PolinSAR Training Course 2026

Application: Snow Height Estimation

Irena Hajnsek

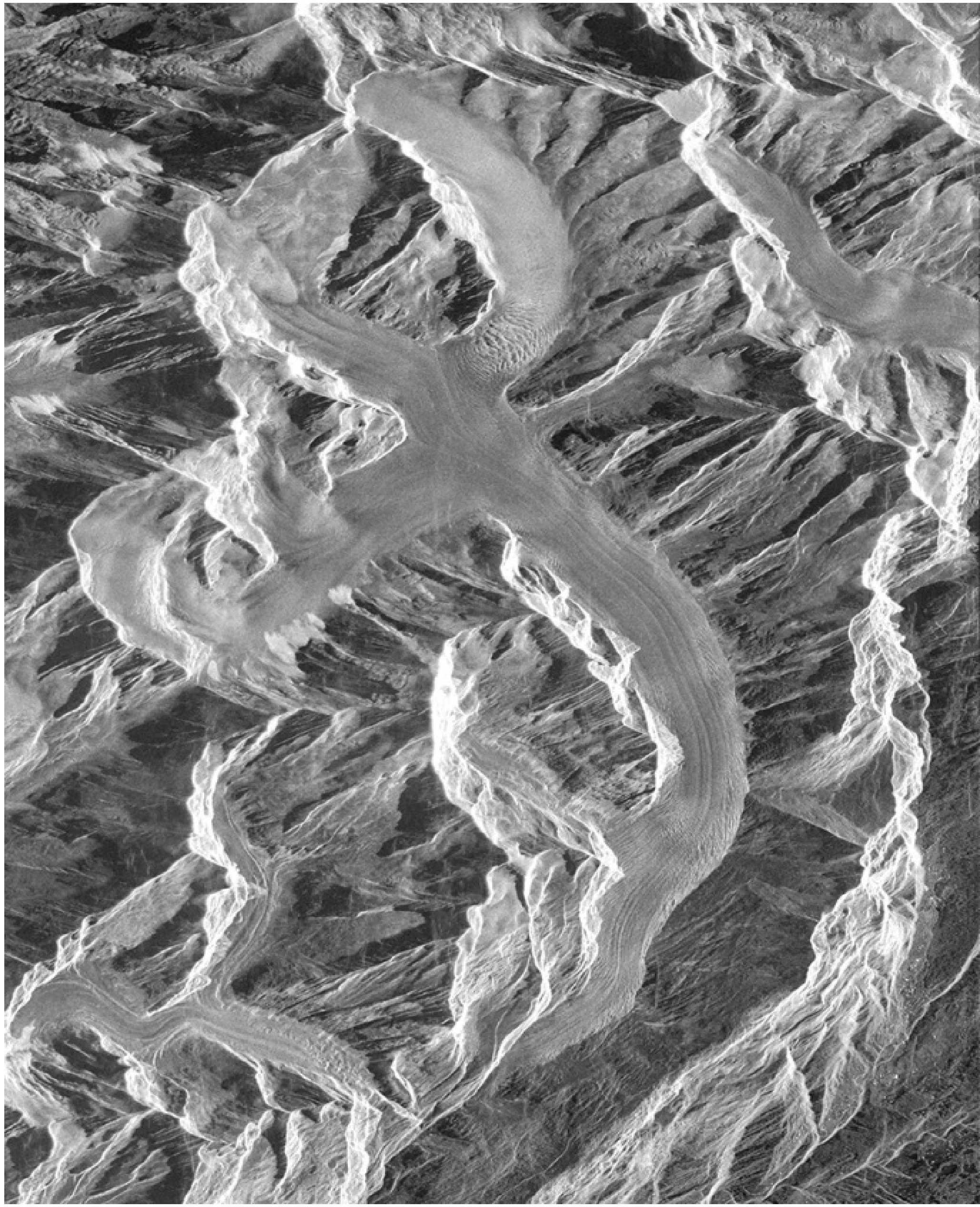
Microwaves and Radar Institute, DLR, Oberpfaffenhofen

Environmental Engineering, ETH, Zurich

DLR

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)

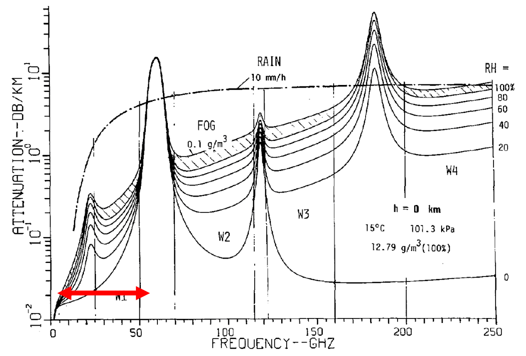
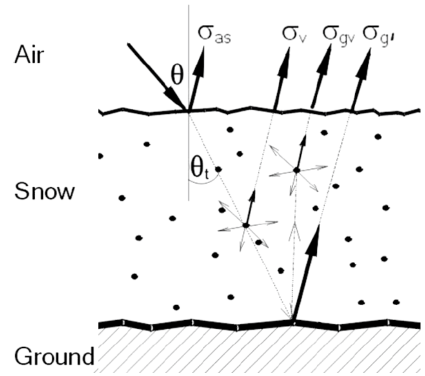


Fig. 1. Specific attenuation at sea level over the frequency range 1–250 GHz for various relative humidities (0 to 100 percent), including fog (0.1 g/m³) and rain (R = 10 mm/h).

Liebe 1983, *IEEE Trans. Antennas Propag.*

Typical interactions of microwave and snow and ice:

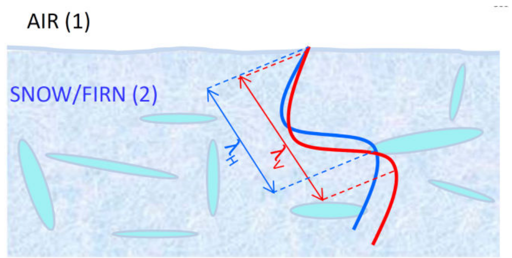
- Total penetration (T ≪ 0°C, n ≪ 10 GHz)
- Total reflection at the surface (T ≥ 0°C)
- Volume scattering (T < 0°C, n > 5 GHz, depth > 2 m)



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:

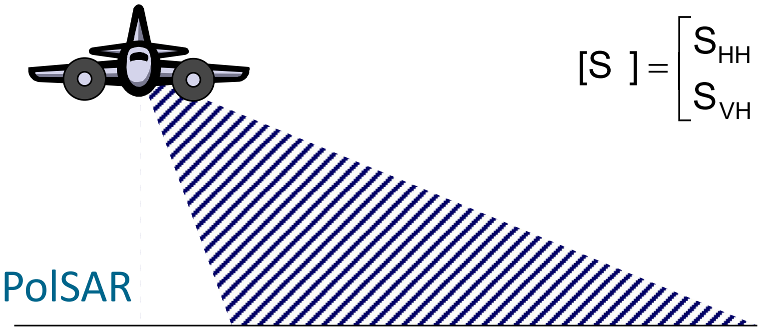
$$[C_3] := \langle \vec{k}_{3L} \cdot \vec{k}_{3L}^{*} \rangle = \begin{bmatrix} \langle |S_{HH}|^2 \rangle & \sqrt{2} \langle S_{HH} S_{HV}^{*} \rangle & \langle S_{HH} S_{VV}^{*} \rangle \\ \sqrt{2} \langle S_{HV} S_{HH}^{*} \rangle & 2 \langle |S_{HV}|^2 \rangle & \sqrt{2} \langle S_{HV} S_{VV}^{*}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

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

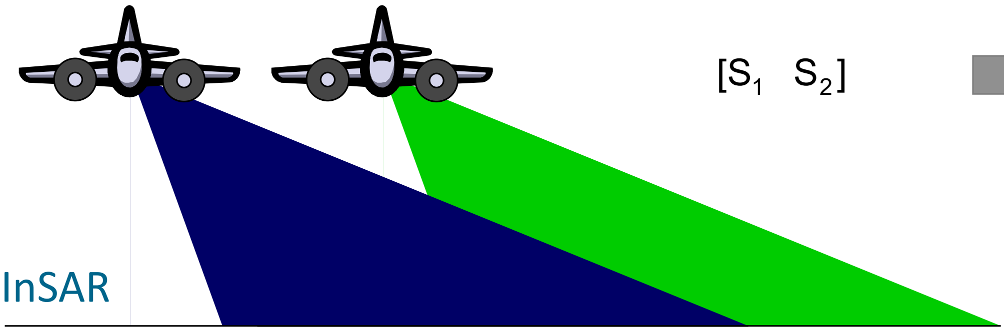


PolSAR

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

Polarimetric Coherences

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

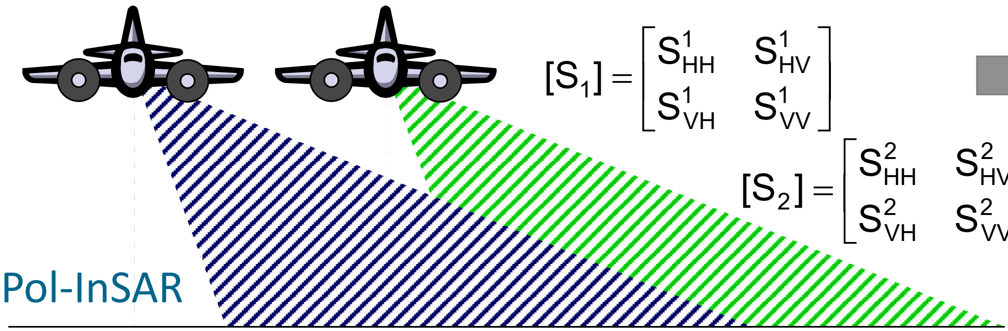


InSAR

$$[S_1 \quad S_2]$$

Interferometric Coherences

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



Pol-InSAR

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

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

Polarimetric / Interferometric Coherences

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

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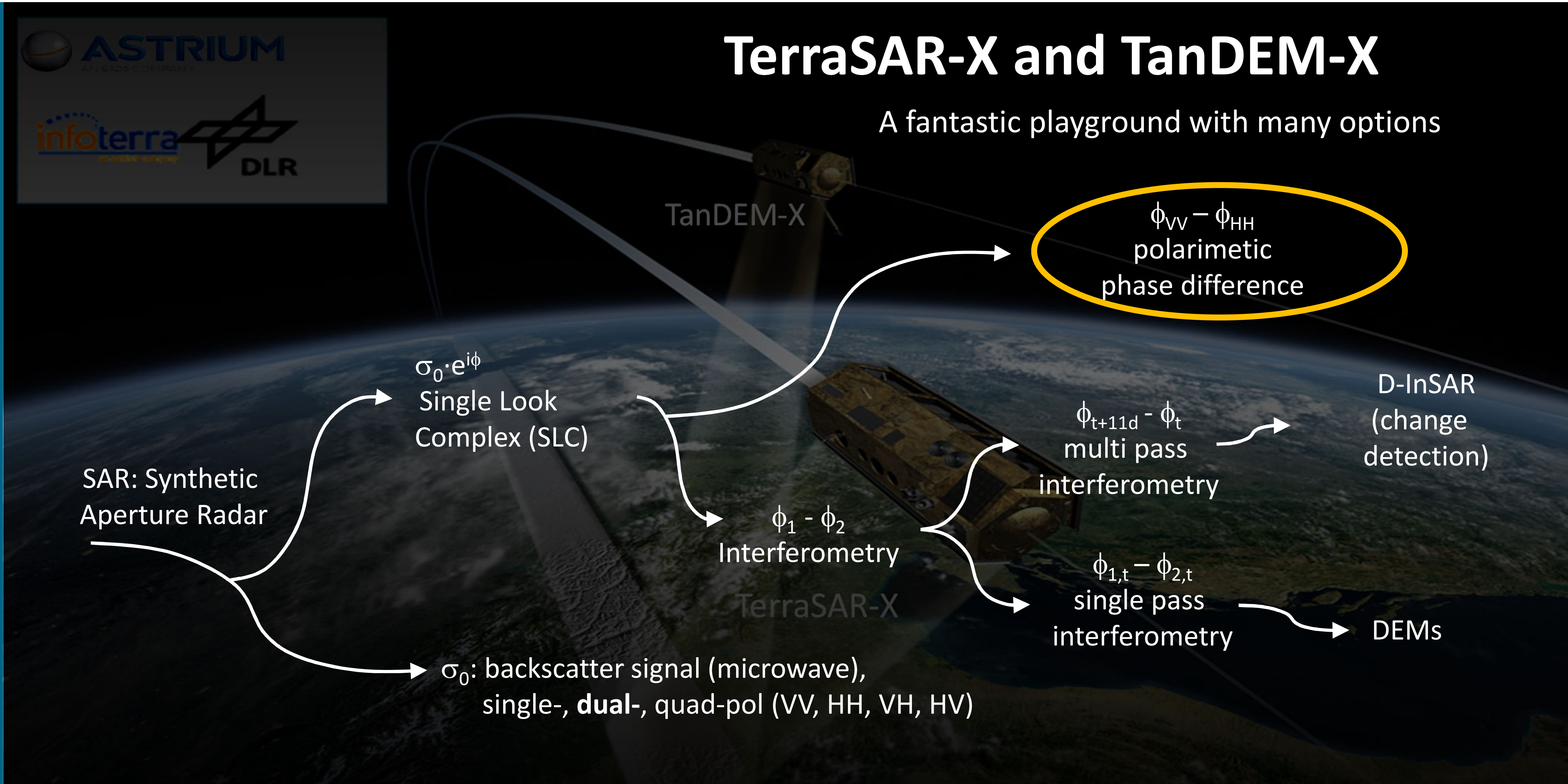
TerraSAR-X and TanDEM-X

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

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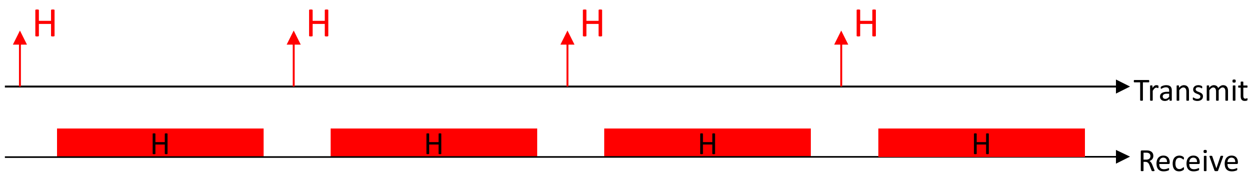
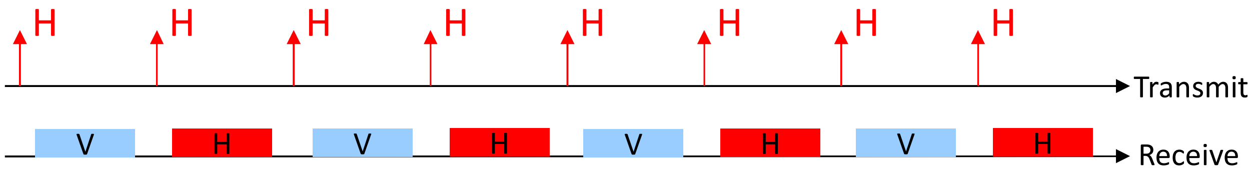
Polarization Modes @ TerraSAR-X/TanDEM-X

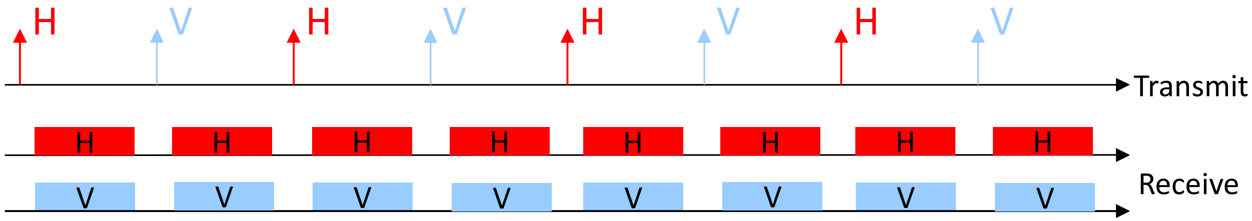
Single Polarization
- 1 polarization channel, {HH, VV}
- stripmap, spotlight, ScanSAR



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



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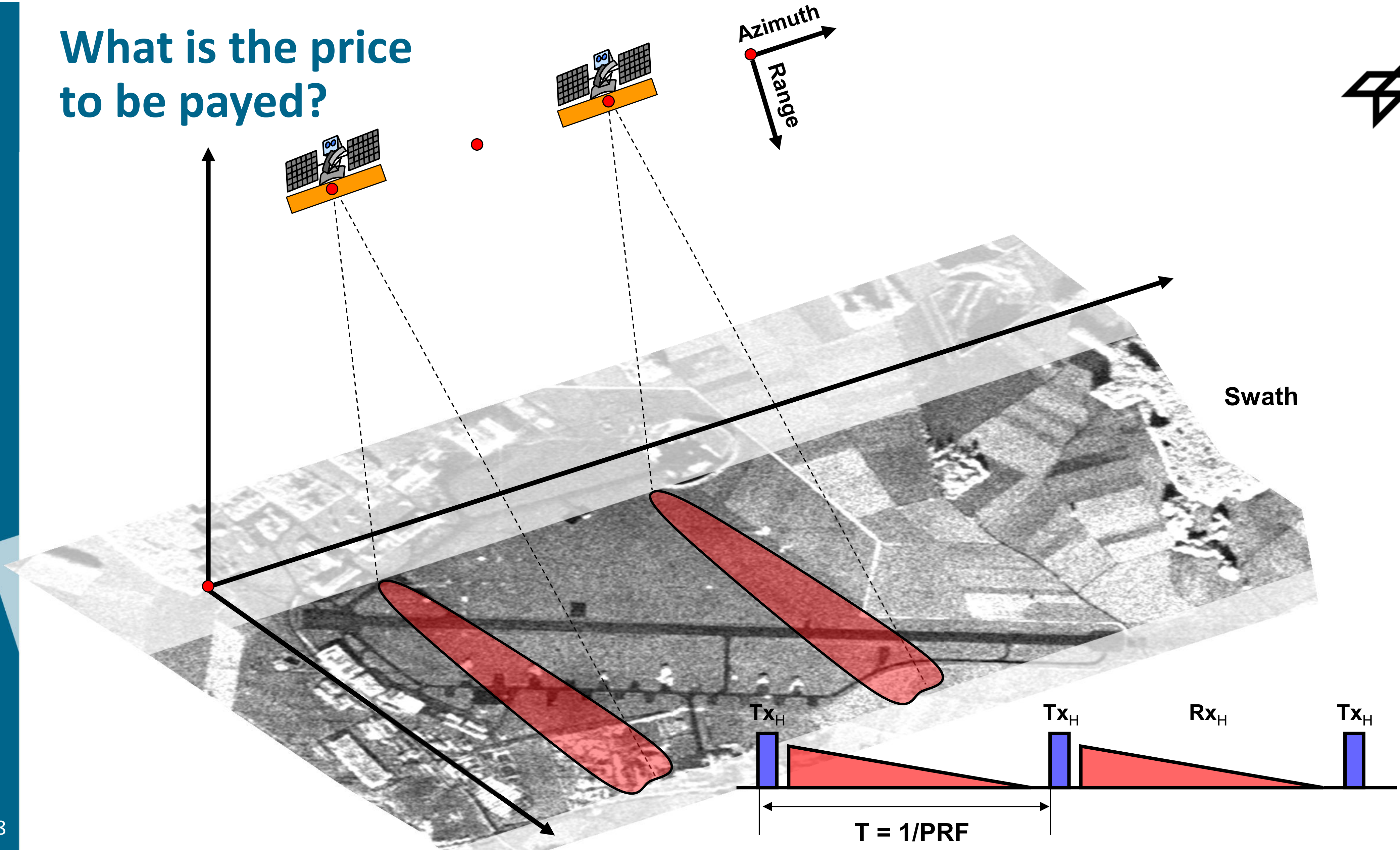
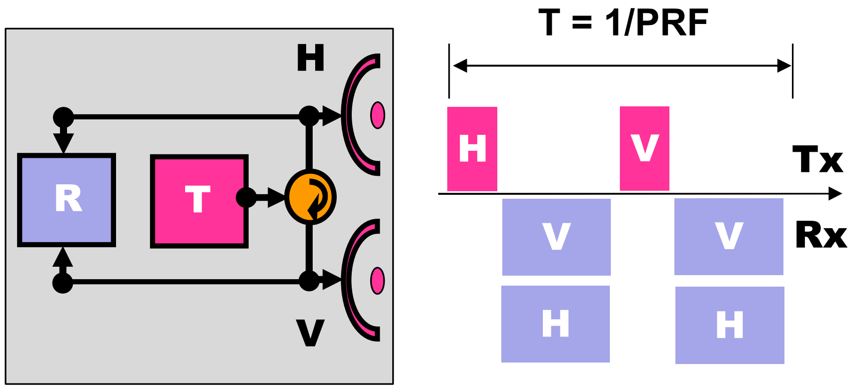
What is the price to be payed?



Quad Polarimetric Observation

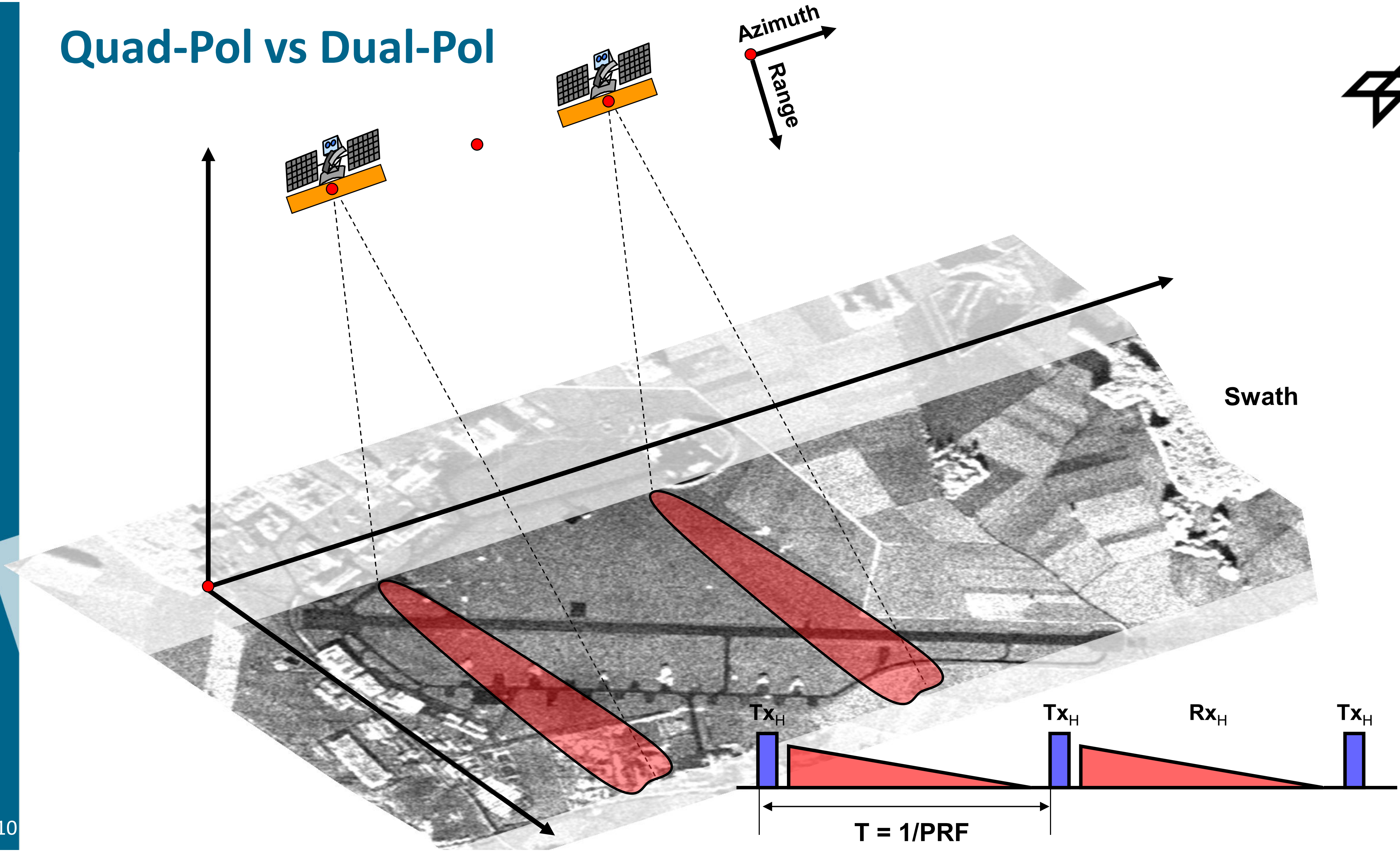


Quad Pol

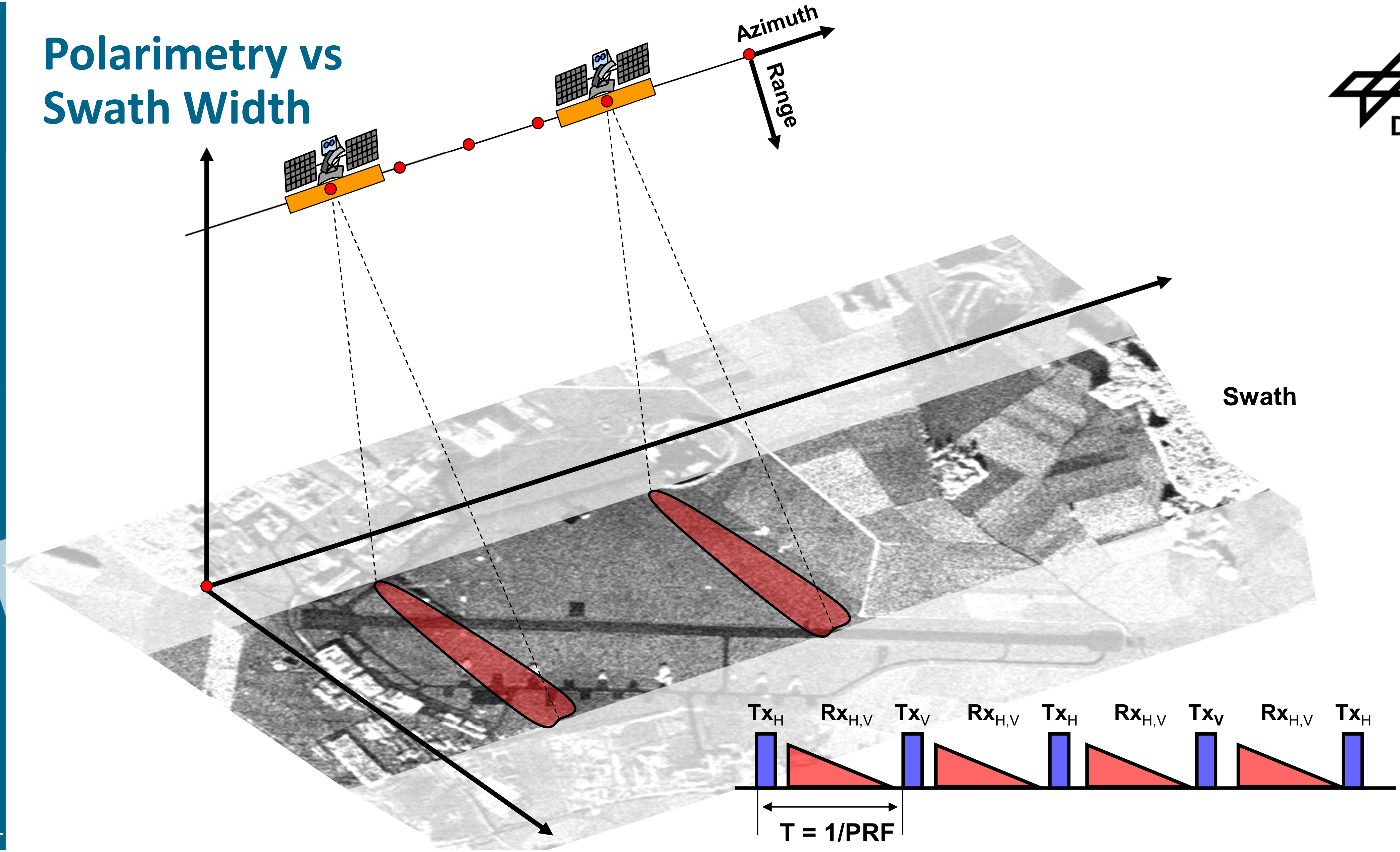
H (transmit) $\begin{bmatrix} E_H^T \\ E_V^T \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$ **H, V** (receive) $\begin{bmatrix} E_H^R \\ E_V^R \end{bmatrix} = \begin{bmatrix} S_{HH} & S_{HV} \\ S_{VH} & S_{VV} \end{bmatrix} \begin{bmatrix} E_H^T \\ E_V^T \end{bmatrix} = \begin{bmatrix} S_{HH}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

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

Quad-Pol vs Dual-Pol



Polarimetry vs Swath Width



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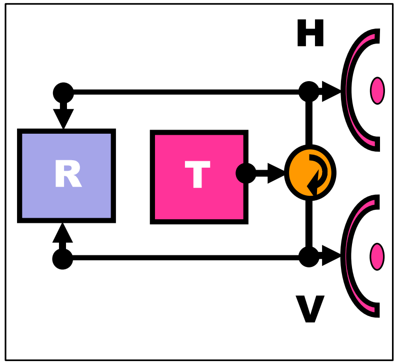
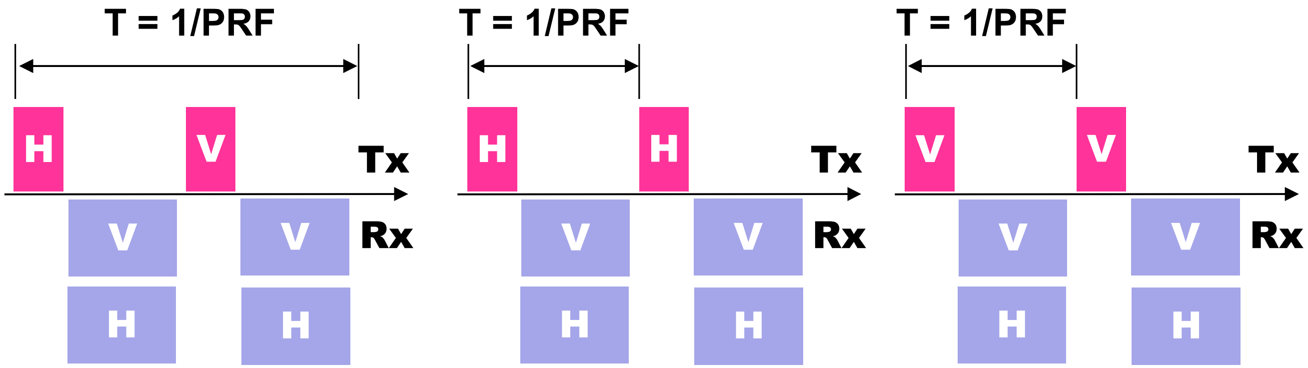
Quad vs Dual Polarimetric Observations





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

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

3D Coherence (Covariance) Matrix

9 Parameters

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

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

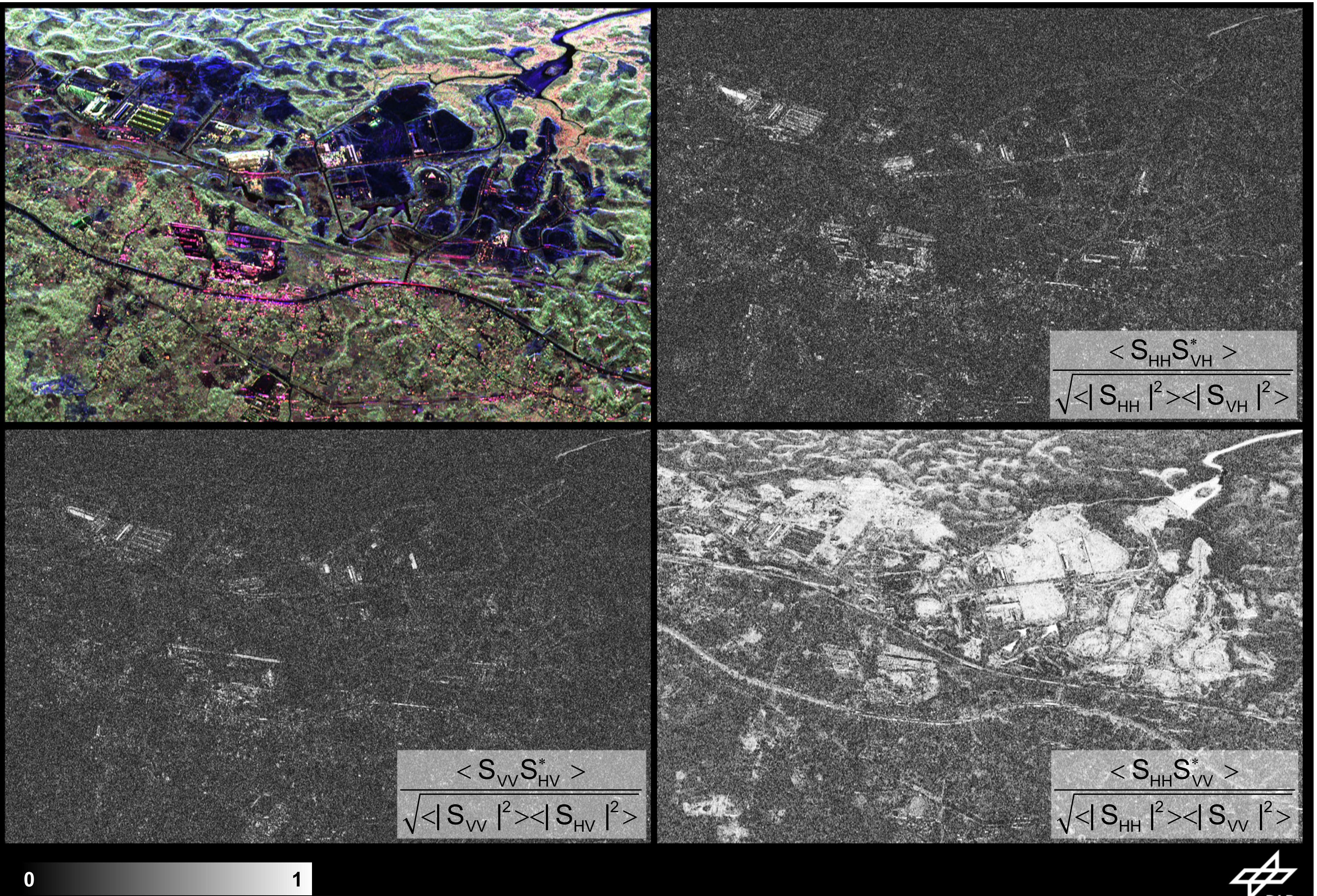
$$[M] = \begin{bmatrix} 1 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix} \Rightarrow [C_2] = \begin{bmatrix} <|S_{HH}|^2> & <S_{HH} S_{VH}^*> \\ <S_{VH} S_{HH}^*> & <|S_{HV}|^2> \end{bmatrix}$$

Case 2: VV-HV

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

Case 3: HH-VV

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



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

Dual Polarimetry – 2nd Order Descriptors

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

3D Coherence (Covariance) Matrix

9 Parameters

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

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

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

Case 2: VV-HV

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

Case 3: HH-VV

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

2-dim Polarimetry: 2nd Order Statistical Parameters

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

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

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

Entropy	Anisotropy	Alpha Angle
$H := \sum_{i=1}^{3} P_i \log_3 P_i$	$A := \frac{P_2 - P_3}{P_2 + P_3}$	$\alpha := \sum_{i=1}^{3} P_i \, \alpha_i$

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

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

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

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

Entropy	Anisotropy	Alpha Angle
$H := \sum_{i=1}^{2} P_i \log_2 P_i$	$A := \frac{P_1 - P_2}{P_1 + P_2}$	$\alpha := \sum_{i=1}^{2} P_i \, \alpha_i$
randomness		scat.mechan.

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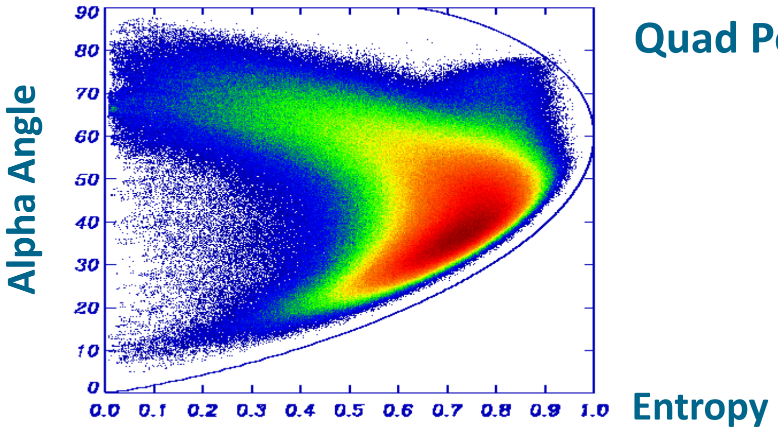
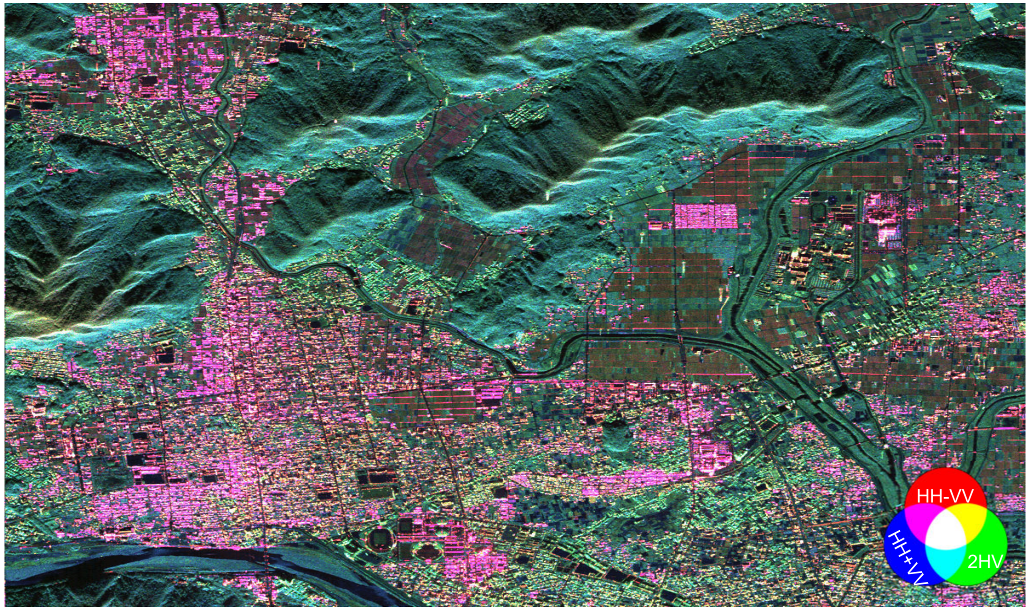
2-dim Polarimetry – 2nd Order

Example X-band from PI-SAR Test Site: Gifu

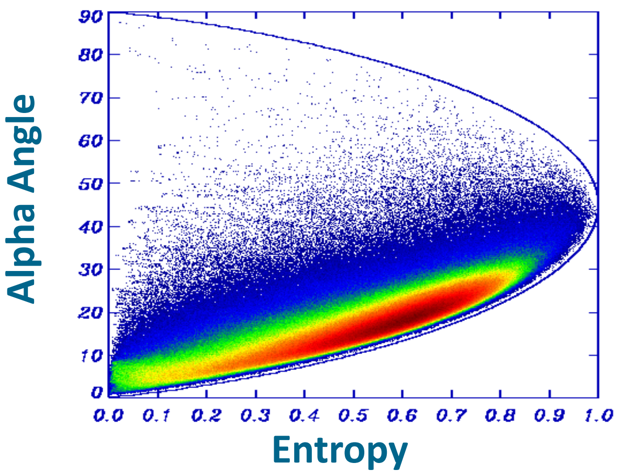
Quad Pol



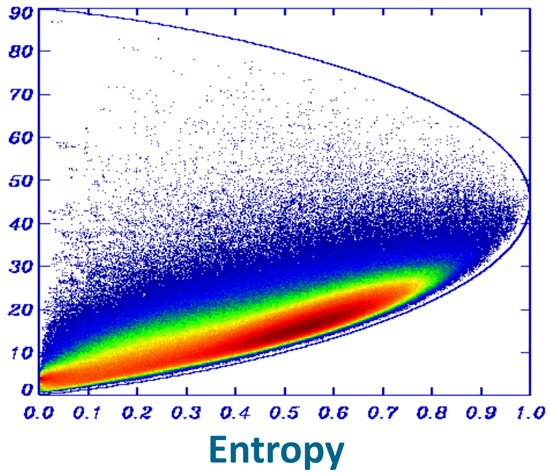


PI-SAR / Test Site: Gifu, Japan

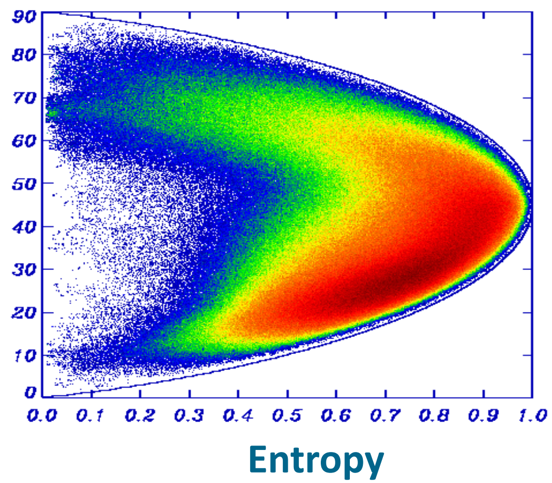
Dual Pol Case 1: Tx: H



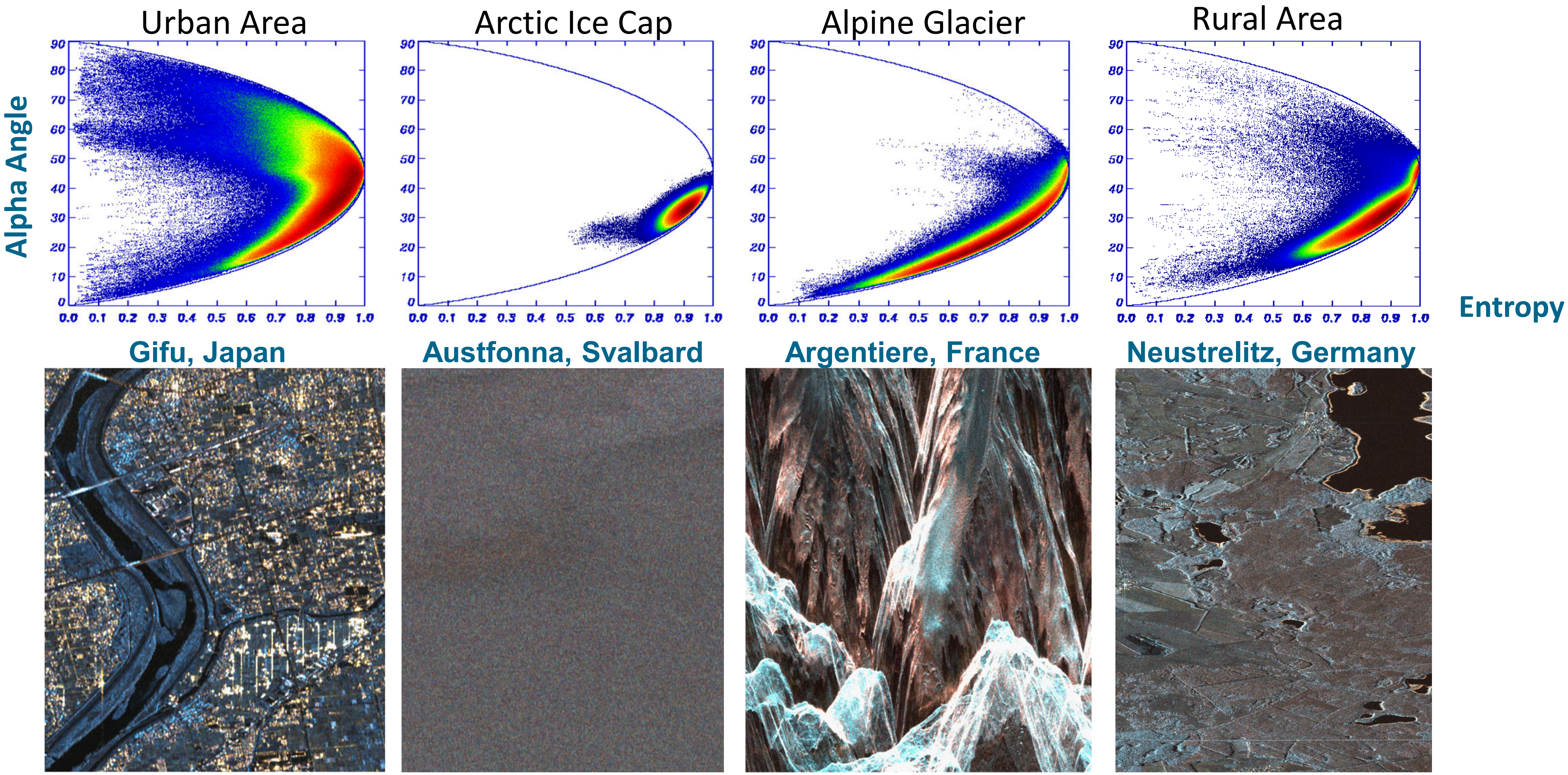
Dual Pol Case 2: Tx: V



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

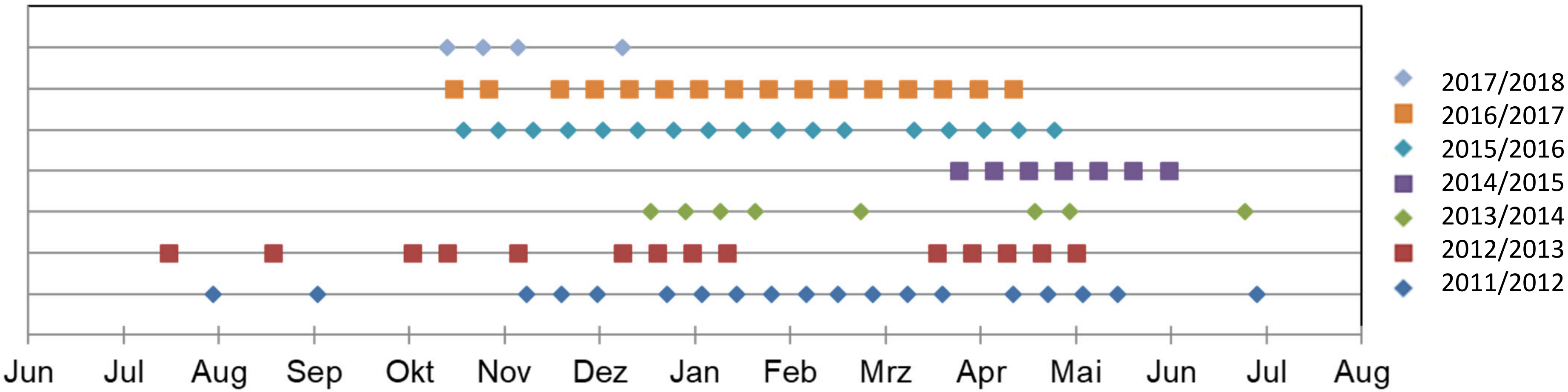
- ✓ Length 23 km
- ✓ Surface 86 km^3
- ✓ From ~1800 m to ~3500 m altitude
- ✓ Negative mass balance since 1881
- ✓ Front reatreats up to 4 m/year
- ✓ Equilibrium Line at 3000 m

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 $\theta_{inc} = 31{,}6°$



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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)

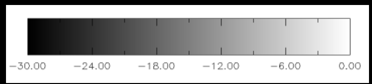
L. Leinss

Earth Observation and Remote Sensing

TERRASAR X

Aletschgletscher, Switzerland

2011 - 2012 Time series σ^0_{HH}




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

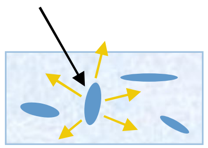

02. Jun 2012

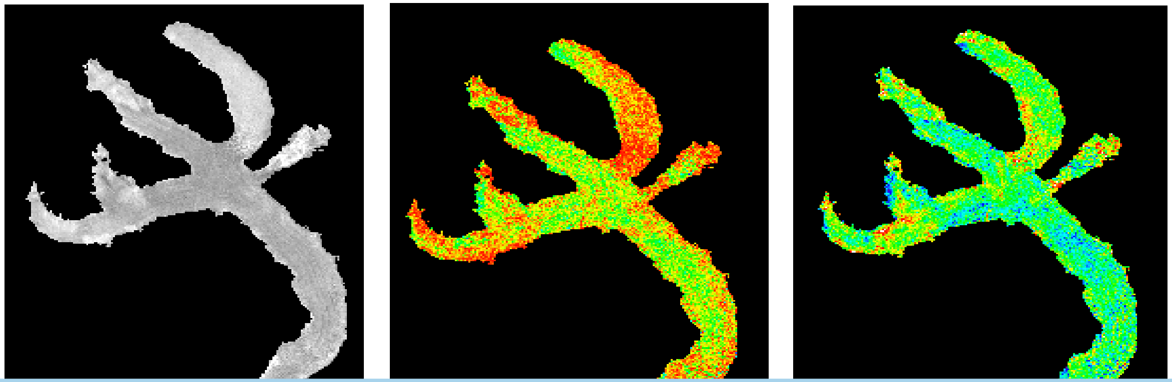

16. Jul 2012

Polarimetric Analysis: Sensitivity to Seasonal Dynamics

✓ Wet and dry glacier conditions

Winter image
08.02.2013

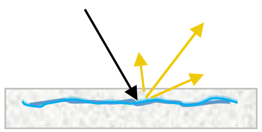


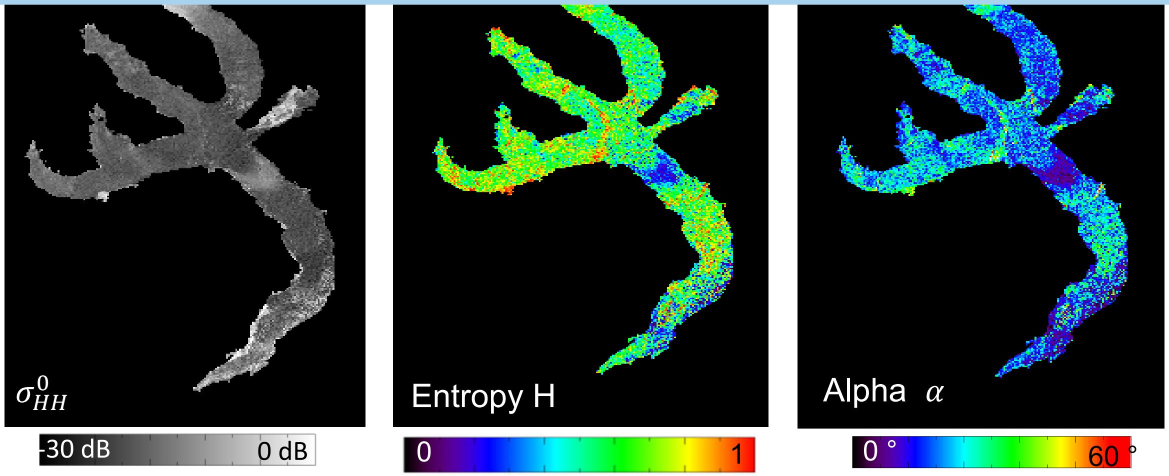


Scattering mechanisms vary with snow/ice conditions…

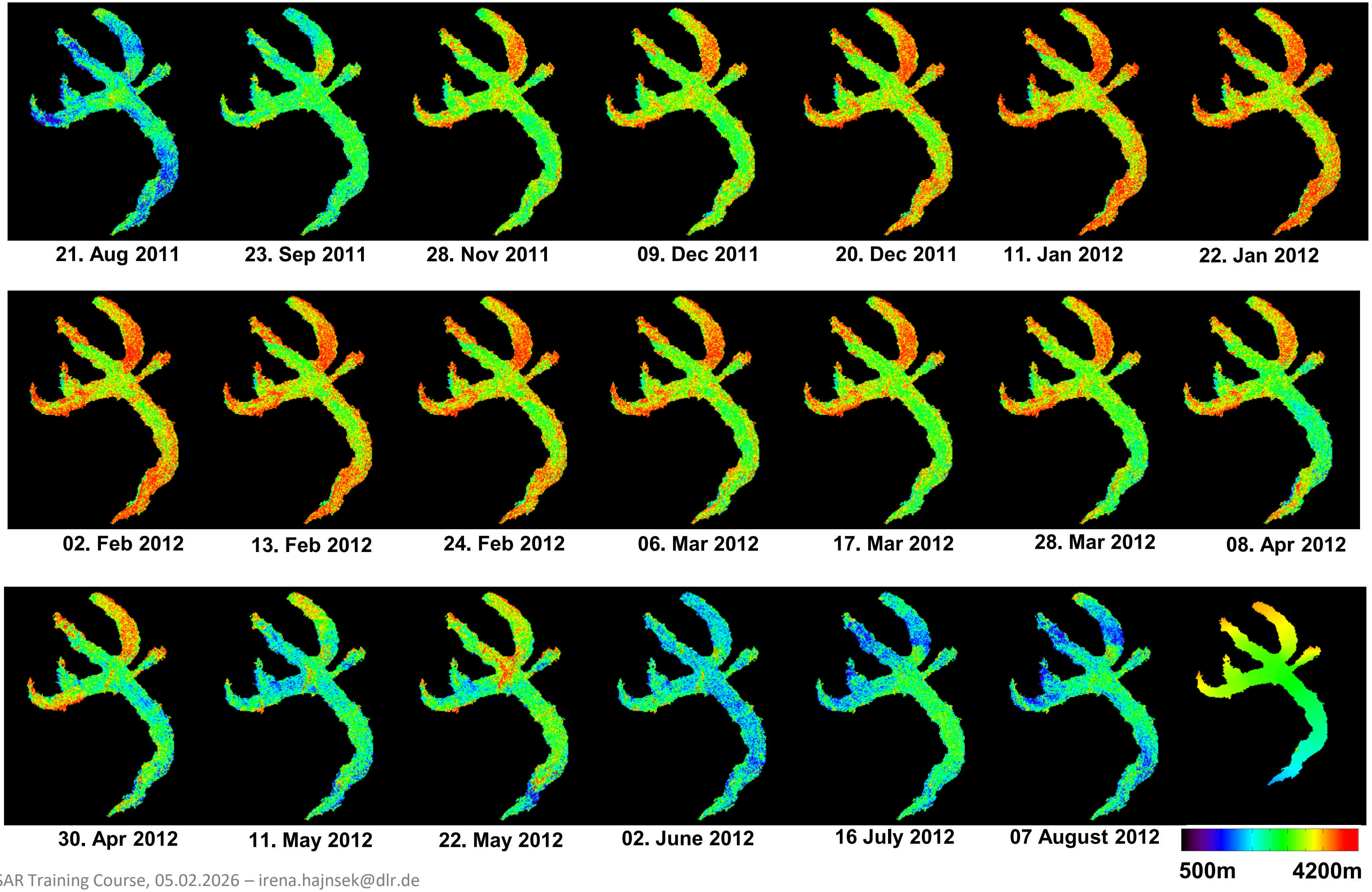
…but also within a single scene!

Su
09.05.2013

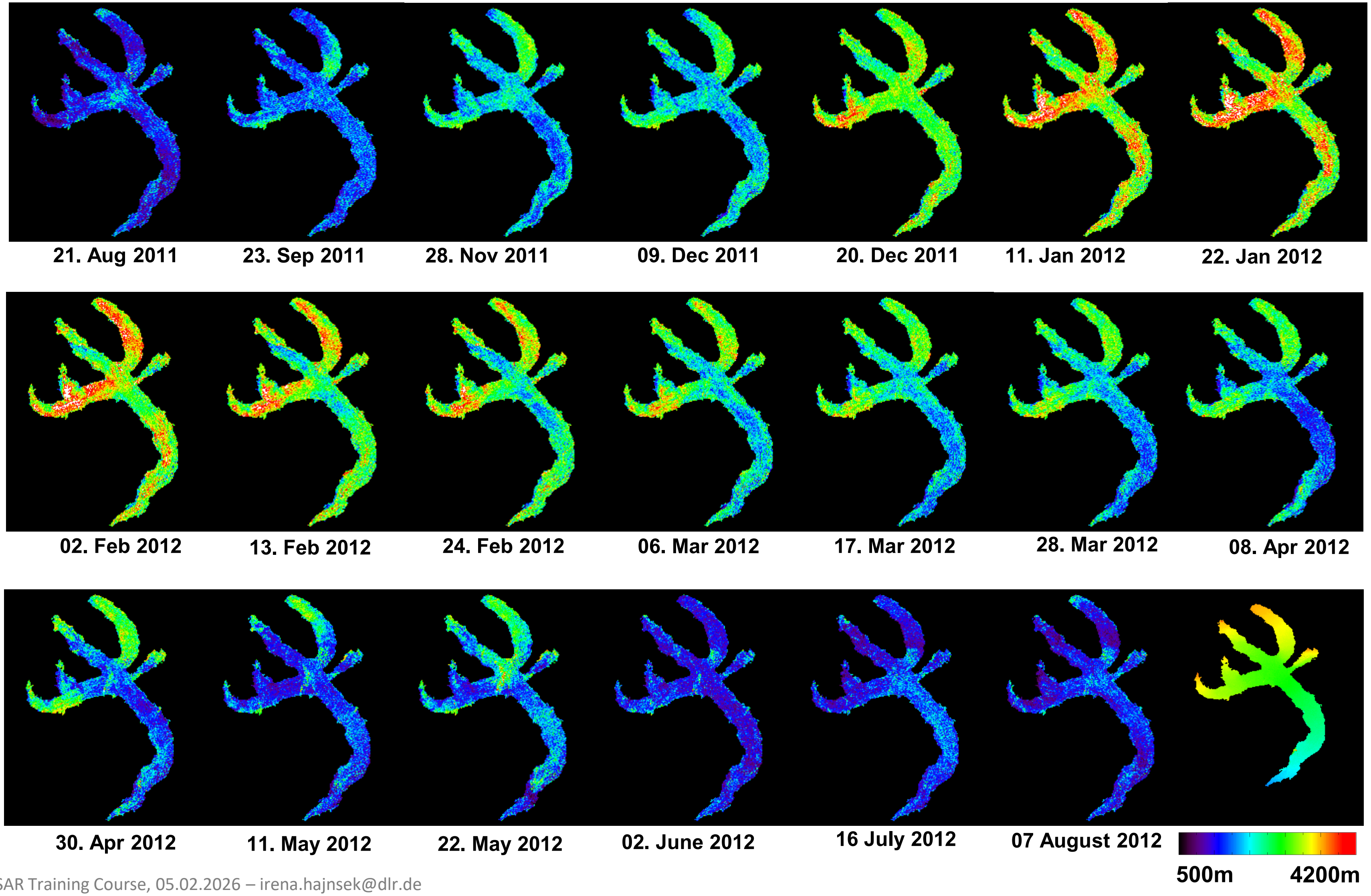




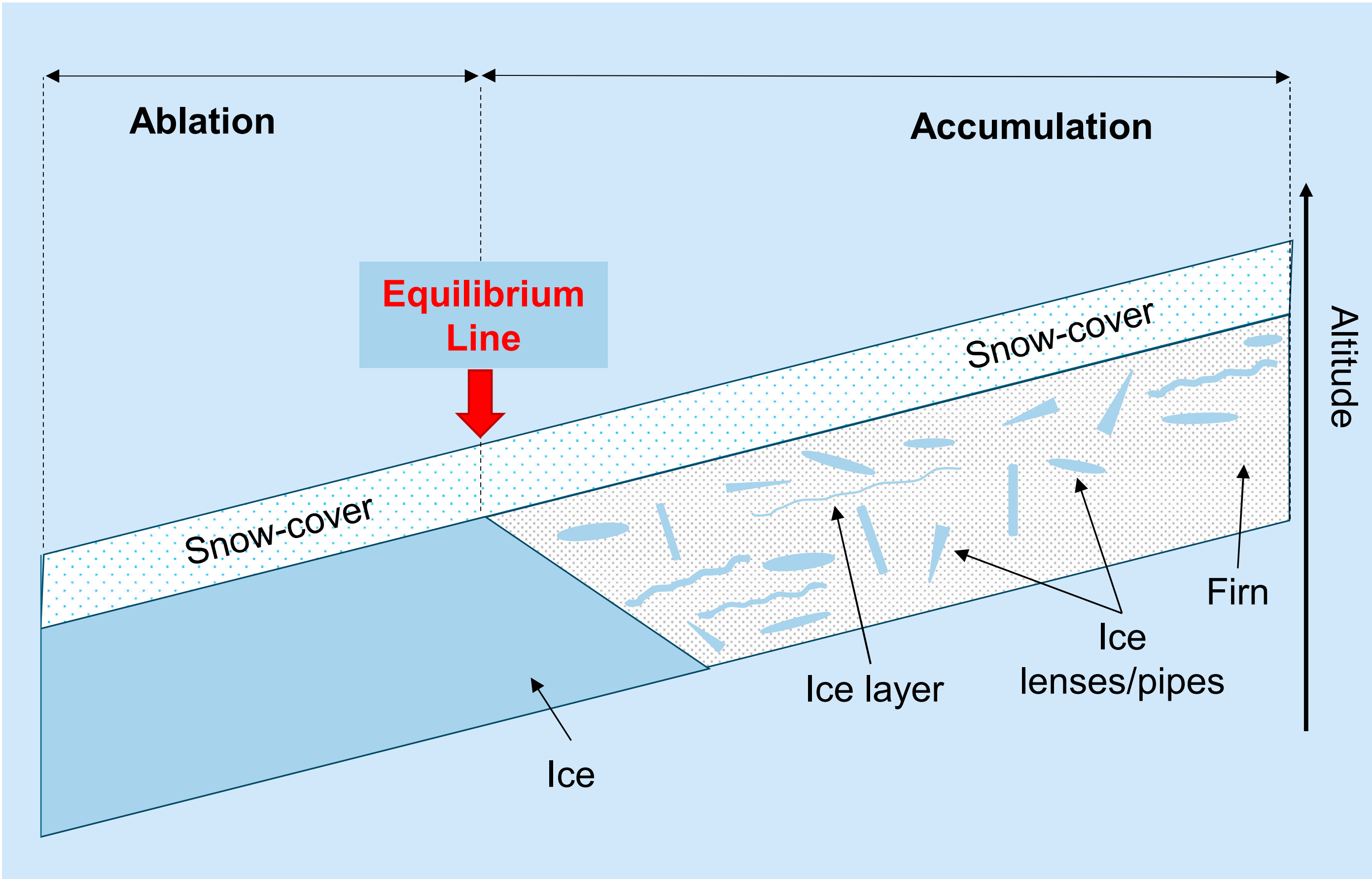
Entropy Time Series 2011/012



Alpha Angle Time Series 2011/012

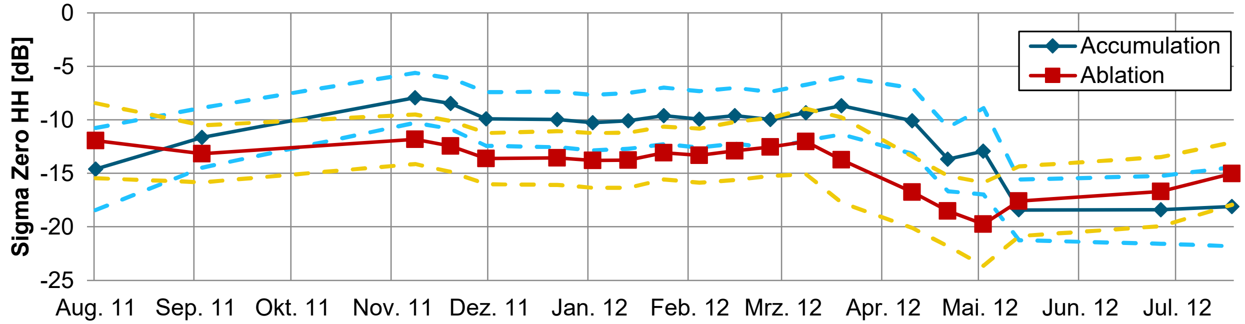


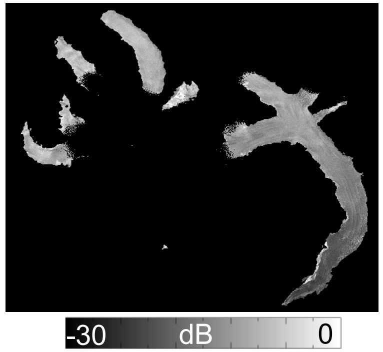
Basics of Glaciology

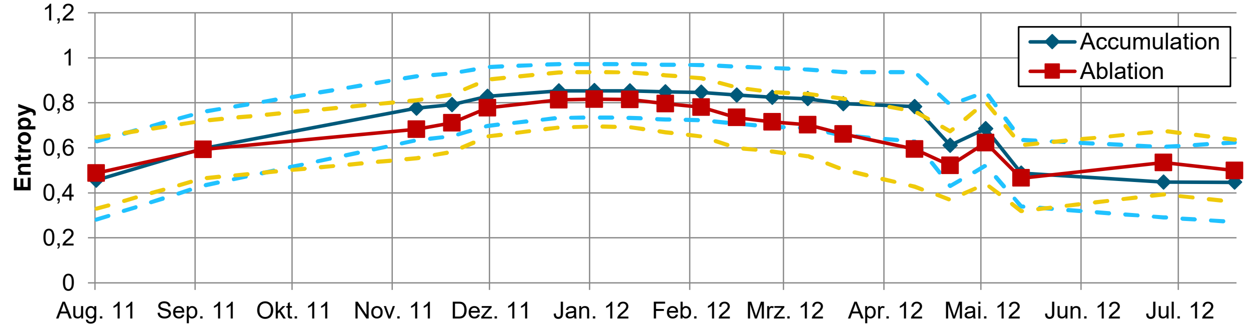


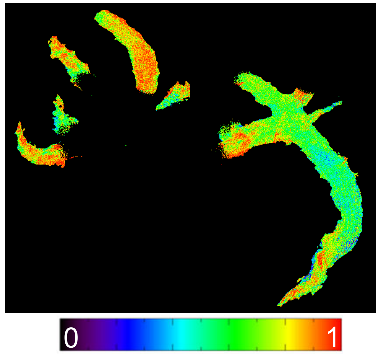
The **equilibrium-line (ELA) altitude** is a **line** on the **glacier** where accumulation equals ablation

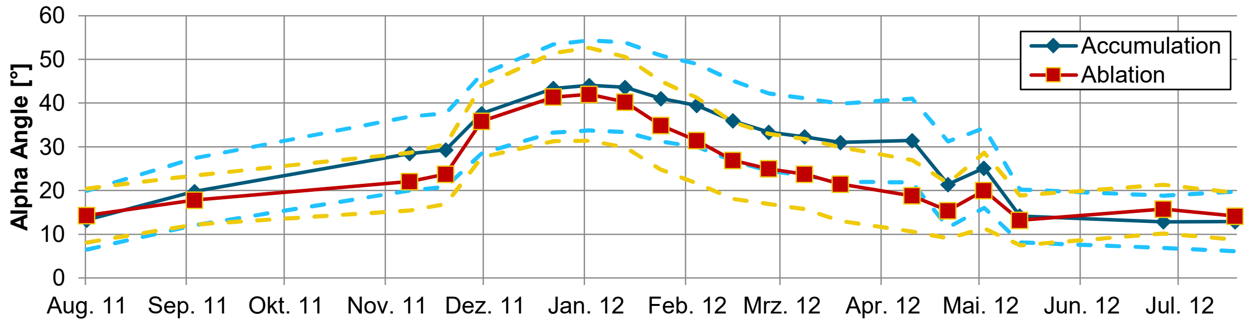
Polarimetric Analysis: Seasonal Dynamics of Glacier Zones

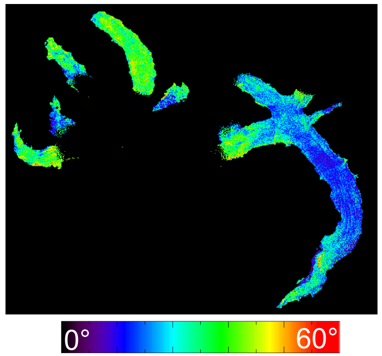




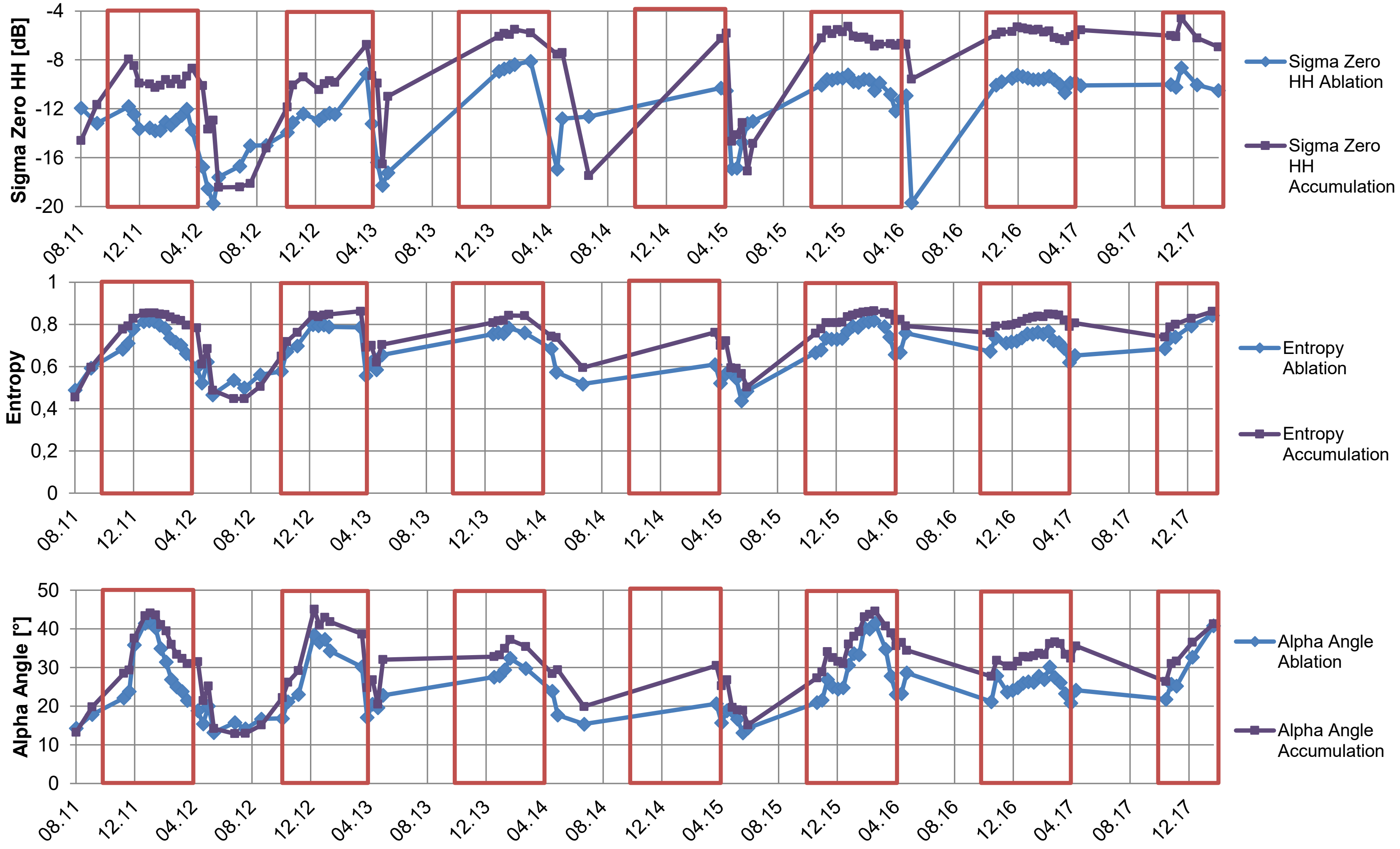




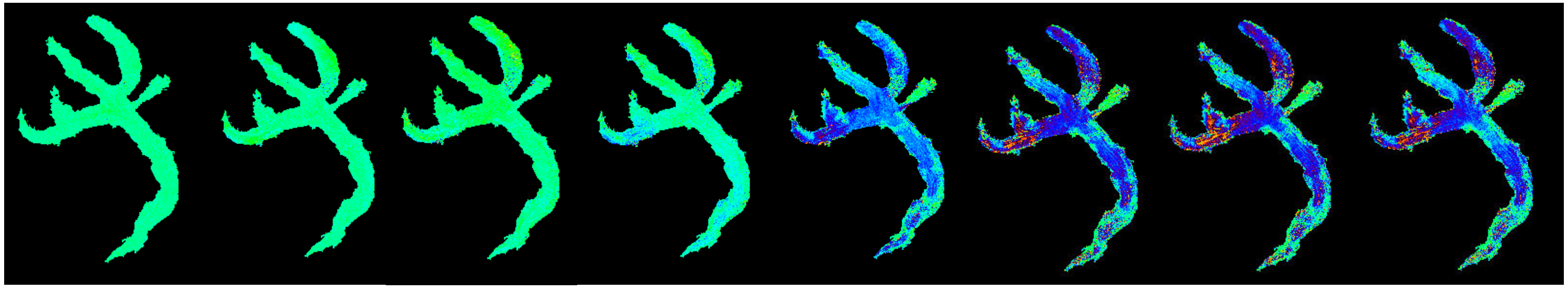




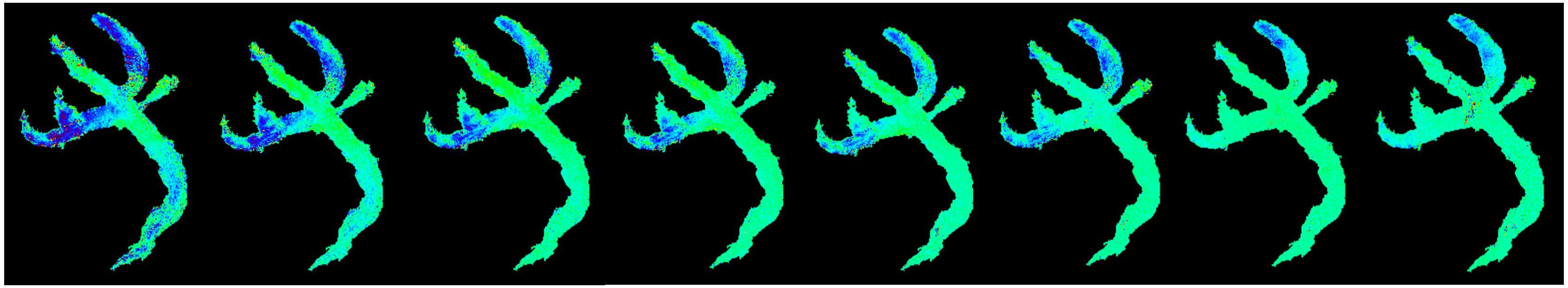
Polarimetric Analysis: Interannual Dynamics of Glacier Zones



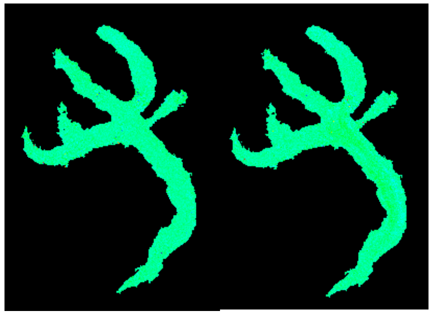
Polarimetric Phase Diff. and Snow Accumulation



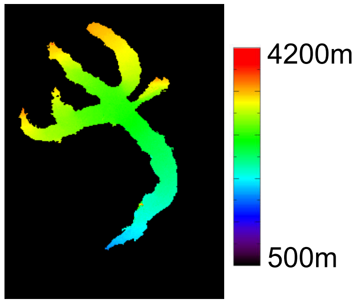
21. Aug 2011 | 23. Sep 2011 | 28. Nov 2011 | 09. Dec 2011 | 20. Dec 2011 | 11. Jan 2012 | 22. Jan 2012 | 02. Feb 2012



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

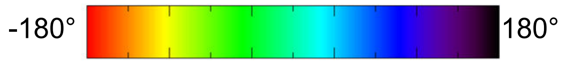


02. Jun 2012 | 16. Jul 2012



✓ Polarimetric Phase difference ϕ_{VV-HH}

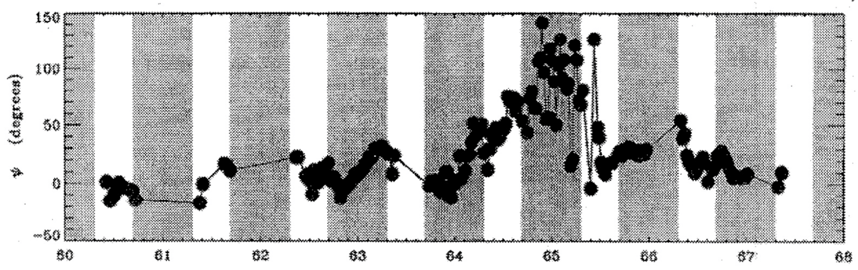
$$\phi_{VV-HH} = \angle(<S_{VV}S_{HH}^{*}>)$$



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

- 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**.

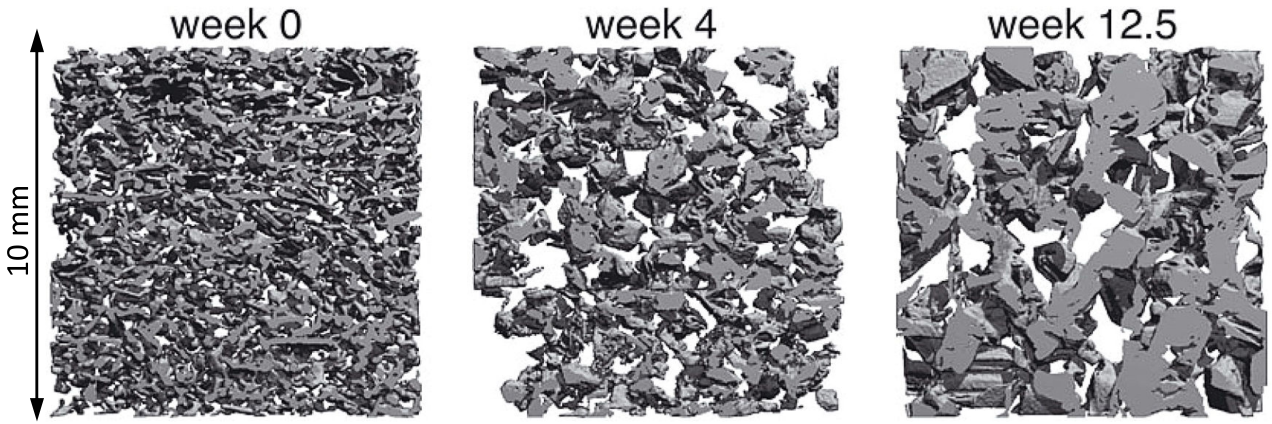
  Parrella, G. "On the Interpretation of L- and P-band PolSAR Signatures of Polithermal Glaciers", *POLInSAR,* ***2013***
  Leinss, S***. "***Anisotropy of seasonal snow measured by polarimetric phase differences in radar time series. *The Cryosphere* ***2016"***

- 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 (ϕ_{VV} - ϕ_{HH})?

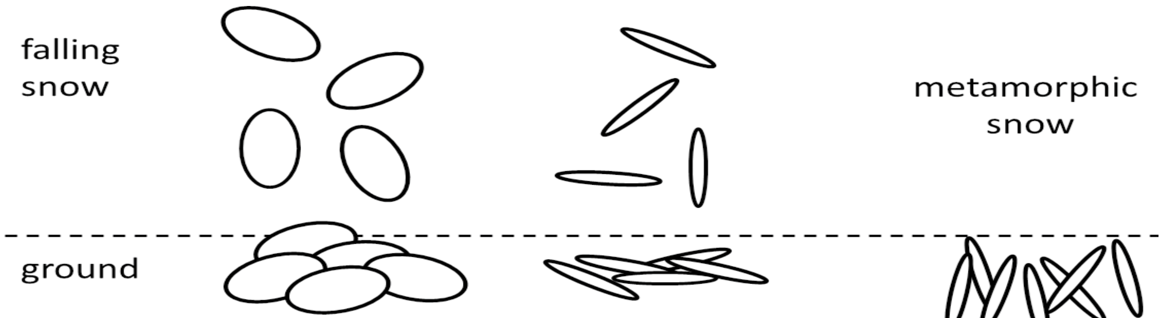
DLR



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.

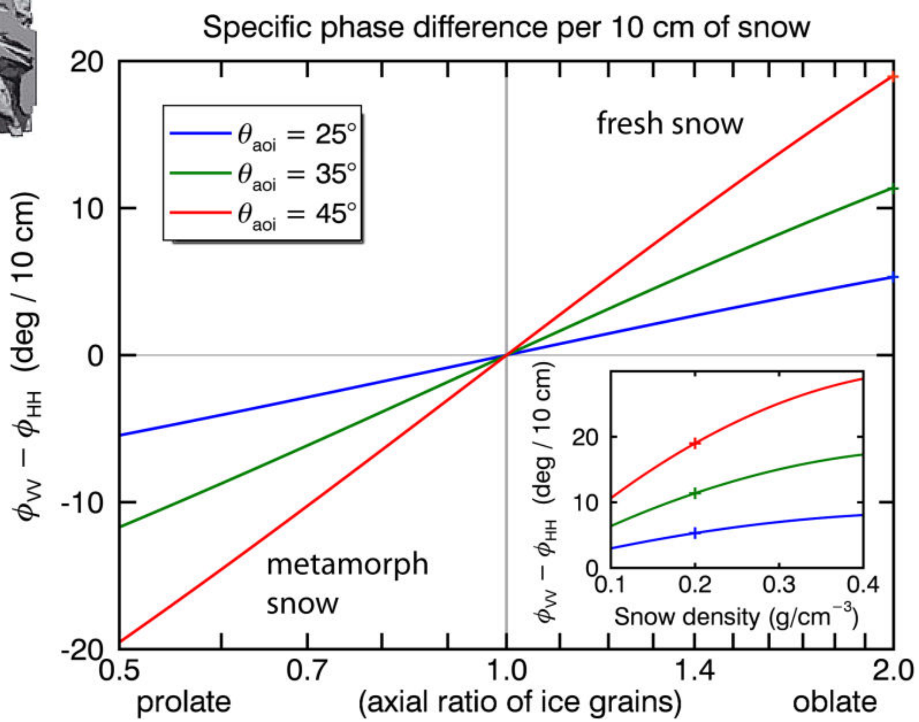
Simplification for model:



horizontally extended

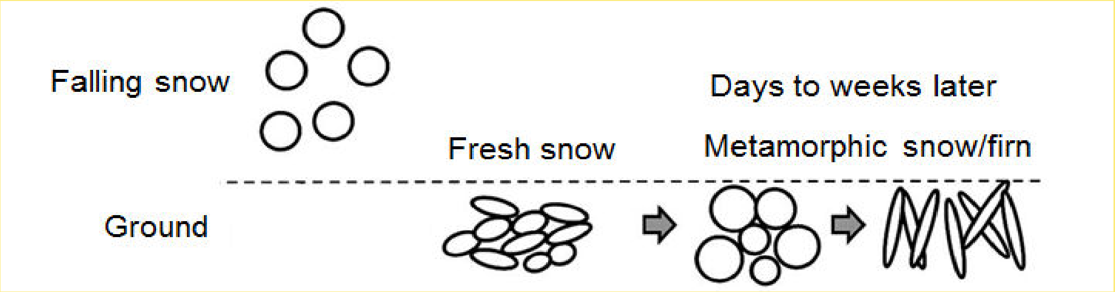
Vertically extended

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



Isotropic medium	Anisotropic medium	Isotropic medium	Anisotropic medium

Modelling anisotropic snow

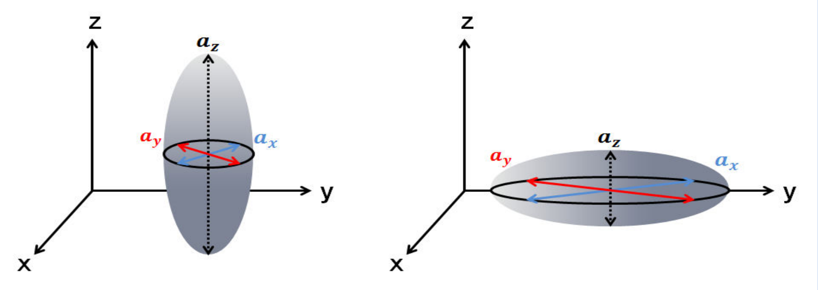
✓ Two phase mixture of air and ice inclusions

✓ Spheroidal grains described by degree of anisotropy $DoA = \frac{a_z}{a_x}$

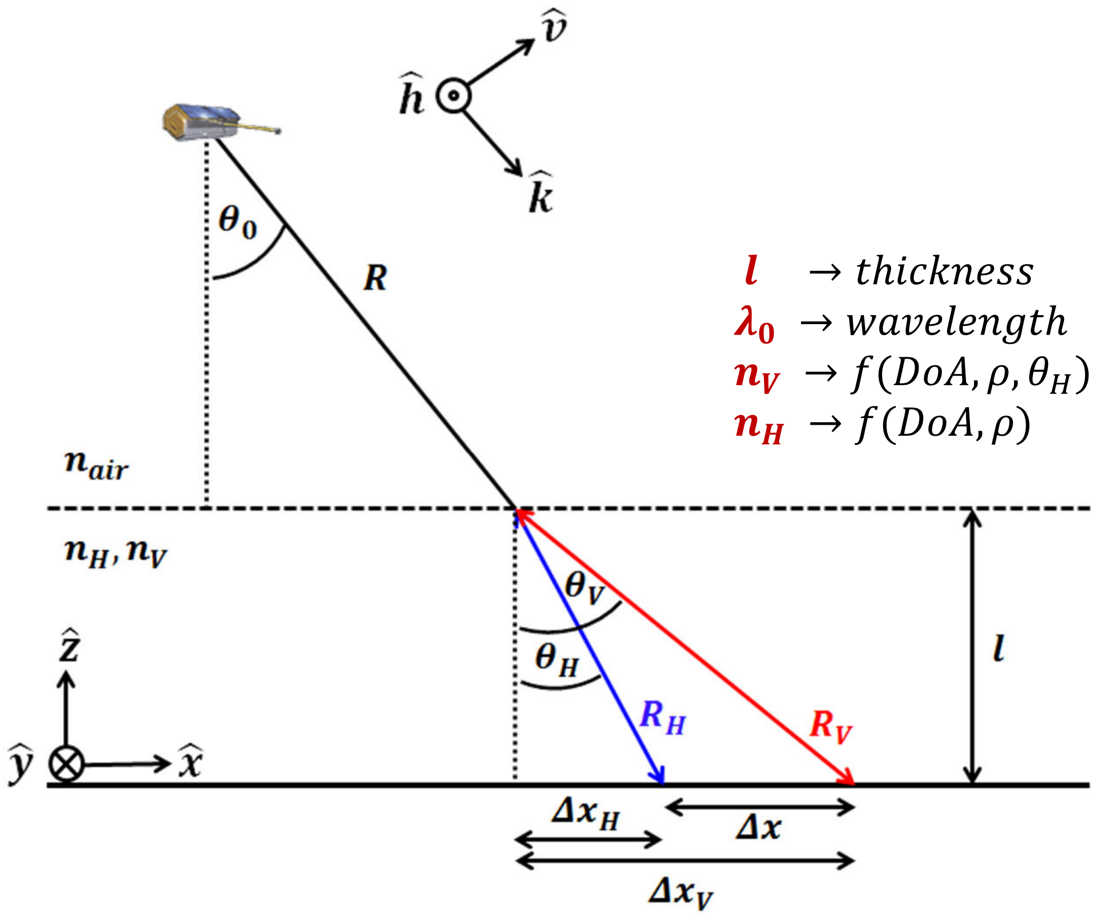
✓ Effective permitivity components depend on DoA and volume fraction (density)

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

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



Propagation Model to Invert Snow Accumulation



$l \rightarrow thickness$

$\lambda_0 \rightarrow wavelength$

$n_V \rightarrow f(DoA, \rho, \theta_H)$

$n_H \rightarrow f(DoA, \rho)$

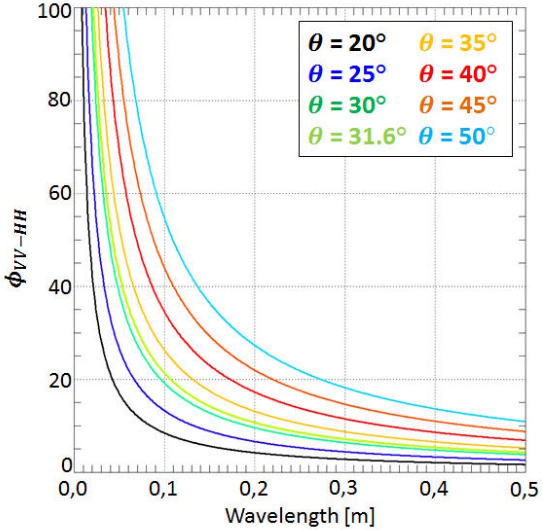
- ✓ Transformation from **(x,y,z) → (H,V)** coordinate system
- ✓ H component $n_H = n_{x,y}$
- ✓ V component $n_V = \sqrt{n_x^2 cos^2\theta_H + n_z^2 sin^2\theta_H}$

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

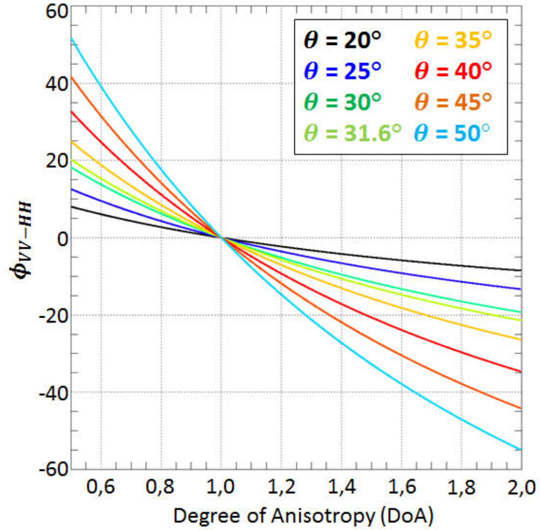
$$R_V = \frac{\cos\theta_V}{l} \qquad R_H = \frac{\cos\theta_H}{l}$$

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

Propagation Model: Sensitivity Analysis

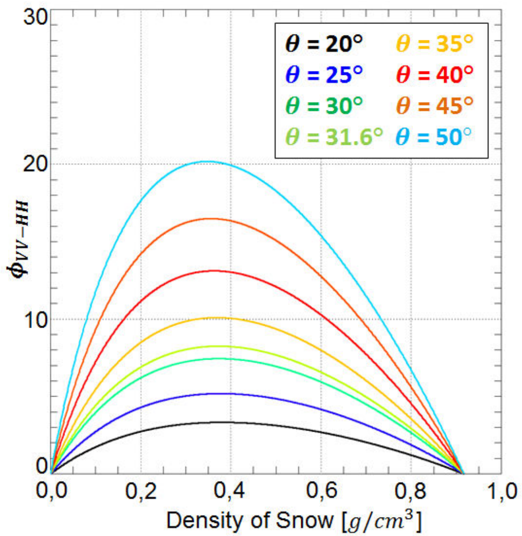


- ✓ Sensitivity increases with frequency

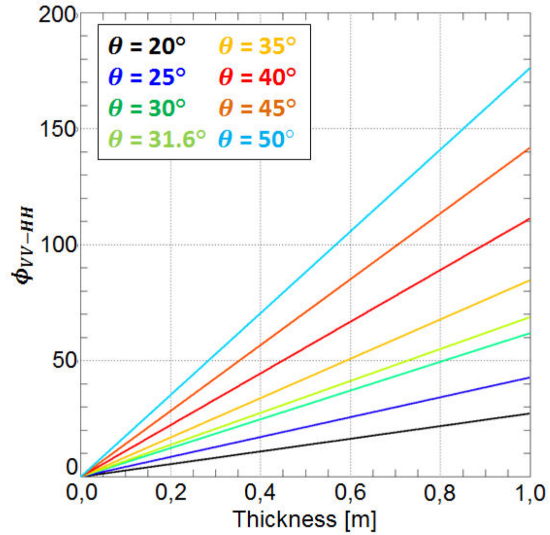


$$\rho = 0{,}2\ g/cm^3$$
$$DoA = 0{,}8$$
$$l = 0{,}1m$$
$$\lambda = 0{,}031m$$

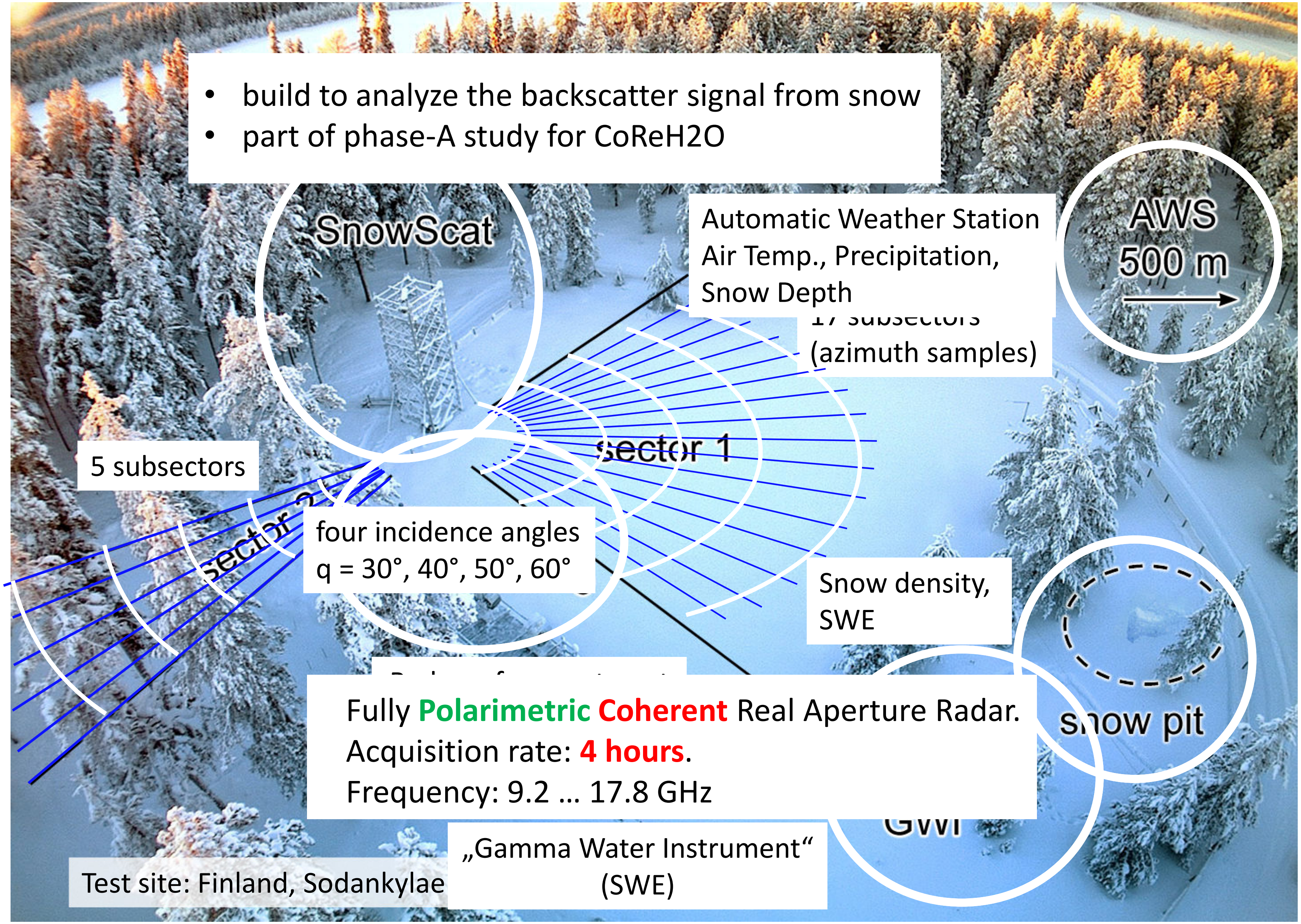
- ✓ More sensitive for higher anisotropy



- ✓ Increasing until medium is too dense



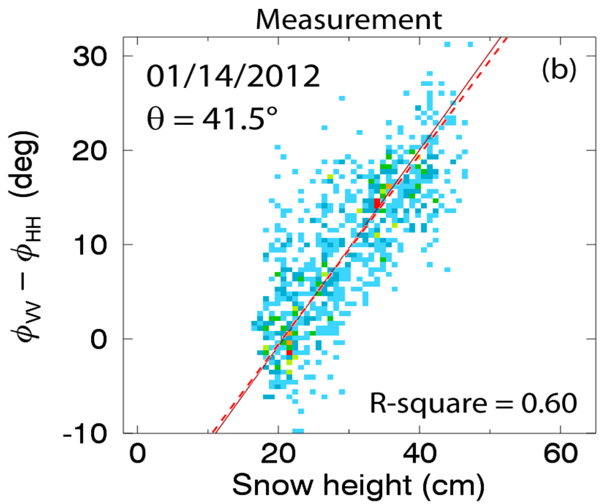
- ✓ Linear dependency on thickness

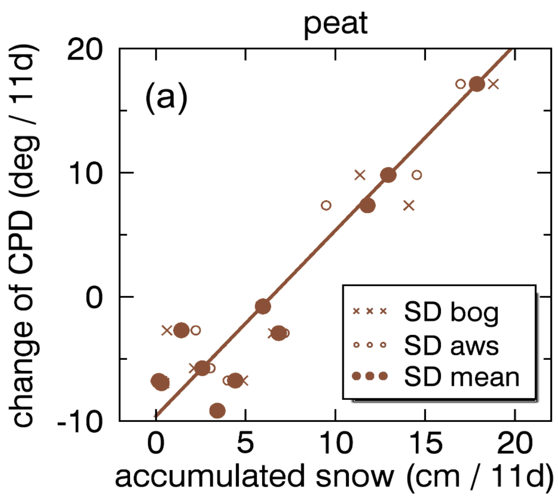


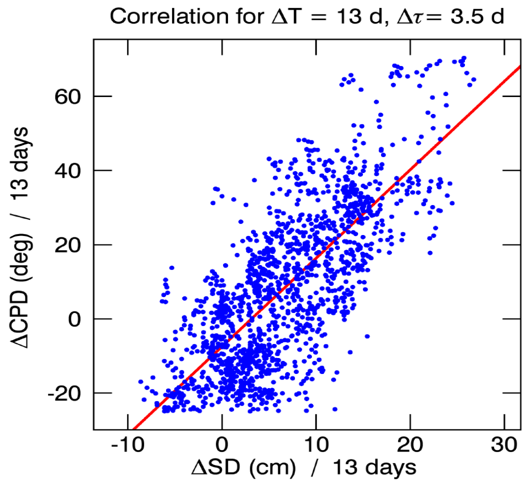
• build to analyze the backscatter signal from snow
• part of phase-A study for CoReH2O
SnowScat
Automatic Weather Station
Air Temp., Precipitation,
Snow Depth
AWS
500 m
(azimuth samples)
sector 1
5 subsectors
four incidence angles
q = 30°, 40°, 50°, 60°
Snow density,
SWE
Fully **Polarimetric** **Coherent**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



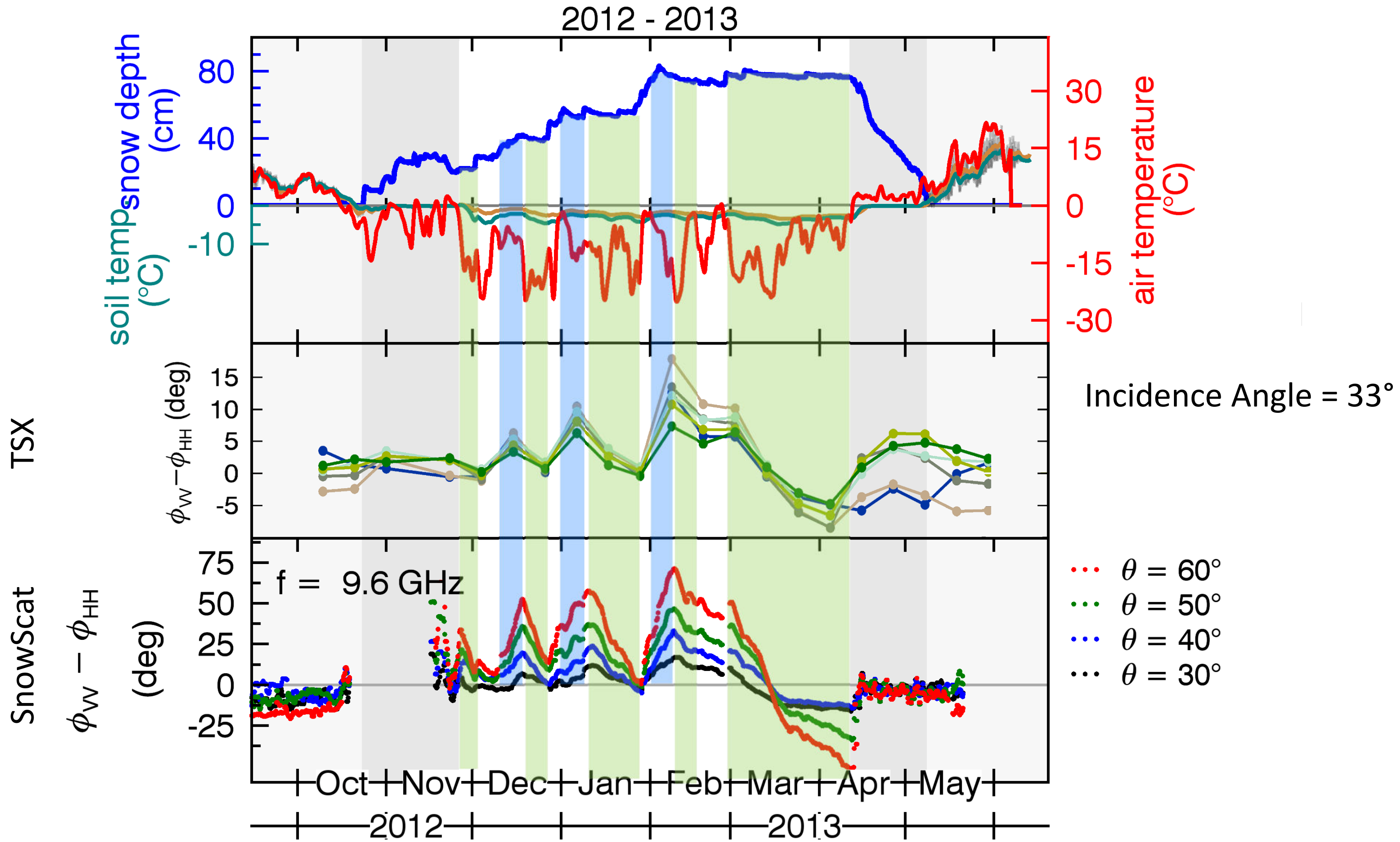




- TerraSAR-X:
  Total snow height after 30 days of snowfall (spatial correlation)
- TerraSAR-X:
  Change of snow height within 11 days (temporal correlation)
- SnowScat:
  Change of snow height within 13 days. (temporal correlation)

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

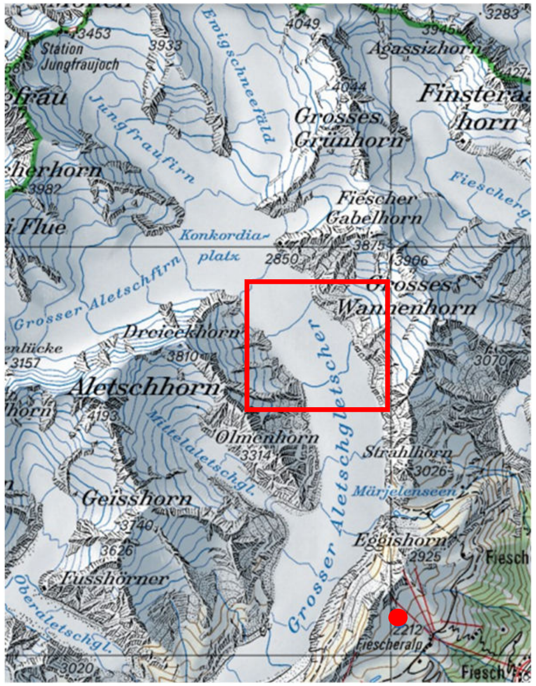
Time series: TSX and SnowScat

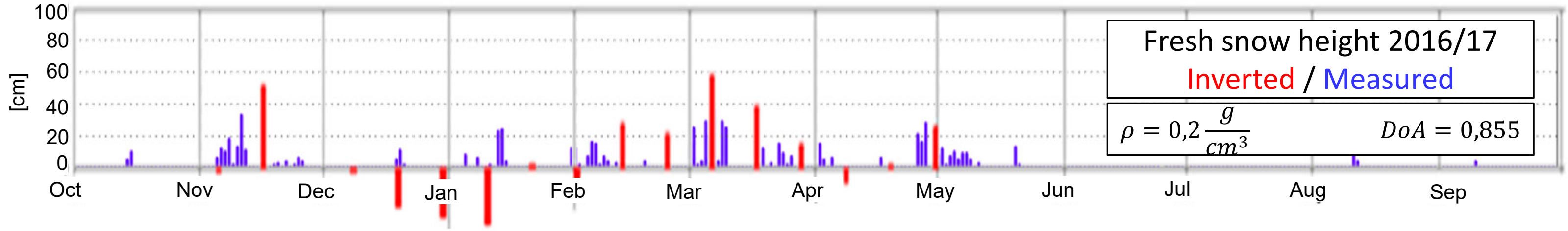


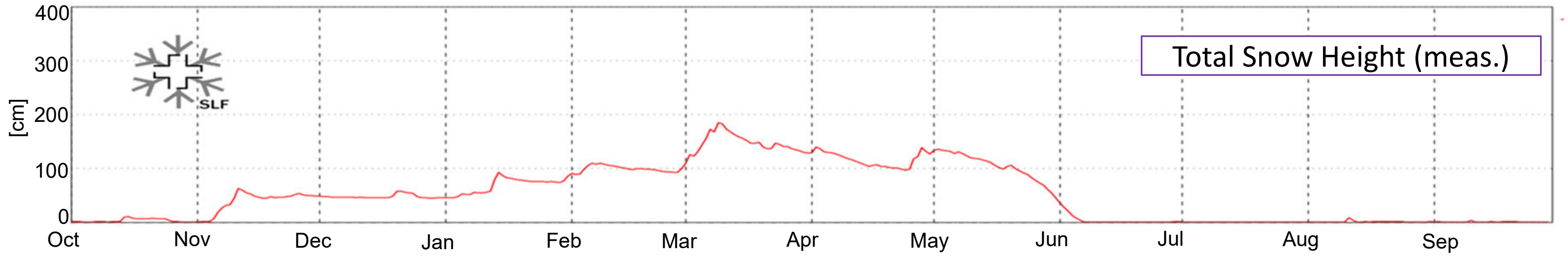
SnowScat shows same result, but with > 50x better temporal resolution

Available Ground Measurements

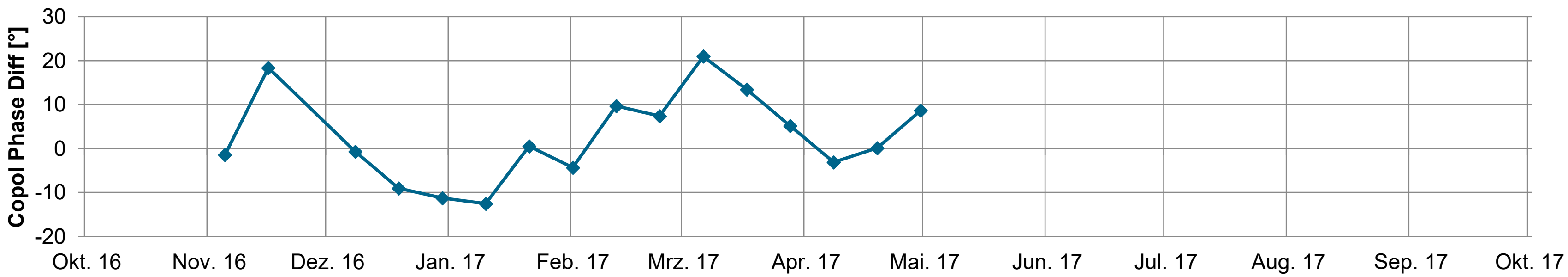
- ✓ With ϕ_{VV-HH} and Propagation Model the aim is to monitor snow accumulation of the Aletsch Glacier
- ✓ Ground measurements provided by the Institute for Snow and Avalanche Research (SLF)
- ✓ Automatic station at 2500 m provides:
  - ✓ Fresh snow height
  - ✓ Total snow height (daily)
  - ✓ Wind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





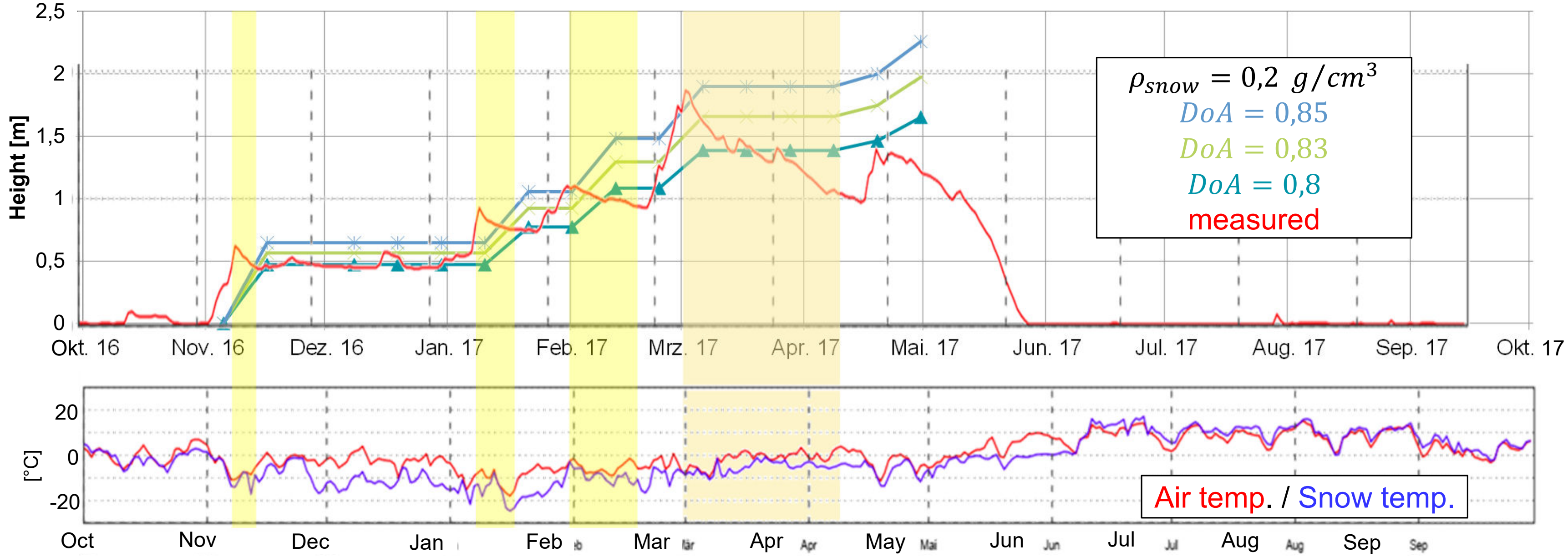


Inversion of Total Snow Height (2016-17)

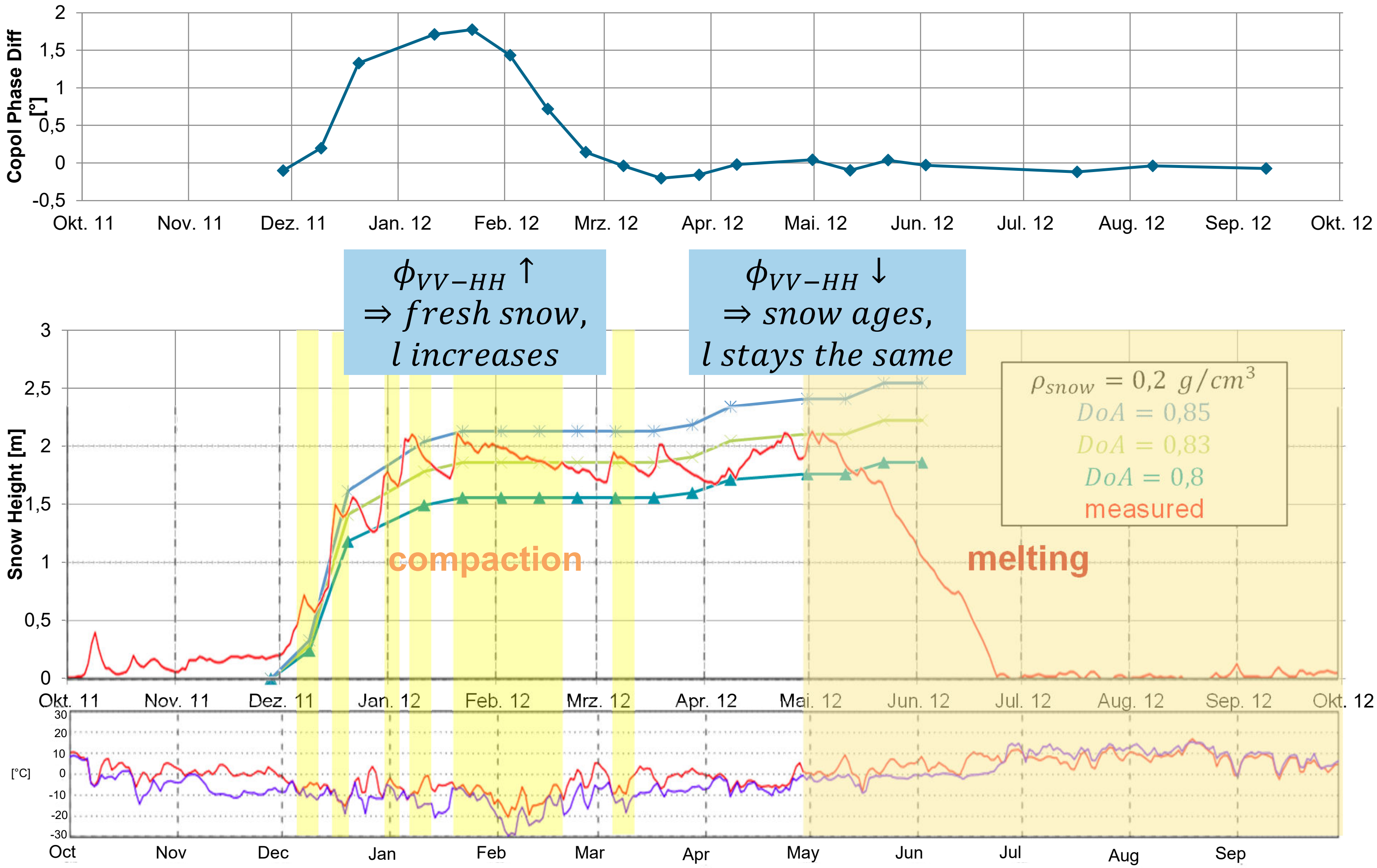


$\phi_{VV-HH} \uparrow$
$\Rightarrow fresh\ snow,$
$l\ increases$

$\phi_{VV-HH} \downarrow$
$\Rightarrow snow\ ages,$
$l\ stays\ the\ same$



Tentative Total Snow Height Estimation (2011-12)



Limitations of Snow Height Estimation Approach

DLR

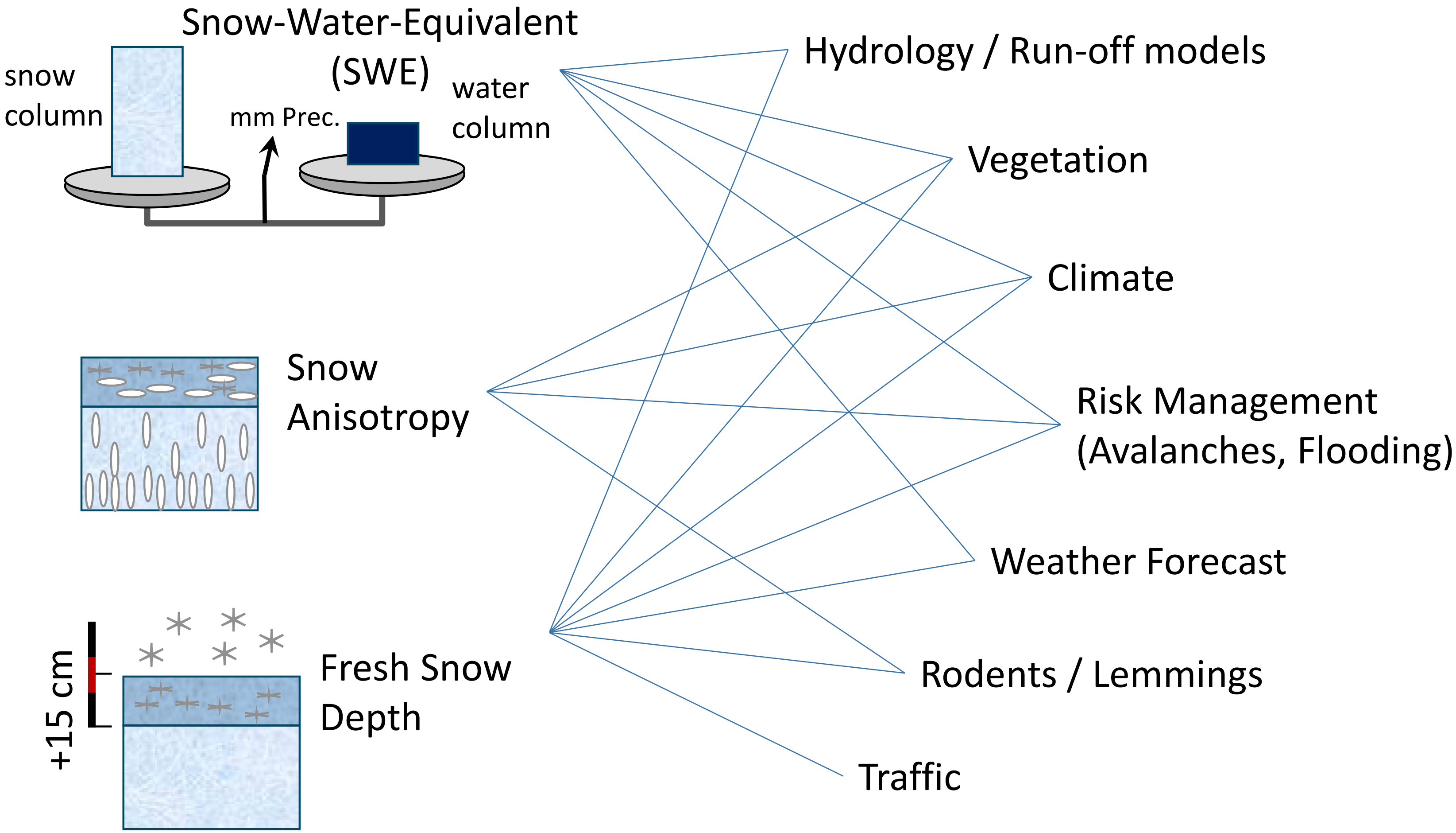
Snow Melting if T > 0°C

- ✓ 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?



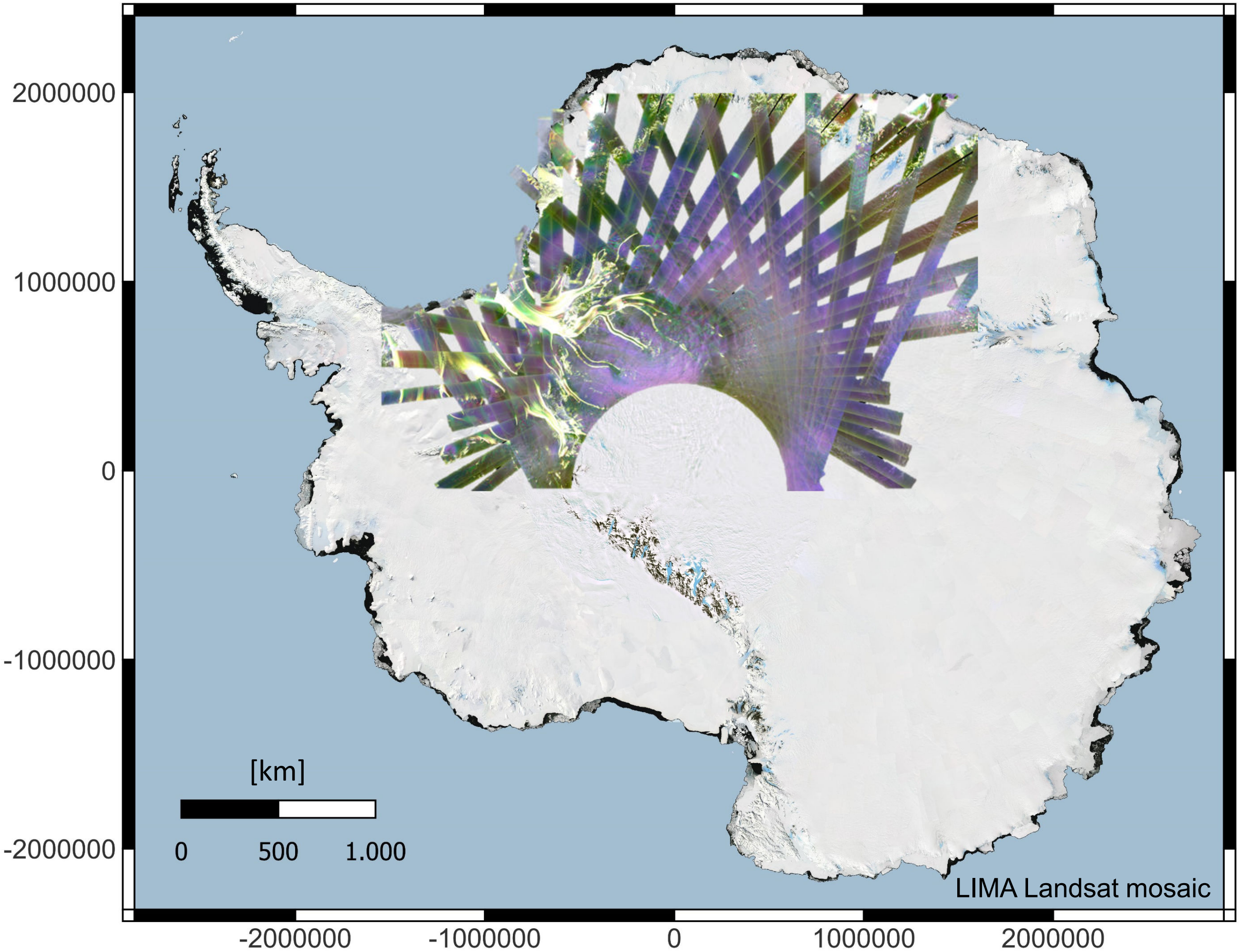
Irena Hajnsek, PolinSAR Training Course, 05.02.2026 – irena.hajnsek@dlr.de

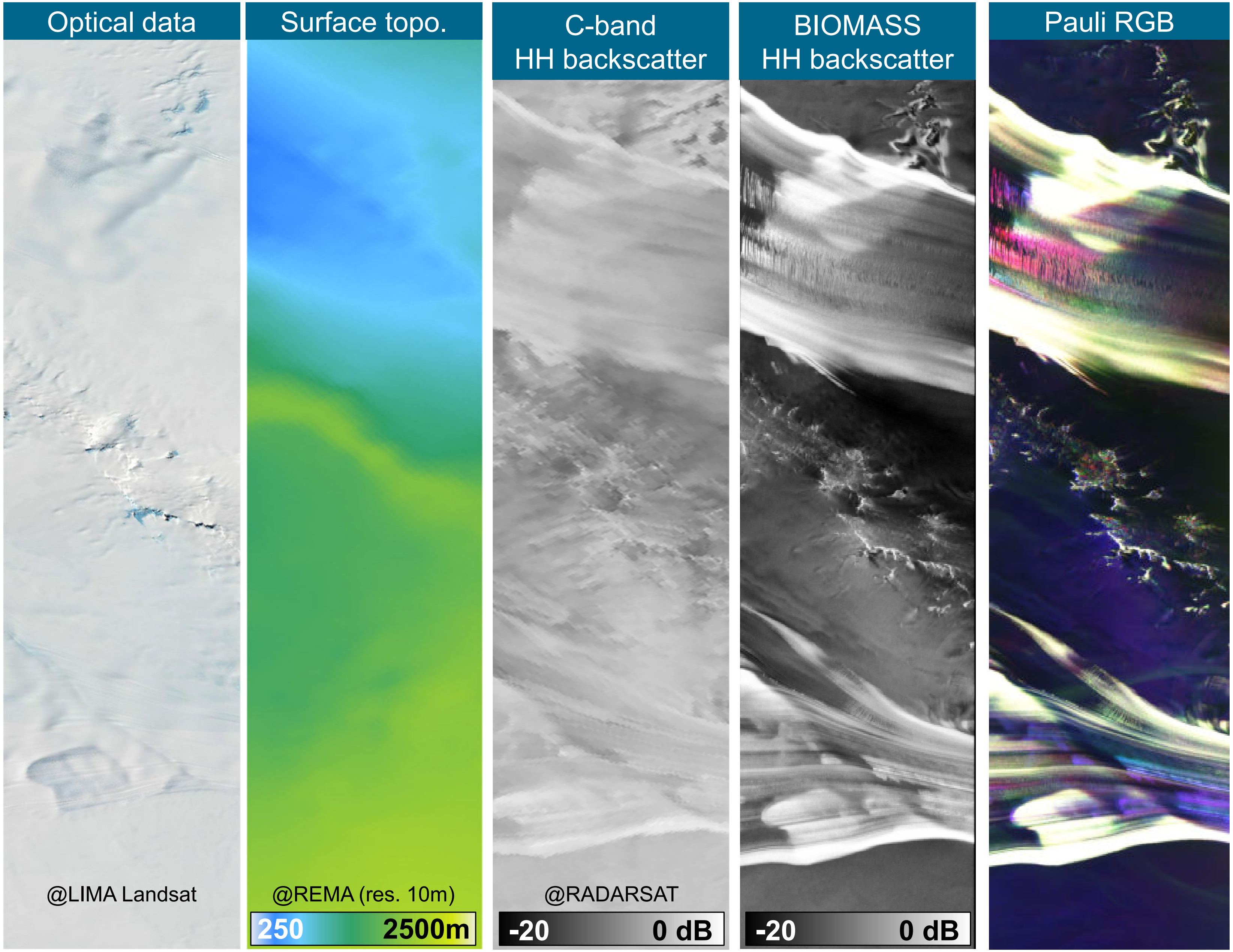
biomass

- Long-wavelength P-band penetrates dry snow and ice
- Sensitivity to internal layering

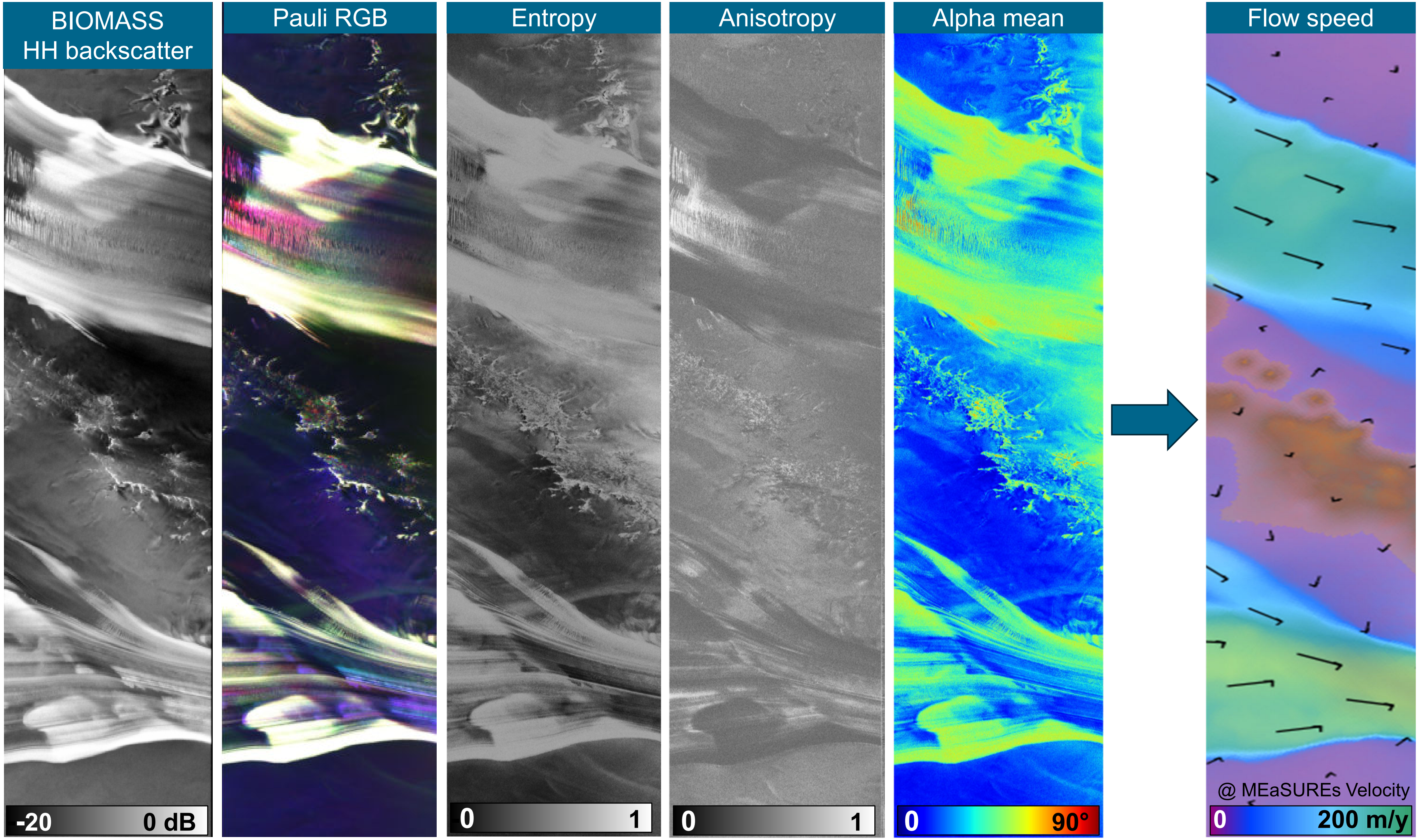
→ Polarimetry separates scattering mechanisms

→ Revealing subsurface ice structures



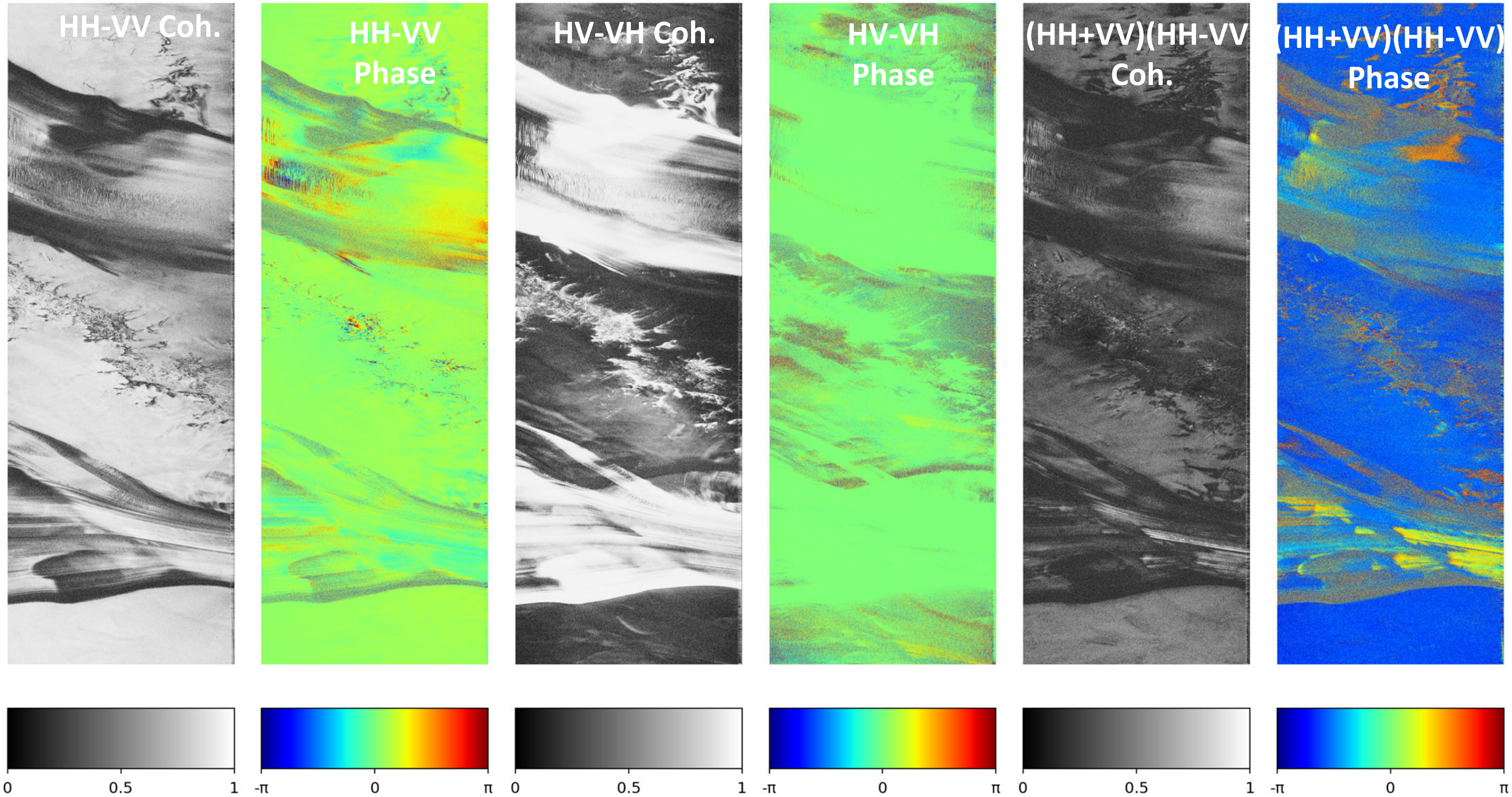


Detection of glacier flow patterns


BIOMASS
HH backscatter
-20
0 dB
Pauli RGB
Entropy
0
1
Anisotropy
0
1
Alpha mean
0
90°
Flow speed
@ MEaSUREs Velocity
0
200 m/y

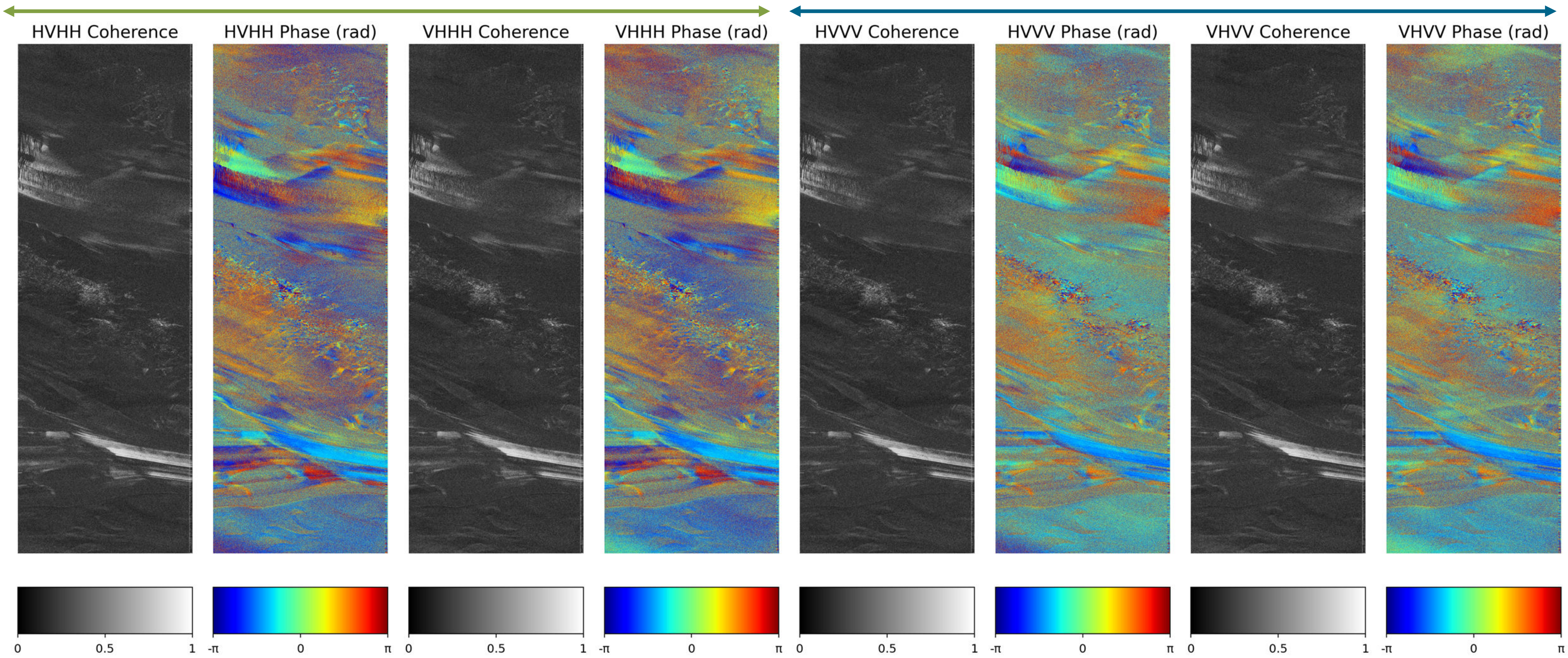
Polarimeric Coherence (Co and Cross Pol)

- Co-Pol coherence are high and descent phase variations over the moving glacier
- HV-VH coherence is a good noise identicator for monostatic acquisitions



Polarimeric Coherence (Co and Cross Pol)

- No difference between HVVV or VHVV and HVHH or VHHH
- But slight difference between Co/Cross HVVV and HVHH in Coherence and Phase

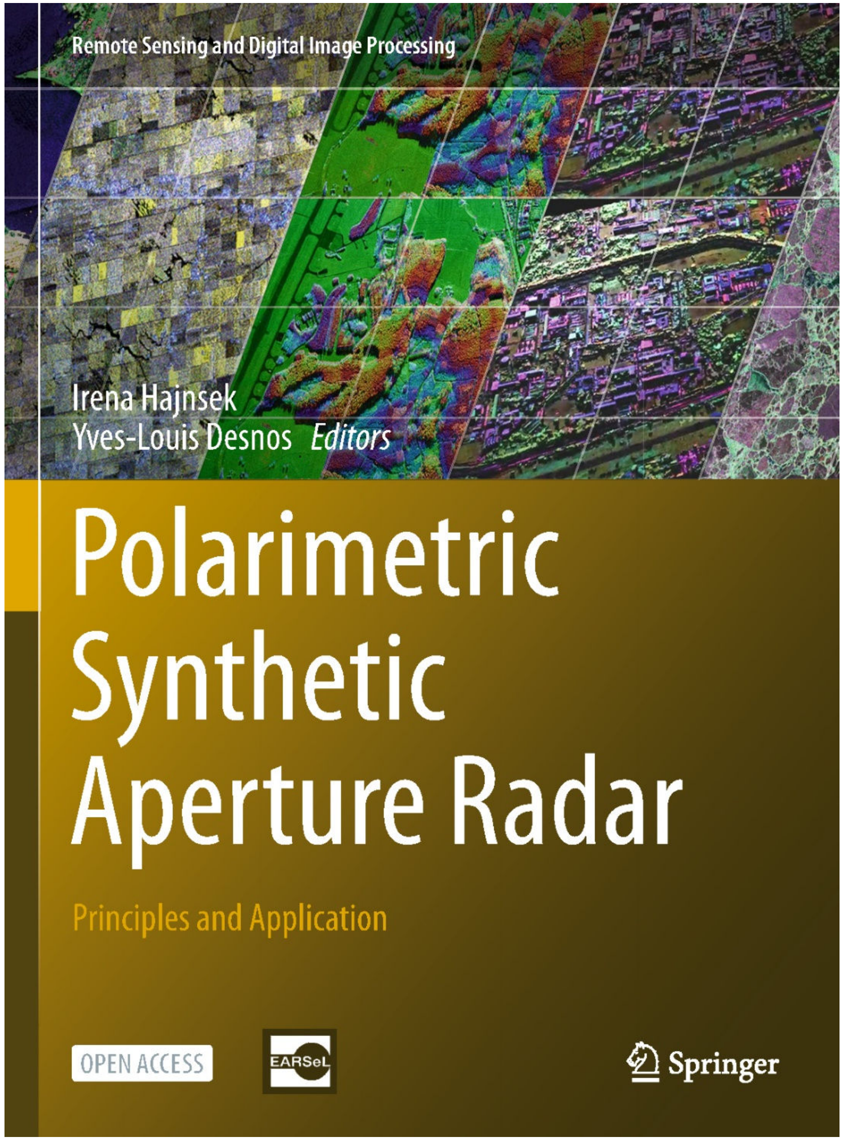


Polarimetric Applications

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

Coherence calculation:

```
def calculate_covariance(im1, im2, looksr, looksa) :
    corr = uniform_filter(np.real(im1*np.conj(im2)), [looksa,looksr]) + 1j* \
    uniform_filter(np.imag(im1*np.conj(im2)), [looksa,looksr]) return corr
```

I am happy to answer your question?