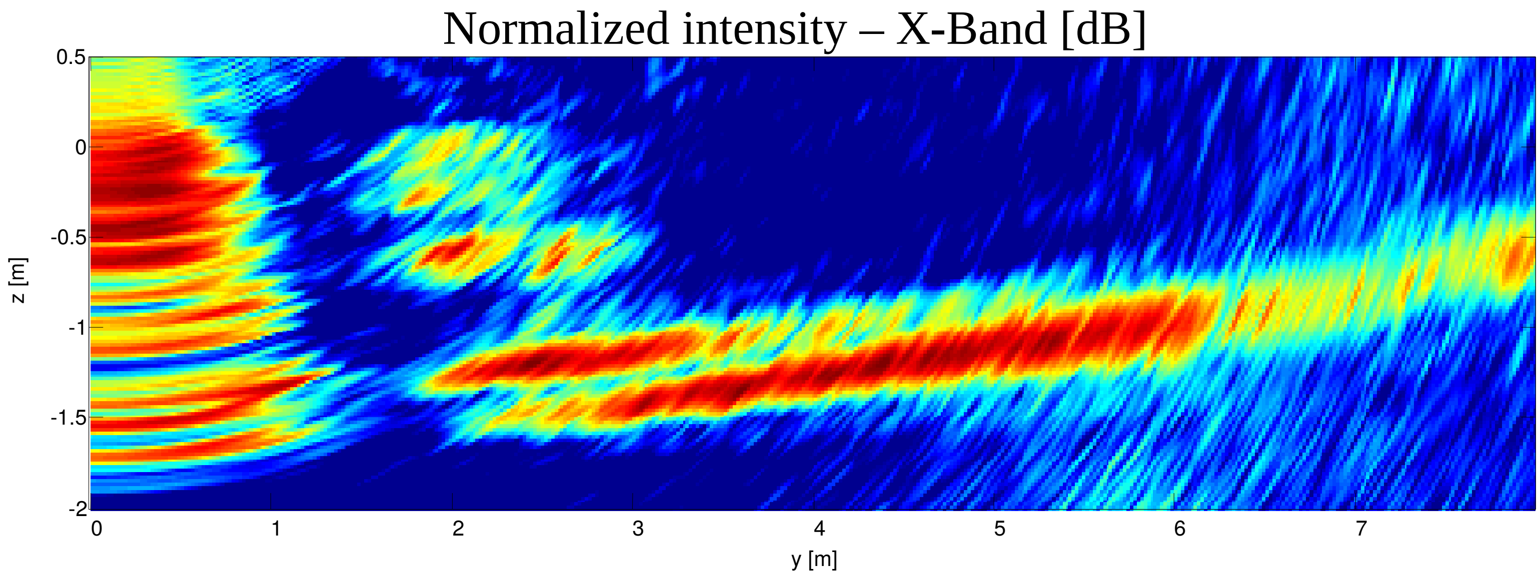


- GB-SAR operated at X and Ku-Band
  - Total transmitted bandwidth = 4 + 4 GHz
  - Range resolution ≈ 4 cm
  - Azimuth resolution ≈ 2 cm

- Multiple multistatic passes
  - Vertical resolution ≈ 10 cm (Ku-band), 15 cm (X-Band)

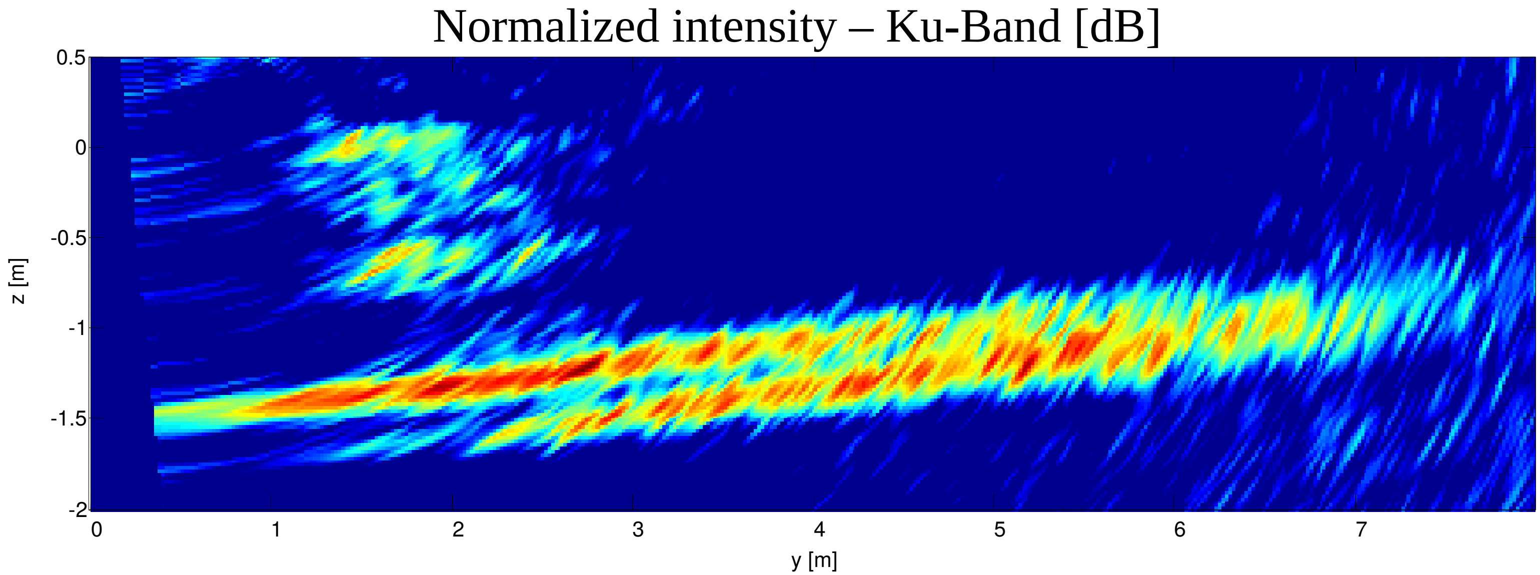
Rotmoos – X-Band

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



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

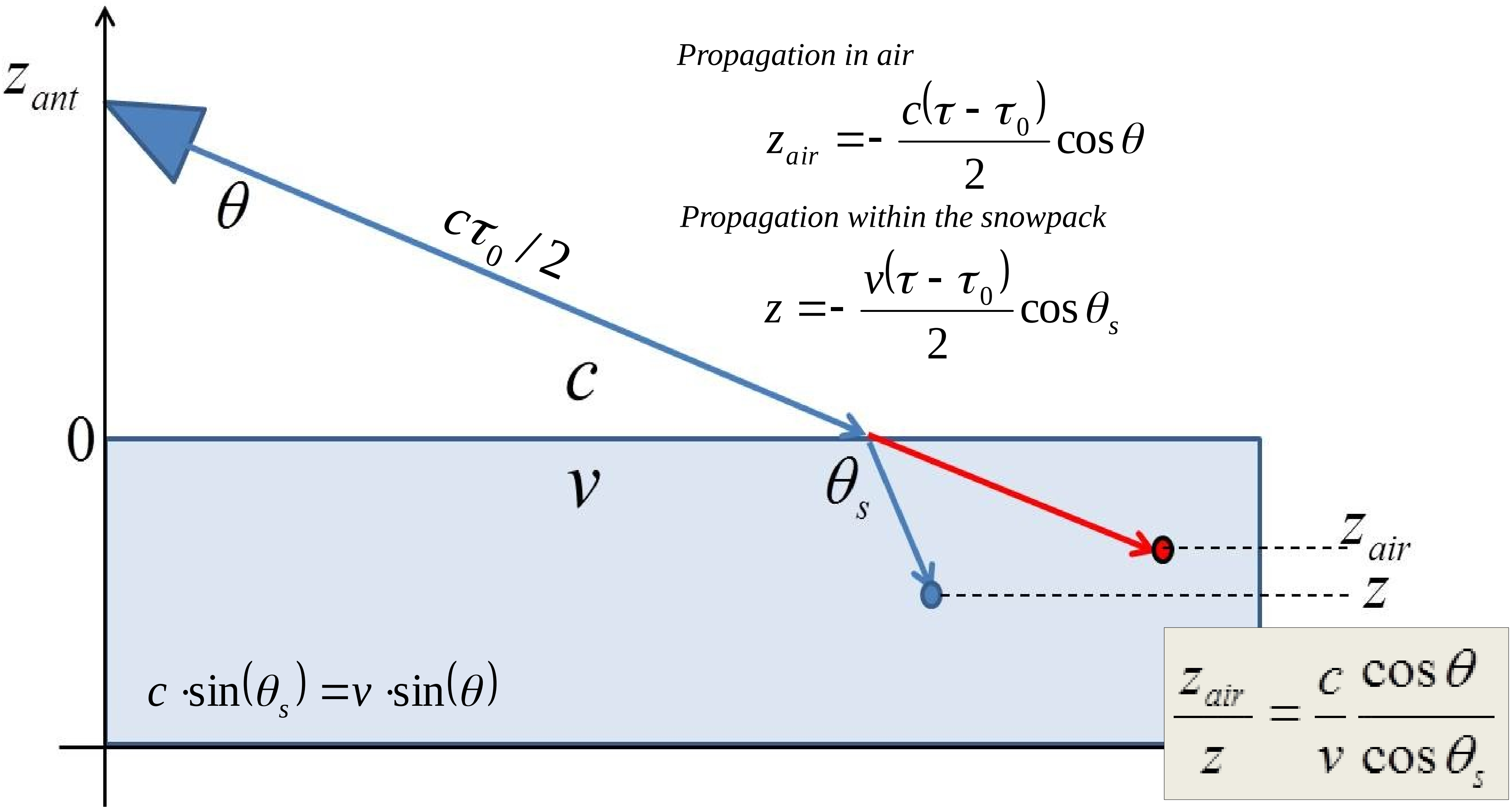
ii) wave direction on the receiving array, that provides the incidence angle

Propagation in air

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

Propagation within the snowpack

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

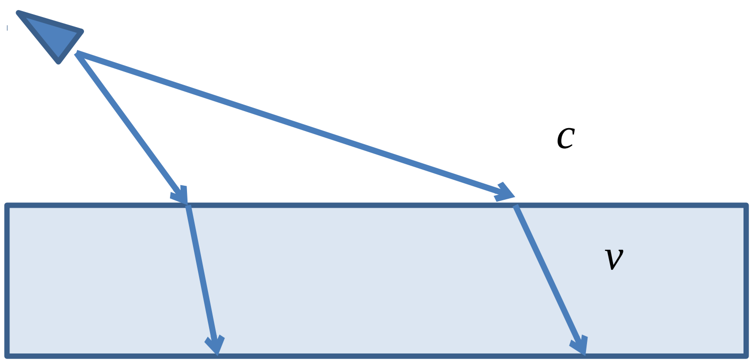


$$c \cdot \sin(\theta_s) = v \cdot \sin(\theta)$$

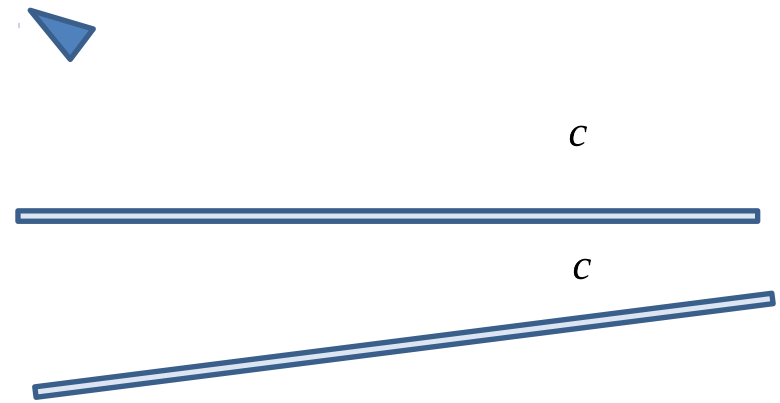
$$\frac{z_{air}}{z} = \frac{c}{v}\frac{\cos\theta}{\cos\theta_s}$$

Effect of propagation velocity

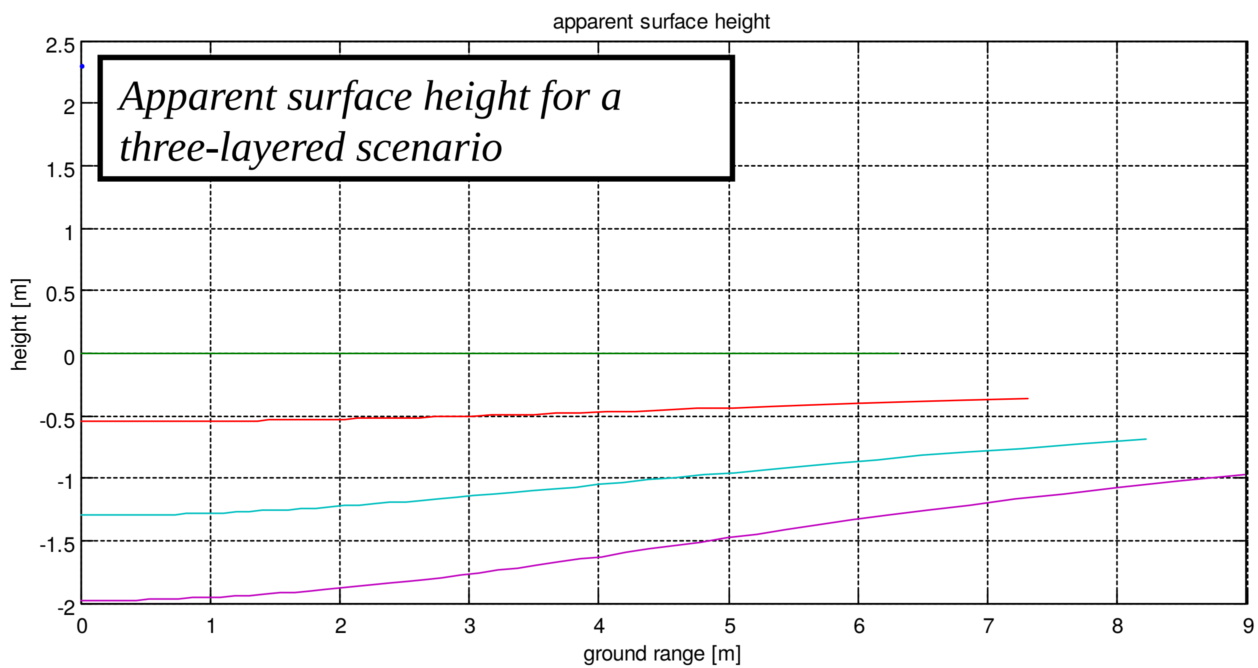
Real scenario



Resulting vertical section



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



Rotmoos – X- and Ku-Band

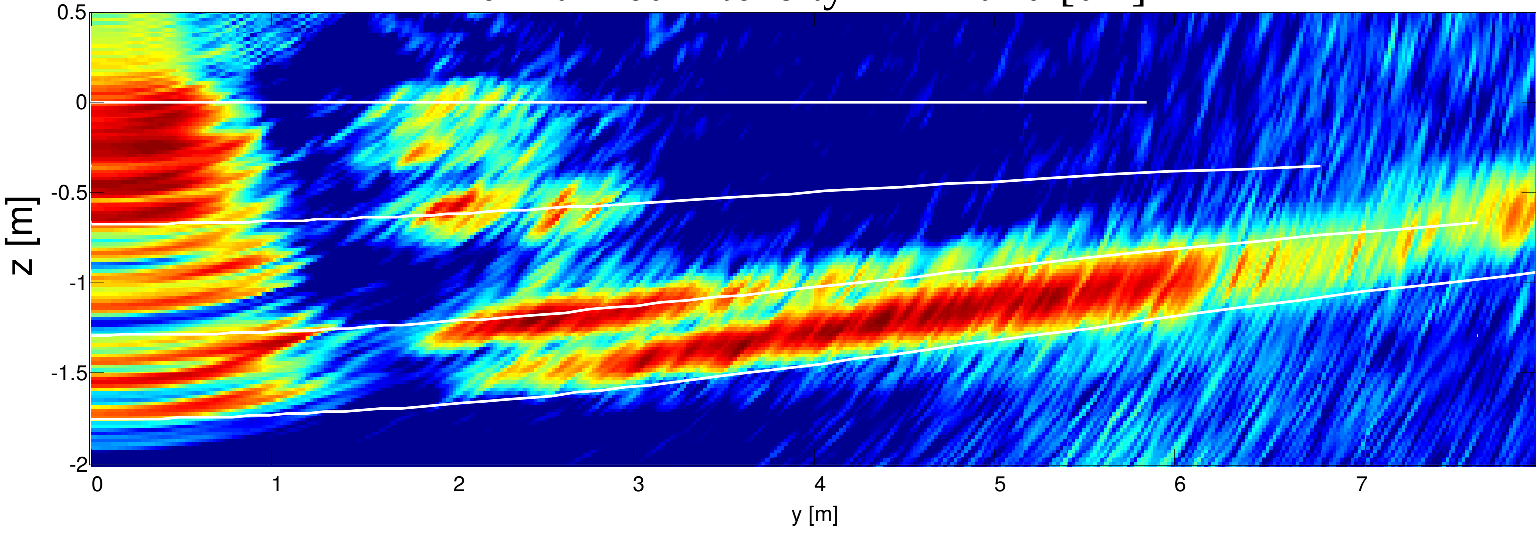
Remarks
- Neat imaging
- 5 surfaces
- Strongest returns are associated with the two bottom layers

Apparent surface heights for v = c/1.25

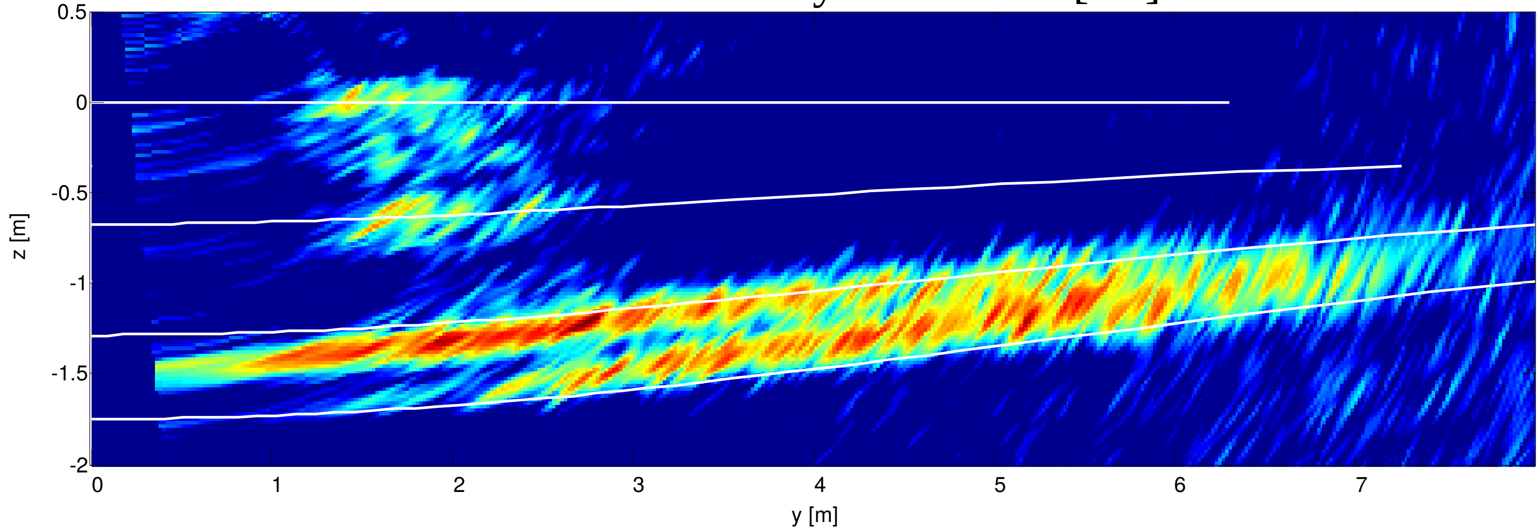
Snowpit data:
snowpack thickness = 140 cm

Normalized intensity is presented to highlight contrasts

Normalized intensity – X-Band [dB]

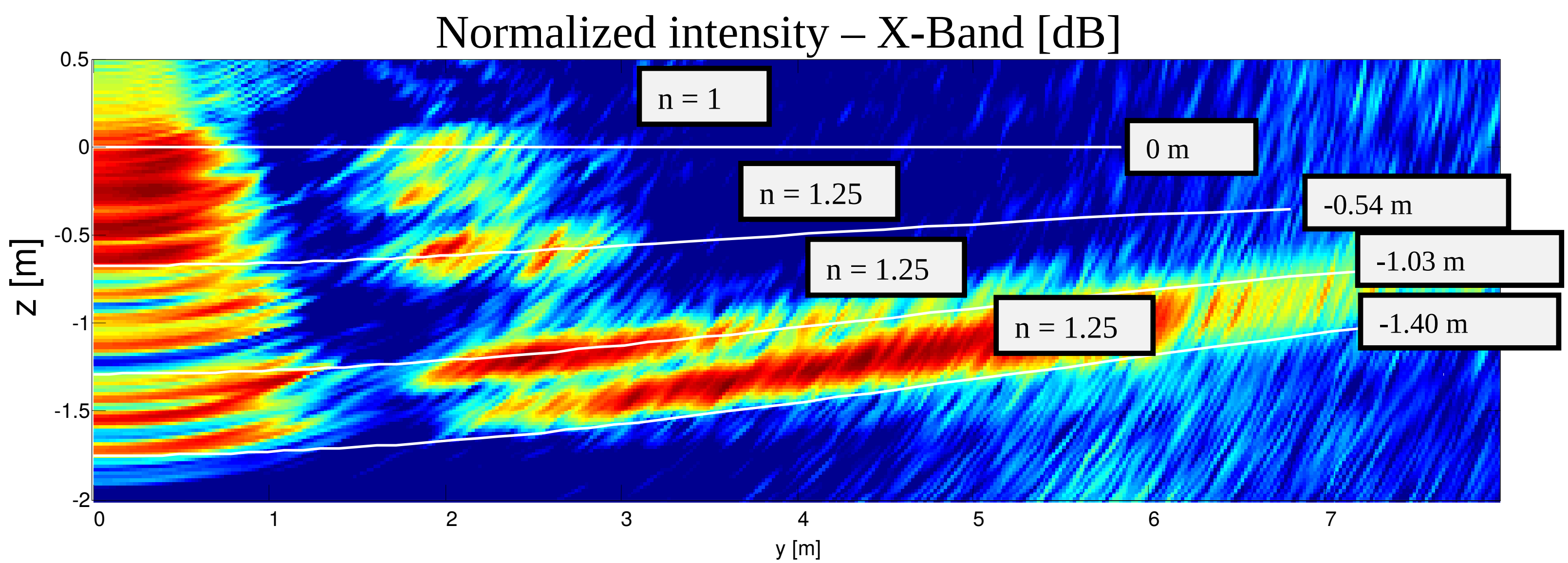


Normalized intensity – Ku-Band [dB]

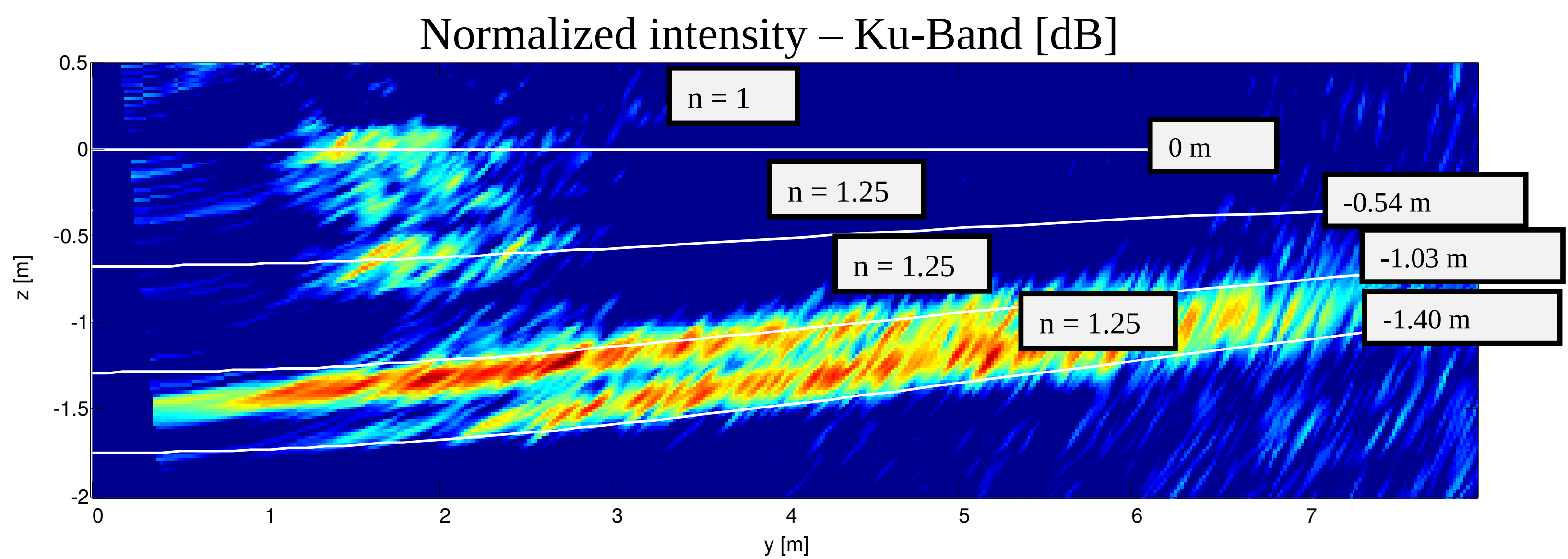


Rotmoos – X- and Ku-Band

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



Apparent surface heights for v = c/1.25



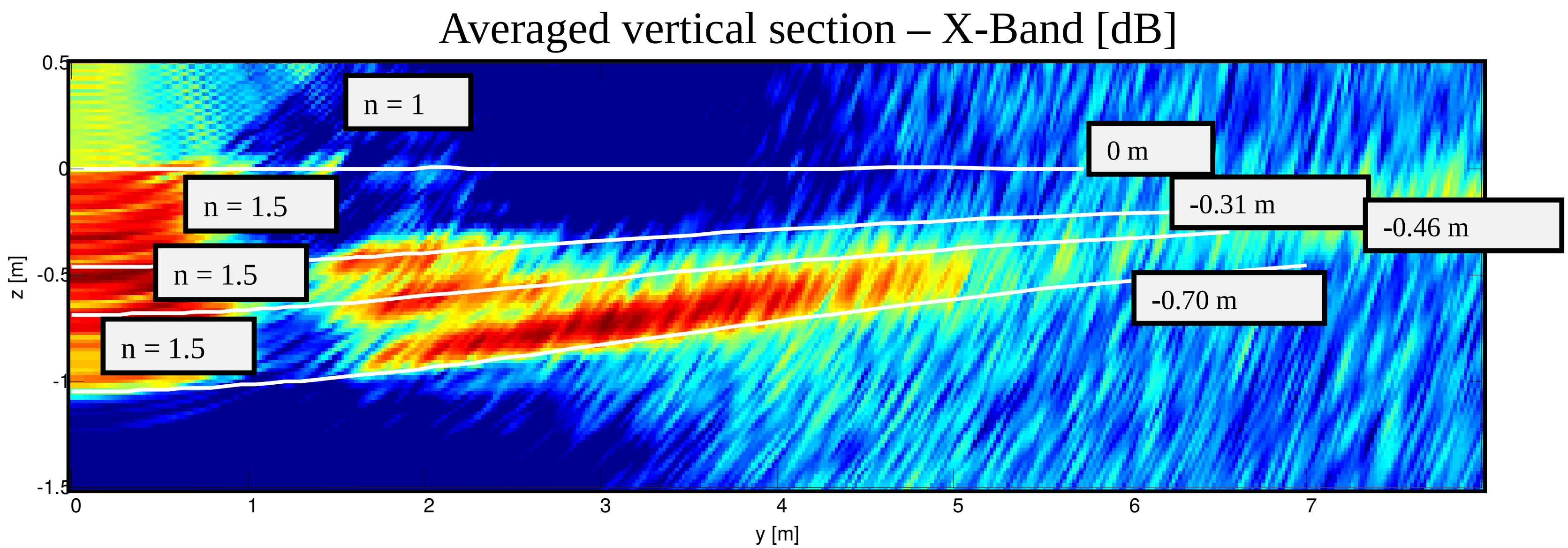
Snowpit data:
snowpack thickness = 140 cm

Normalized intensity is presented to highlight contrasts

Leutasch – X- and Ku-Band

Remarks

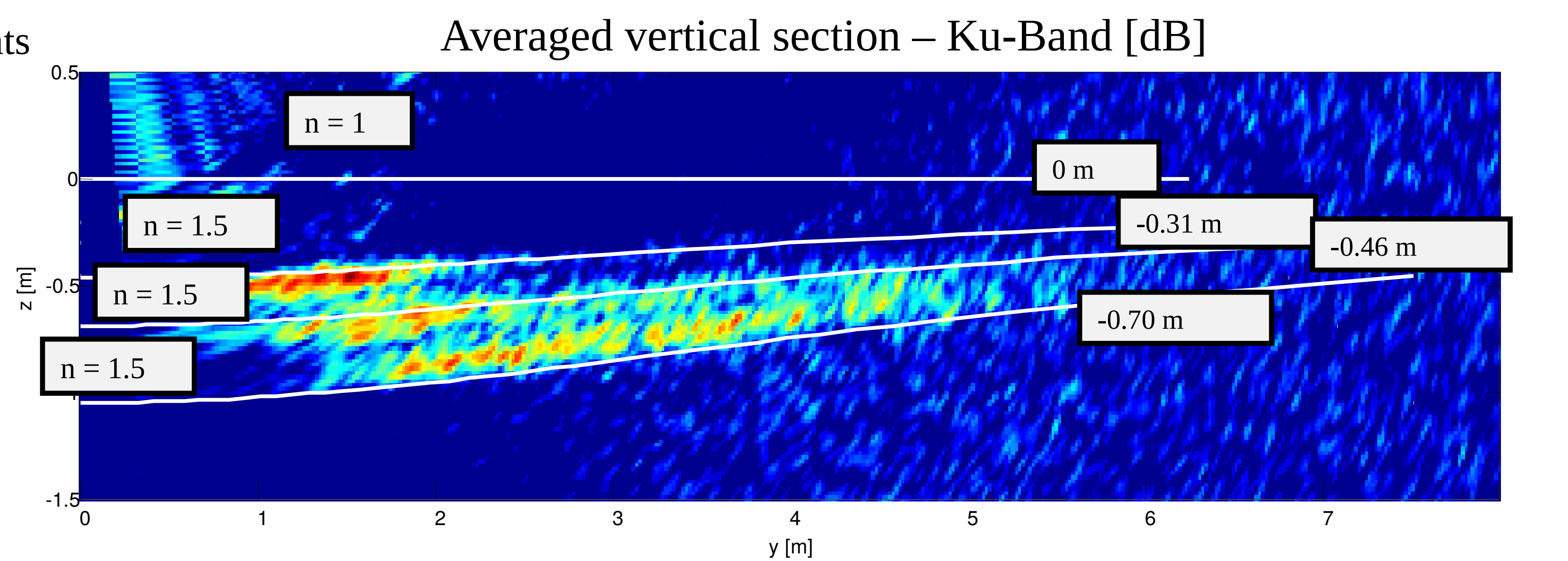
- Neat imaging
- 4 surfaces
- Weak returns from the snow/air interface
- Strongest returns are associated with the bottom layers (X-Band) or middle (Ku-Band) layer



Apparent surface heights for v = c/1.5

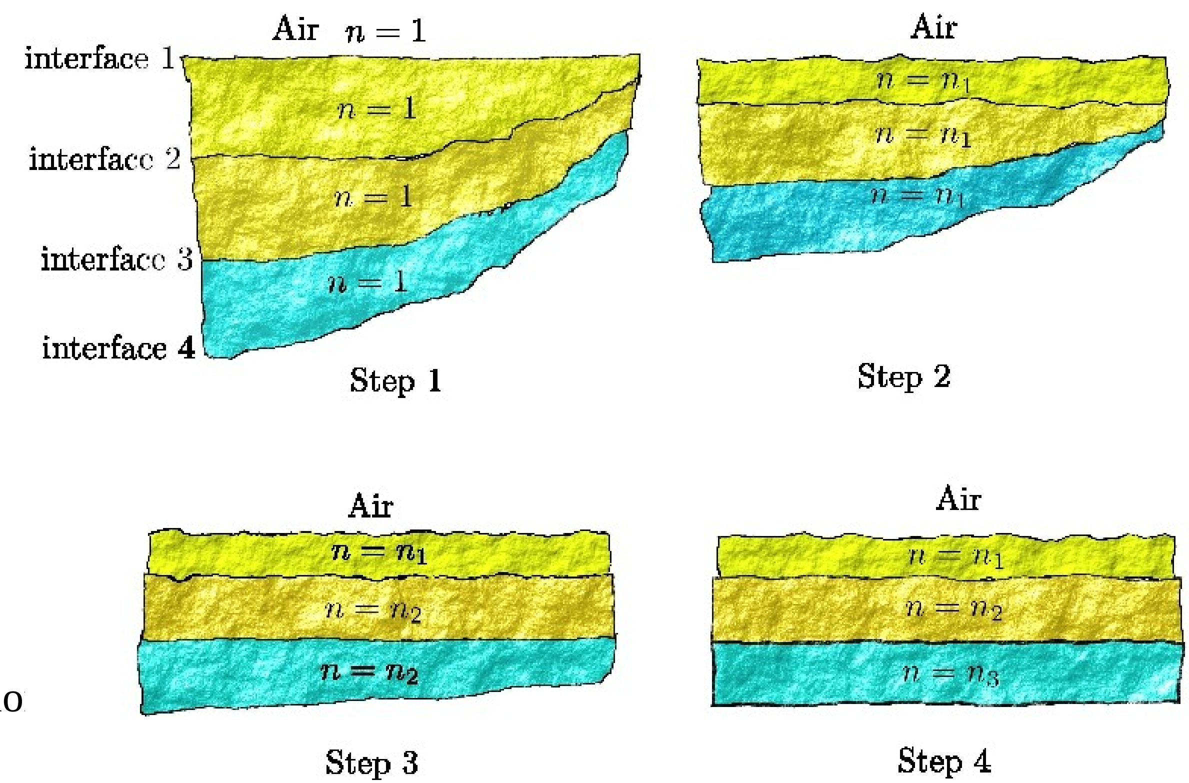
Snowpit data:
snowpack thickness = 70 cm

Normalized intensity is presented to highlight contrasts



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 :



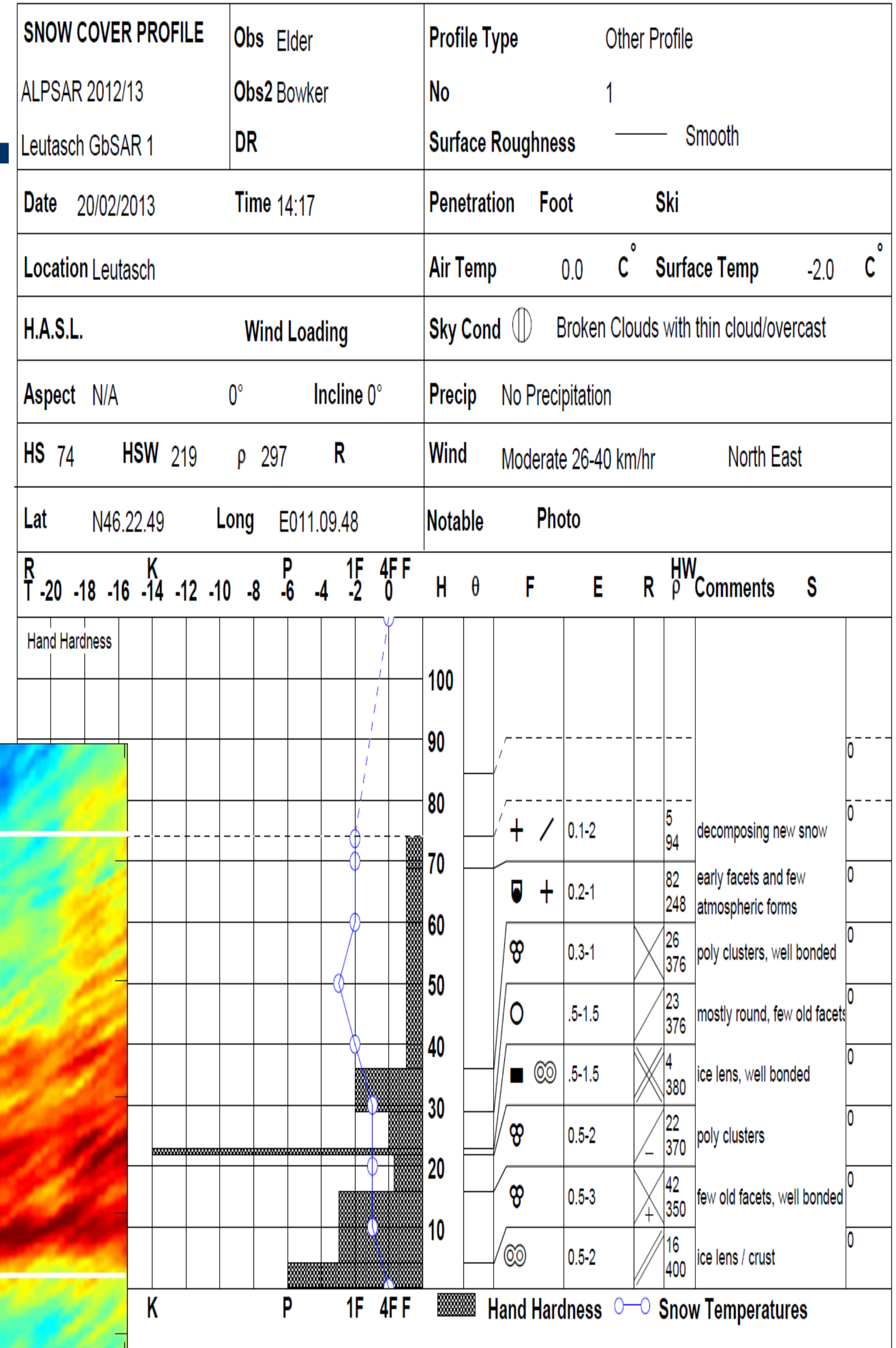
- Distance computatio

$$\left\|\vec{\nabla} \mathrm{d}(\vec{r}, \vec{r_a})\right\|^2 = n^2(\vec{r})$$

Connection to in-situ data: Leutasch

- Dominant scattering from bottom layers
- Results are largely independent on the incidence angle

☺ Retrieved vertical structure consistent with snowpack hand-hardness from snow-pit measurement

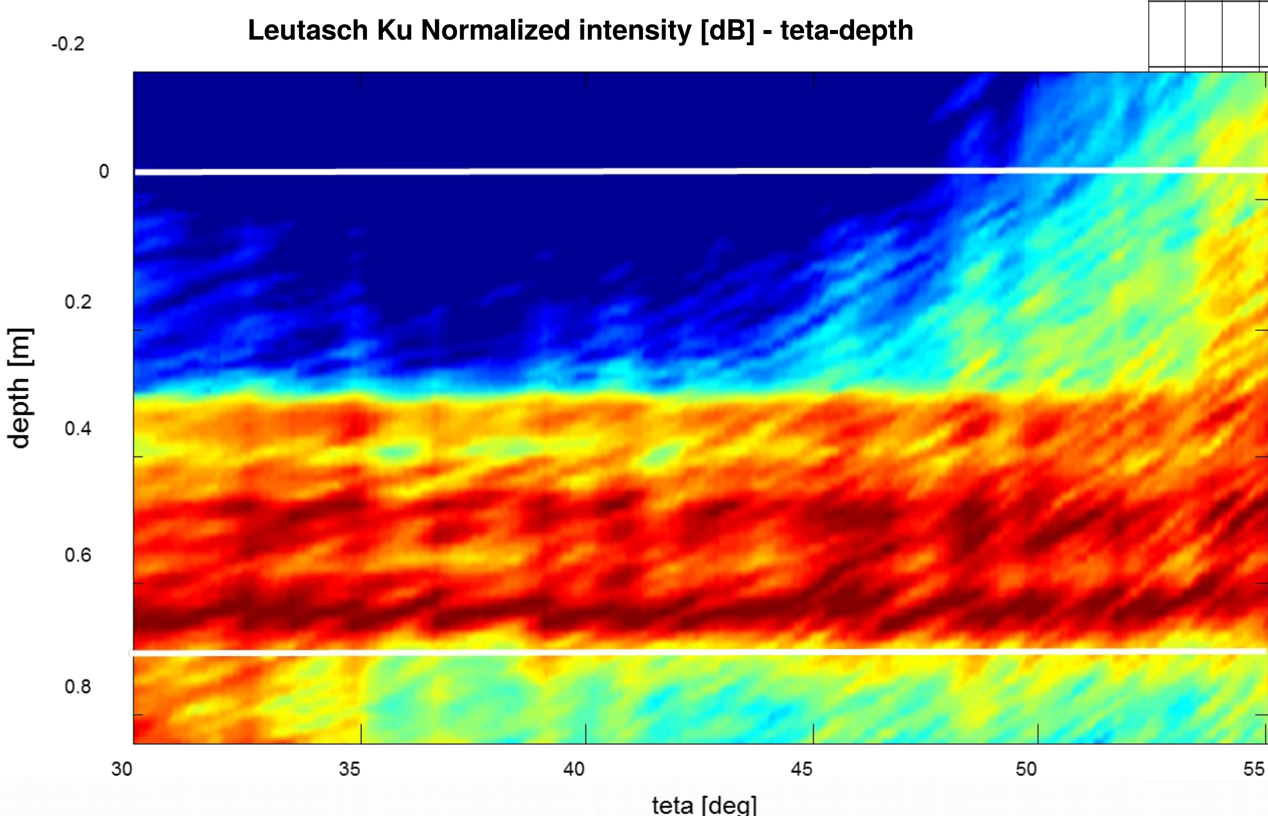

SNOW COVER PROFILE | Obs Elder | Profile Type Other Profile
ALPSAR 2012/13 | Obs2 Bowker | No 1
Leutasch GbSAR 1 | DR | Surface Roughness —— Smooth
Date 20/02/2013 Time 14:17 | Penetration Foot Ski
Location Leutasch | Air Temp 0.0 °C Surface Temp -2.0 °C
H.A.S.L. Wind Loading | Sky Cond Broken Clouds with thin cloud/overcast
Aspect N/A 0° Incline 0° | Precip No Precipitation
HS 74 HSW 219 ρ 297 R | Wind Moderate 26-40 km/hr North East
Lat N46.22.49 Long E011.09.48 | Notable Photo

R T -20 -18 -16 K -14 -12 -10 -8 P -6 -4 1F -2 4F 0 F H θ F E R HW ρ Comments S

Hand Hardness

H	F	E	HW / ρ	Comments	S
70–80	+ /	0.1-2	5 / 94	decomposing new snow	0
60–70	+	0.2-1	82 / 248	early facets and few atmospheric forms	0
50–60		0.3-1	26 / 376	poly clusters, well bonded	0
40–50	O	.5-1.5	23 / 376	mostly round, few old facets	0
30–40	■	.5-1.5	4 / 380	ice lens, well bonded	0
20–30		0.5-2	22 / 370	poly clusters	0
10–20		0.5-3	42 / 350	few old facets, well bonded	0
0–10		0.5-2	16 / 400	ice lens / crust	0

K P 1F 4F F Hand Hardness Snow Temperatures



Connection to in-situ data: Rotmoos

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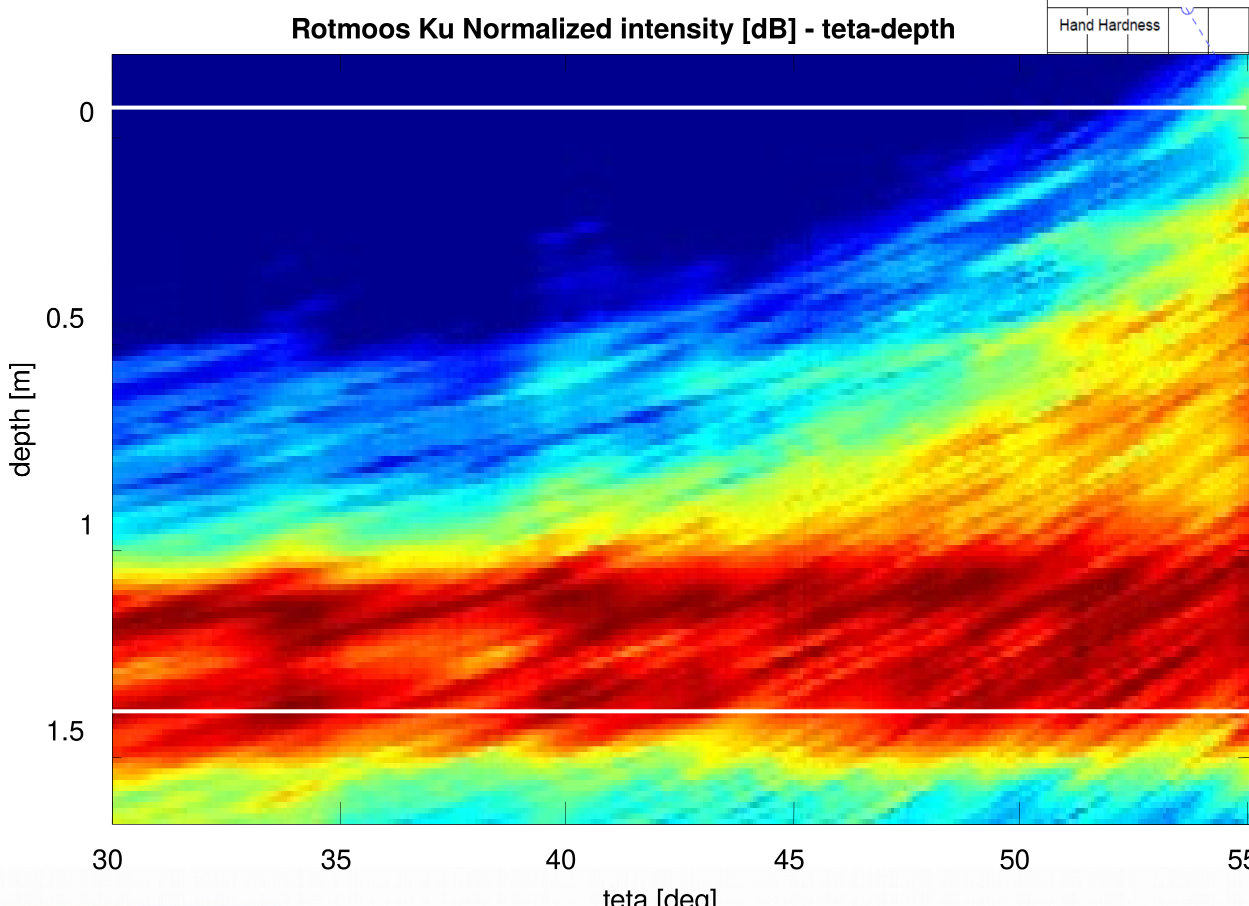
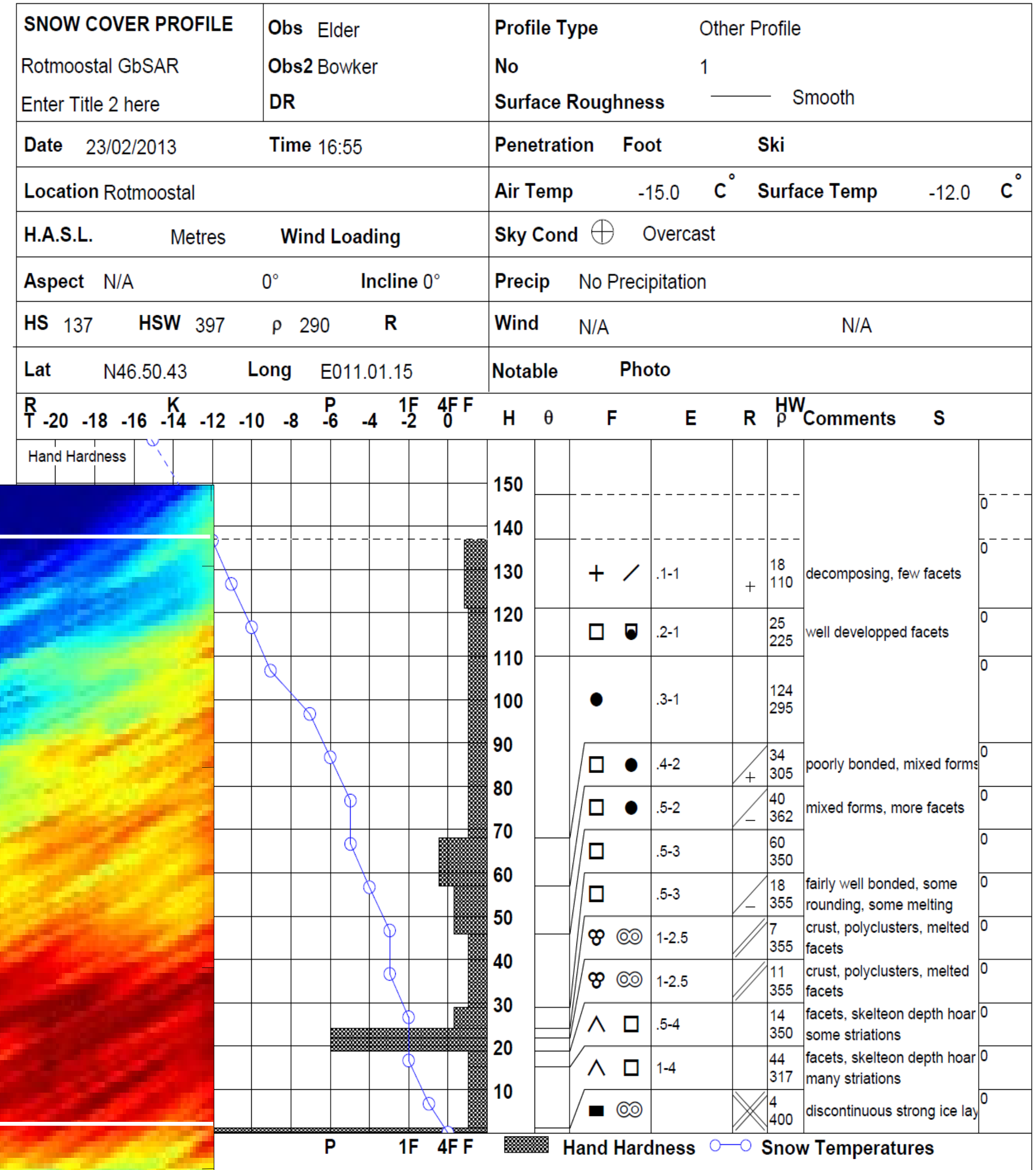
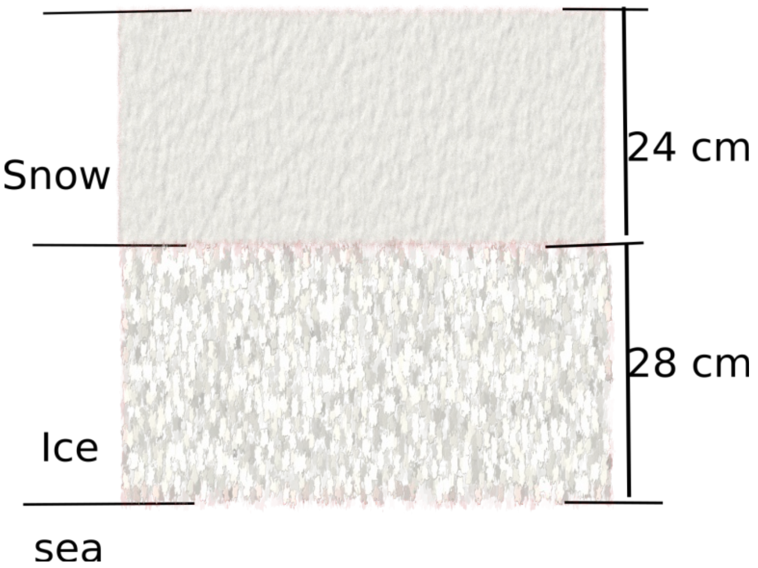
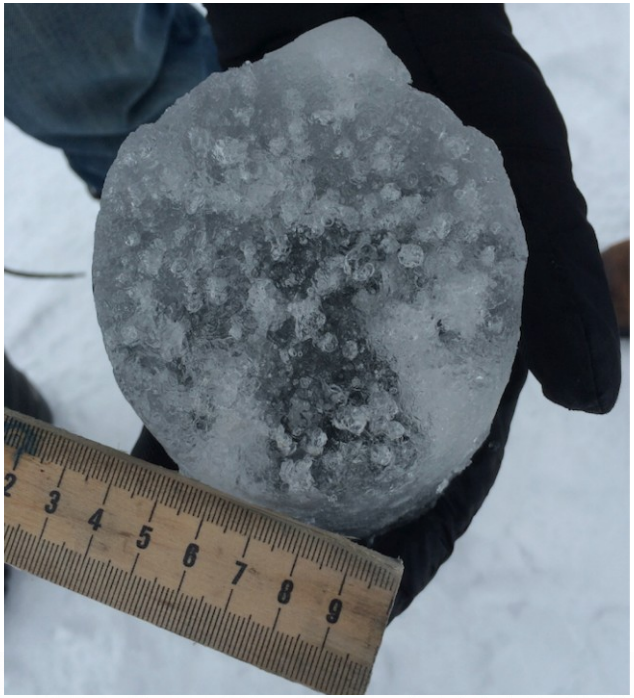




Data acquisition carried out in March 2013 at the Kattfjord, Tromsø, Norway

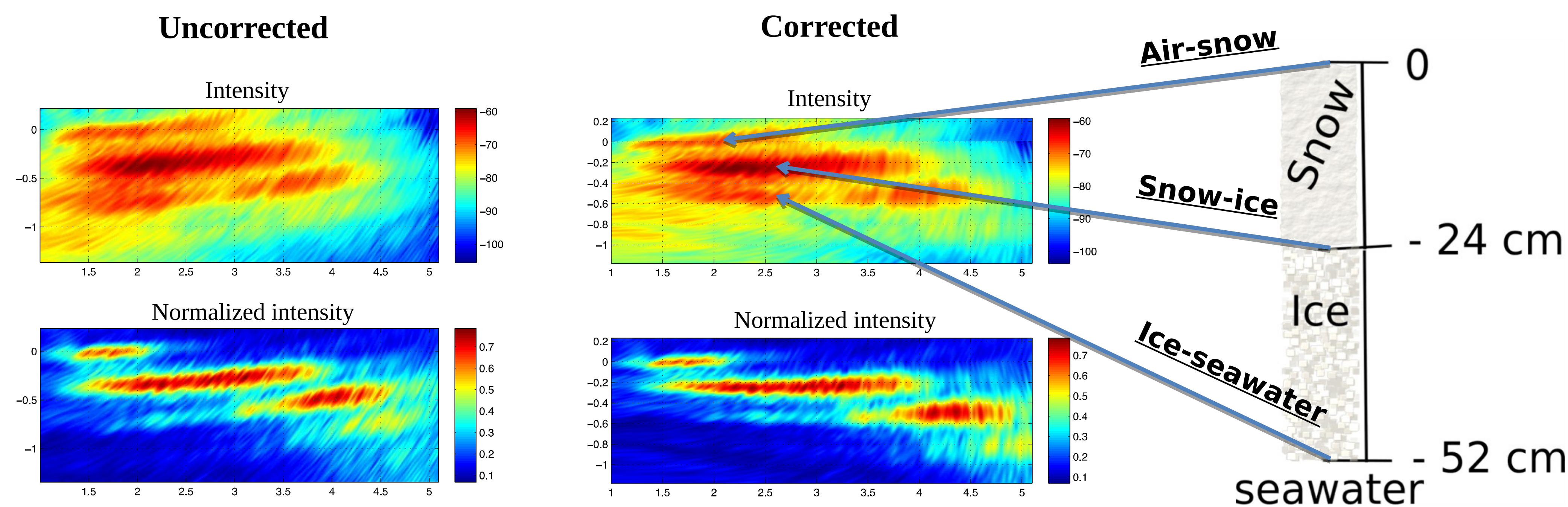


- Seasonal ice – life of 3-4 months
- Tomographic X-band measurements at VV and HV
- Temperature from -8° to -2°
- The fjord ice can be representative of low salinity sea ice (fresh water from surrounding mountains)
- Dry snow cover on top
- Significant amount air bubbles within the ice layer
  - 0.5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



SAR Tomography over fjord ice

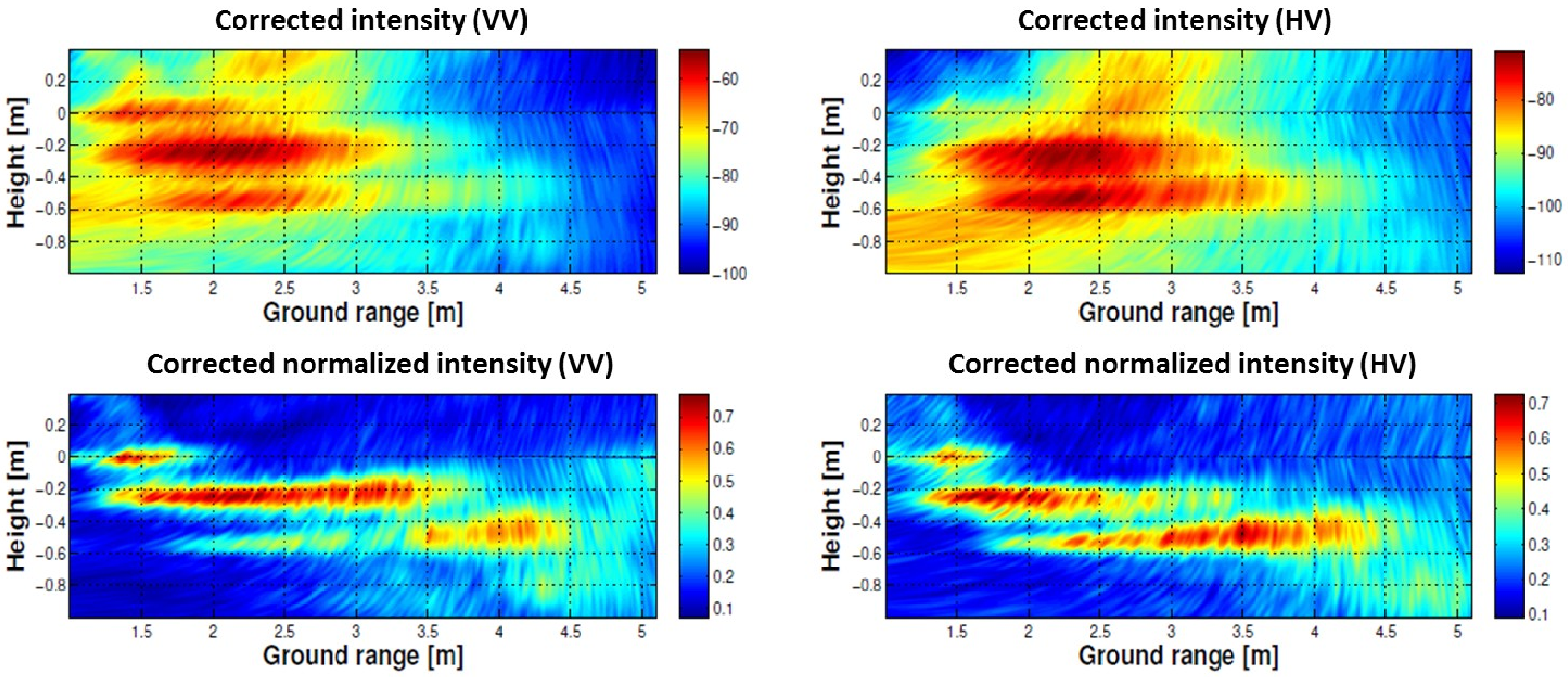
- Same tilt effect as snow-pack tomography
- Corrected assuming
  - refractive index of snow = 1.4
  - refractive index of fjord ice = 1.7
- Normalized intensity is presented to highlight contrasts (interfaces)



- 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

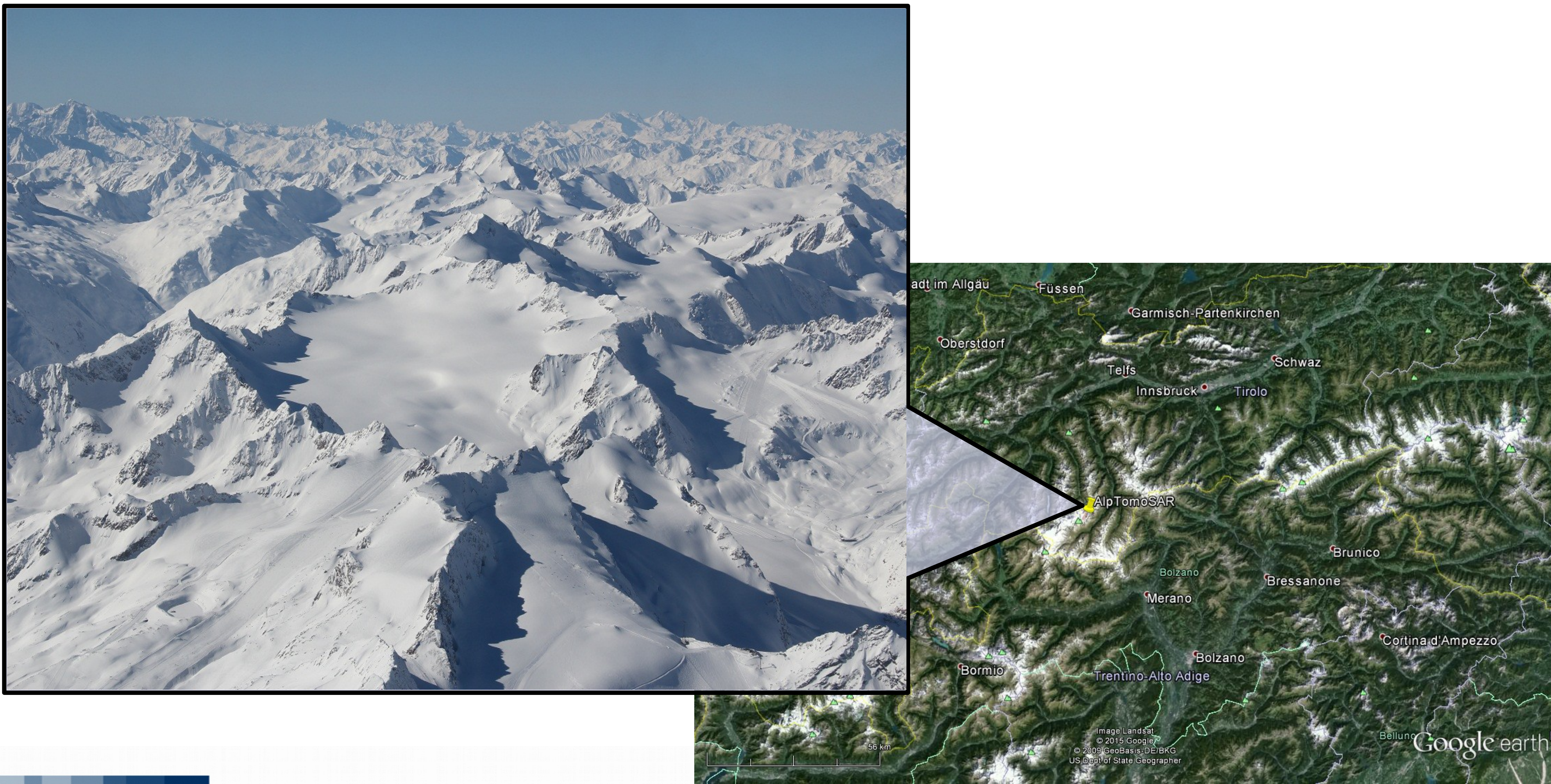
⇒ Mostly polarized contributions from regular spherical snow grains

⇒ Depolarized contributions from irregular air bubbles in the ice layer

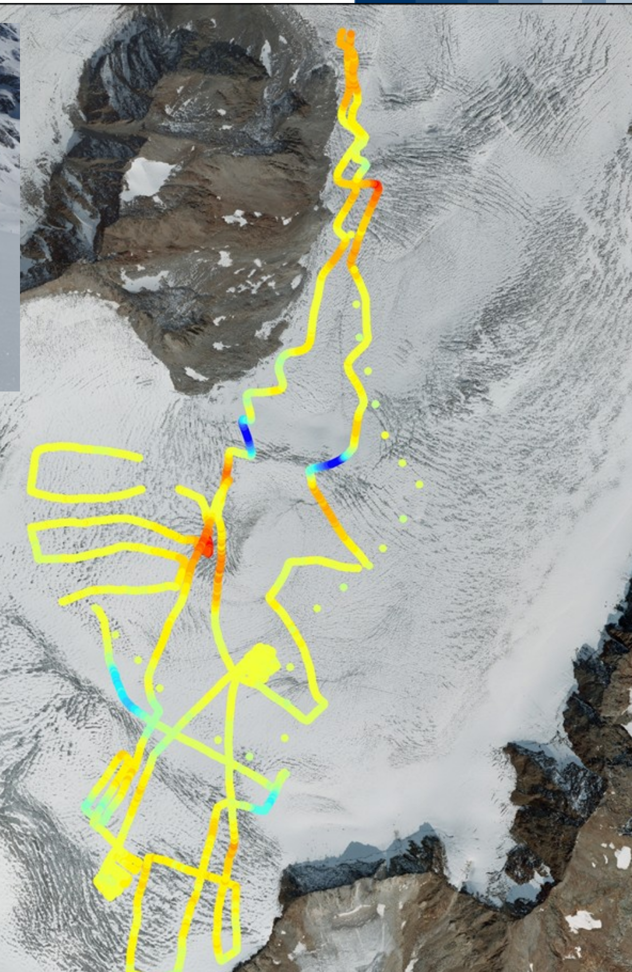
Test site

***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

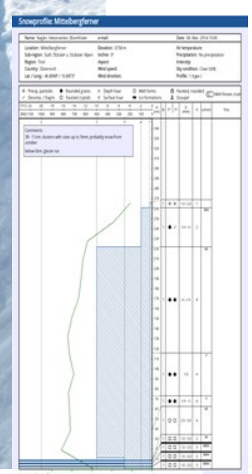


Field activities

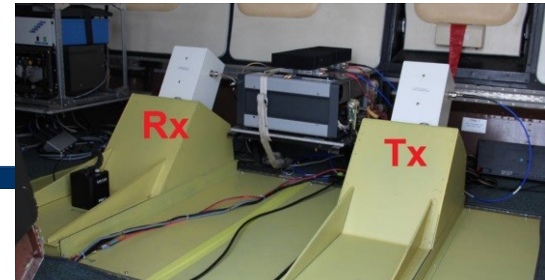
- Setting up Corner Reflectors
- Stratigraphy of winter snow pack
  - Density / Hardness, ice layers, grain size
- Transects of snow depth
- GPR Measurements

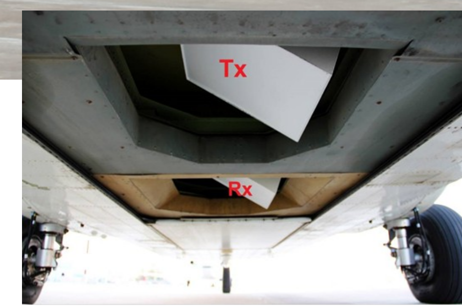
GPR Equipment:

- 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)

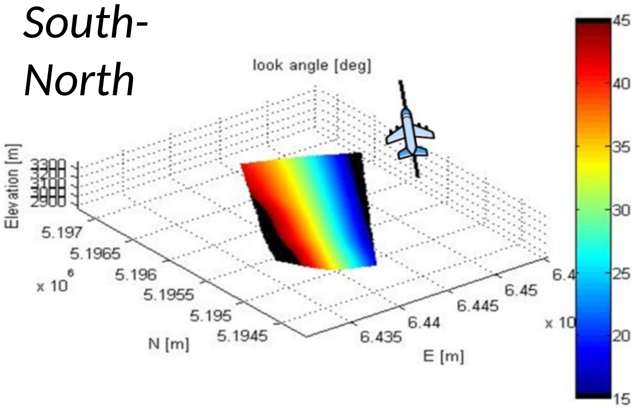
Aircraft

- CASA C-212 operated by CGR

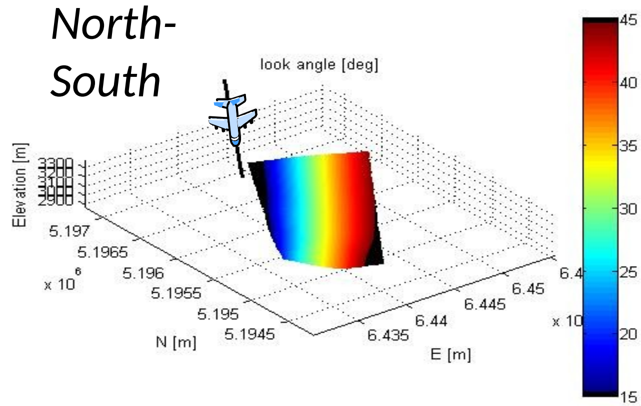
Flights:

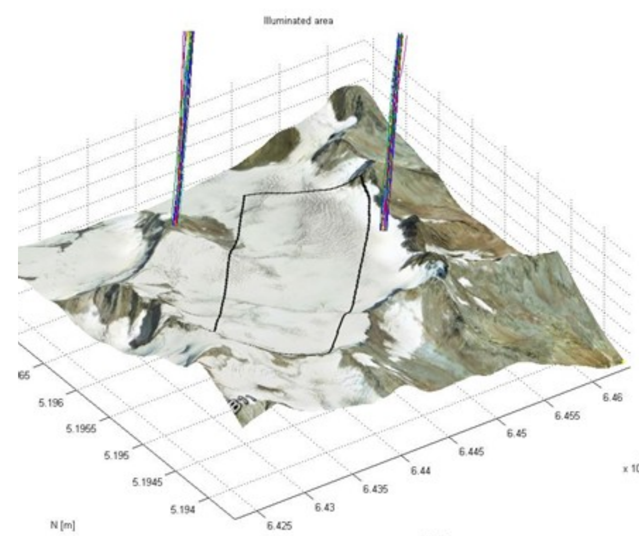
- Two flight directions
- 20+20 passes

South-North



North-South

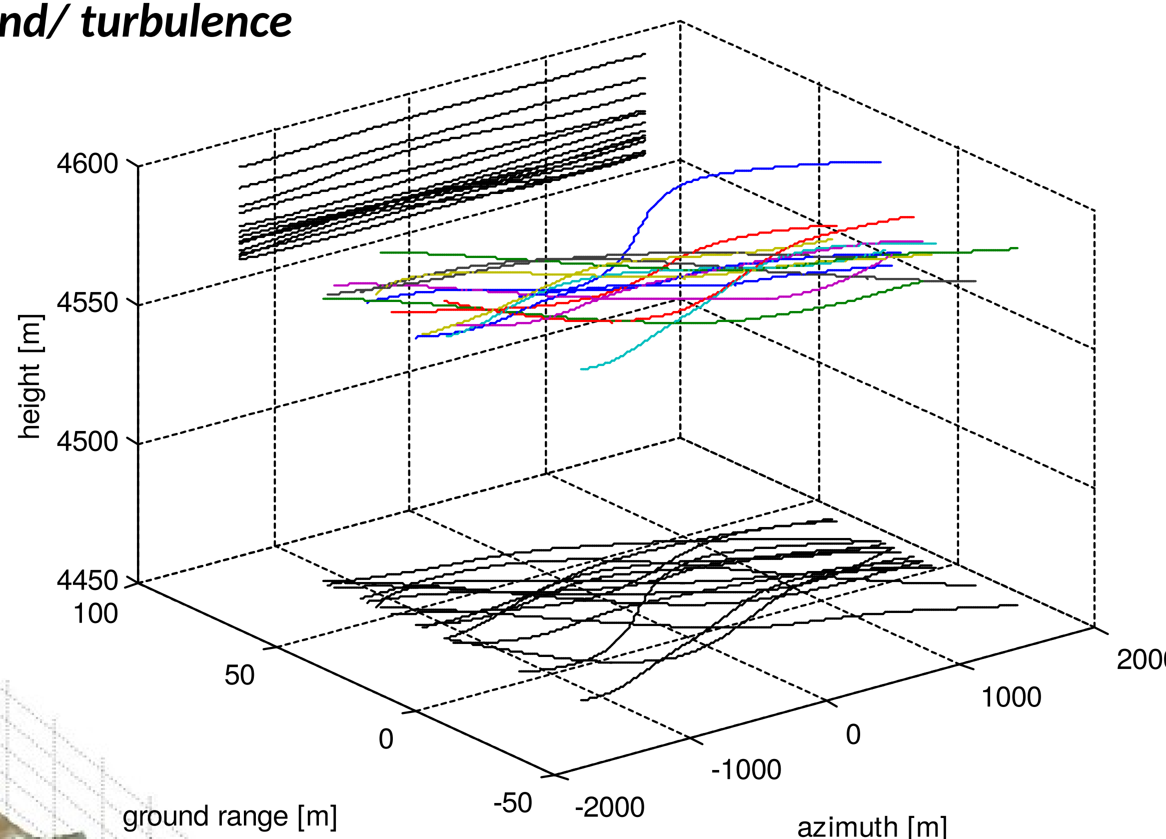


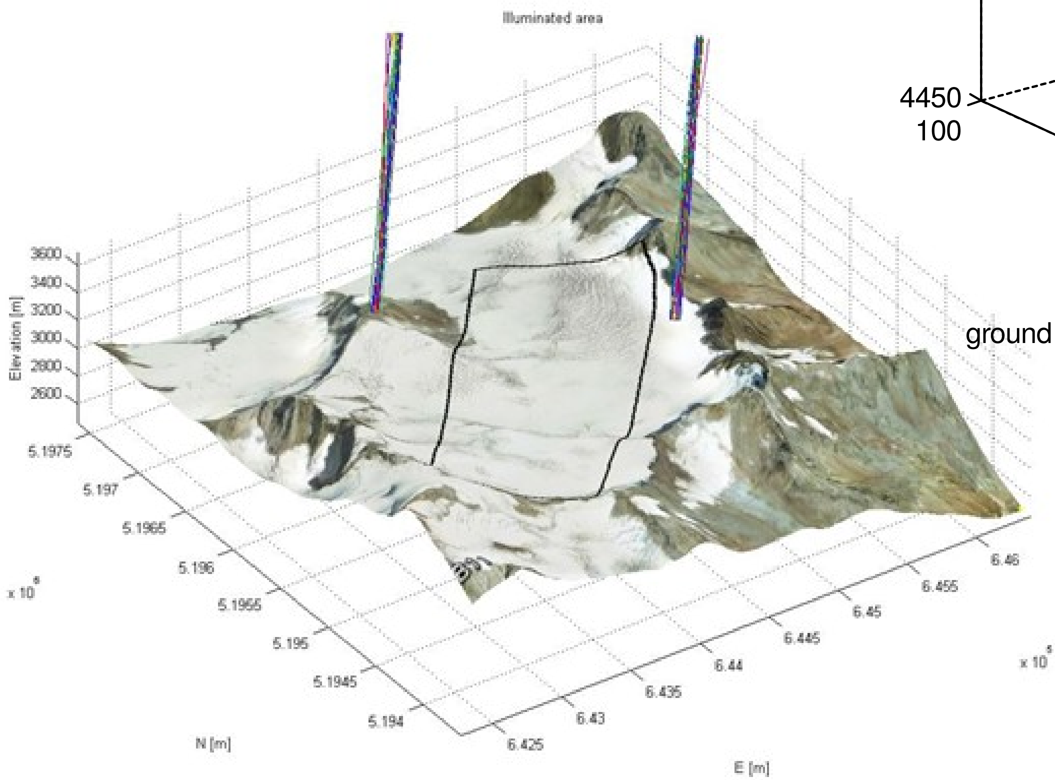


Flight Trajectories

Strong trajectory perturbation caused by wind/ turbulence

- Max along track variation > 50 m
- No auto-piloting system
- Proximity to mountain peaks

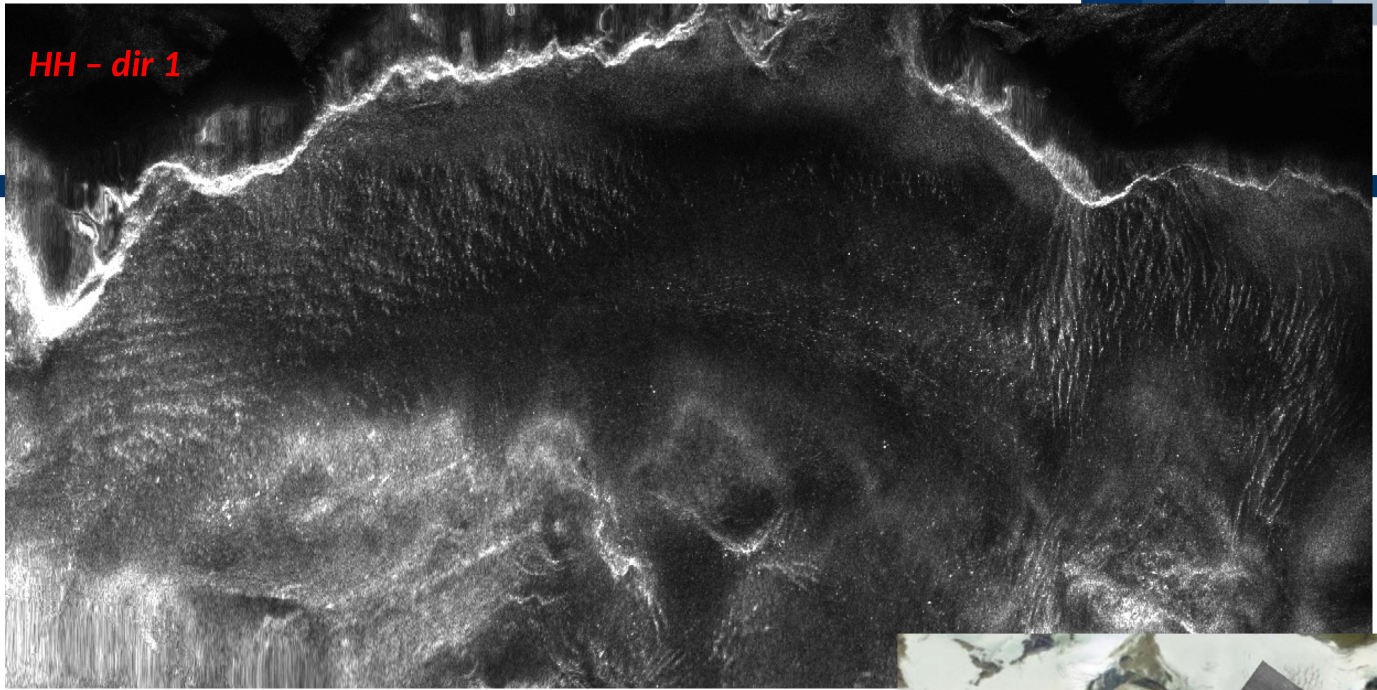


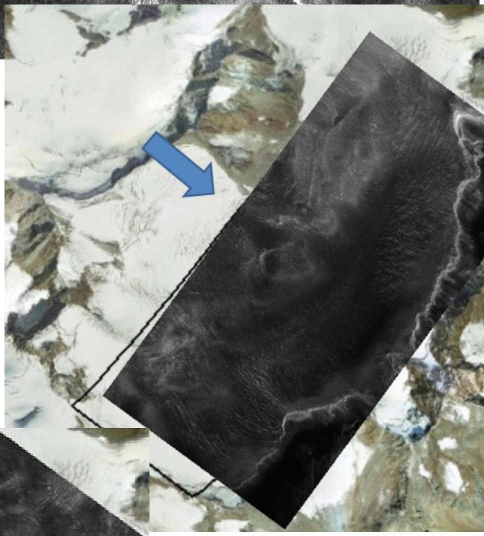


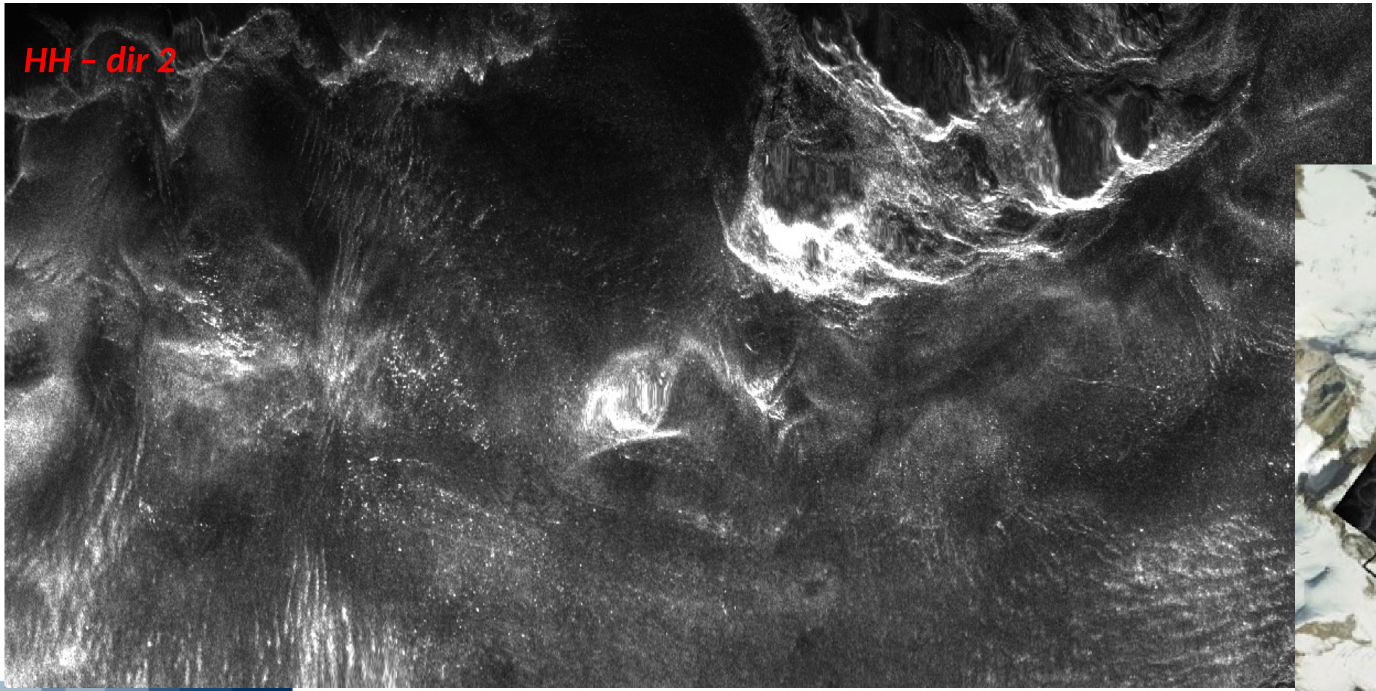
2D Focusing

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

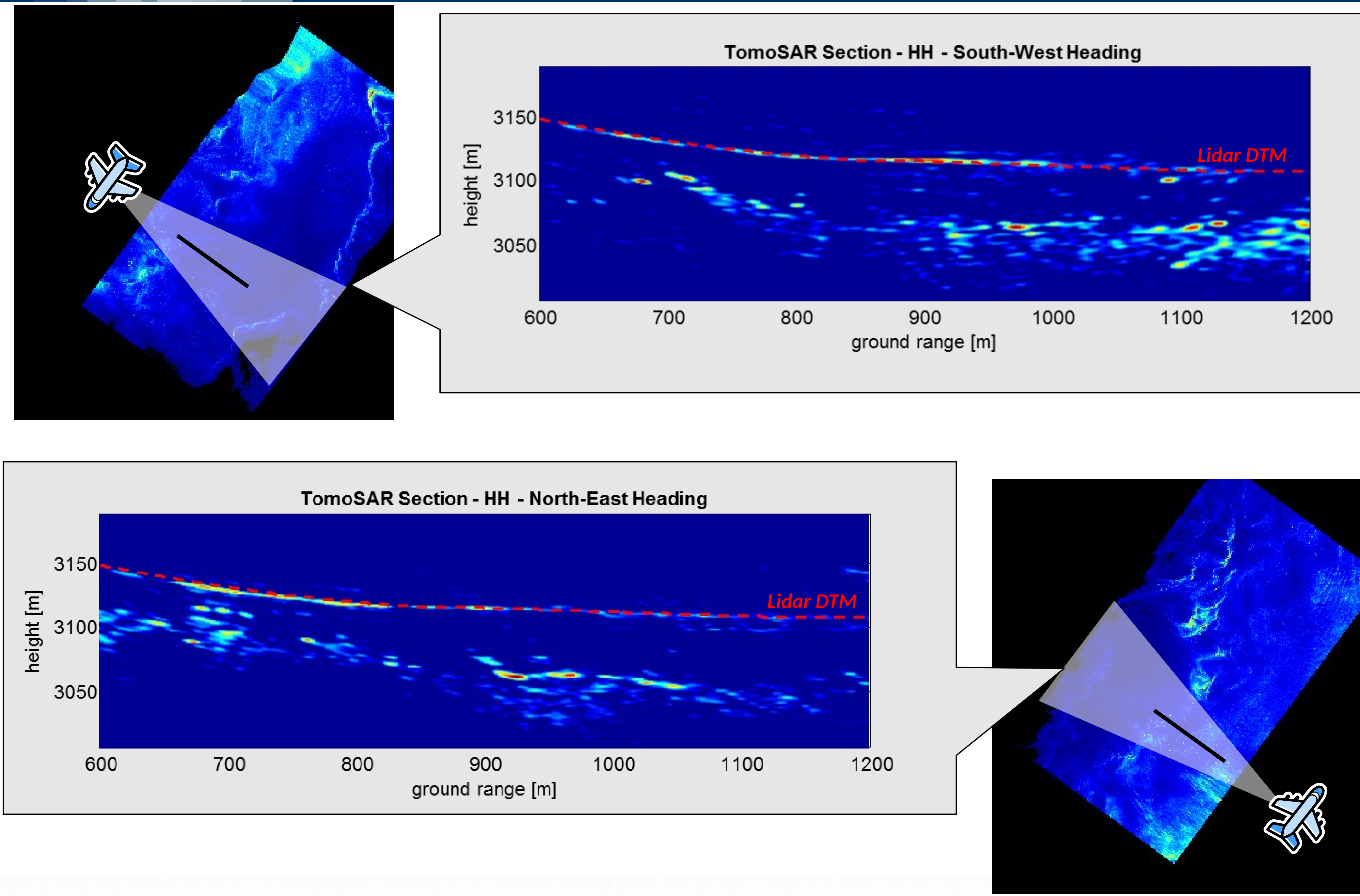
- Optimal motion compensation
- Common target wavenumbers in all passes
- Automatic coregistration at the reference elevation



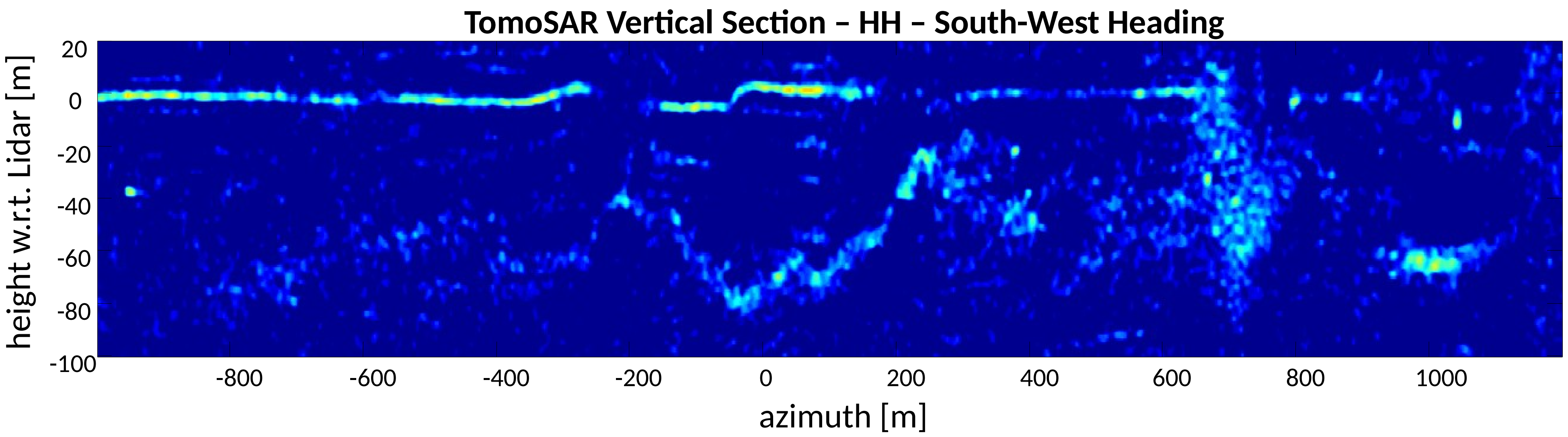




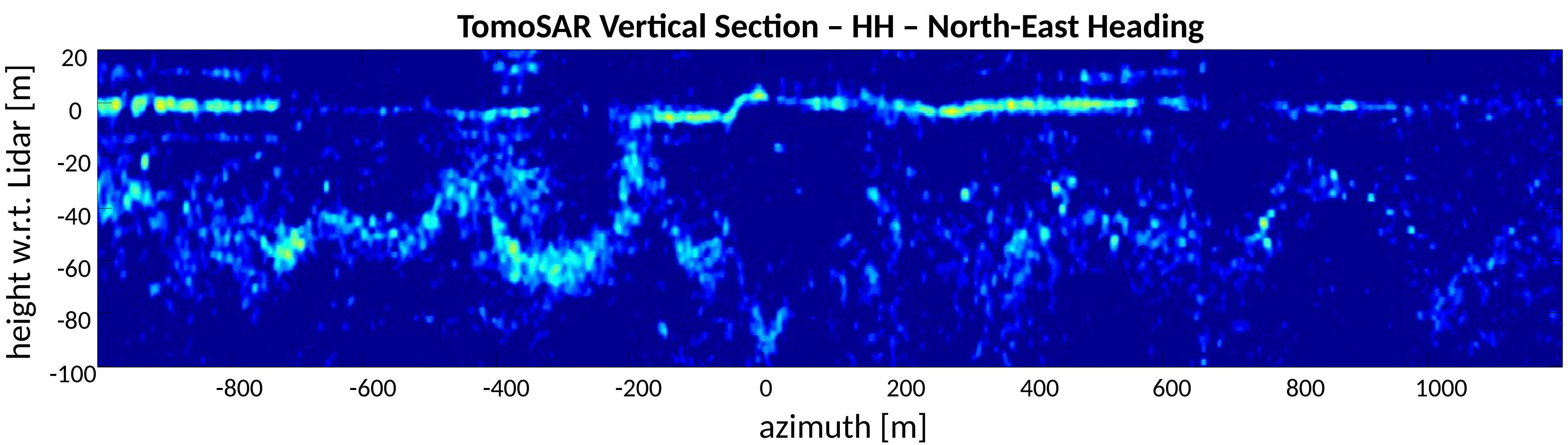
3D Focusing


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

3D Focusing

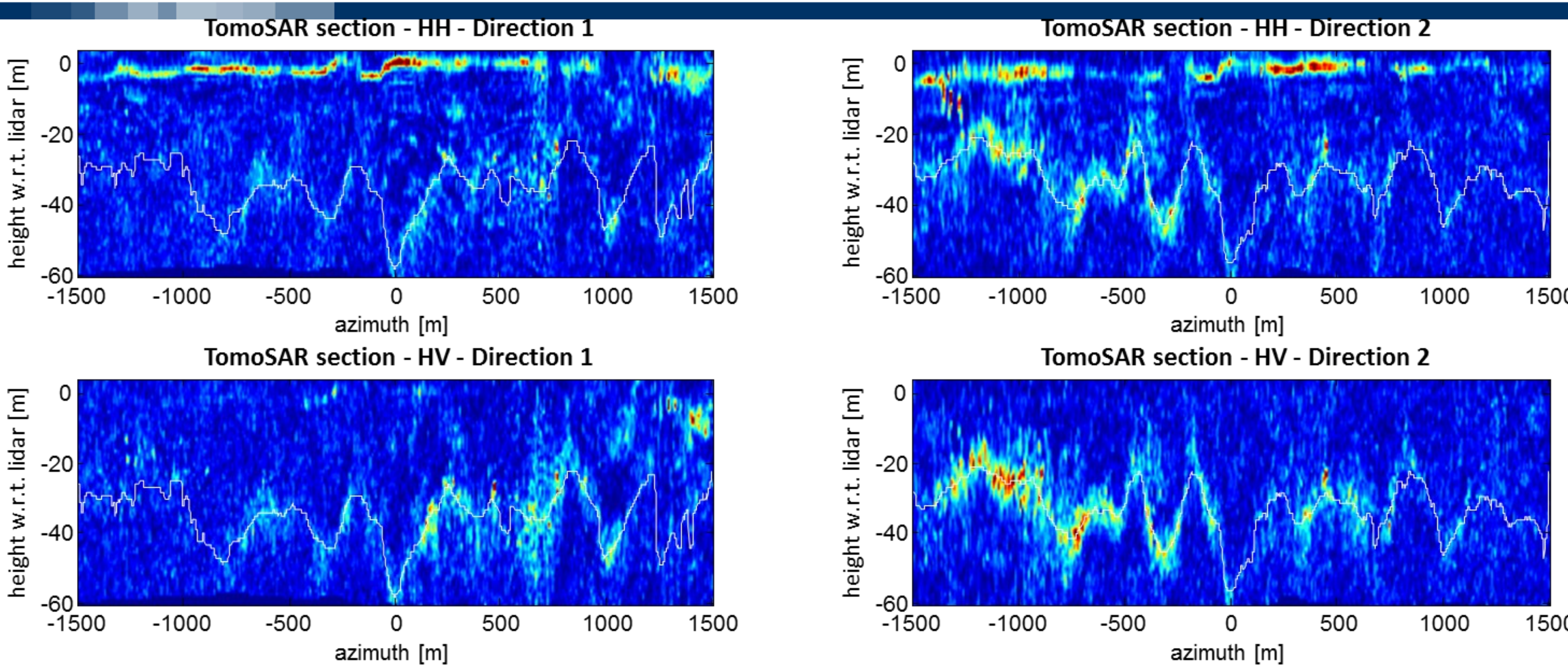


TomoSAR Vertical Section – HH – South-West Heading
height w.r.t. Lidar [m]
20
0
-20
-40
-60
-80
-100
-800
-600
-400
-200
0
200
400
600
800
1000
azimuth [m]



TomoSAR Vertical Section – HH – North-East Heading
height w.r.t. Lidar [m]
20
0
-20
-40
-60
-80
-100
-800
-600
-400
-200
0
200
400
600
800
1000
azimuth [m]

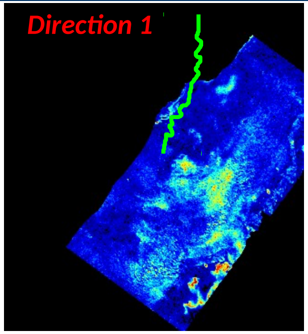
Physical Analysis – Lower Horizon

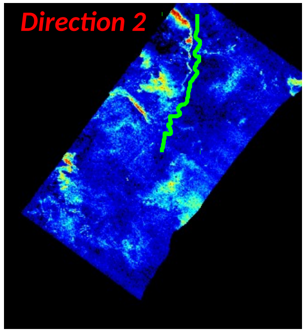


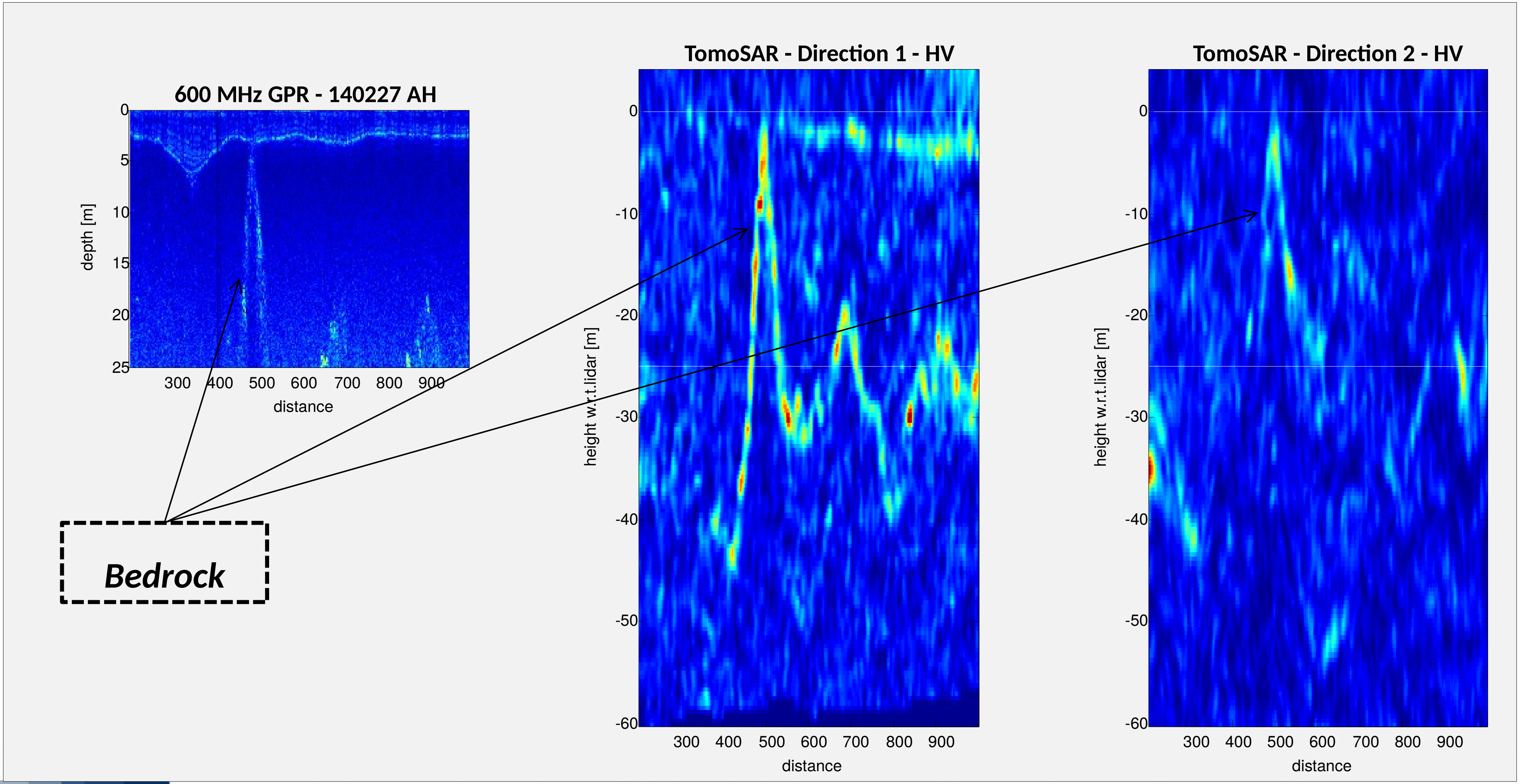
- Clear signal from the ice/snow interface in co-polarized channels
- Clear signal from down to 60 m beneath in all polarizations

Comparison to 600 MHz GPR Transects

- TomoSAR vs GPR comparison by sampling TomoSAR cubes along GPR transects
- 600 MHz GPR transects processed down to 25 m
- TomoSAR transects processed down to 60 m







Comparison to 600 MHz GPR Transects

- TomoSAR vs GPR comparison by sampling TomoSAR cubes along GPR transects
- 600 MHz GPR transects processed down to 25 m
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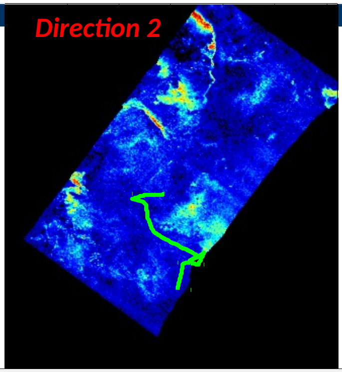
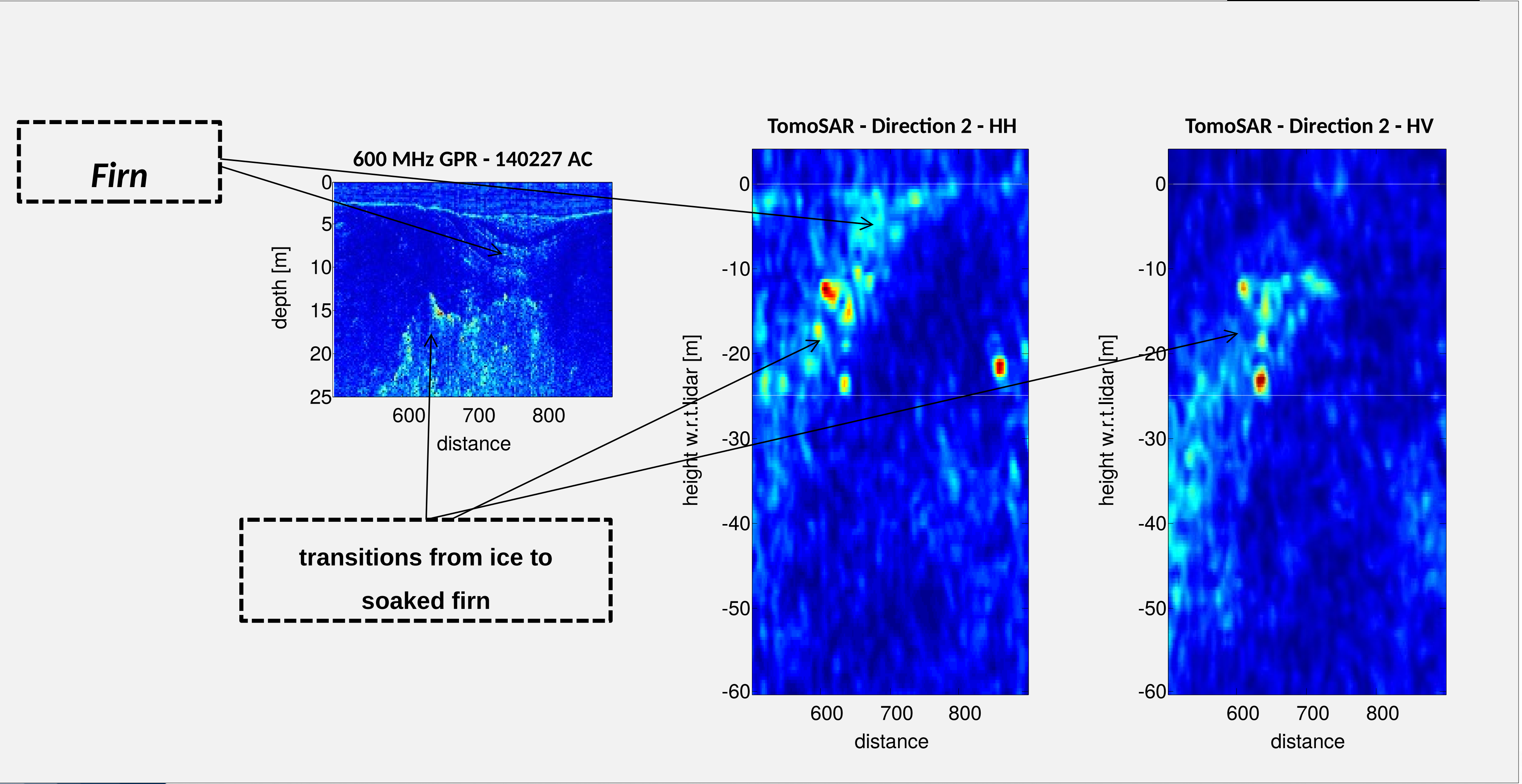
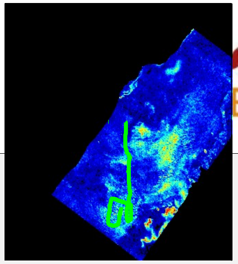
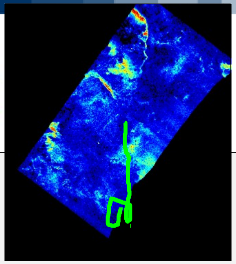
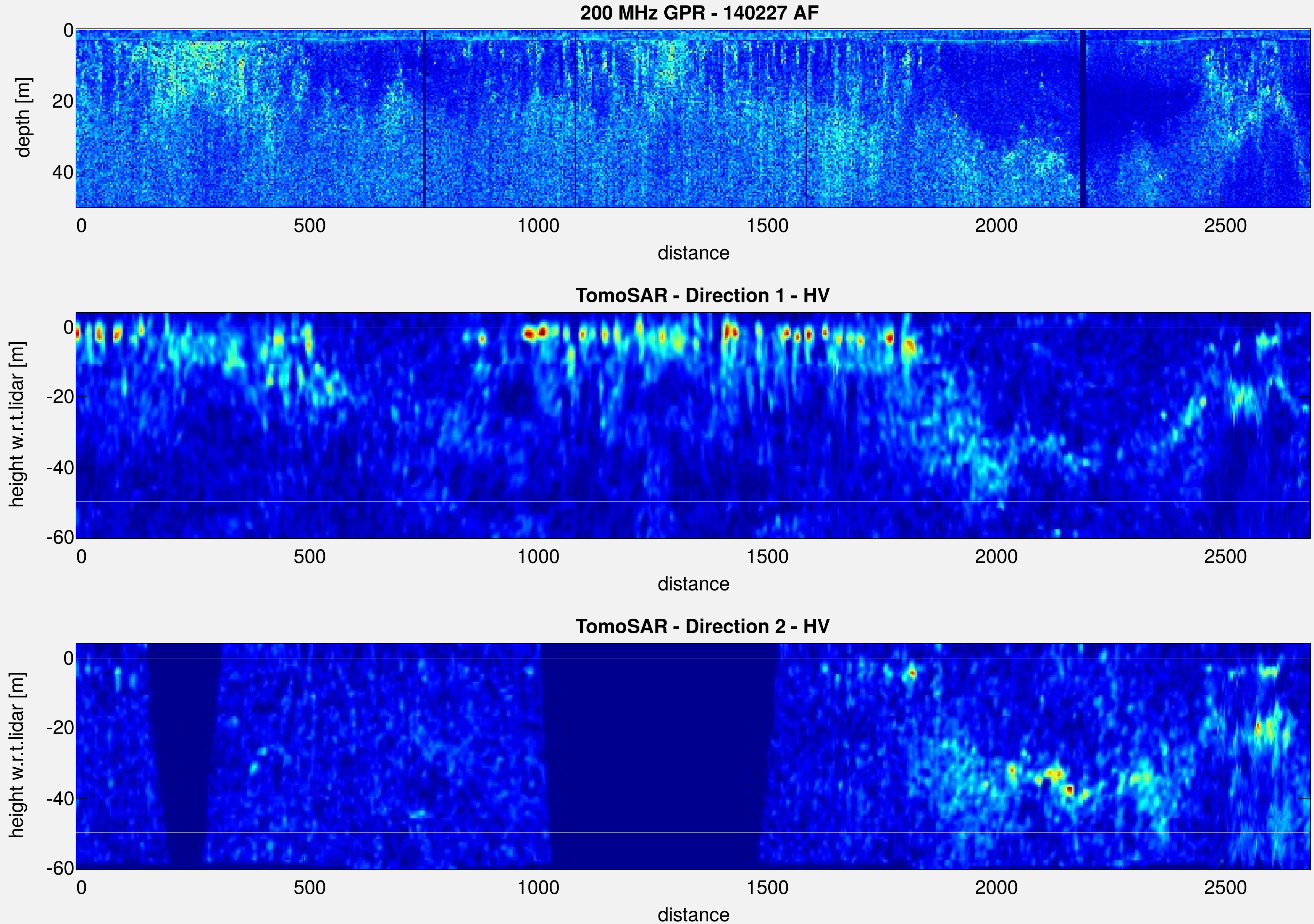




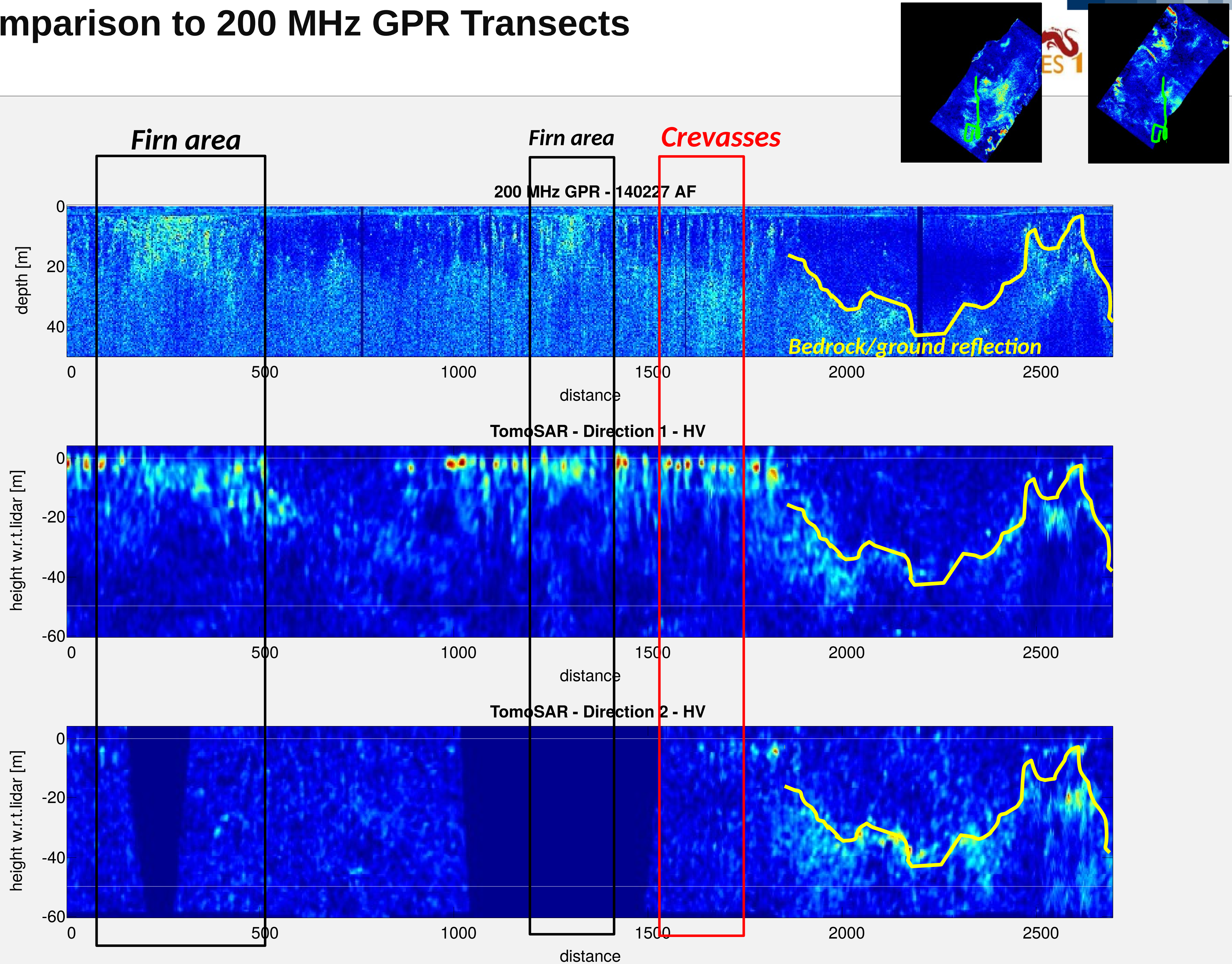
Comparison to 200 MHz GPR Transects





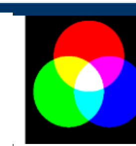


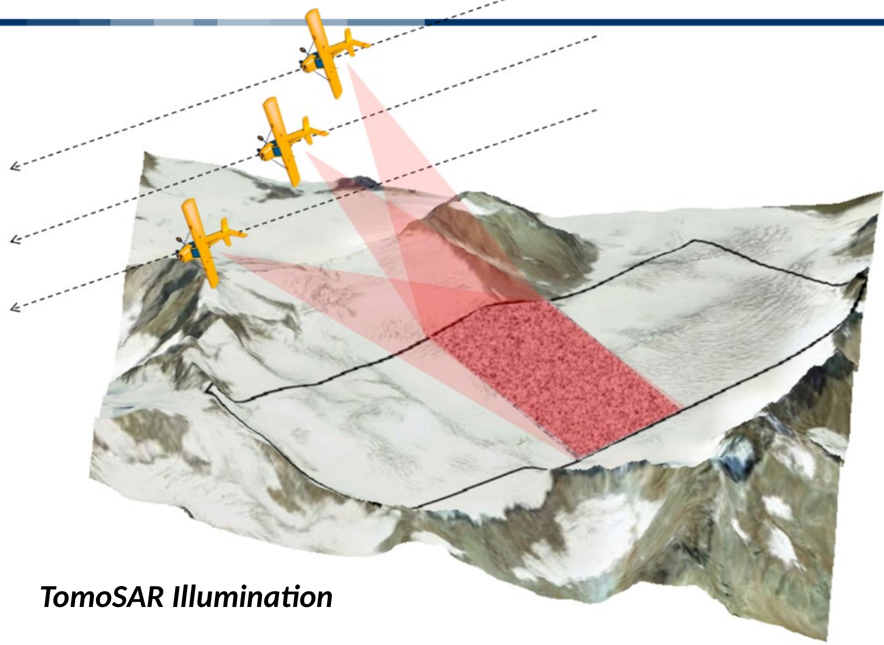
Comparison to 200 MHz GPR Transects



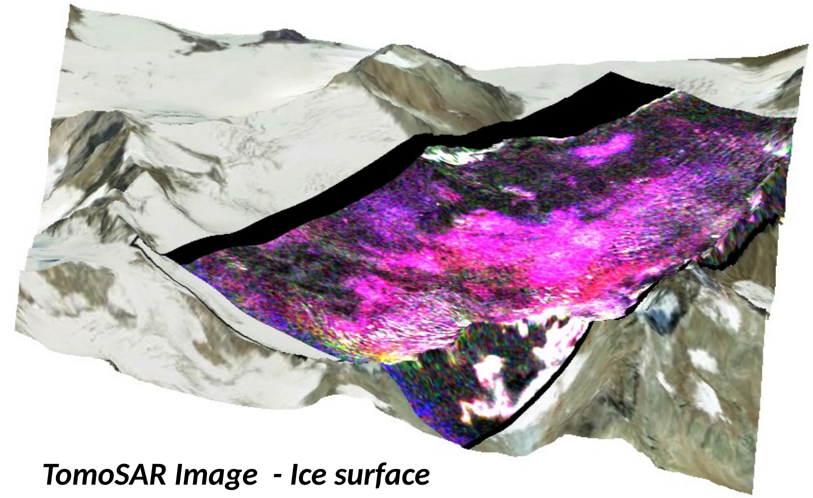
3D Polarimetry

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

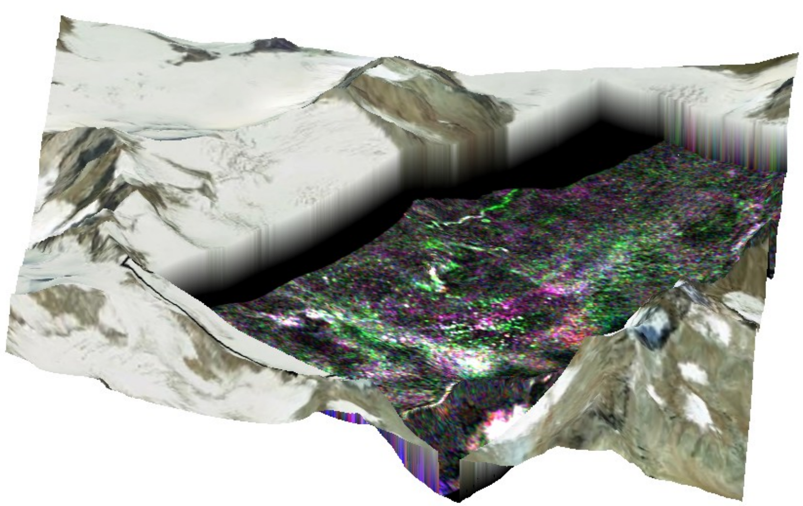




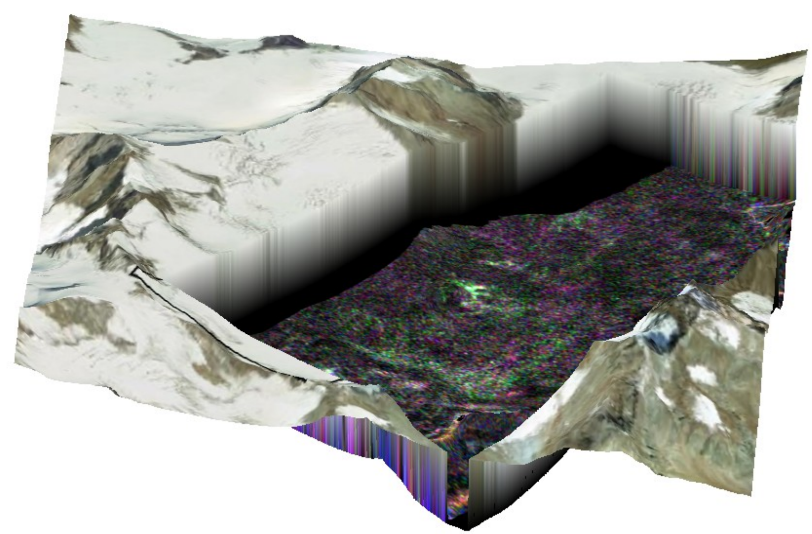
TomoSAR Illumination



TomoSAR Image - Ice surface



TomoSAR Image - 25 m below the Ice surface



TomoSAR Image - 50 m below the Ice surface