PolinSAR Training Course 2023

Application: Snow Height Estimation

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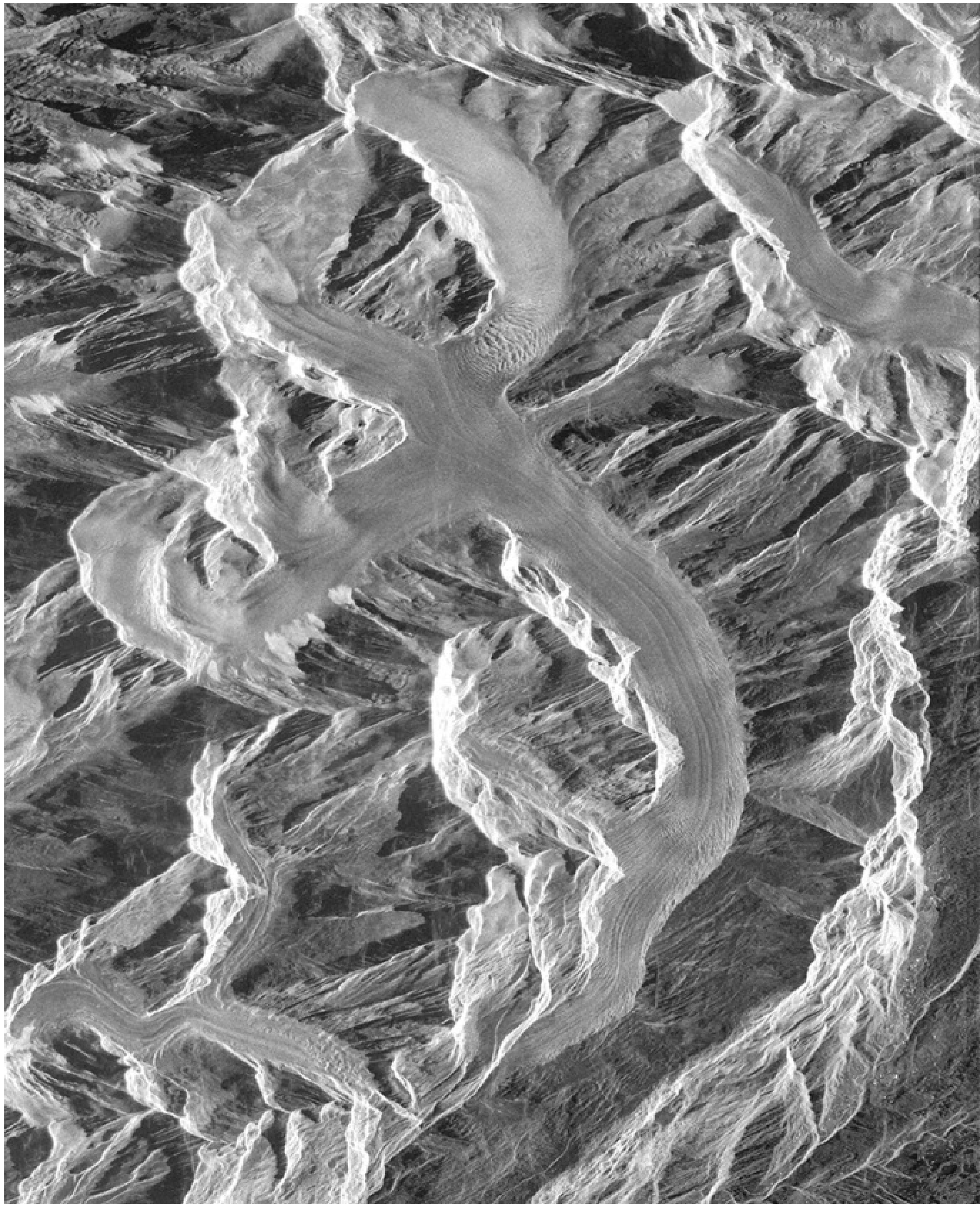
Introduction

- Why is SAR good for snow parameter estimation?
- Introduction of the co-pol phase difference (CPD)
- TanDEM-X a co-pol system
- Testsite Great Aletschglacier
- Propagation model to estimate snow height



Why Radar Techniques for Snow?

- Optical methods sample only the snow surface
- Microwave penetrate into snow
- High frequency required to avoid total penetration: 5 - 50 GHz (note: stronger atmosphere influence)

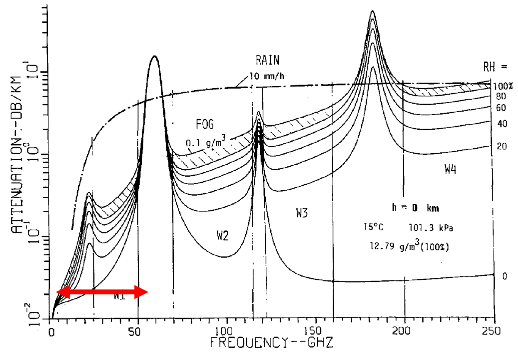
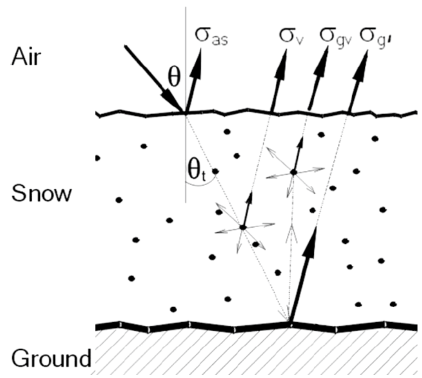


Fig. 1. Specific attenuation at sea level over the frequency range 1–250 GHz for various relative humidities (0 to 100 percent), including fog (0.1 g/m³) and rain (R = 10 mm/h).

Liebe 1983, *IEEE Trans. Antennas Propag.*

Typical interactions of microwave and snow and ice:

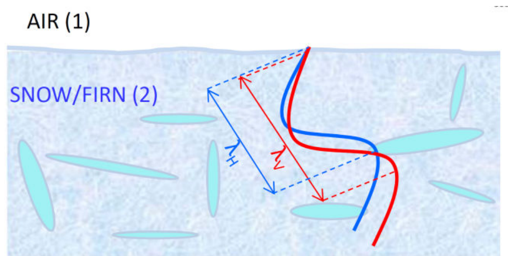
- Total penetration ($T \ll 0°C$, $n \ll 10$ GHz)
- Total reflection at the surface ($T \geq 0°C$)
- Volume scattering ($T < 0°C$, $n > 5$ GHz, depth > 2 m)



Rott et al, 2010, *IEEE Proc.*

Interferometric applications for snow and ice:

- Multipass coherence decay: Snowfall / Melting
- Single pass: DEM-comparison based on surface reflection (deep firn, glacier mass balance)
- D-InSAR: freezing ground deformation, additional scatterers, complex path delays, atmosphere
- Polarimetric Phase differences (co-pol phase differences - CPD)



Parrella, PolInSAR 2013

Leinss et al. 2016, The Cryosphere

Co-Polariemtric Phase Differences

$$[S] = \begin{bmatrix} S_{HH} & S_{HV} \\ S_{VH} & S_{VV} \end{bmatrix} \Rightarrow \vec{k}_{3L} = \begin{bmatrix} S_{HH} \\ \sqrt{2} \cdot S_{XX} \\ S_{VV} \end{bmatrix}$$

Lexicographic Scattering Vector

$$S_{HV} = S_{VH} = S_{XX}$$

Covariance Matrix:

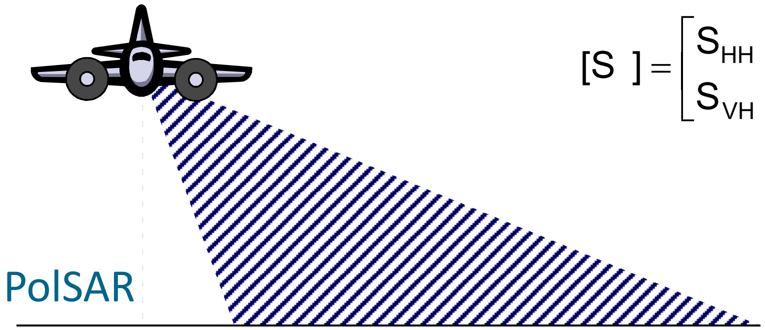
$$[C_3] := \langle \vec{k}_{3L} \cdot \vec{k}_{3L}^* \rangle = \begin{bmatrix} \langle |S_{HH}|^2 \rangle & \sqrt{2} \langle S_{HH} S_{HV}^* \rangle & \langle S_{HH} S_{VV}^* \rangle \\ \sqrt{2} \langle S_{HV} S_{HH}^* \rangle & 2 \langle |S_{HV}|^2 \rangle & \sqrt{2} \langle S_{HV} S_{VV}^* \rangle \\ \langle S_{VV} S_{HH}^* \rangle & \sqrt{2} \langle S_{VV} S_{HV}^* \rangle & \langle |S_{VV}|^2 \rangle \end{bmatrix}$$

Co-Pol Phase Difference:

$$\varphi_{CPD} = \arctan \frac{\mathrm{Im}\{\langle S_{VV} S_{HH}^* \rangle\}}{\mathrm{Re}\{\langle S_{VV} S_{HH}^* \rangle\}}$$

[C] is by definition hermitian positive semi-definite matrices (i.e. have positive eigenvalues)

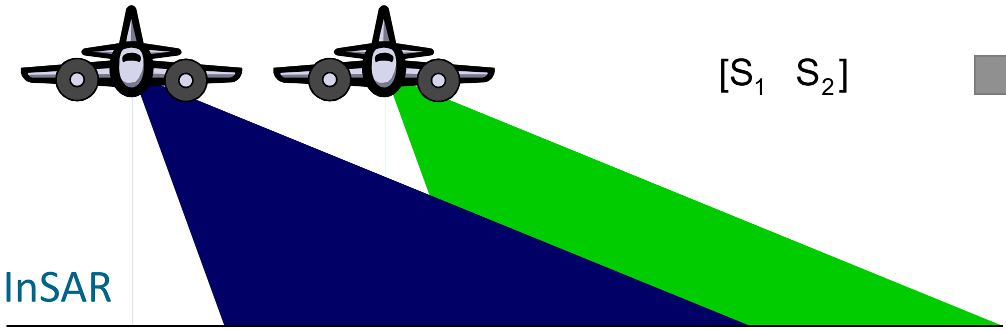
Types of Coherences



$$[S] = \begin{bmatrix} S_{HH} & S_{HV} \\ S_{VH} & S_{VV} \end{bmatrix}$$

Polarimetric Coherences

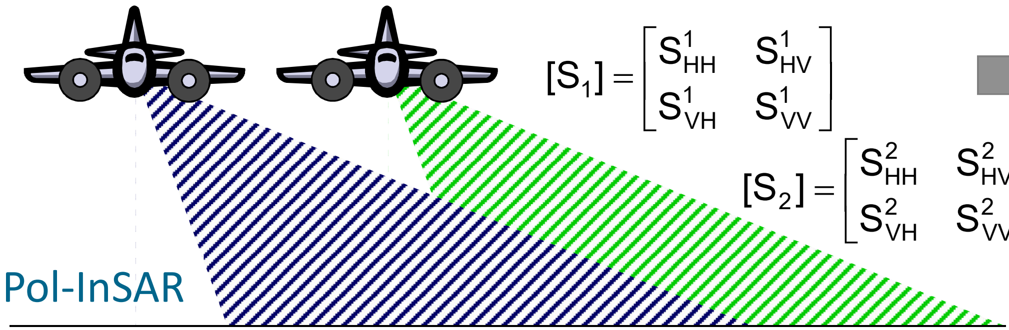
$$\tilde{\gamma}(S_{ij}\ S_{mn}) = \frac{< S_{ij}\ S_{mn}^{*} >}{\sqrt{< S_{ij}\ S_{ij}^{*} > < S_{mn}\ S_{mn}^{*} >}}$$



$$[S_1\ \ S_2]$$

Interferometric Coherences

$$\tilde{\gamma}(S_1\ S_2) = \frac{< S_1\ S_2^{*} >}{\sqrt{< S_1\ S_1^{*} > < S_2\ S_2^{*} >}}$$



$$[S_1] = \begin{bmatrix} S_{HH}^{1} & S_{HV}^{1} \\ S_{VH}^{1} & S_{VV}^{1} \end{bmatrix}$$

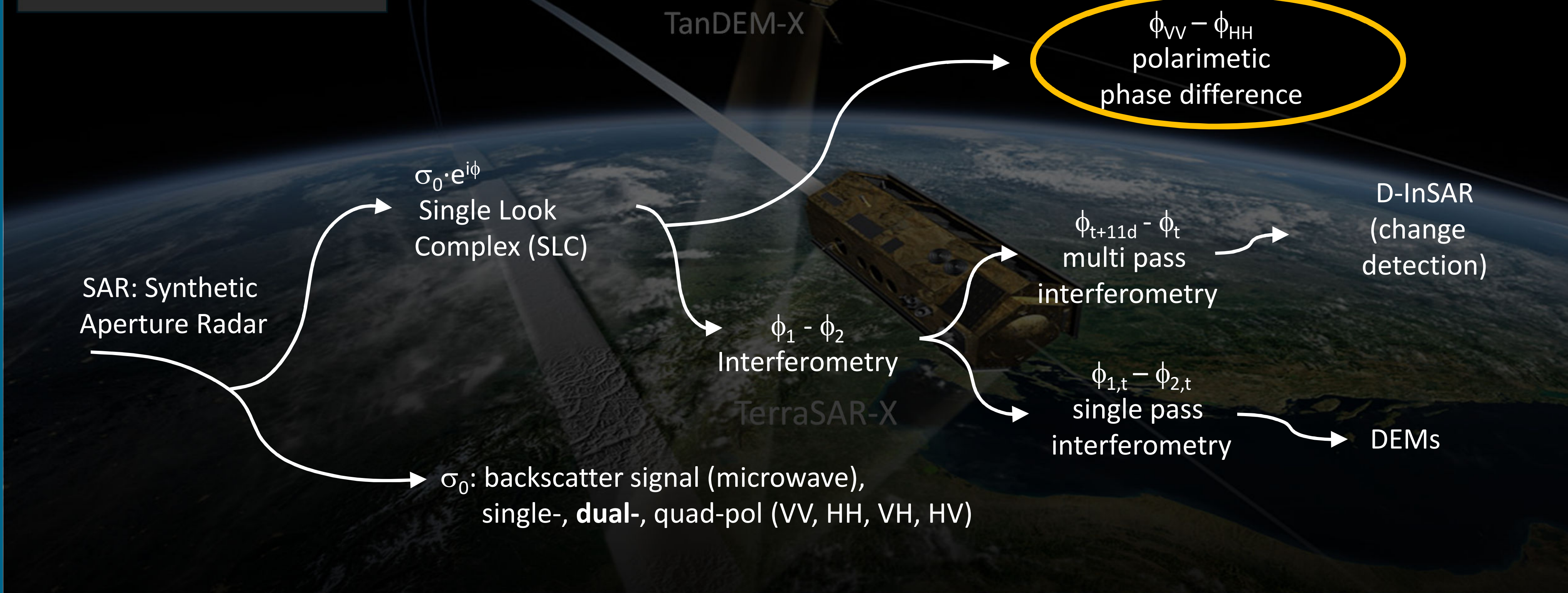
$$[S_2] = \begin{bmatrix} S_{HH}^{2} & S_{HV}^{2} \\ S_{VH}^{2} & S_{VV}^{2} \end{bmatrix}$$

Polarimetric / Interferometric Coherences

$$\tilde{\gamma}(S_{ij}^{1}\ S_{mn}^{2}) = \frac{< S_{ij}^{1}\ S_{mn}^{2\,*} >}{\sqrt{< S_{ij}^{1}\ S_{ij}^{1*} > < S_{mn}^{2}\ S_{mn}^{2\,*} >}}$$

TerraSAR-X and TanDEM-X

A fantastic playground with many options



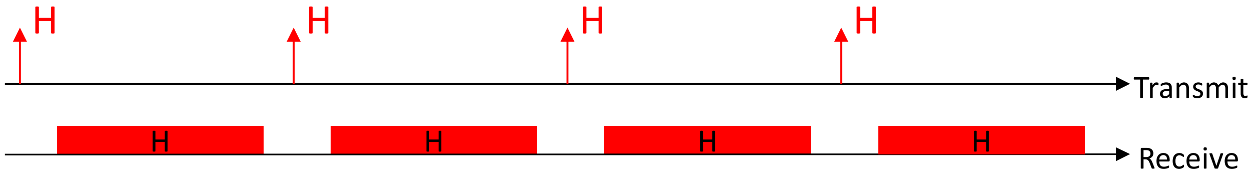
- X-Band: n = 9.65 GHz, l = 3 cm, Resolution: 3 m, Repeat cycle: 11 days
- Monostatic **multi-pass** Interferometry: Dt = 11 days
- Bistatic **single-pass** Interferometry: Dt = 0

6

Polarization Modes @ TerraSAR-X/TanDEM-X

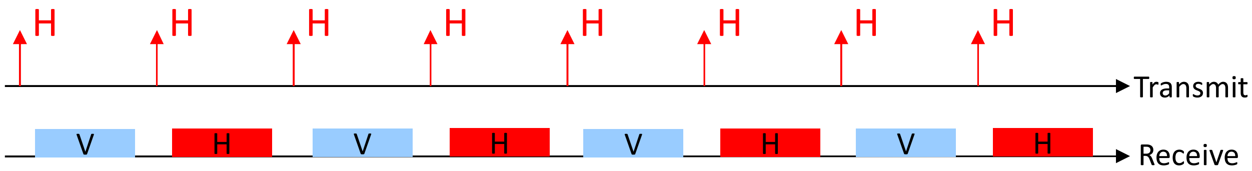
Single Polarization

- 1 polarization channel, {HH, VV}
- stripmap, spotlight, ScanSAR



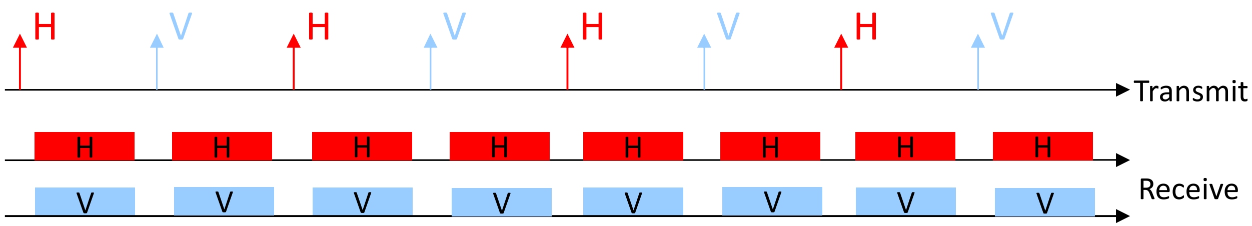
Dual Polarization

- 2 polarization channels, {HH/VV, HH/HV, VV/HV}
- stripmap, spotlight
- coherent pol. phase
- smaller elevation beam

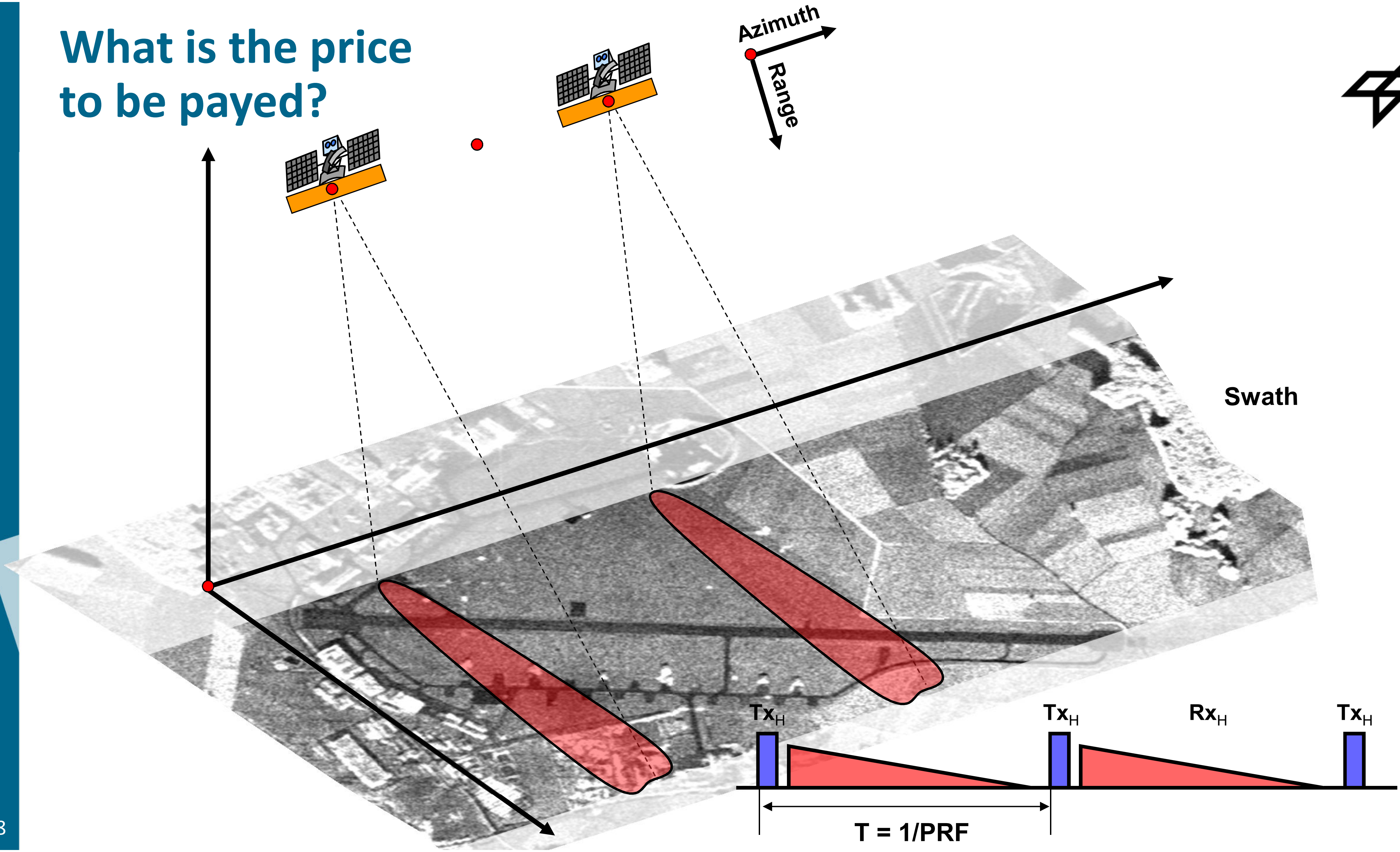


Quad Polarization

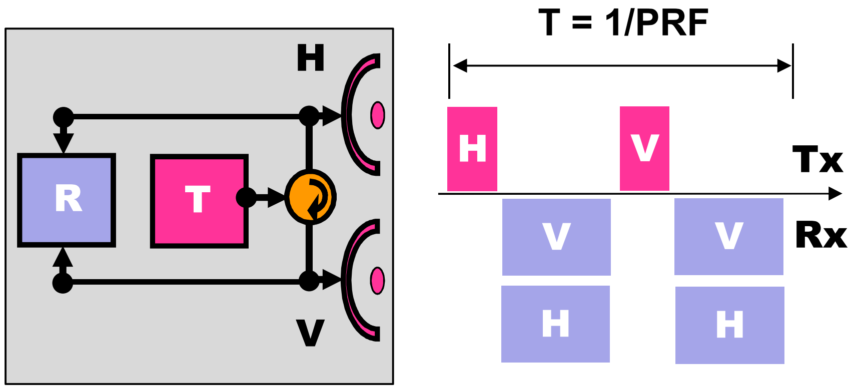
- All 4 pol. channels
- Stripmap
- coherent pol. Phase
- smaller elevation beam
- Experimental product



What is the price to be payed?



Quad Polarimetric Observation

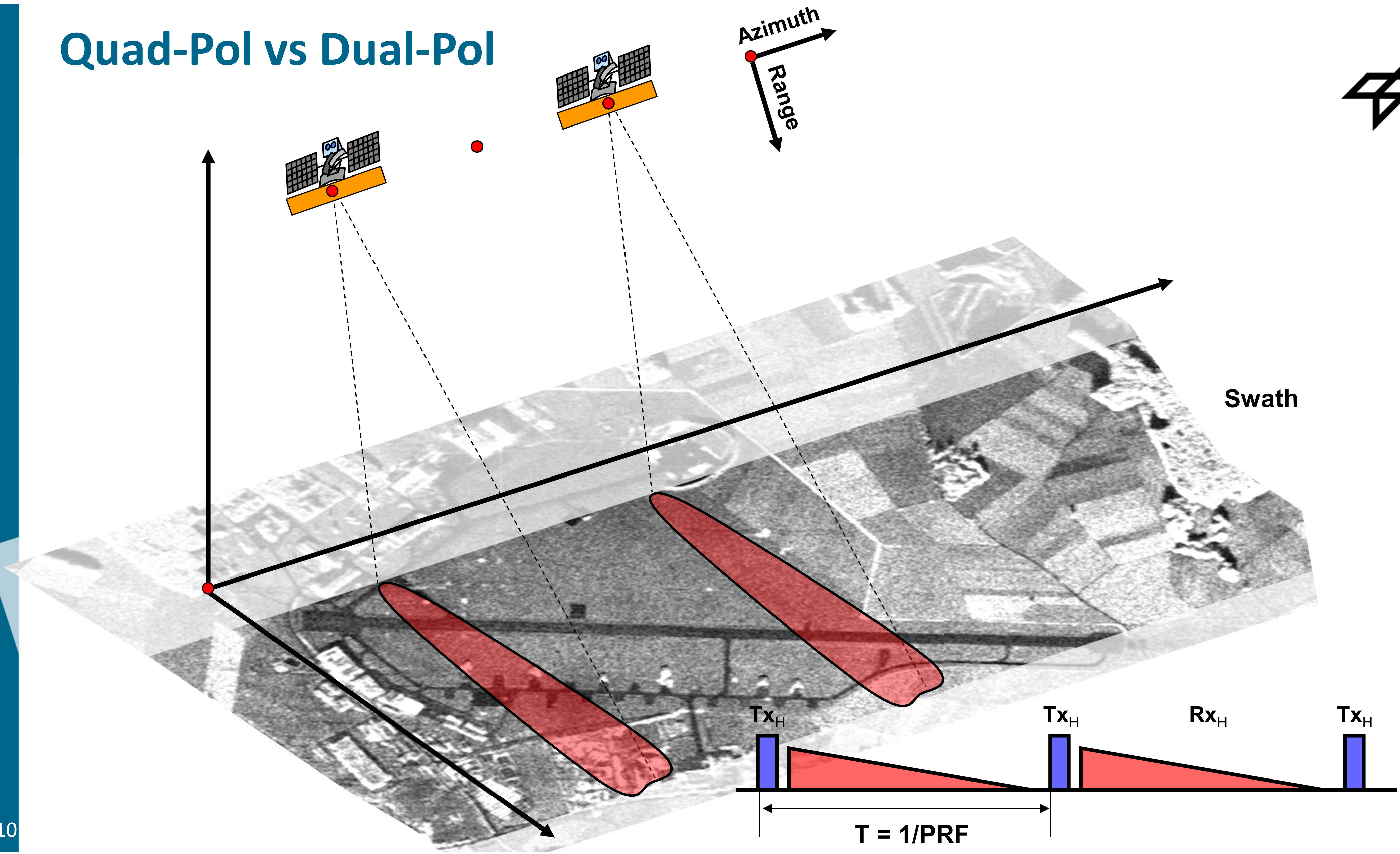


Quad Pol

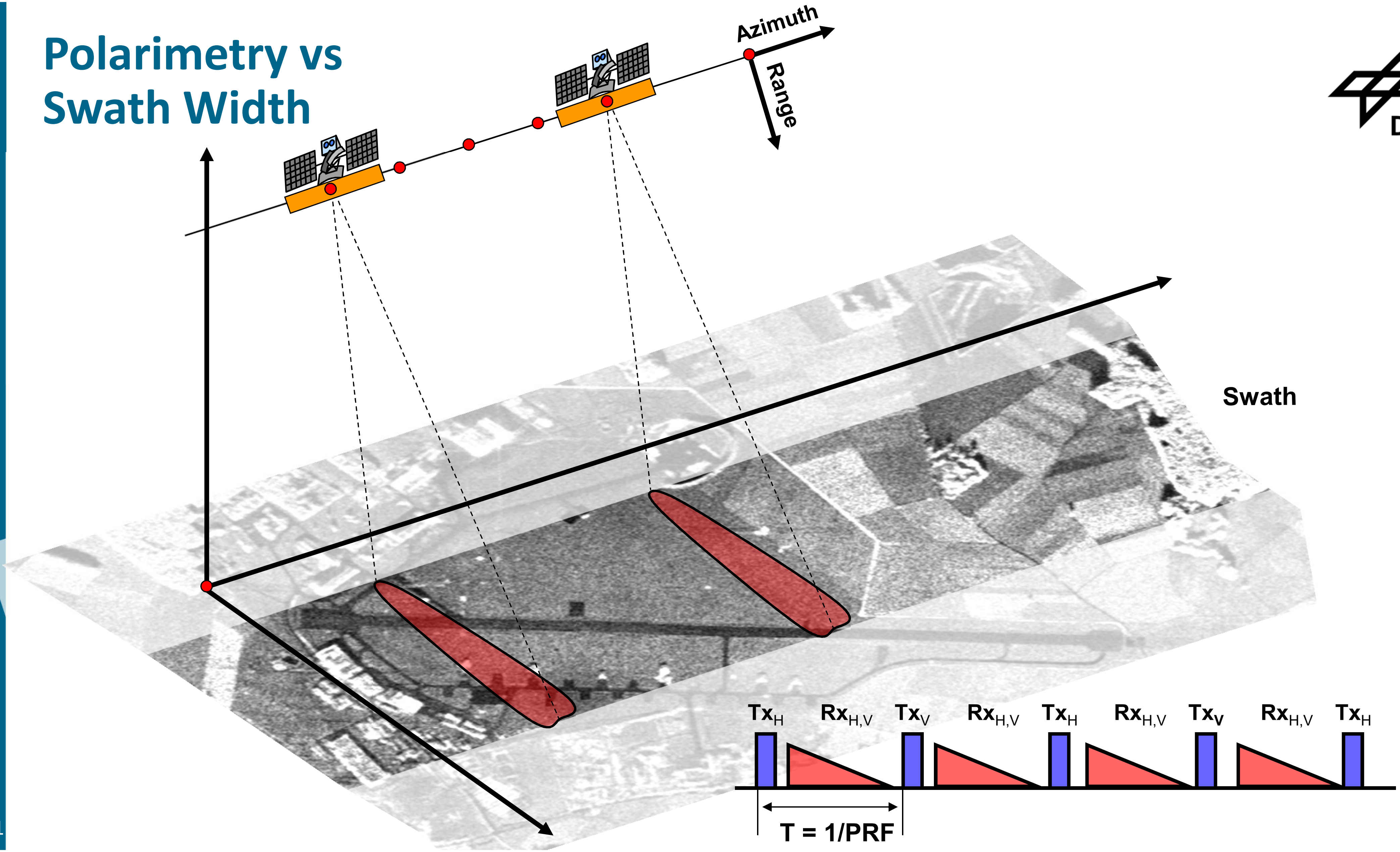
H: $\begin{bmatrix} E_H^T \\ E_V^T \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$ H, V: $\begin{bmatrix} E_H^R \\ E_V^R \end{bmatrix} = \begin{bmatrix} S_{HH} & S_{HV} \\ S_{VH} & S_{VV} \end{bmatrix} \begin{bmatrix} E_H^T \\ E_V^T \end{bmatrix} = \begin{bmatrix} S_{HH} & S_{HV} \\ S_{VH} & S_{VV} \end{bmatrix} \begin{bmatrix} 1 \\ 0 \end{bmatrix} = \begin{bmatrix} S_{HH} \\ S_{VH} \end{bmatrix}$

V: $\begin{bmatrix} E_H^T \\ E_V^T \end{bmatrix} = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$ H, V: $\begin{bmatrix} E_H^R \\ E_V^R \end{bmatrix} = \begin{bmatrix} S_{HH} & S_{HV} \\ S_{VH} & S_{VV} \end{bmatrix} \begin{bmatrix} E_H^T \\ E_V^T \end{bmatrix} = \begin{bmatrix} S_{HH} & S_{HV} \\ S_{VH} & S_{VV} \end{bmatrix} \begin{bmatrix} 0 \\ 1 \end{bmatrix} = \begin{bmatrix} S_{HV} \\ S_{VV} \end{bmatrix}$

Quad-Pol vs Dual-Pol

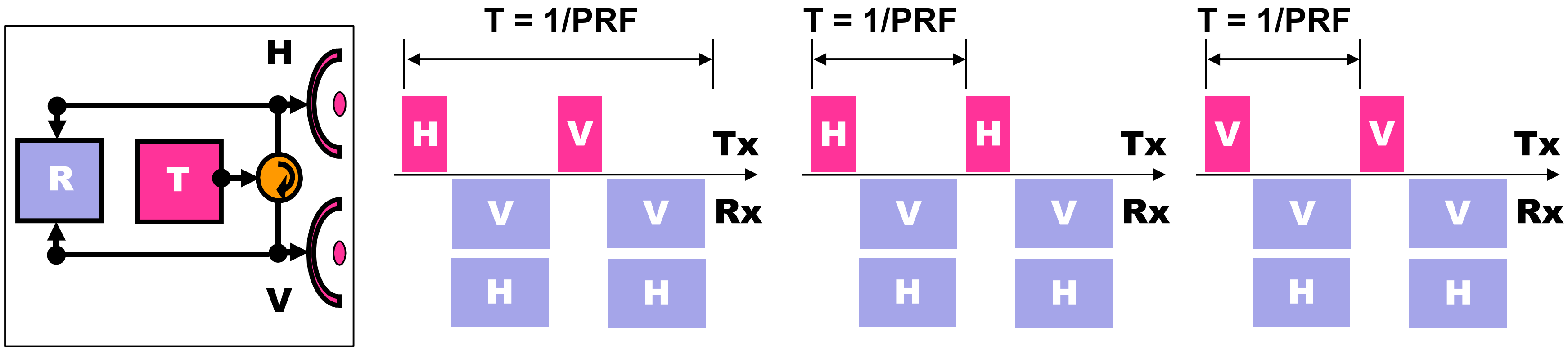


Polarimetry vs Swath Width



DLR

Quad vs Dual Polarimetric Observations



Quad Pol

H $\begin{bmatrix}E_H^T\\E_V^T\end{bmatrix}=\begin{bmatrix}1\\0\end{bmatrix}$ H V $\begin{bmatrix}E_H^R\\E_V^R\end{bmatrix}=\begin{bmatrix}S_{HH}&S_{HV}\\S_{VH}&S_{VV}\end{bmatrix}\begin{bmatrix}E_H^T\\E_V^T\end{bmatrix}=\begin{bmatrix}S_{HH}&S_{HV}\\S_{VH}&S_{VV}\end{bmatrix}\begin{bmatrix}1\\0\end{bmatrix}=\begin{bmatrix}S_{HH}\\S_{VH}\end{bmatrix}$

V $\begin{bmatrix}E_H^T\\E_V^T\end{bmatrix}=\begin{bmatrix}0\\1\end{bmatrix}$ H V $\begin{bmatrix}E_H^R\\E_V^R\end{bmatrix}=\begin{bmatrix}S_{HH}&S_{HV}\\S_{VH}&S_{VV}\end{bmatrix}\begin{bmatrix}E_H^T\\E_V^T\end{bmatrix}=\begin{bmatrix}S_{HH}&S_{HV}\\S_{VH}&S_{VV}\end{bmatrix}\begin{bmatrix}0\\1\end{bmatrix}=\begin{bmatrix}S_{HV}\\S_{VV}\end{bmatrix}$

Dual Pol H

H $\begin{bmatrix}E_H^T\\E_V^T\end{bmatrix}=\begin{bmatrix}1\\0\end{bmatrix}$ H V $\begin{bmatrix}E_H^R\\E_V^R\end{bmatrix}=\begin{bmatrix}S_{HH}&S_{HV}\\S_{VH}&S_{VV}\end{bmatrix}\begin{bmatrix}E_H^T\\E_V^T\end{bmatrix}=\begin{bmatrix}S_{HH}&S_{HV}\\S_{VH}&S_{VV}\end{bmatrix}\begin{bmatrix}1\\0\end{bmatrix}=\begin{bmatrix}S_{HH}\\S_{VH}\end{bmatrix}$

Dual Pol V

V $\begin{bmatrix}E_H^T\\E_V^T\end{bmatrix}=\begin{bmatrix}0\\1\end{bmatrix}$ H V $\begin{bmatrix}E_H^R\\E_V^R\end{bmatrix}=\begin{bmatrix}S_{HH}&S_{HV}\\S_{VH}&S_{VV}\end{bmatrix}\begin{bmatrix}E_H^T\\E_V^T\end{bmatrix}=\begin{bmatrix}S_{HH}&S_{HV}\\S_{VH}&S_{VV}\end{bmatrix}\begin{bmatrix}0\\1\end{bmatrix}=\begin{bmatrix}S_{HV}\\S_{VV}\end{bmatrix}$

Dual Polarimetry – 2nd Order Descriptors

$$[C_3] = \langle \vec{k}_{3L} \cdot \vec{k}_{3L}^{+} \rangle = \begin{bmatrix} C_{11} & C_{12} & C_{13} \\ C_{21} & C_{22} & C_{23} \\ C_{31} & C_{32} & C_{33} \end{bmatrix}$$

3D Coherence (Covariance) Matrix

9 Parameters

$$[C_2] = \langle \vec{k}_{2D} \cdot \vec{k}_{2D}^{+} \rangle = \left\langle \begin{bmatrix} S_A \\ S_B \end{bmatrix} \begin{bmatrix} S_A^* & S_B^* \end{bmatrix} \right\rangle = \begin{bmatrix} \langle |S_A|^2 \rangle & \langle S_A S_B^* \rangle \\ \langle S_B S_A^* \rangle & \langle |S_B|^2 \rangle \end{bmatrix}$$

2D Covariance (Coherence) Matrix

4 Parameters

$$[C_2] = [M][C_3][M]^T \quad \text{with} \quad [M] = \begin{bmatrix} m_{11} & m_{12} & m_{13} \\ m_{21} & m_{22} & m_{23} \end{bmatrix}$$

Case 1: HH-VH

$$[M] = \begin{bmatrix} 1 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix} \Rightarrow [C_2] = \begin{bmatrix} \langle |S_{HH}|^2 \rangle & \langle S_{HH} S_{VH}^* \rangle \\ \langle S_{VH} S_{HH}^* \rangle & \langle |S_{HV}|^2 \rangle \end{bmatrix}$$

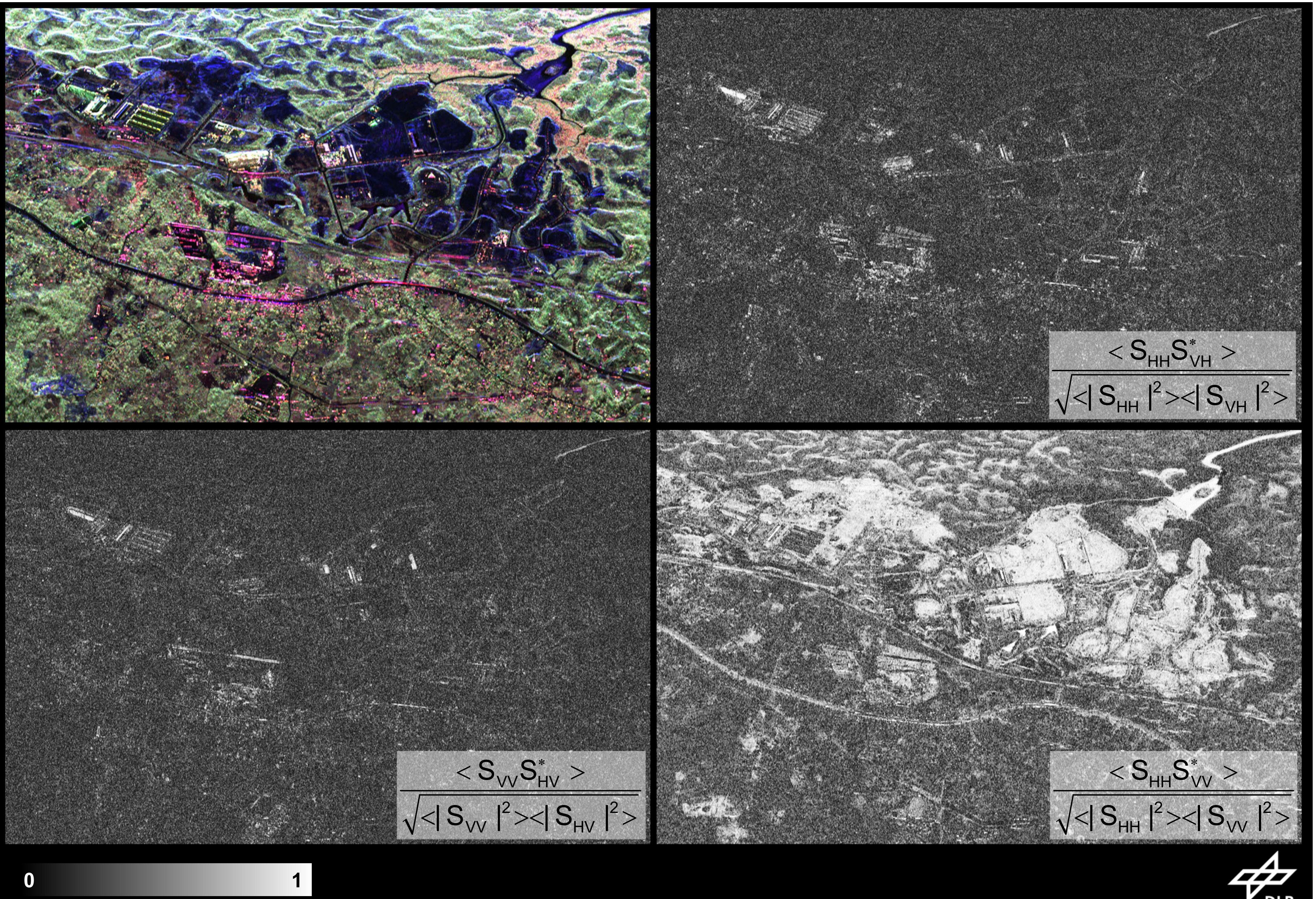
Case 2: VV-HV

$$[M] = \begin{bmatrix} 1 & -1 & 0 \\ 0 & 0 & 0 \end{bmatrix} \Rightarrow [C_2] = \begin{bmatrix} \langle |S_{VV}|^2 \rangle & \langle S_{VV} S_{HV}^* \rangle \\ \langle S_{HV} S_{VV}^* \rangle & \langle |S_{HV}|^2 \rangle \end{bmatrix}$$

Case 3: HH-VV

$$[M] = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix} \Rightarrow [C_2] = \begin{bmatrix} \langle |S_{HH}|^2 \rangle & \langle S_{HH} S_{VV}^* \rangle \\ \langle S_{HH} S_{VV}^* \rangle & \langle |S_{VV}|^2 \rangle \end{bmatrix}$$

Irena Hajnsek, PolinSAR Training Course, 15.06.2023 – irena.hajnsek@dlr.de


$\frac{\langle S_{HH} S_{VH}^{*} \rangle}{\sqrt{\langle |S_{HH}|^2 \rangle \langle |S_{VH}|^2 \rangle}}$
$\frac{\langle S_{VV} S_{HV}^{*} \rangle}{\sqrt{\langle |S_{VV}|^2 \rangle \langle |S_{HV}|^2 \rangle}}$
$\frac{\langle S_{HH} S_{VV}^{*} \rangle}{\sqrt{\langle |S_{HH}|^2 \rangle \langle |S_{VV}|^2 \rangle}}$
0
1

Dual Polarimetry – 2nd Order Descriptors

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3D Coherence (Covariance) Matrix

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2D Covariance (Coherence) Matrix

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Case 1: HH-VH

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Case 2: VV-HV

$$[M] = \begin{bmatrix} 1 & -1 & 0 \\ 0 & 0 & 0 \end{bmatrix} \Rightarrow [C_2] = \begin{bmatrix} \langle |S_{VV}|^2 \rangle & \langle S_{VV} S_{HV}^* \rangle \\ \langle S_{HV} S_{VV}^* \rangle & \langle |S_{HV}|^2 \rangle \end{bmatrix} = \begin{bmatrix} \langle |S_{VV}|^2 \rangle & 0 \\ 0 & \langle |S_{HV}|^2 \rangle \end{bmatrix}$$

Case 3: HH-VV

$$[M] = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix} \Rightarrow [C_2] = \begin{bmatrix} \langle |S_{HH}|^2 \rangle & \langle S_{HH} S_{VV}^* \rangle \\ \langle S_{HH} S_{VV}^* \rangle & \langle |S_{VV}|^2 \rangle \end{bmatrix}$$

2-dim Polarimetry: 2nd Order Statistical Parameters

$$[T_3] := \langle \vec{k}_{3P} \cdot \vec{k}_{3P}^{+} \rangle \;\Rightarrow\; [T_3] = [U_3][\Lambda_3][U_3]^{-1}$$

$$[\Lambda_3] = \begin{bmatrix} \lambda_1 & 0 & 0 \\ 0 & \lambda_2 & 0 \\ 0 & 0 & \lambda_3 \end{bmatrix} \qquad [U_3] = \begin{bmatrix} | & | & | \\ \vec{e}_1 & \vec{e}_2 & \vec{e}_3 \\ | & | & | \end{bmatrix}$$

$$P_i := \frac{\lambda_i}{\sum \lambda_i} \qquad \vec{e}_i = \begin{bmatrix} \cos\alpha_i \exp(j\varphi_{i1}) \\ \sin\alpha_i \cos\beta \exp(j\varphi_{i2}) \\ \sin\alpha_i \sin\beta \exp(j\varphi_{i3}) \end{bmatrix}$$

$$H := \sum_{i=1}^{3} P_i \log_3 P_i \qquad A := \frac{P_2 - P_3}{P_2 + P_3} \qquad \alpha := \sum_{i=1}^{3} P_i \; \alpha_i$$

Entropy **Anisotropy** **Alpha Angle**

$$[T_2] := \langle \vec{k}_2 \cdot \vec{k}_2^{+} \rangle \;\Rightarrow\; [T_2] = [U_2][\Lambda_2][U_2]^{-1}$$

$$[\Lambda_2] = \begin{bmatrix} \lambda_1 & 0 \\ 0 & \lambda_2 \end{bmatrix} \qquad [U_2] = \begin{bmatrix} | & | \\ \vec{e}_1 & \vec{e}_2 \\ | & | \end{bmatrix}$$

$$P_i := \frac{\lambda_i}{\sum \lambda_i} \qquad \vec{e}_i = \begin{bmatrix} \cos\alpha_i \exp(j\varphi_{i1}) \\ \sin\alpha_i \exp(j\varphi_{i2}) \end{bmatrix}$$

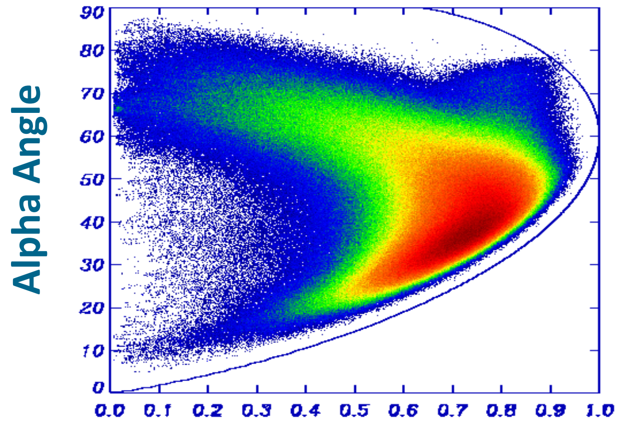
$$\alpha_1 \; ; \; \alpha_2 = \frac{\pi}{2} - \alpha_1$$

$$H := \sum_{i=1}^{2} P_i \log_2 P_i \qquad A := \frac{P_1 - P_2}{P_1 + P_2} \qquad \alpha := \sum_{i=1}^{2} P_i \; \alpha_i$$

Entropy **Anisotropy** **Alpha Angle**

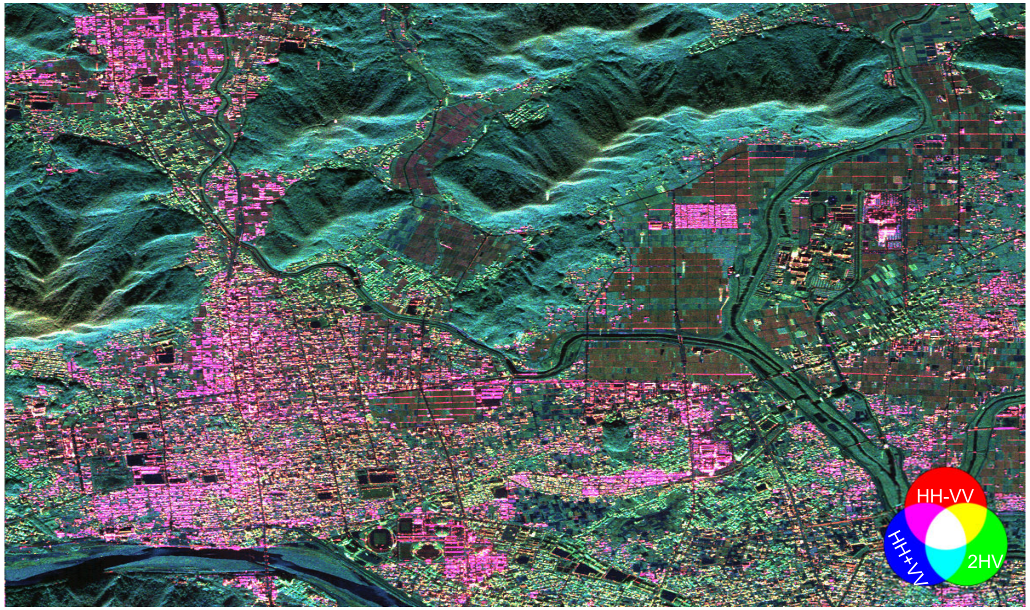
randomness scat.mechan.

2-dim Polarimetry – 2nd Order
Example X-band from PI-SAR Test Site: Gifu



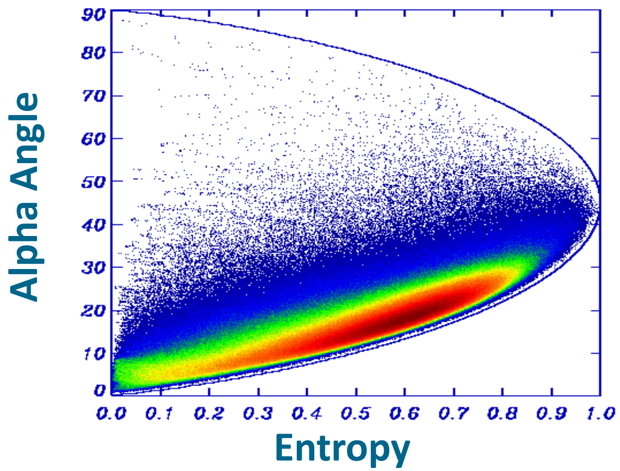
Quad Pol

Entropy

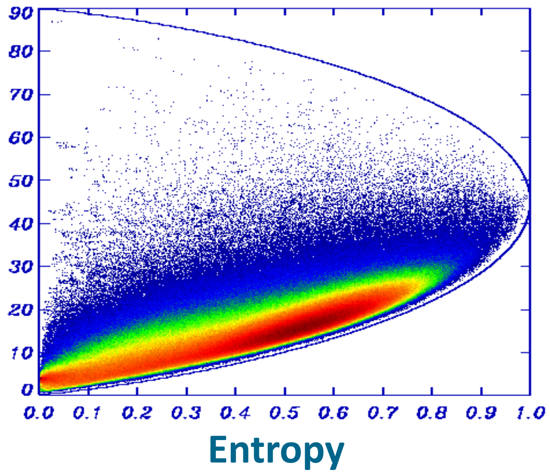


PI-SAR / Test Site: Gifu, Japan

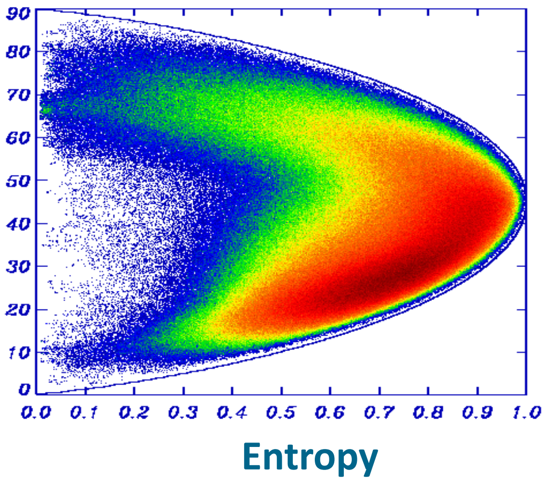
Dual Pol Case 1: Tx: H



Dual Pol Case 2: Tx: V

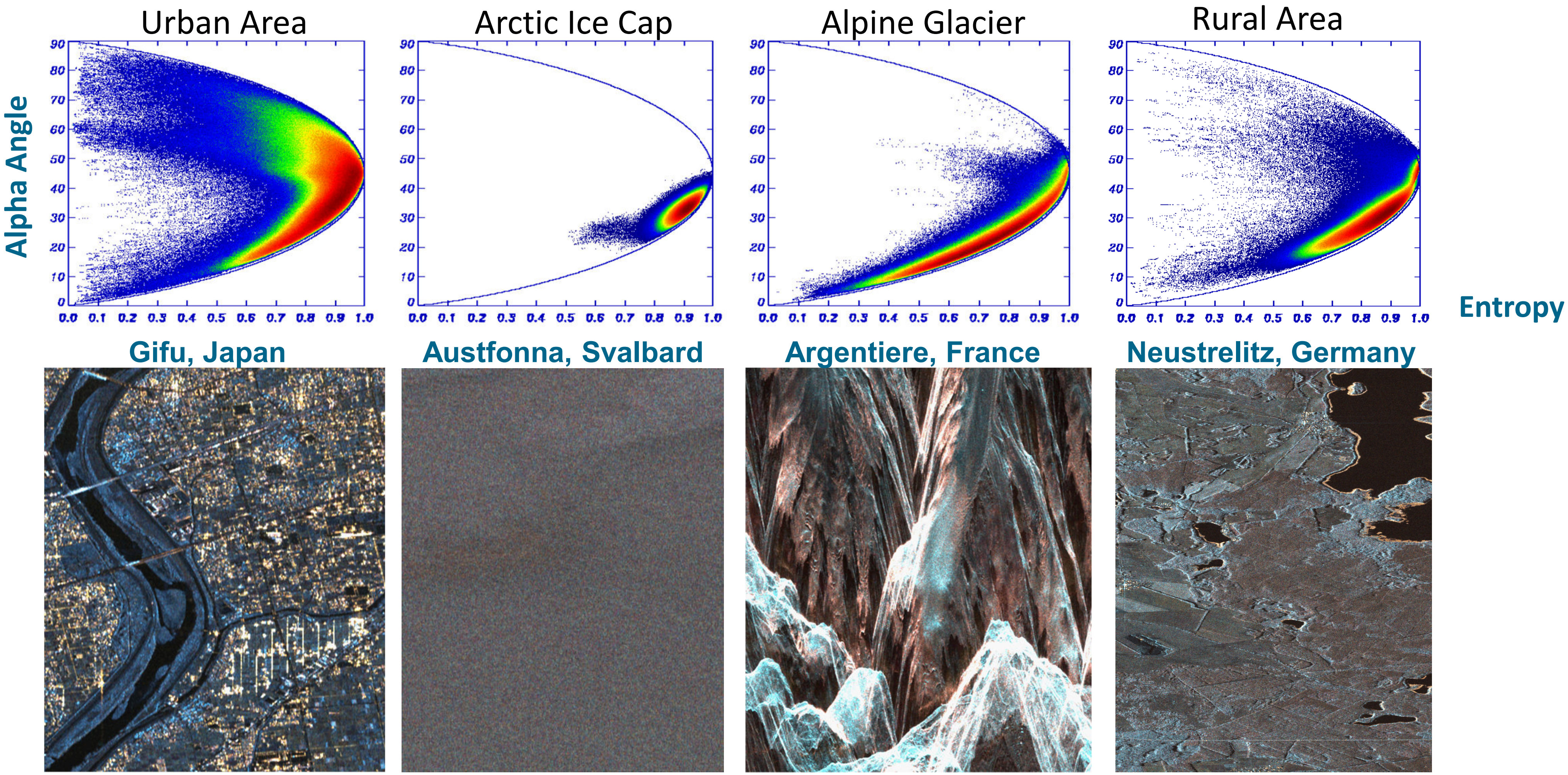


Dual Pol Case 3: Tx: H & V



2-dim Polarimetry – 2nd Order

Example from TerraSAR-X for different surface types



TanDEM-X: The Great Aletsch Glacier and Available Data

The Great Aletsch Glacier

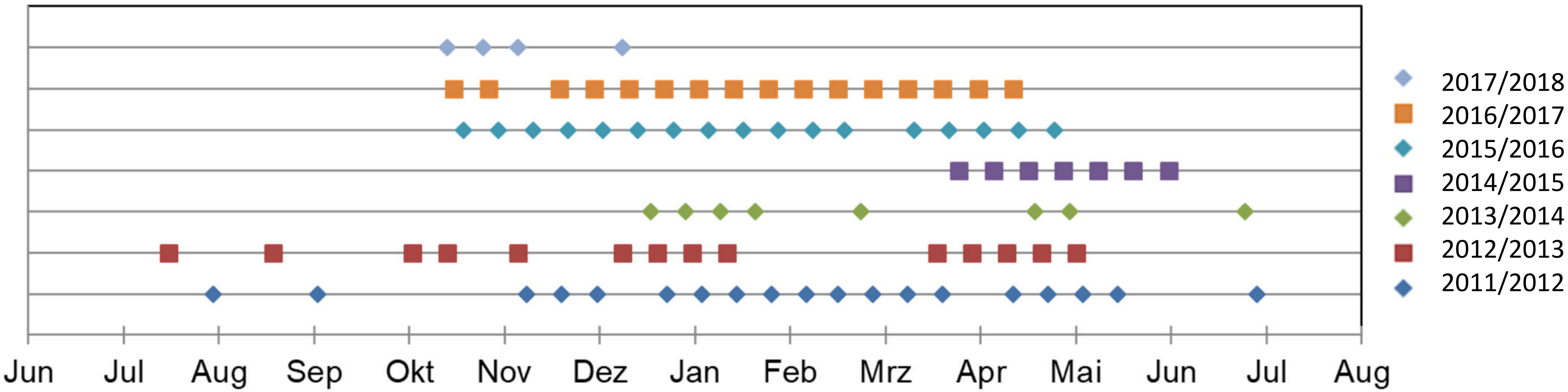
- ✓ Length 23 km
- ✓ Surface 86 km^3
- ✓ From ~1800 m to ~3500 m altitude
- ✓ Negative mass balance since 1881
- ✓ Front reatreats up to 4 m/year
- ✓ Equilibrium Line at 3000 m

Map of Switzerland, Aletsch is marked

Source: Map.geo.admin.ch (Schweizerische Eidgenossenschaft), Date: 25.06.18

SAR Data

- ✓ TanDEM-X time series
- ✓ Dual-Pol (HH and VV)
- ✓ 7-year time period (2011-2018)
- ✓ 86 acquisitions from same orbit
- ✓ rg x az = 1,76 x 6,6 m resolution
- ✓ Incidence angle $\theta_{inc} = 31{,}6°$



Great Aletsch Glacier / Grosser Aletschgletscher

- 23 km long
- Covers 80 square kilometers
- over 800 meters thick ice
- 15 cubic kilometers of ice
- 20% of the entire Swiss Ice mass

- expected to lose 90% of it's mass until 2100.

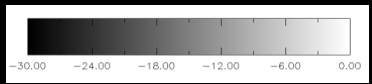
Jouvet et al. J. Glac. (2011)

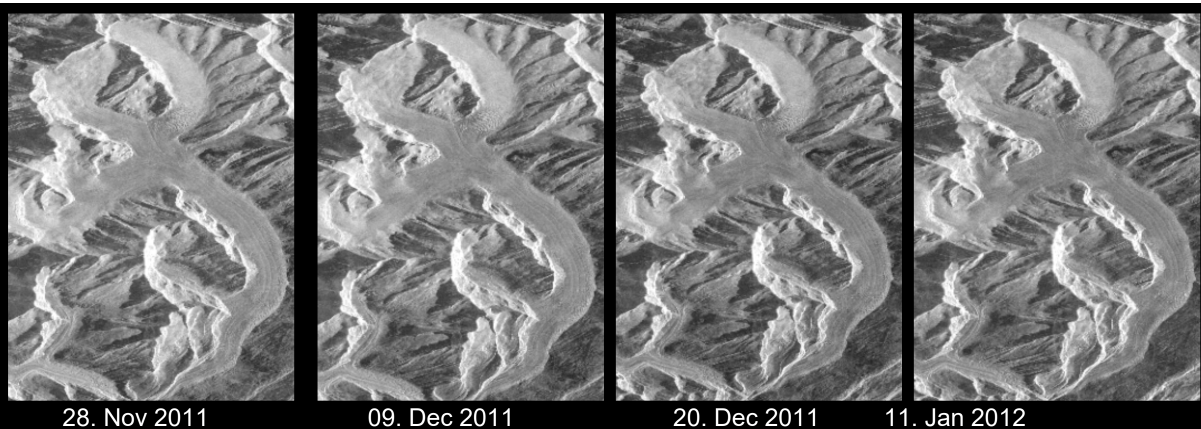
L. Leinss

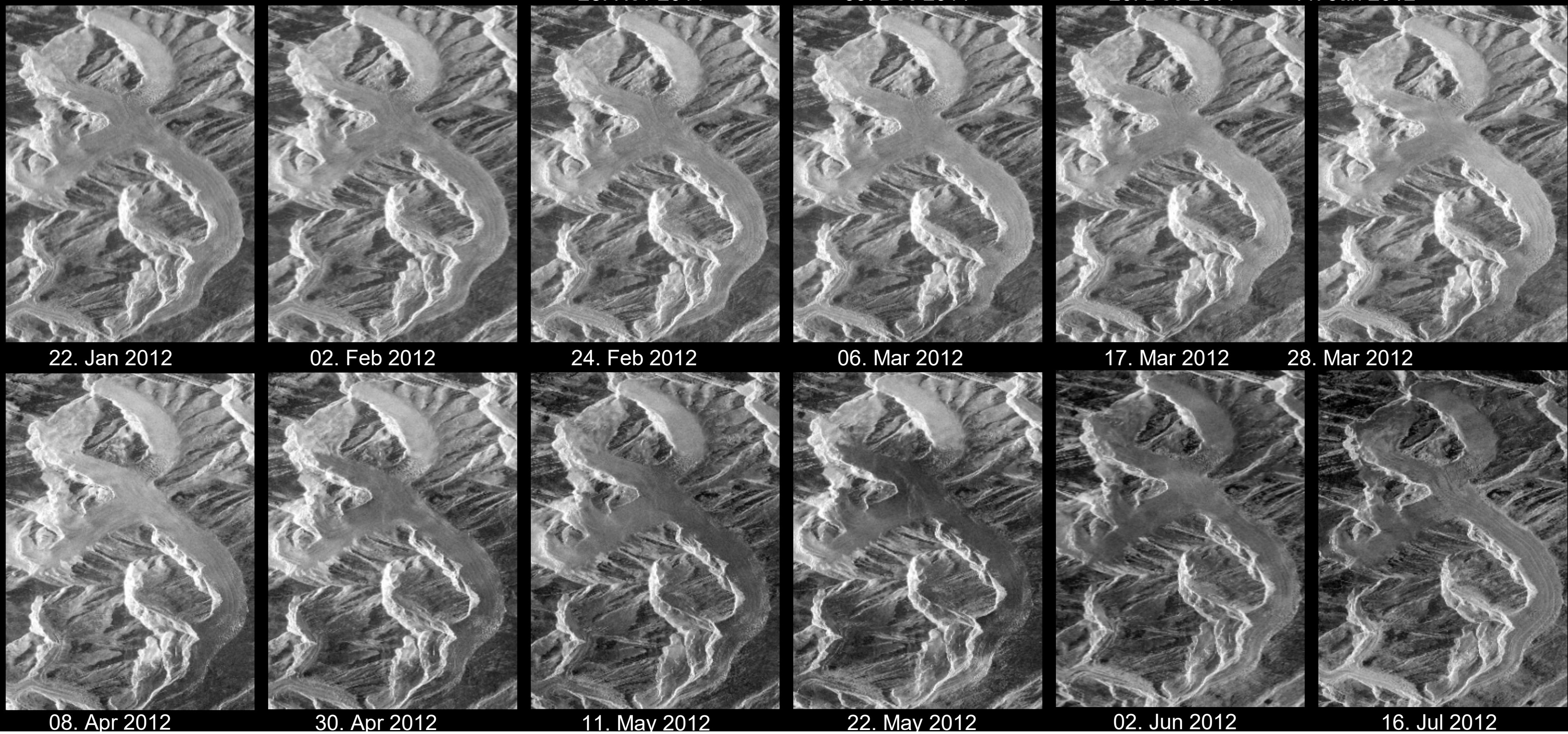
Earth Observation and Remote Sensing

Aletschgletscher, Switzerland

2011 - 2012 Time series σ^0_{HH}



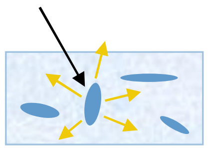


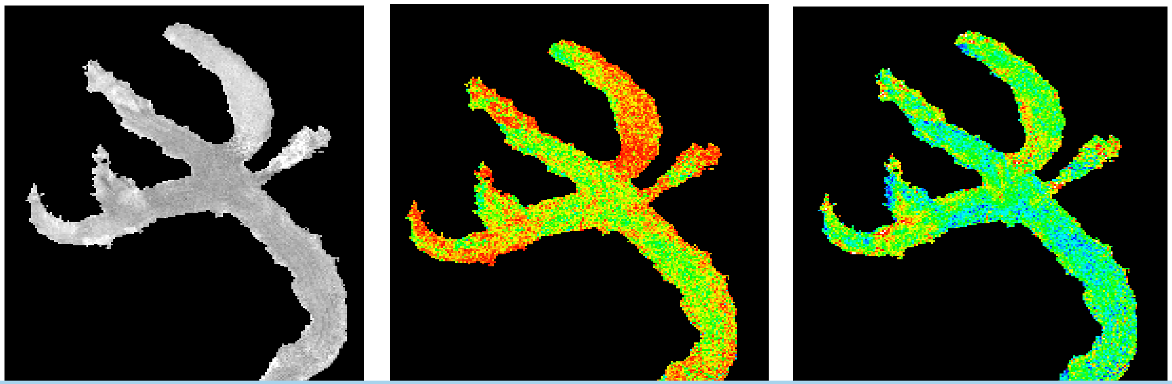


Polarimetric Analysis: Sensitivity to Seasonal Dynamics

✓ Wet and dry glacier conditions

Winter image
08.02.2013

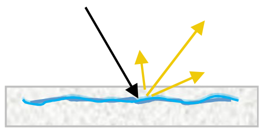


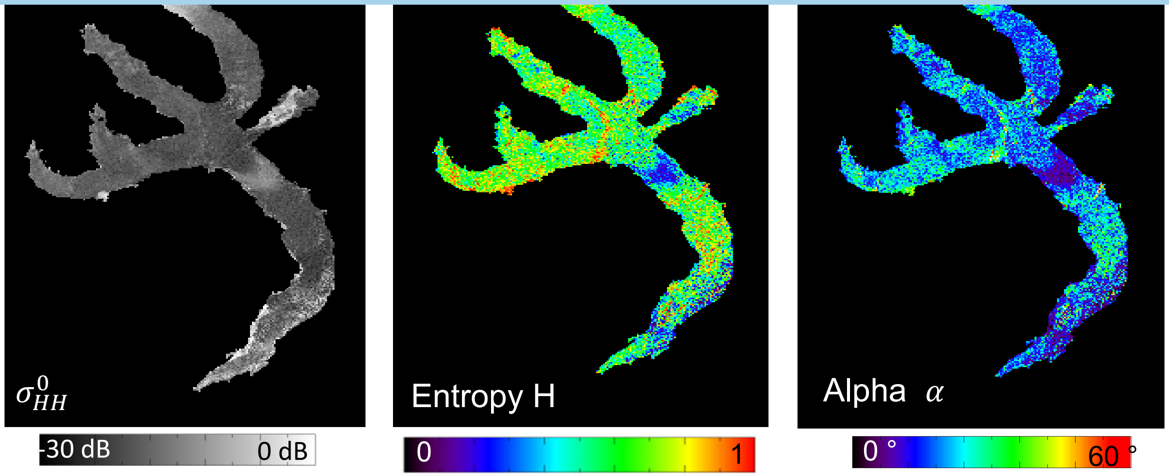


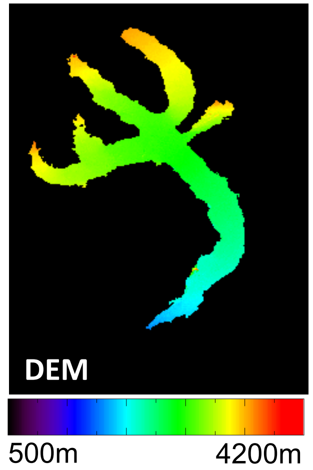
Scattering mechanisms vary with snow/ice conditions…

…but also within a single scene!

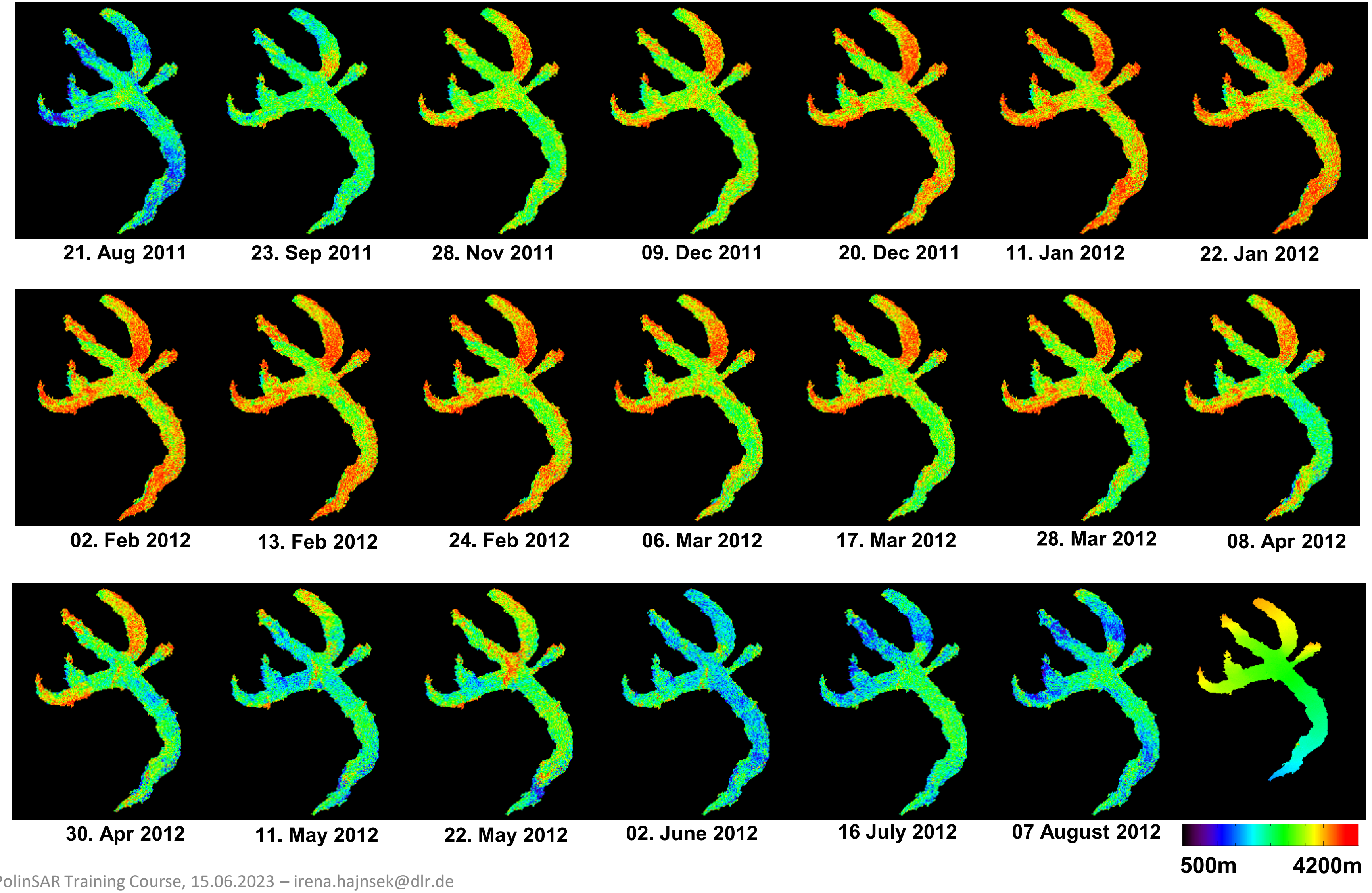
Su
09.05.2013



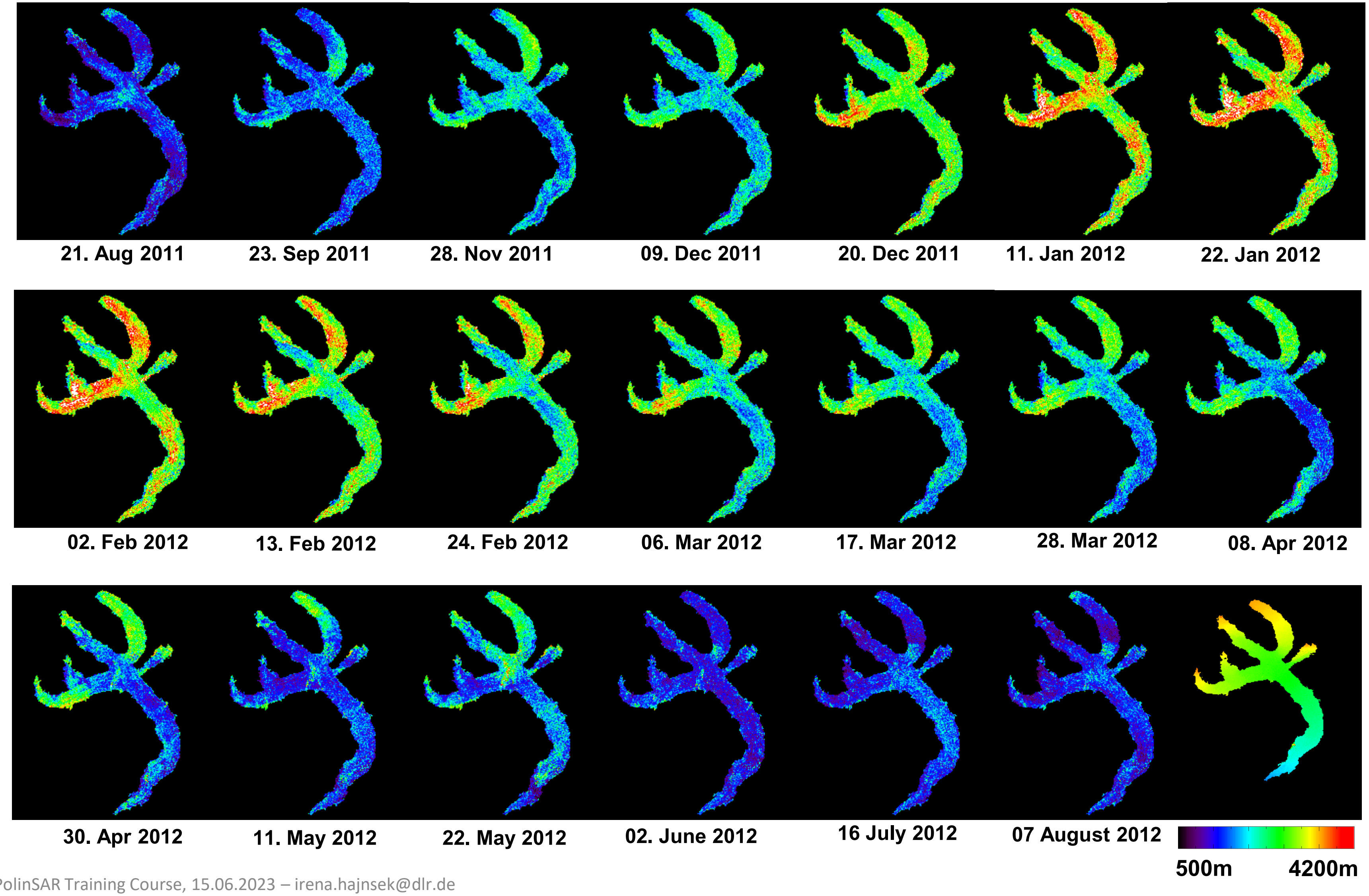




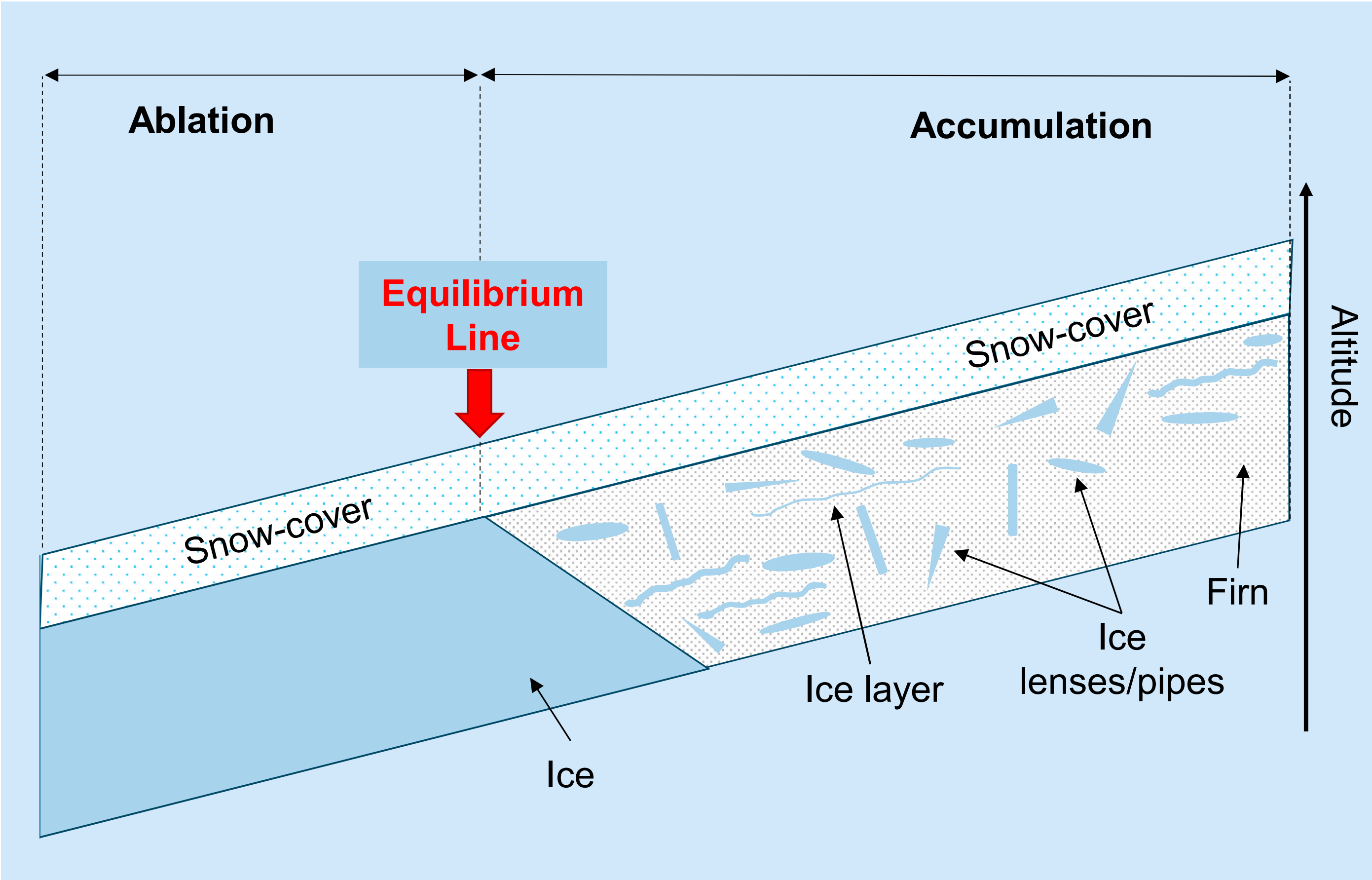
Entropy Time Series 2011/012



Alpha Angle Time Series 2011/012

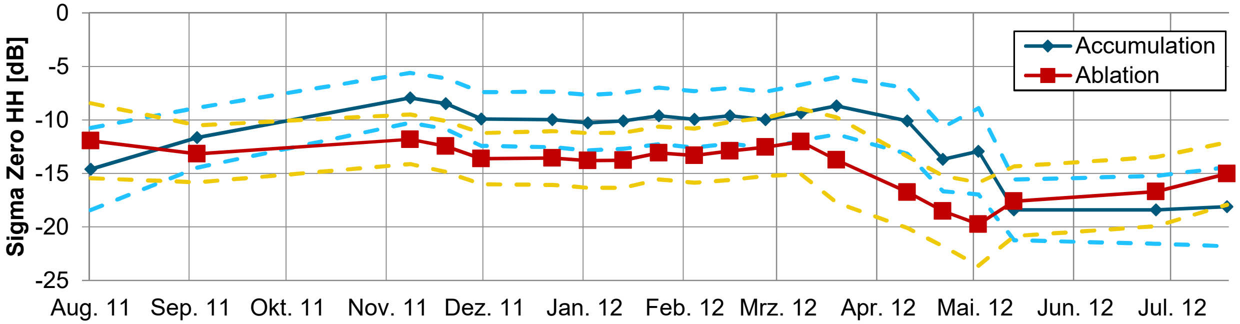


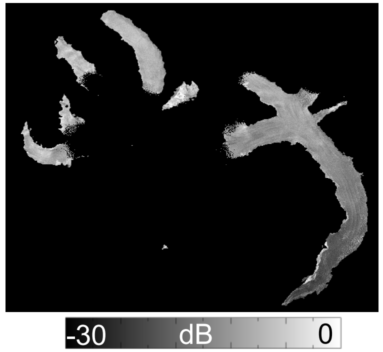
Basics of Glaciology

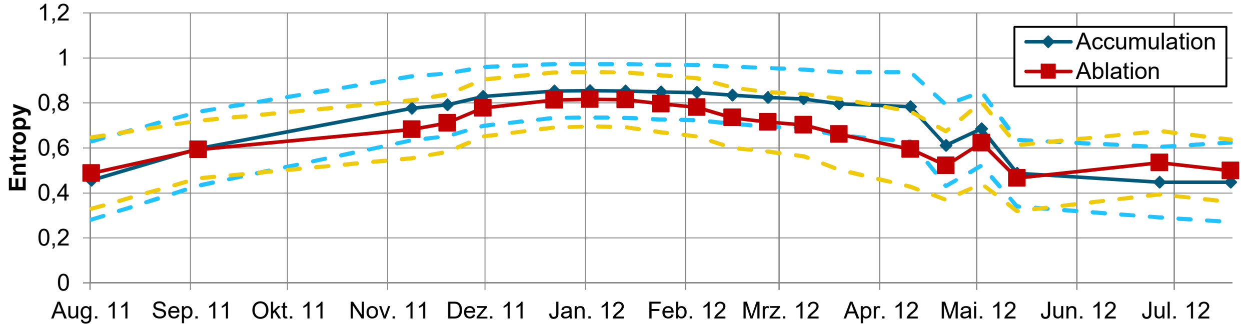


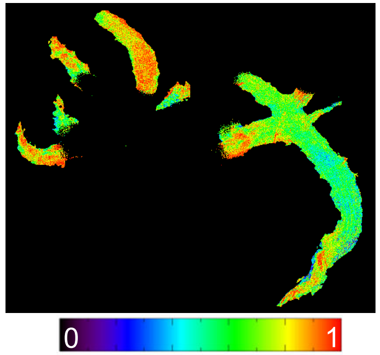
The **equilibrium-line (ELA) altitude** is a **line** on the **glacier** where accumulation equals ablation

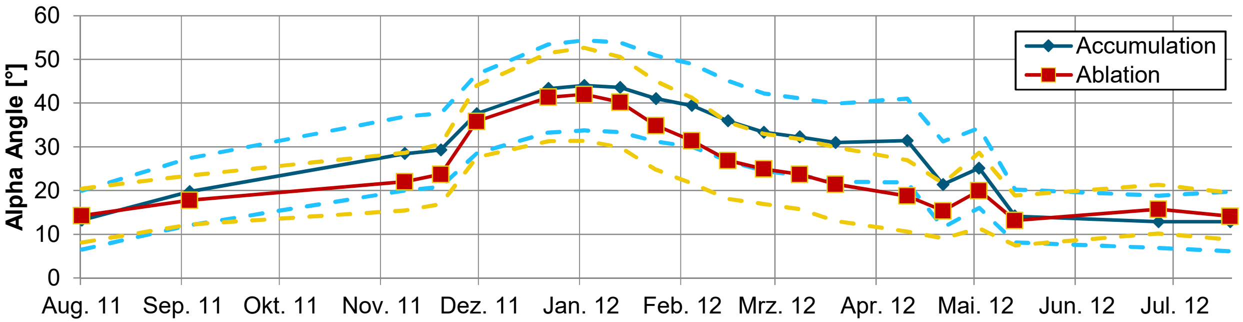
Polarimetric Analysis: Seasonal Dynamics of Glacier Zones

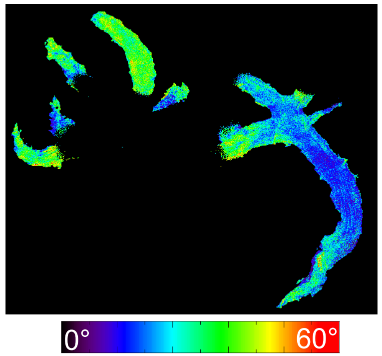




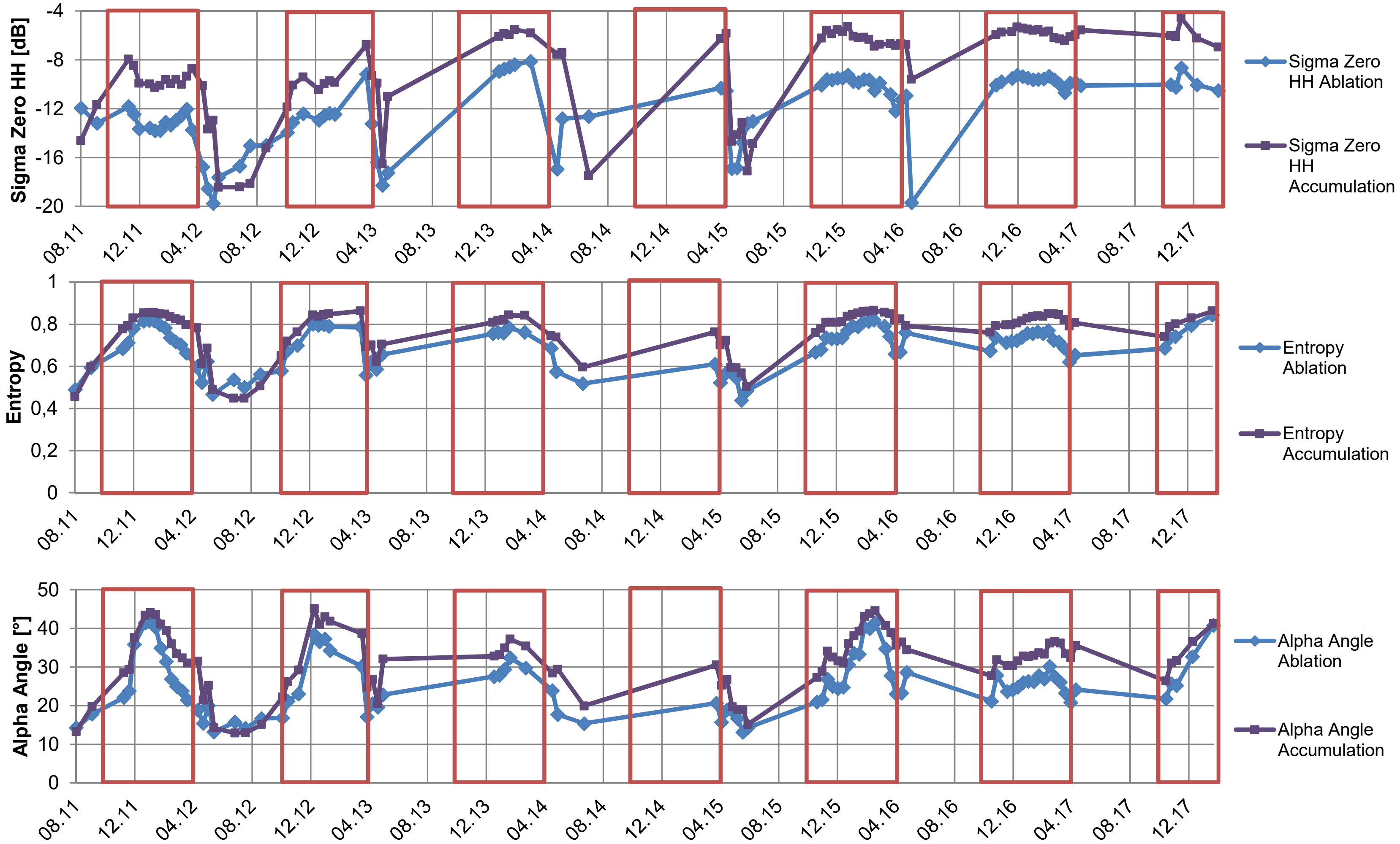




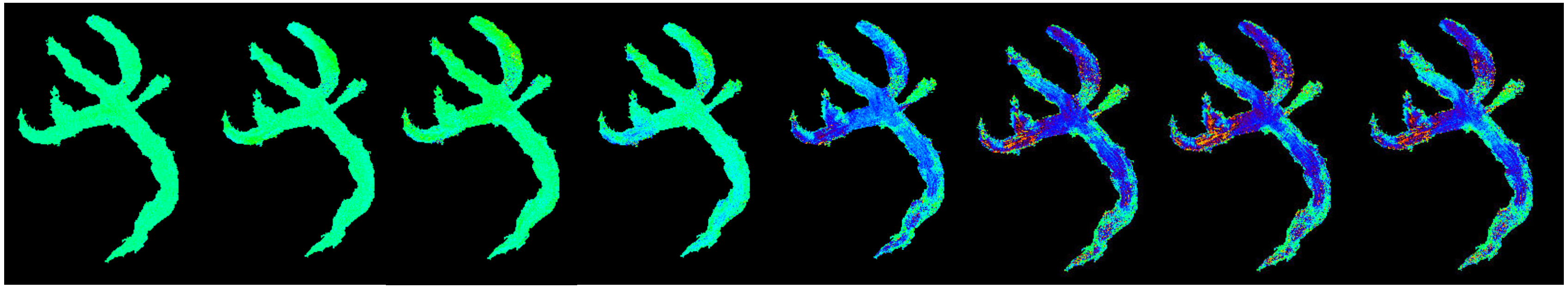




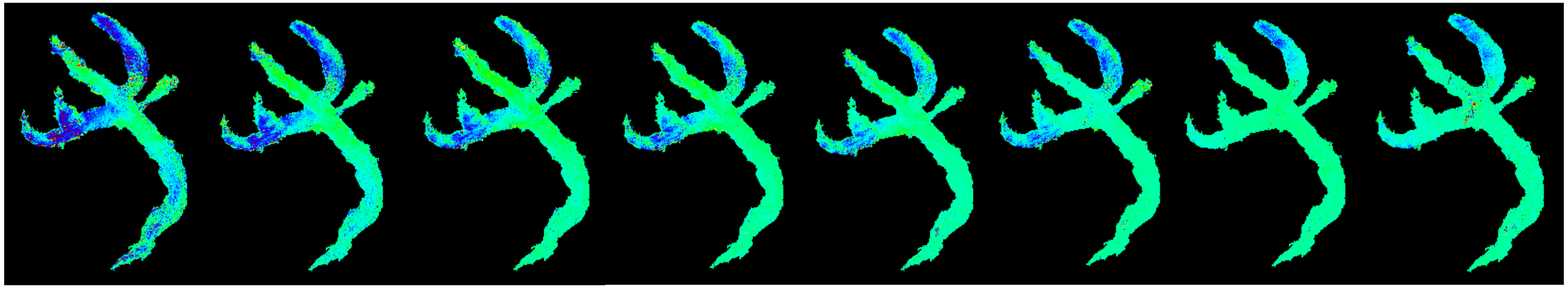
Polarimetric Analysis: Interannual Dynamics of Glacier Zones



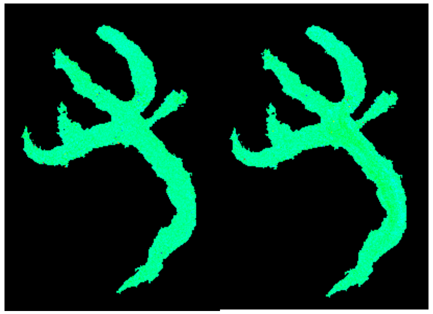
Polarimetric Phase Diff. and Snow Accumulation



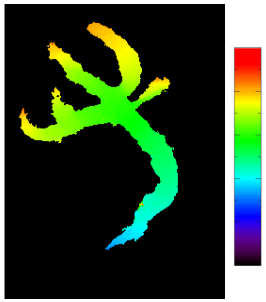
21. Aug 2011 | 23. Sep 2011 | 28. Nov 2011 | 09. Dec 2011 | 20. Dec 2011 | 11. Jan 2012 | 22. Jan 2012 | 02. Feb 2012



24. Feb 2012 | 06. Mar 2012 | 17. Mar 2012 | 28. Mar 2012 | 08. Apr 2012 | 30. Apr 2012 | 11. May 2012 | 22. May 2012

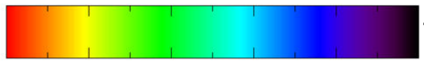


02. Jun 2012 | 16. Jul 2012



✓ Polarimetric Phase difference ϕ_{VV-HH}

$$\phi_{VV-HH} = \angle(<S_{VV}S_{HH}^{*}>)$$



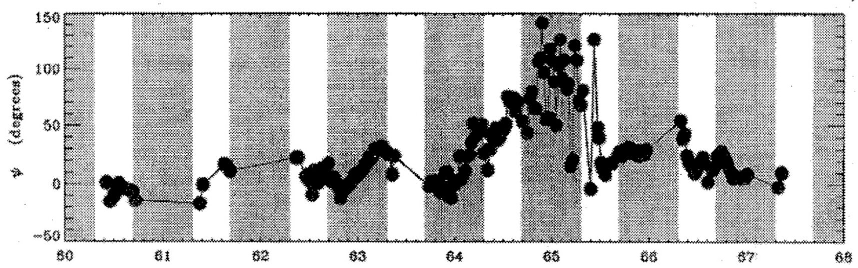
Irena Hajnsek, PolinSAR Training Course, 15.06.2023 – irena.hajnsek@dlr.de

Why is snow depth proportional to (ϕ_{VV} - ϕ_{HH})?

DLR

- Fresh snow causes the highest phase differences
  -> Also observed by [Chang, 1993] at 95 GHz.

  Chang, P. et al. «Polarimetric backscatter from fresh and metamorphic snowcover at millimeter wavelengths», *IEEE Transactions on Antennas and Propagation, ,* **1996**, *44*



- Oriented particles within a volume cause polarization dependent propagation speeds [Cloude, 2000], [Parrella, 2013] & [Leinss, 2016].

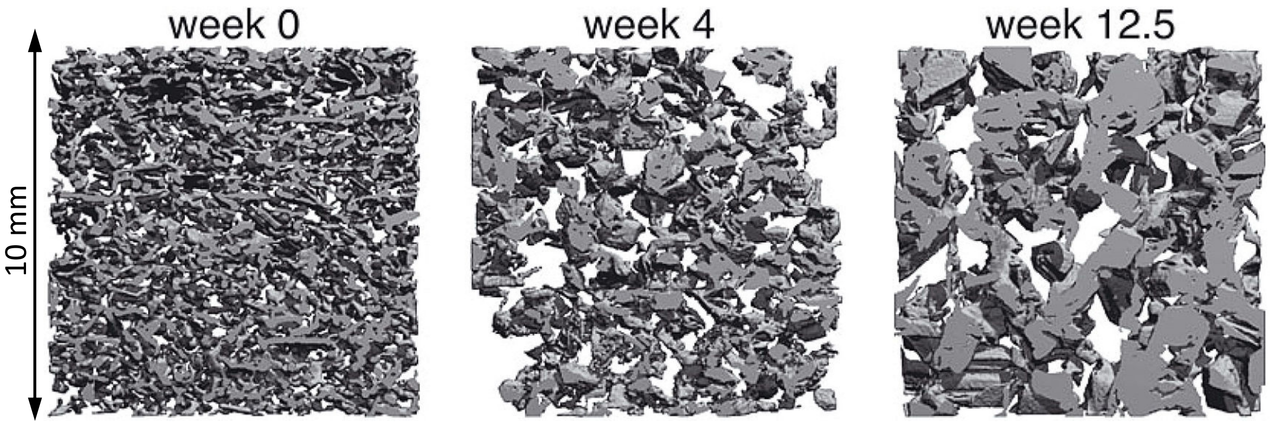
  Cloude et al. «The Remote Sensing of Oriented Volume Scattering Using Polarimetric Radar Interferometry.», *Proceedings of ISAP,* Fukuoka, Japan, **2000**.

  Parrella, G. "On the Interpretation of L- and P-band PolSAR Signatures of Polithermal Glaciers", *POLInSAR, **2013***
  Leinss, S***. "***Anisotropy of seasonal snow measured by polarimetric phase differences in radar time series. *The Cryosphere **2016"***

- Recrystallization of snow changes the shape and orientation of ice grains in a snow cover driven by a vertical temperature gradient. [Riche, 2013]

  Riche, F. et al. "Evolution of crystal orientation in snow during temperature gradient metamorphism", *Journal of Glaciology,* **2013**, *59*, 47-55

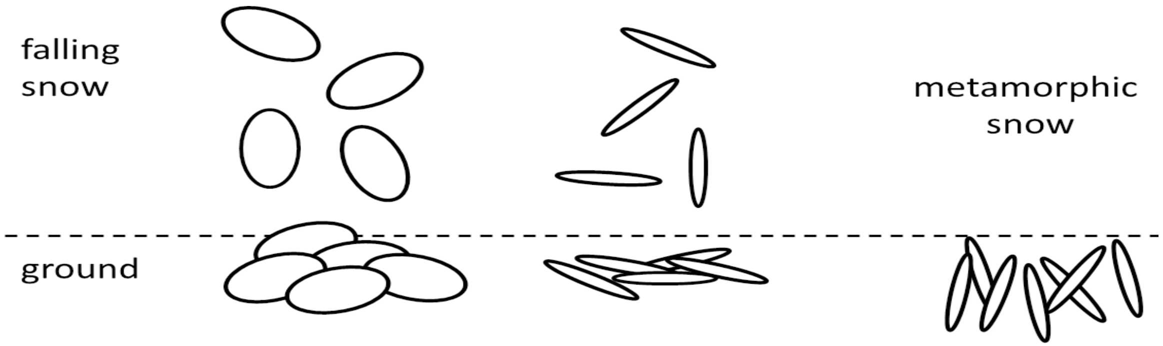
Why is snow depth proportional to ($\phi_{VV} - \phi_{HH}$)?



Riche, F. et al. “Evolution of crystal orientation in snow during temperature gradient metamorphism”, *Journal of Glaciology*, **2013**, *59*, 47-55

> 11 recrystallization cycles after 12 weeks.

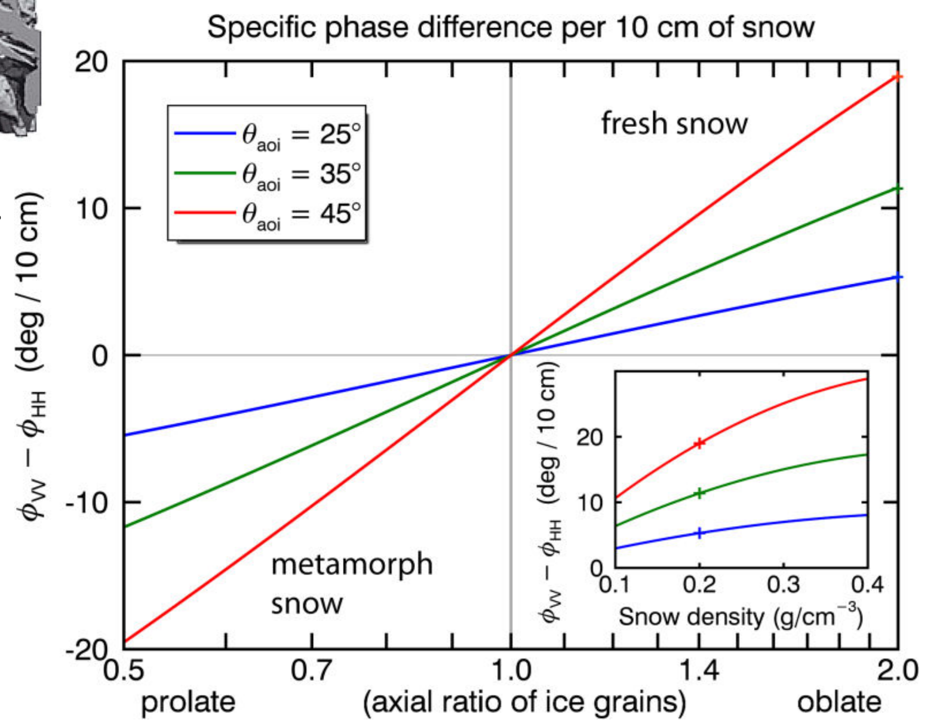
Simplification for model:



horizontally extended

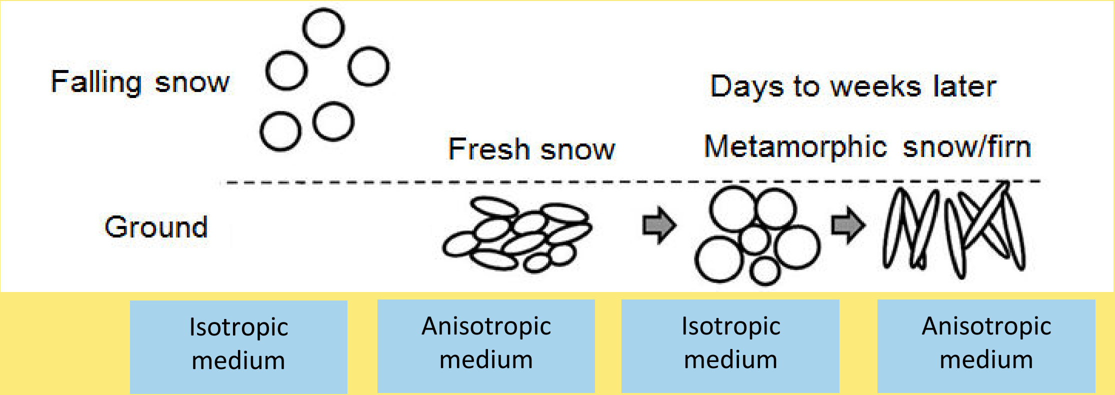
Vertically extended

Recrystallization speed depends on temp. gradient dT/dz



Parrella, G. “On the Interpretation of L- and P-band PolSAR Signatures of Polithermal Glaciers”, *POLinSAR* ***2013***

Propagation Model to Invert Snow Accumulation

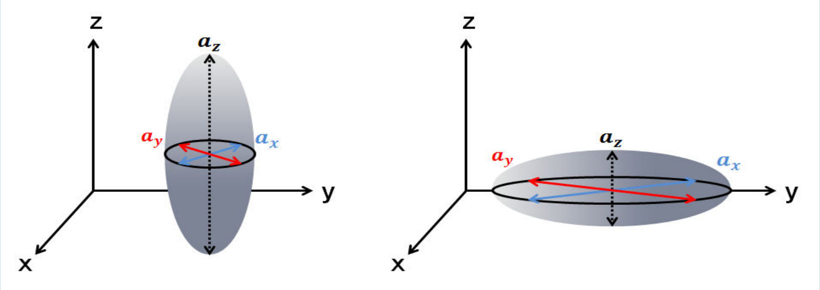


Modelling anisotropic snow

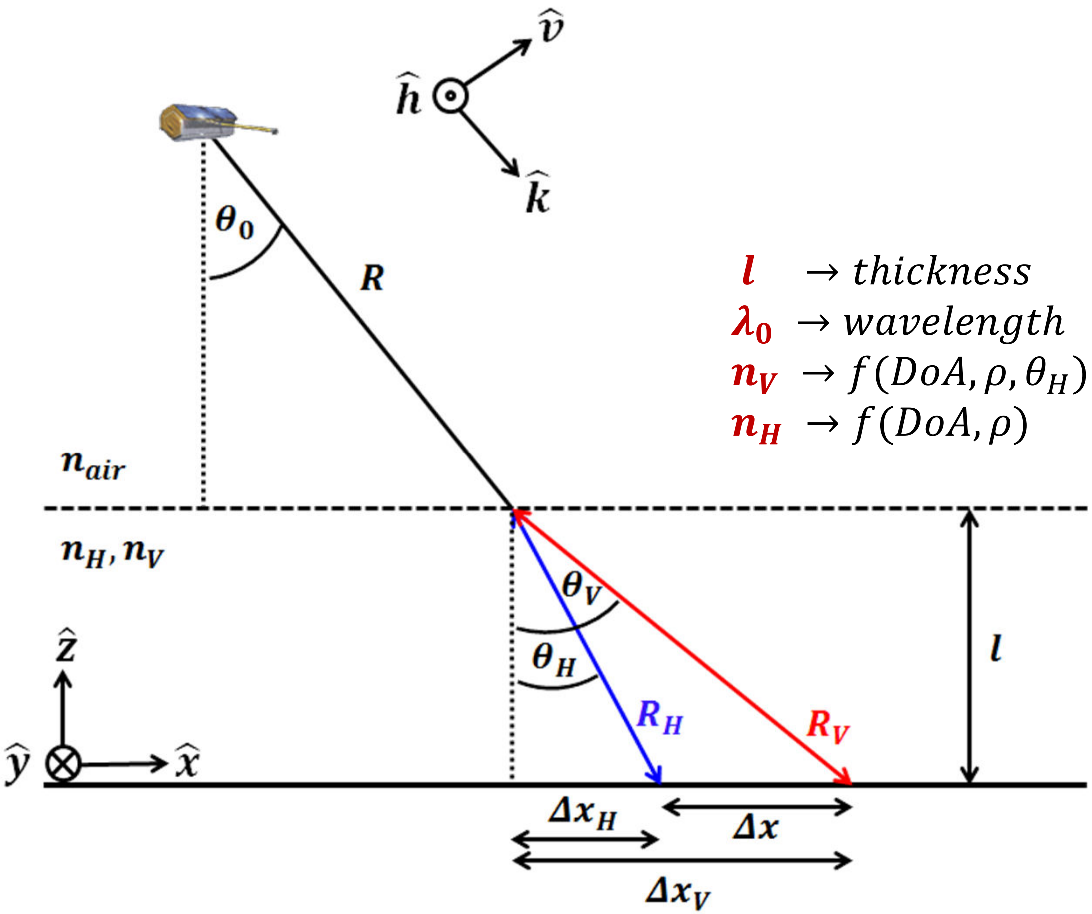
- ✓ Two phase mixture of air and ice inclusions
- ✓ Spheroidal grains described by degree of anisotropy $DoA = \frac{a_z}{a_x}$
- ✓ Effective permitivity components depend on DoA and volume fraction (density)

$$\varepsilon_{eff,x,y,z} = \varepsilon_{air} + \varphi_{vol}\varepsilon_{air}\frac{\varepsilon_{ice}-\varepsilon_{air}}{\varepsilon_{air}+(1-\varphi_{vol})N_{x,y,z}(\epsilon_{ice}-\varepsilon_{air})}$$

- ✓ Refractive indices $n_{x,y}$ and n_z ($n^2 = \varepsilon_r$)



Propagation Model to Invert Snow Accumulation



$l \rightarrow thickness$
$\lambda_0 \rightarrow wavelength$
$n_V \rightarrow f(DoA, \rho, \theta_H)$
$n_H \rightarrow f(DoA, \rho)$

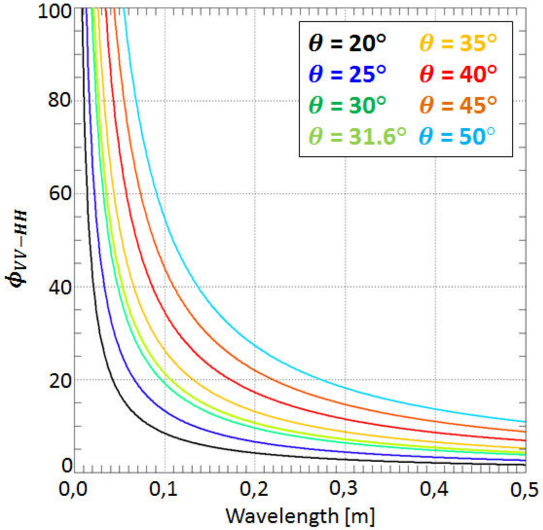
- ✓ Transformation from **(x,y,z) → (H,V)** coordinate system
- ✓ H component $n_H = n_{x,y}$
- ✓ V component $n_V = \sqrt{n_x^2 cos^2\theta_H + n_z^2 sin^2\theta_H}$

$$\phi_{VV-HH} = 2\frac{2\pi}{\lambda_0}(n_V \boldsymbol{R_V} - n_H \boldsymbol{R_H})$$

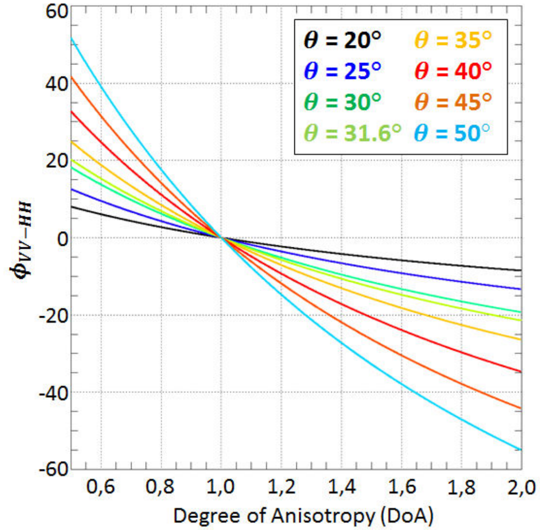
$$R_V = \frac{\cos\theta_V}{l} \qquad R_H = \frac{\cos\theta_H}{l}$$

$$\boldsymbol{\phi_{VV-HH}} = 2\frac{2\pi \cdot \boldsymbol{l}}{\boldsymbol{\lambda}_0}\left(\frac{\boldsymbol{n_V}}{\cos\theta_V} - \frac{\boldsymbol{n_H}}{\cos\theta_H}\right)$$

Propagation Model: Sensitivity Analysis

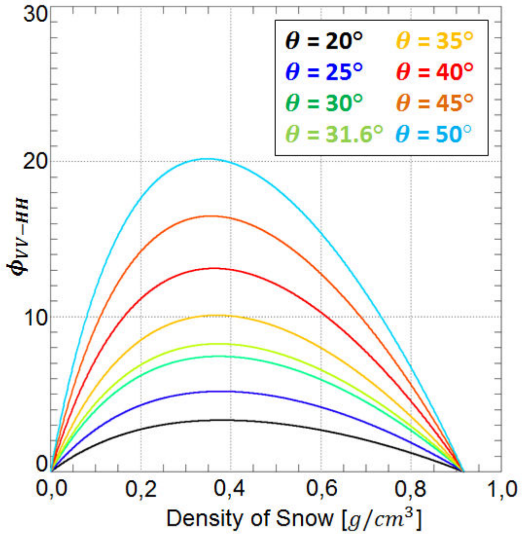


- ✓ Sensitivity increases with frequency

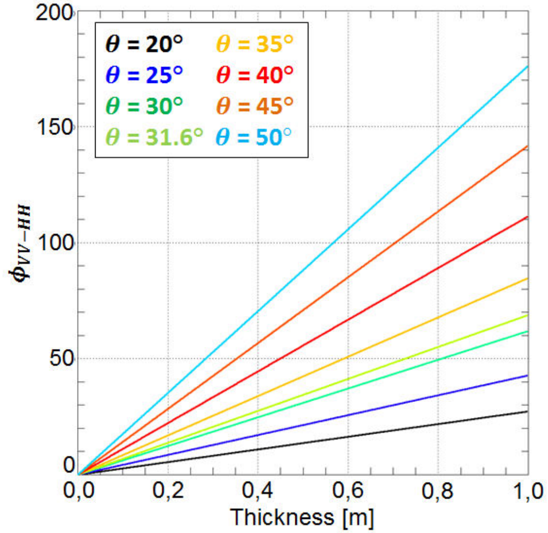


$\rho = 0{,}2\ g/cm^3$
$DoA = 0{,}8$
$l = 0{,}1m$
$\lambda = 0{,}031m$

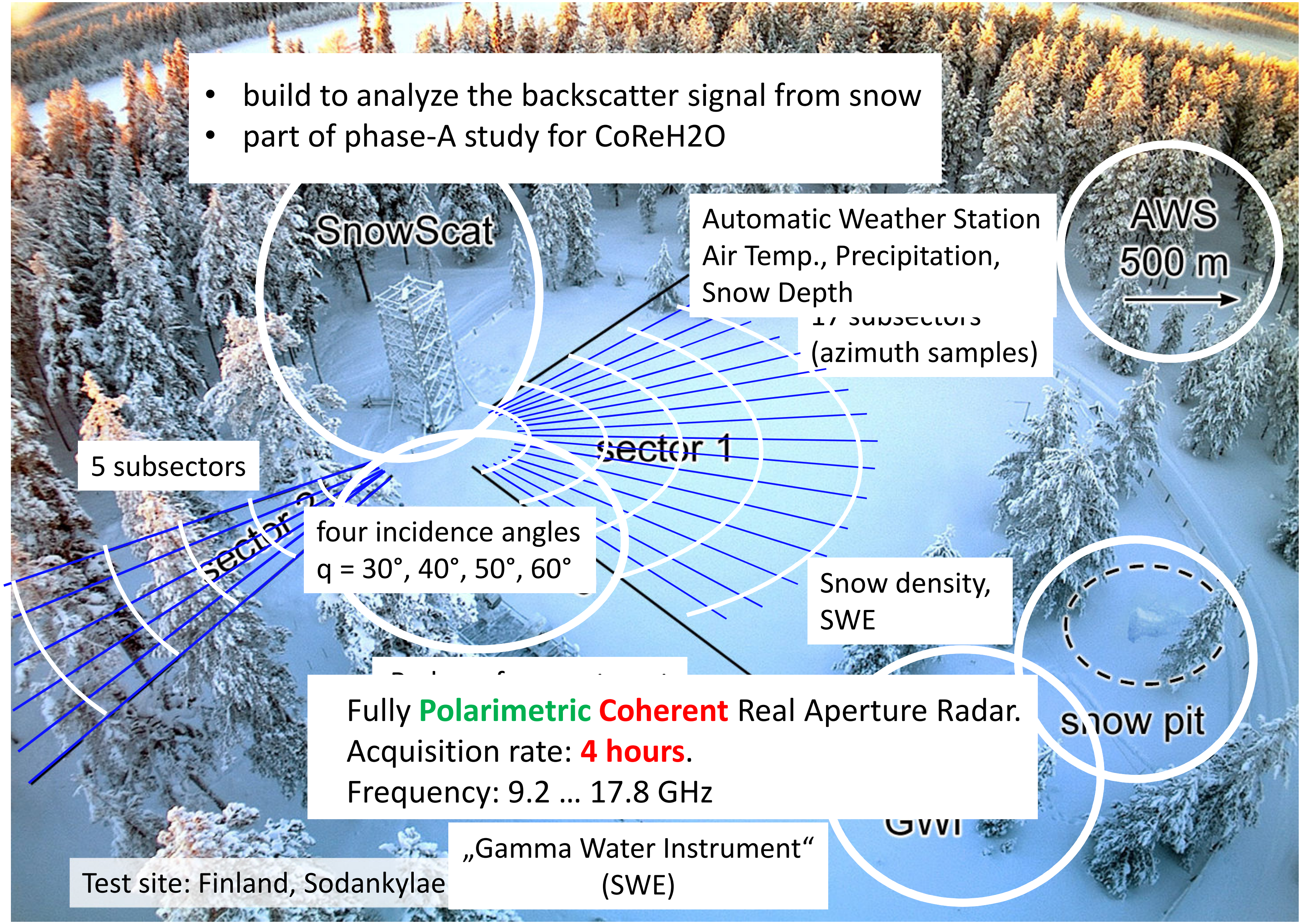
- ✓ More sensitive for higher anisotropy



- ✓ Increasing until medium is too dense



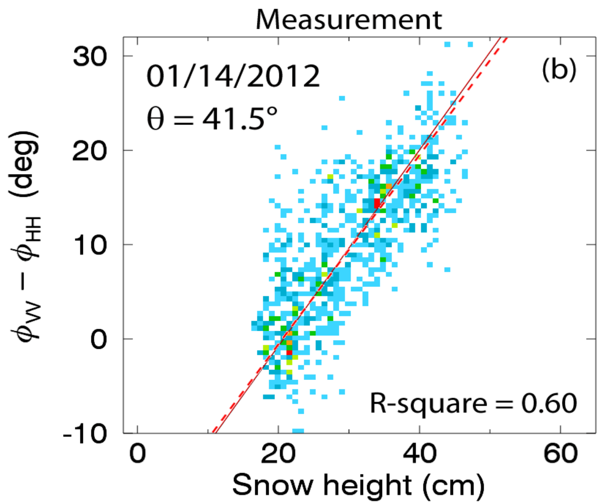
- ✓ Linear dependency on thickness

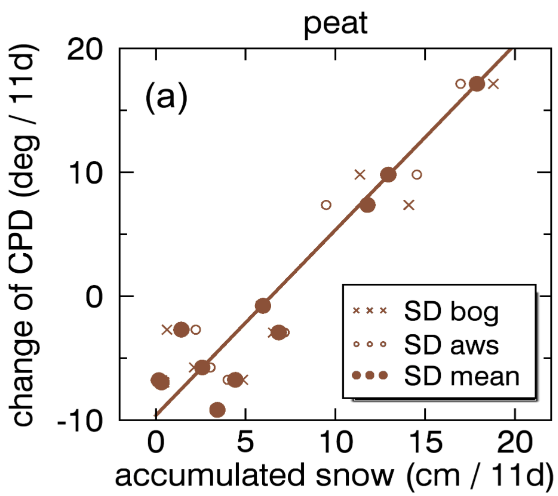


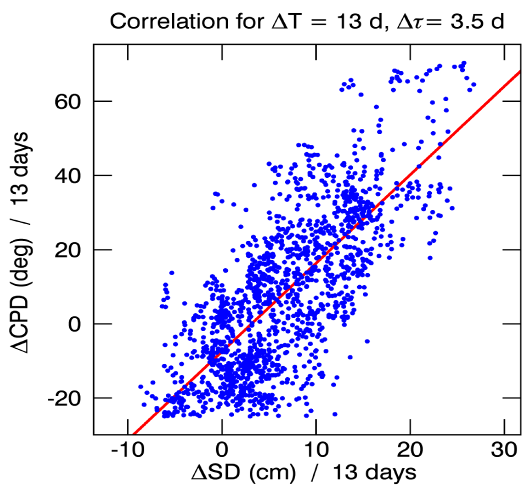
- build to analyze the backscatter signal from snow
- part of phase-A study for CoReH2O
SnowScat
Automatic Weather Station
Air Temp., Precipitation,
Snow Depth
AWS
500 m
(azimuth samples)
sector 1
5 subsectors
four incidence angles
q = 30°, 40°, 50°, 60°
Snow density,
SWE
snow pit
Fully Polarimetric Coherent Real Aperture Radar.
Acquisition rate: 4 hours.
Frequency: 9.2 … 17.8 GHz
„Gamma Water Instrument“
(SWE)
Test site: Finland, Sodankylae

Detection of Fresh Snow

The anisotropic character of fresh snow can be used to determine the amout of fresh snow within the last few days.



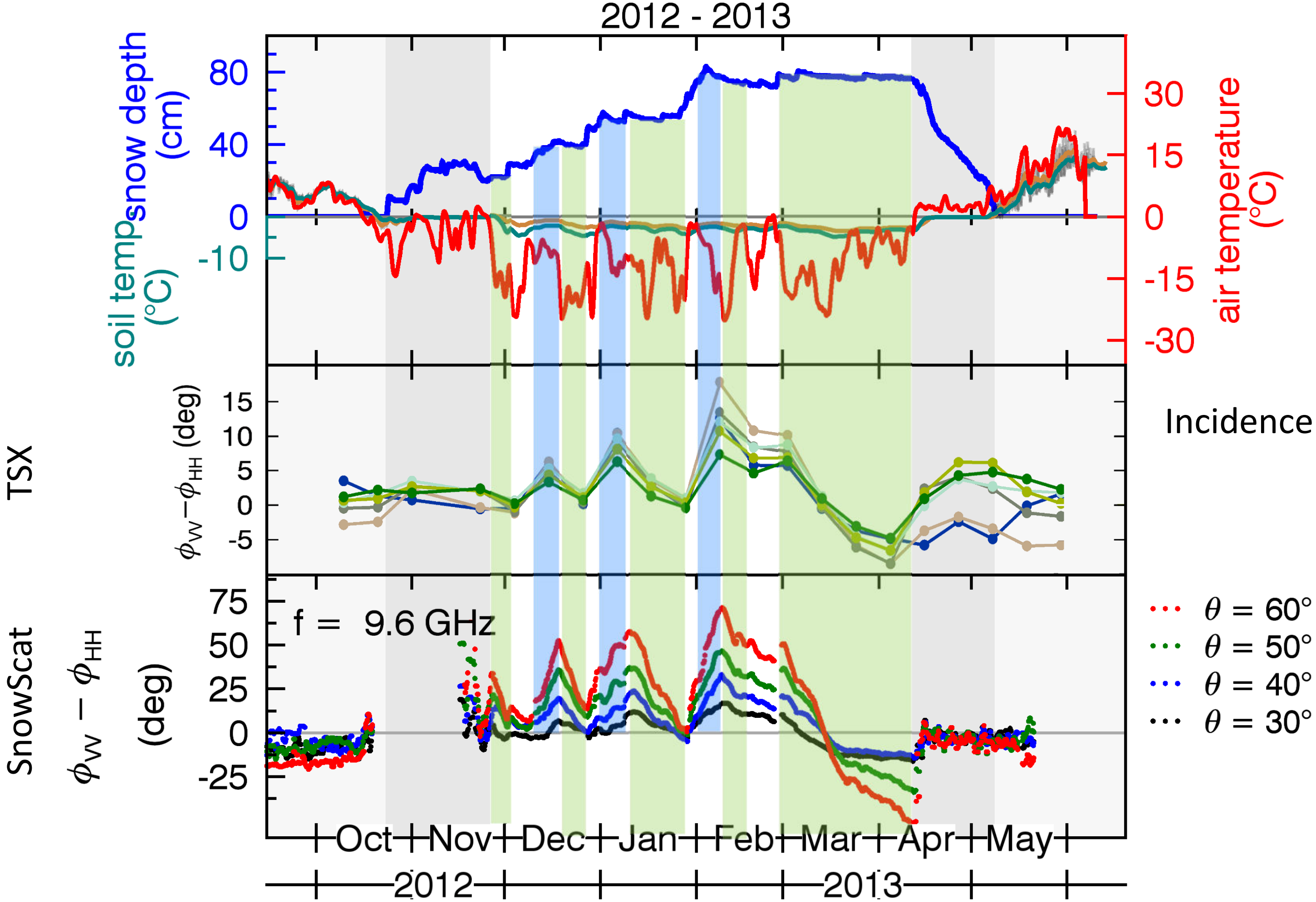




- TerraSAR-X:
  Total snow height after 30 days of snowfall (spatial correlation)
- TerraSAR-X:
  Change of snow height within 11 days (temporal correlation)
- SnowScat:
  Change of snow height within 13 days. (temporal correlation)

Leinss et al., «Snow Height Determination by Polarimetric Phase Differences in X-Band SAR Data» JSTARS vol. 7, no.7 (2014)

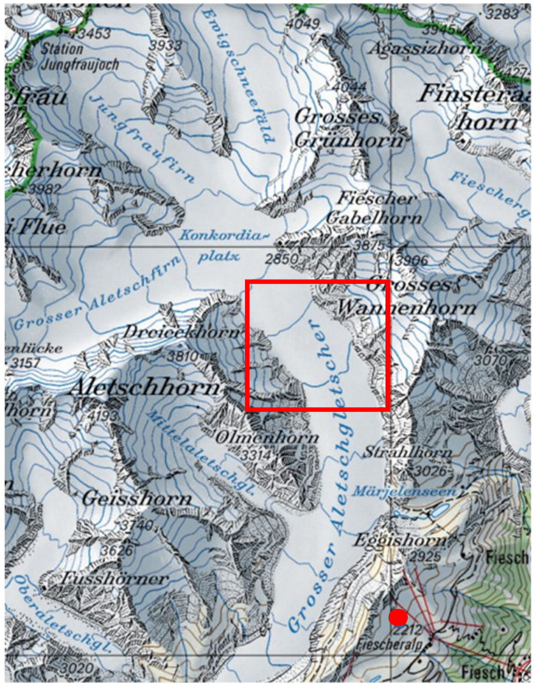
Time series: TSX and SnowScat



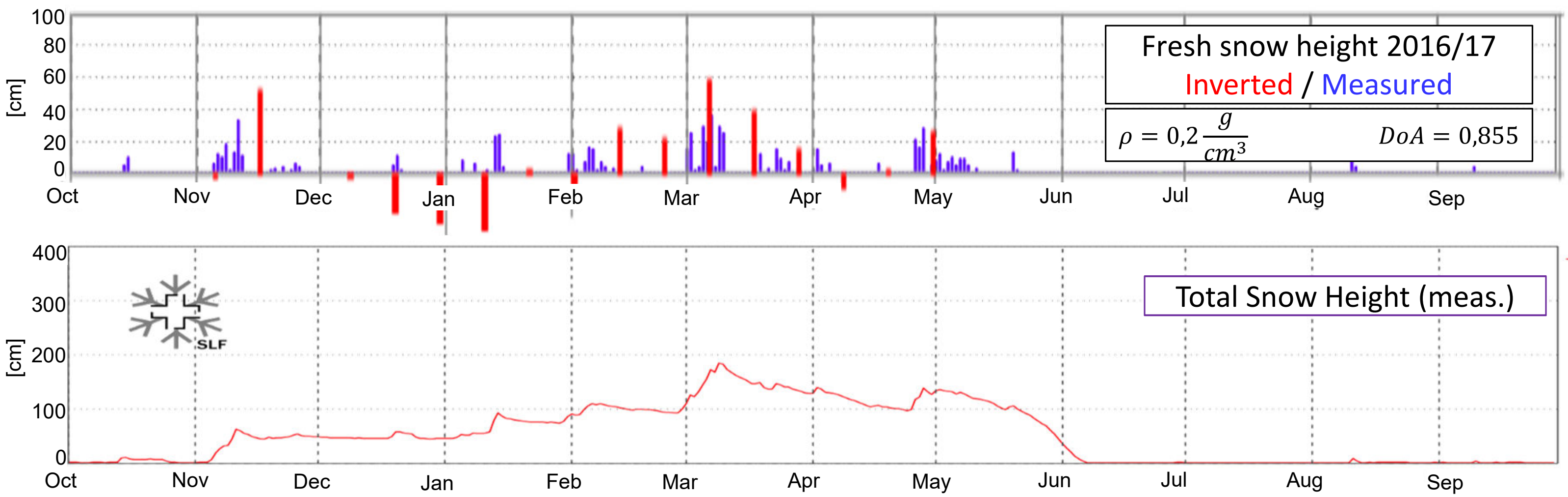
Incidence Angle = 33°

SnowScat shows same result, but with > 50x better temporal resolution

Available Ground Measurements

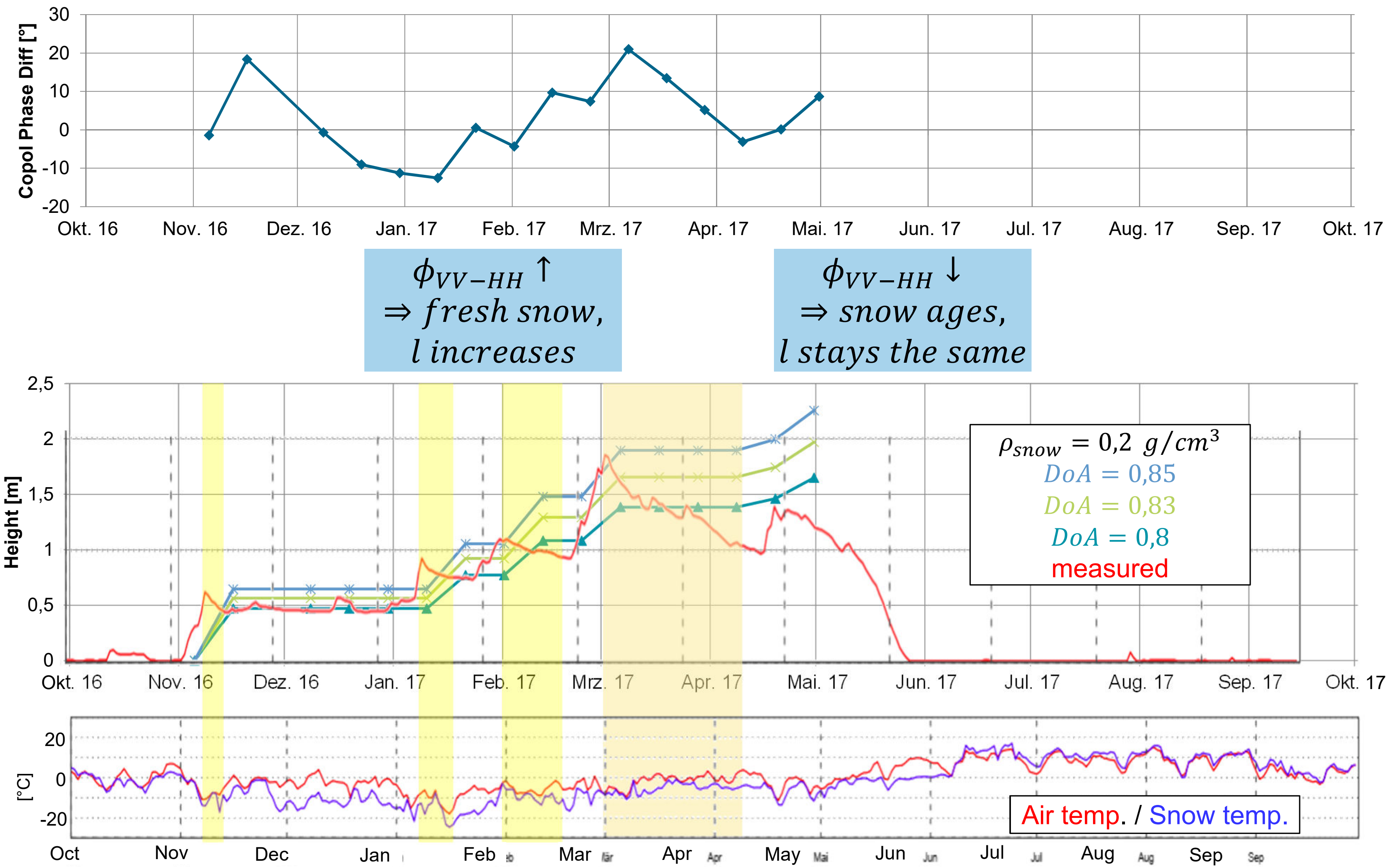


- ✓ With ϕ_{VV-HH} and Propagation Model the aim is to monitor snow accumulation of the Aletsch Glacier
- ✓ Ground measurements provided by the Institute for Snow and Avalanche Research (SLF)
- ✓ Automatic station at 2500 m provides:
  - ✓ Fresh snow height
  - ✓ Total snow height (daily)
  - ✓ Wind speed and direction
  - ✓ Air and snow surface temperature

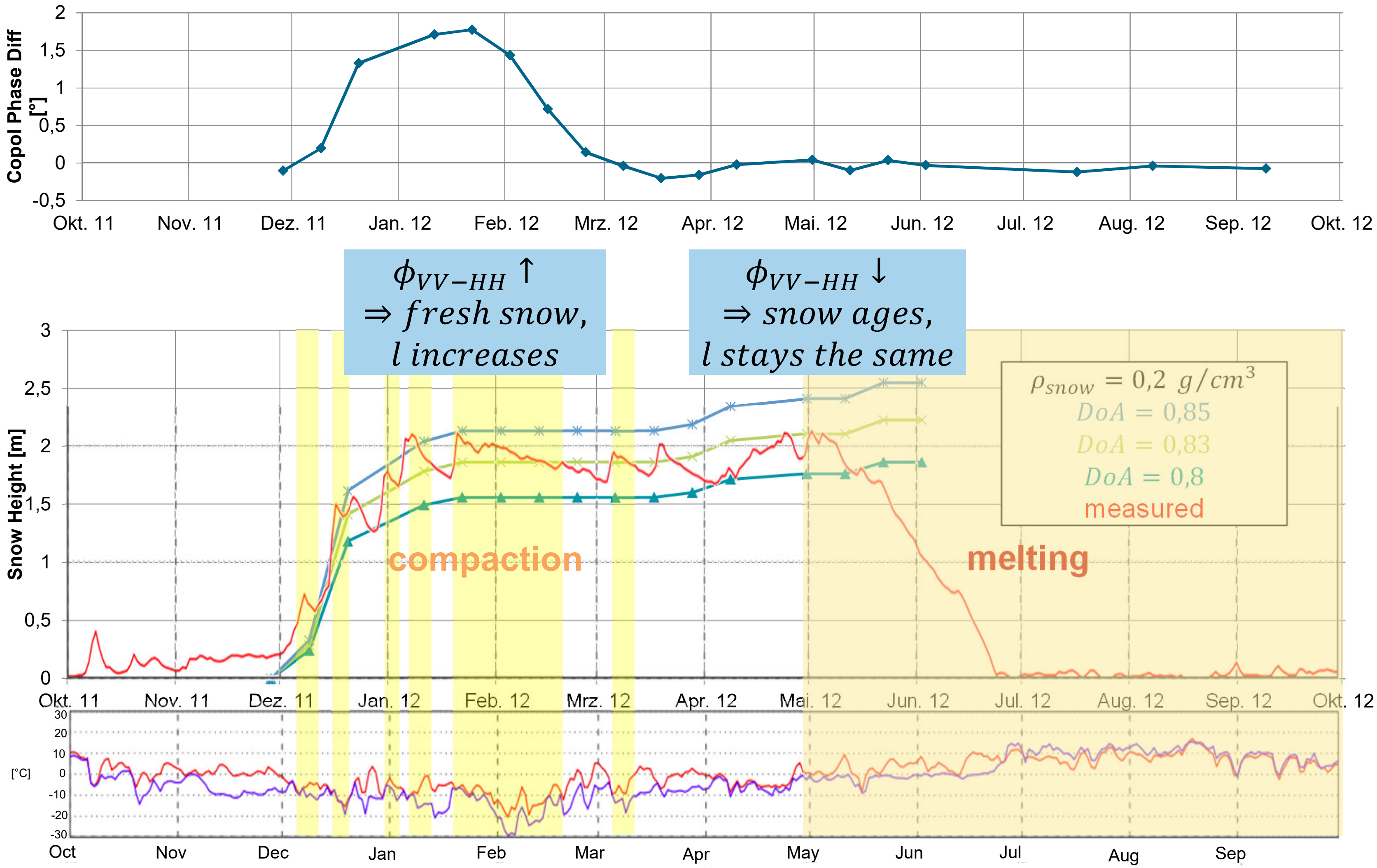


Inversion of Total Snow Height (2016-17)

DLR



Tentative Total Snow Height Estimation (2011-12)



Limitations of Snow Height Estimation Approach

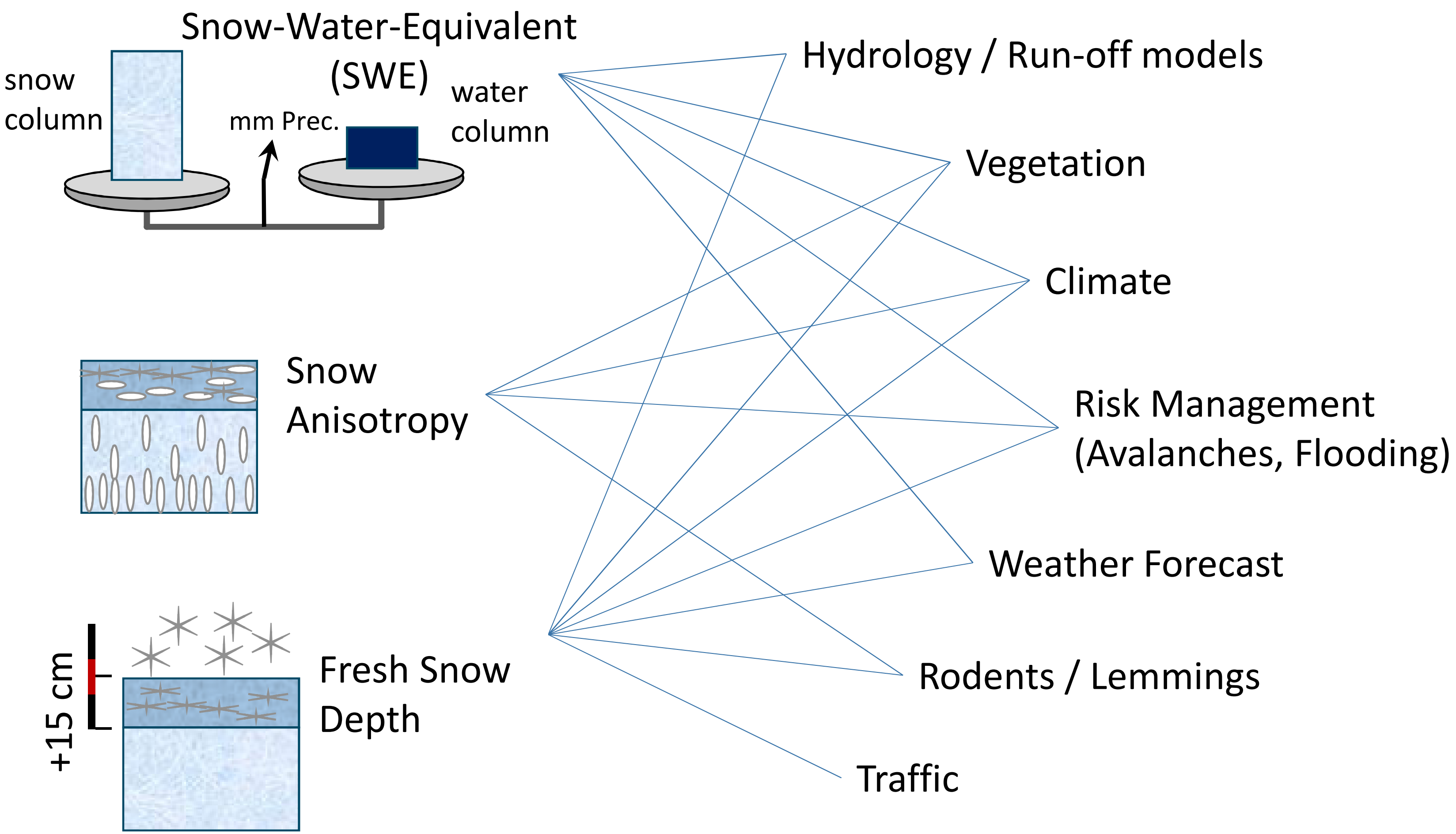
Snow Melting if T > 0°C

- ✓ Snow melting dependent on several parameters
  - ✓ **Temperature**
  - ✓ **Snowpack density**
  - ✓ **Rain**
  - ✓ **Mass of the snowpack**

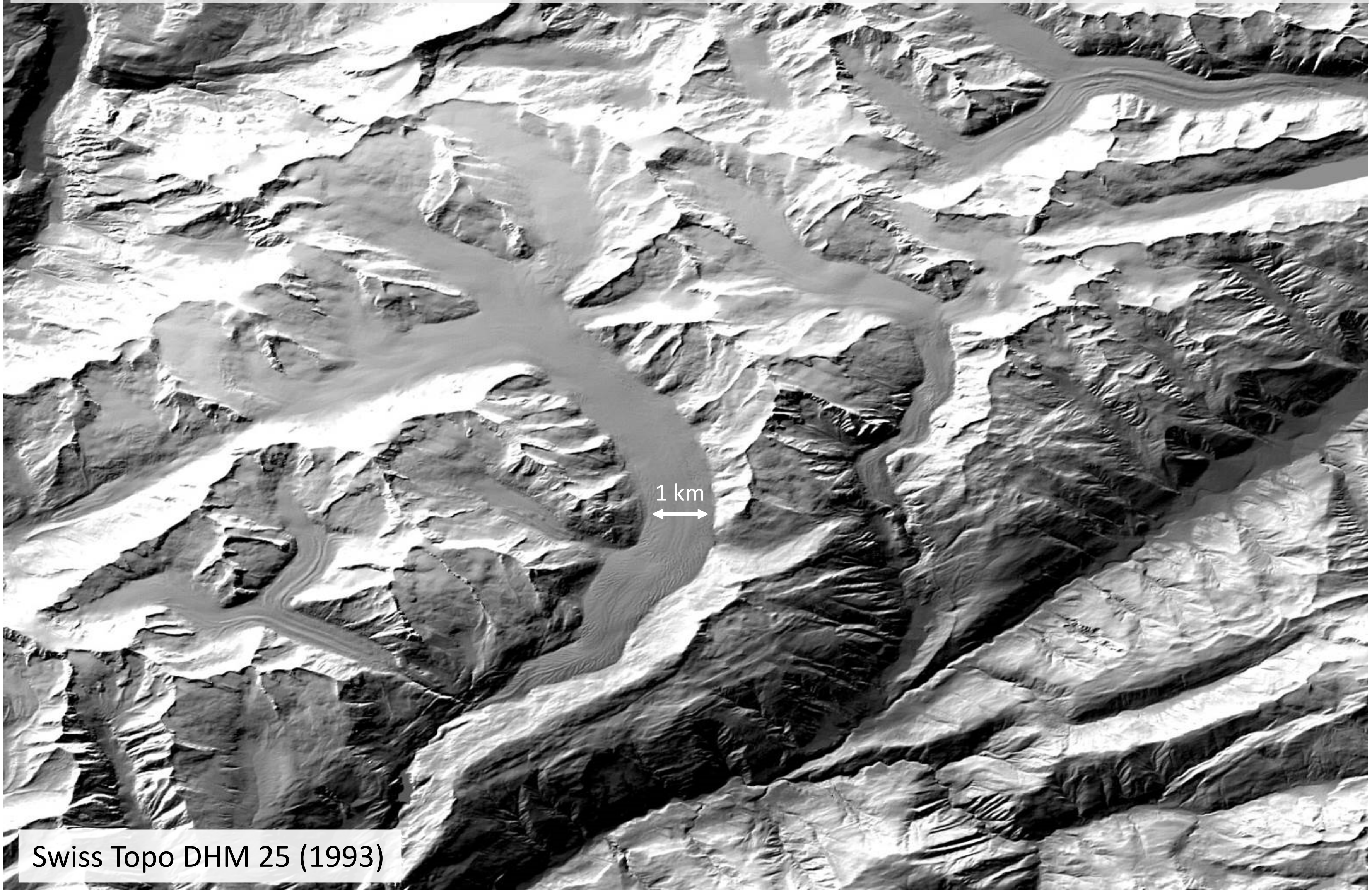
Snow Compaction over Time

- ✓ Snow drift (wind changes density)
- ✓ Snow metamorphism (grains change shape and orientation)
- ✓ Deformation strain (snow compression by its own weight)

Why are snow parameters important?

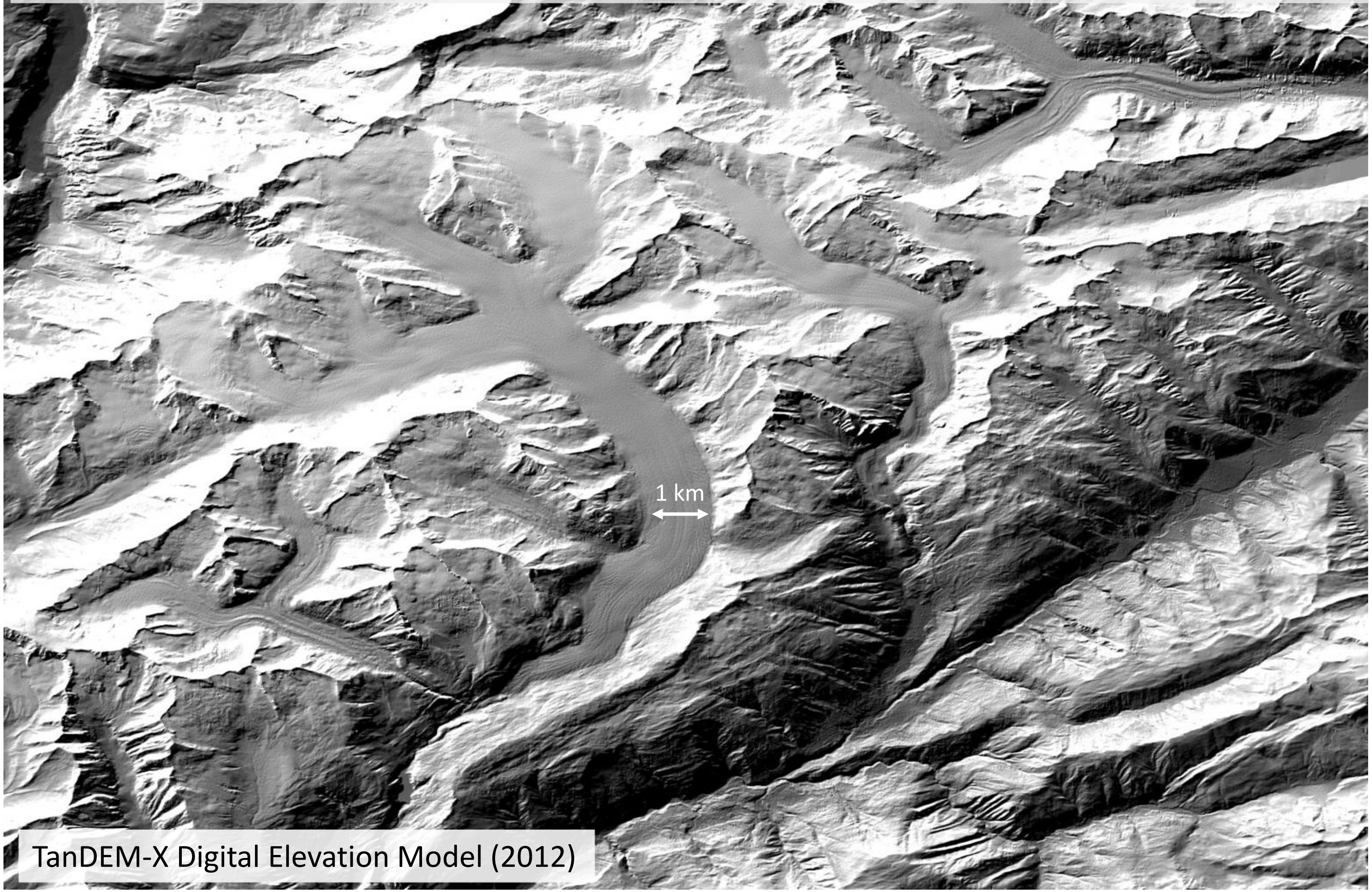


Great Aletsch Glacier: Mass loss estimated with a DEM



Swiss Topo DHM 25 (1993)

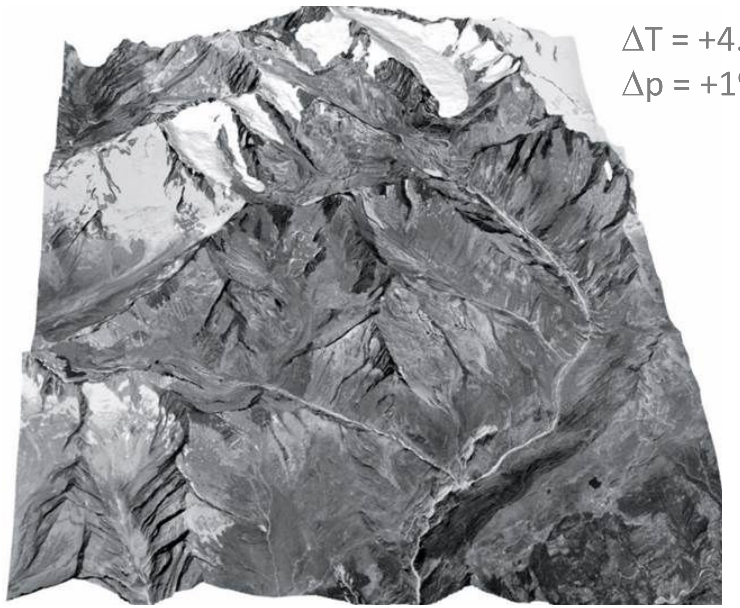
Great Aletsch Glacier: Mass loss estimated with a DEM



TanDEM-X Digital Elevation Model (2012)

Modeled glacier evolution until 2100

initial state (1999)

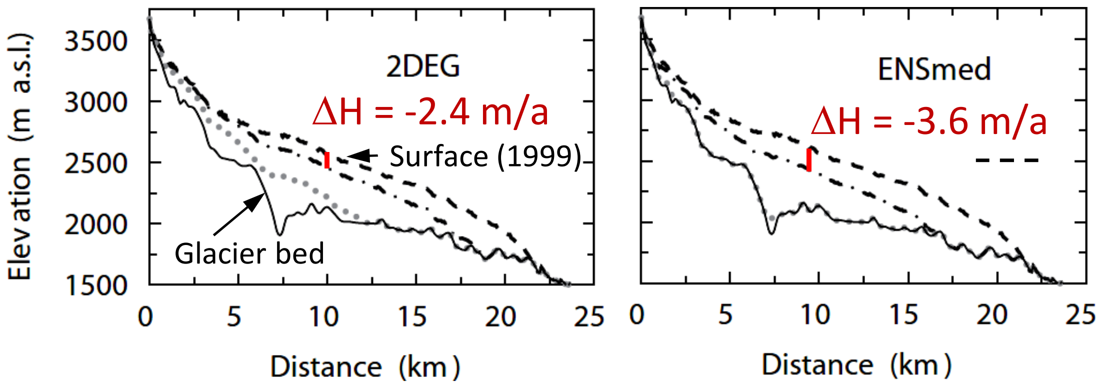


Folisticab2DEGed (2100)

ΔT = +4.4°,
Δp = +1%

Jouvet et al. J. Glac. (2011)

- 3D glacier dynamic model.
- Calibrated with climate data and field observations from 1880 - 1999.
- Forced by different climate scenarios.

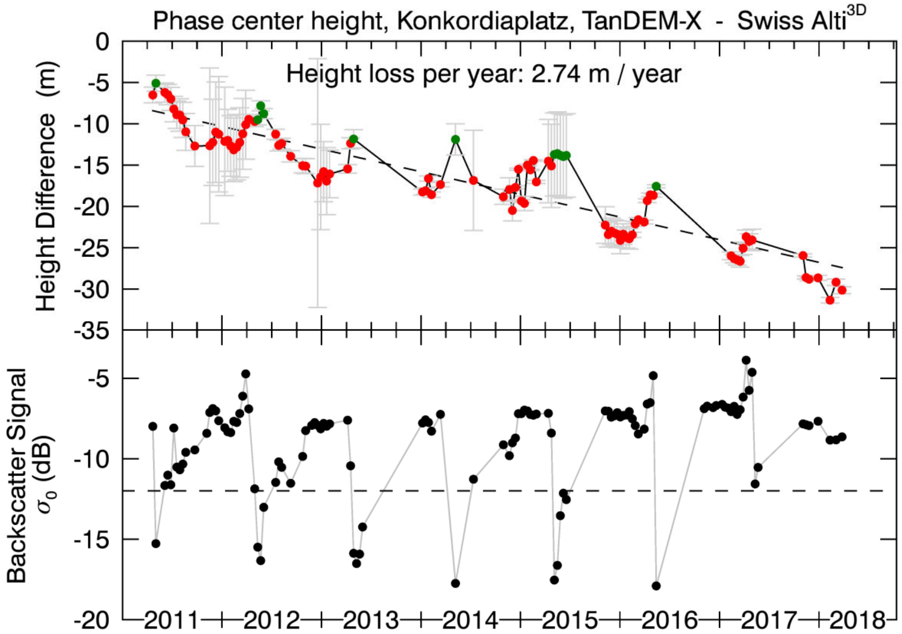


Surface elevation: 1999, 2050, 2100

Height loss of Aletschgletscher 2011 - 2018

TanDEM-X vs. SwissAlti3D (2009)

08.11.2015



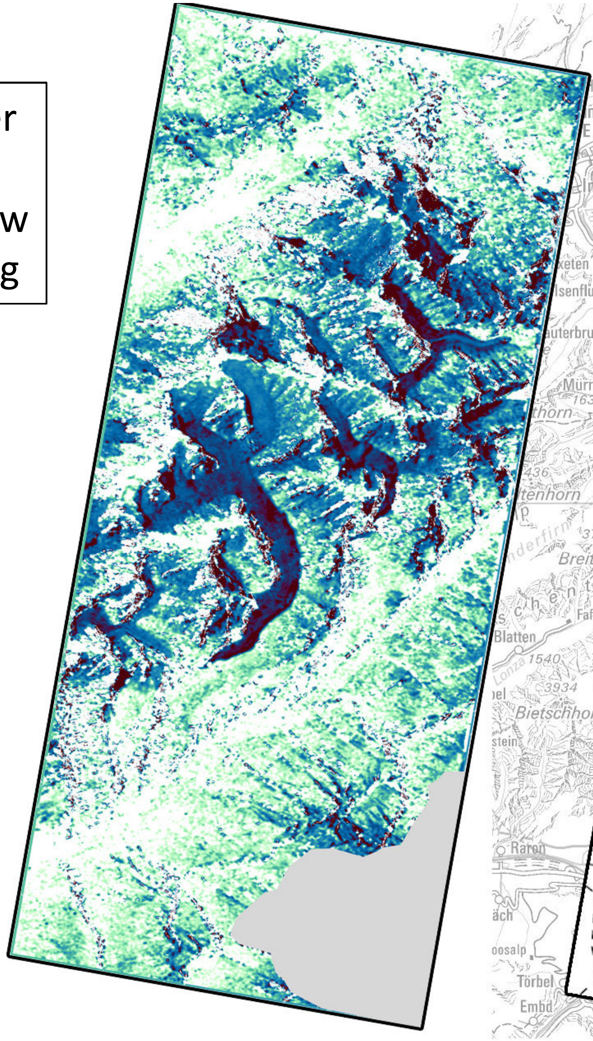
- Agreement with results of climate scenarios:
  DEG2: -2.1 m / year (political aim)
  ENSmed: -3.6 m / year (business as usual)

- Periodic seasonal changes
- Height increase at the onset of snow melt (wet snow detected by low backscatter)

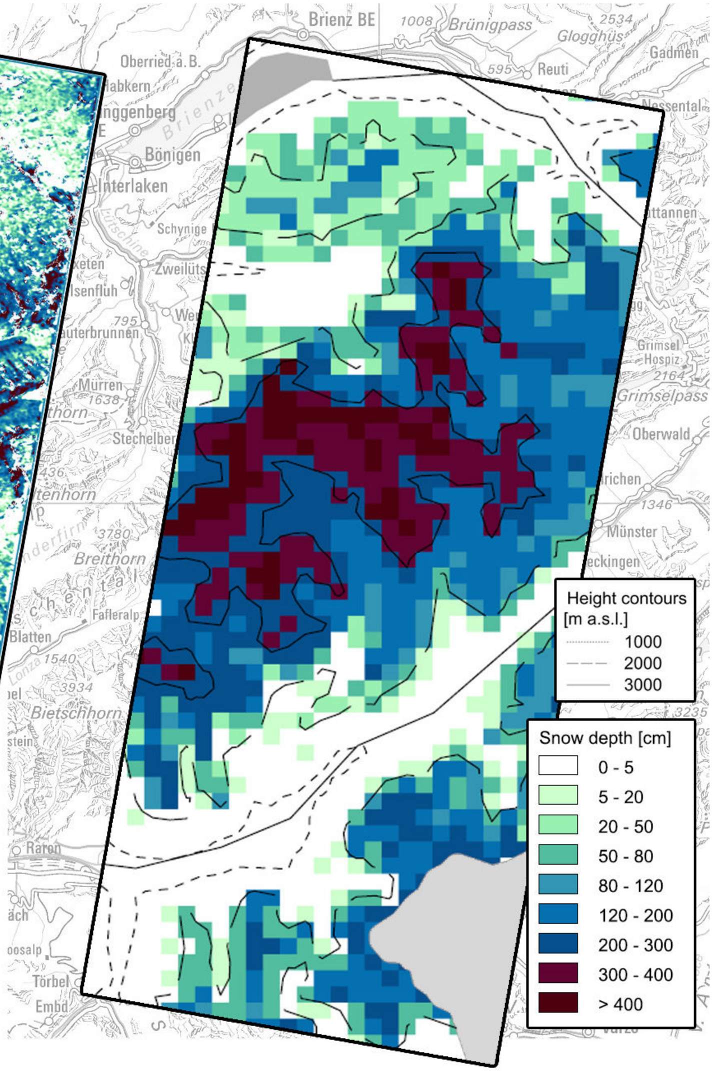
L. Leinss

Snow Depth determined by DEM Differencing

summer
vs.
wet snow
in spring



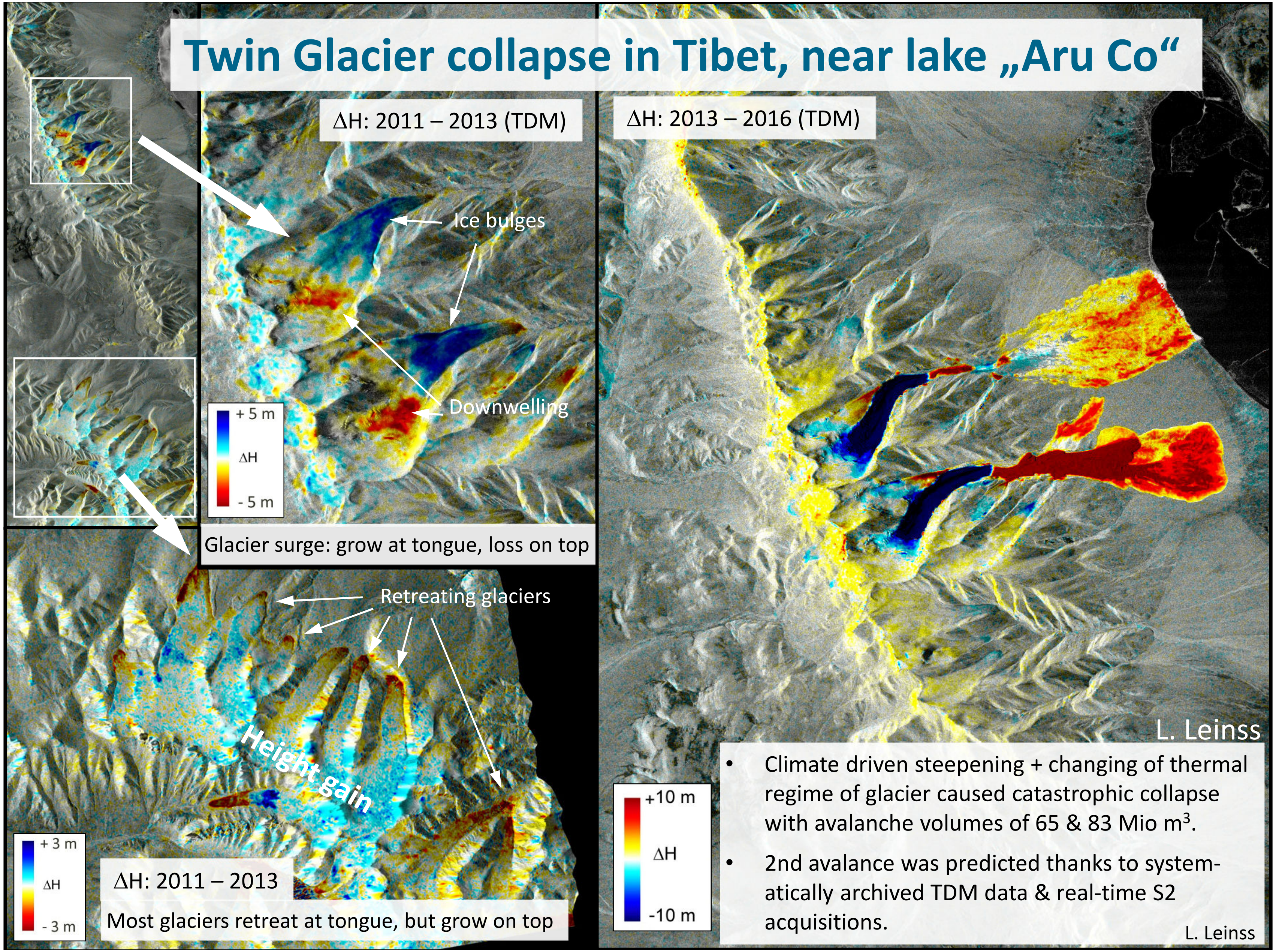
TanDEM-X elevation difference,
02.06.2012 vs. 27.07.2012



SLF, snow depth map, 31.05.2012

L. Leinss

Twin Glacier collapse in Tibet, near lake „Aru Co“



- Climate driven steepening + changing of thermal regime of glacier caused catastrophic collapse with avalanche volumes of 65 & 83 Mio m^3.
- 2nd avalance was predicted thanks to systematically archived TDM data & real-time S2 acquisitions.

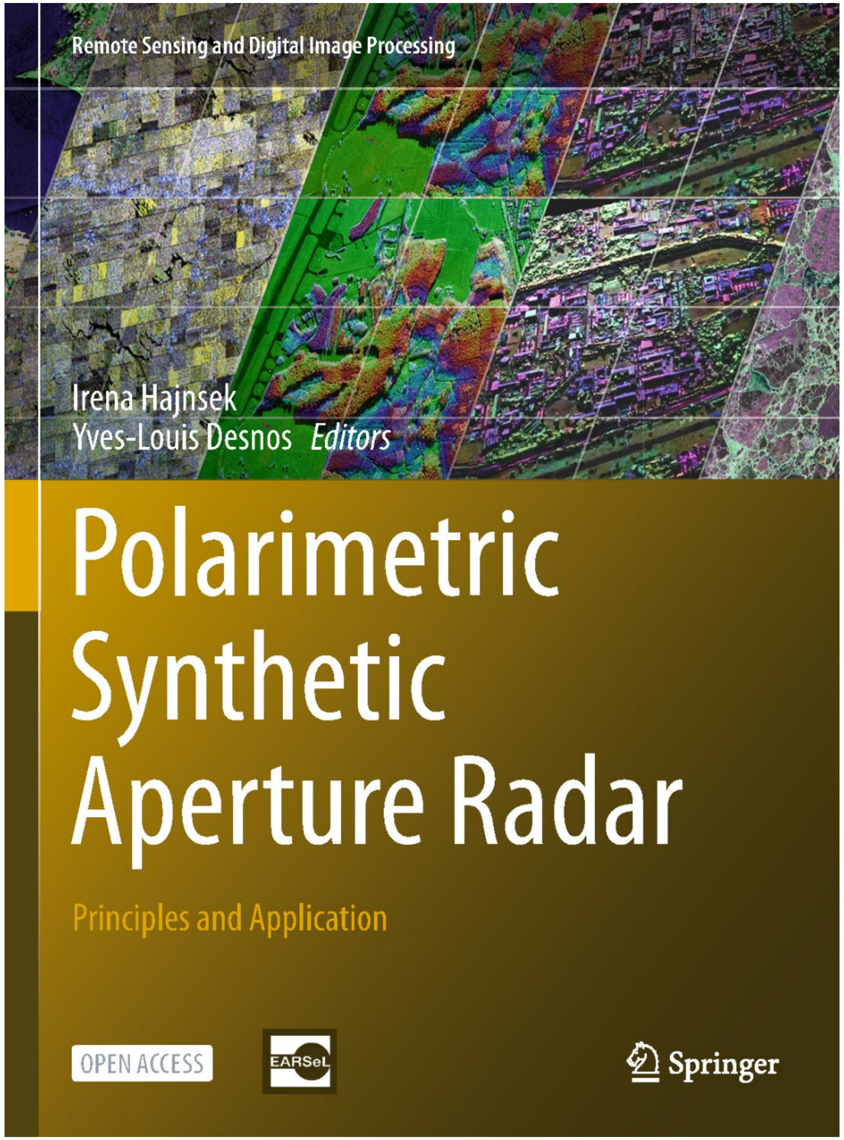
L. Leinss

Polarimetric Applications

https://link.springer.com/book/10.1007%2F978-3-030-56504-6

Open Access Book

- Basic Principles of SAR Polarimetry
- Forest Applications
- Agriculture Wetland Applications
- Cryosphere Applications
- Urban Applications
- Ocean Applications



DLR

I am happy to answer your question?