

Principles and Basics of Pol-InSAR

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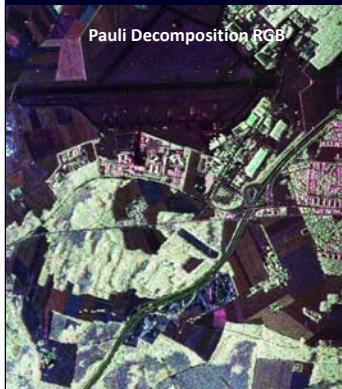
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SAR Polarimetry (PolSAR)

Allows the identification / decomposition of different scattering processes occurring inside the resolution cell



SAR Interferometry (InSAR)

Allows the location of the effective scattering center inside the resolution cell



Polarimetric SAR Interferometry (Pol-InSAR)

Potential to separate in height different scattering processes occurring inside the resolution cell

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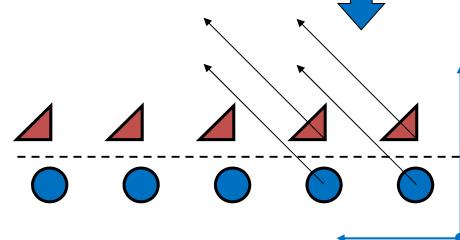
Interferometry vs. Polarimetry

$$S_{HH}^1 = A_D^1 + A_S^1$$

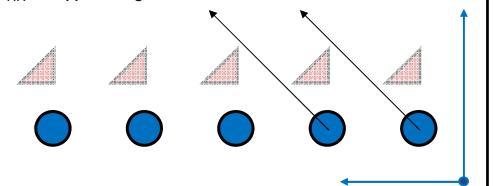


$$\varphi = \arg\{ S_{HH}^1, S_{HH}^{2*} \}$$

$$S_{HH}^2 = A_D^2 + A_S^2$$



$$S_{HH} + S_{VV} = 2A_S$$



$$[S_D] = A_D \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} \text{ Dihedral Reflector}$$

$$[S_S] = A_S \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \text{ Sphere or Trihedral Reflector}$$



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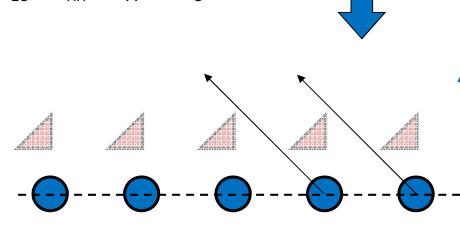
Polarimetric Interferometry

$$i_{1S} = S_{HH}^1 + S_{VV}^1 = 2A_S^1$$



$$\varphi_S = \arg\{ i_{1S}, i_{2S}^* \}$$

$$i_{2S} = S_{HH}^2 + S_{VV}^2 = 2A_S^2$$



$$i_{1D} = S_{HH}^1 - S_{VV}^1 = 2A_D^1$$



$$\varphi_D = \arg\{ i_{1D}, i_{2D}^* \}$$

$$i_{2D} = S_{HH}^2 - S_{VV}^2 = 2A_D^2$$



$$[S_D] = A_D \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} \text{ Dihedral Reflector}$$

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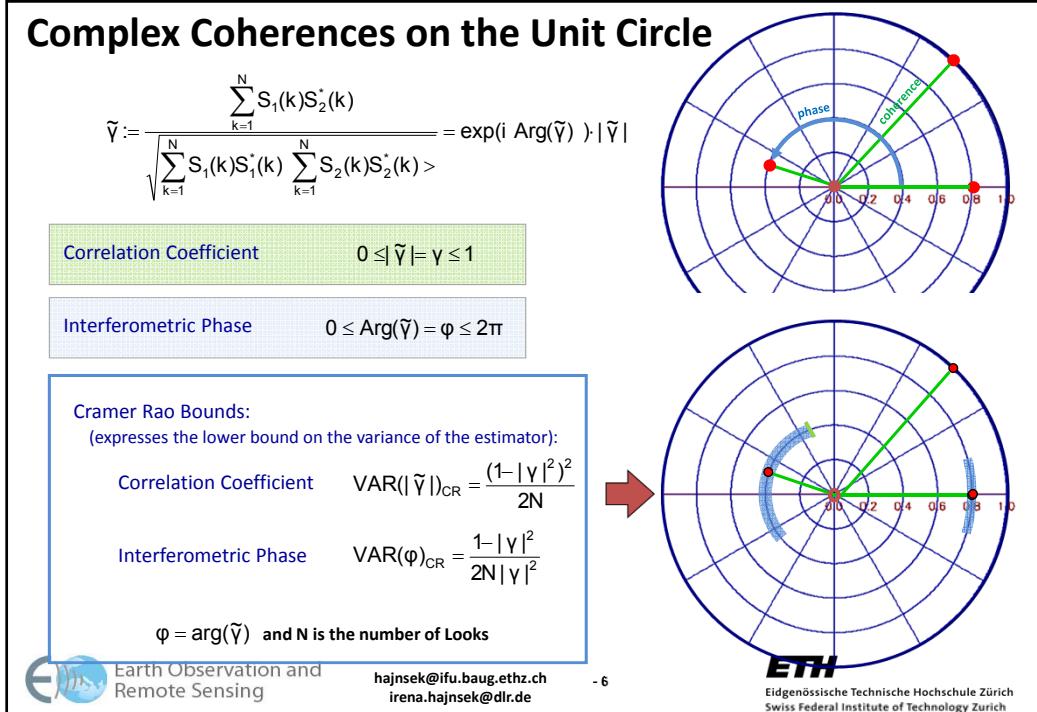
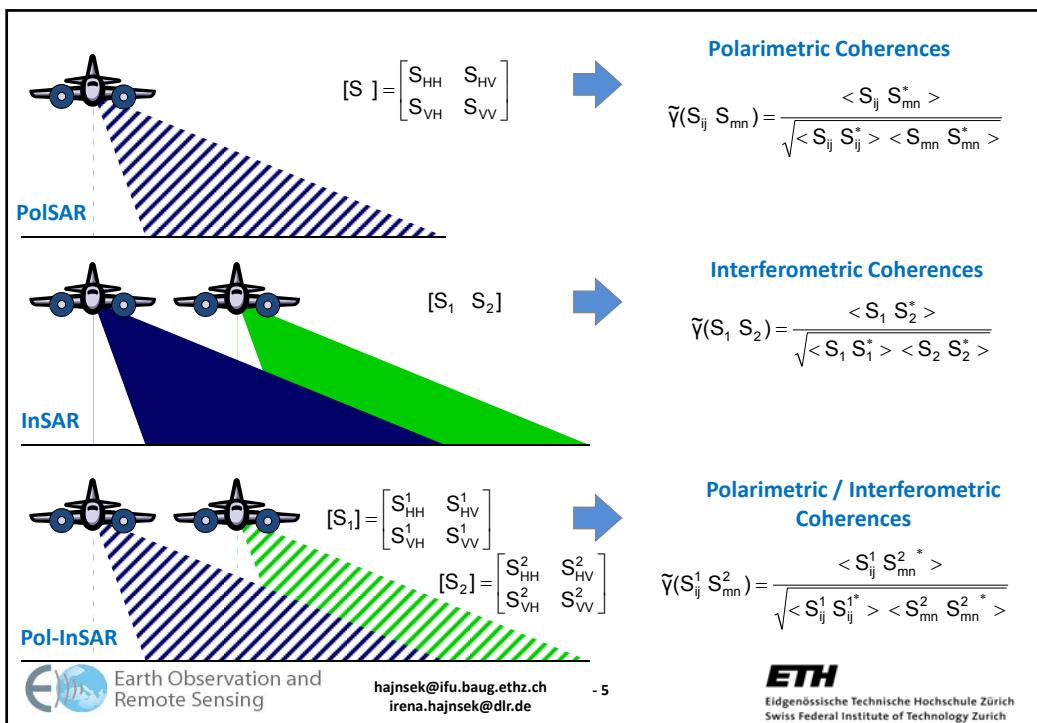
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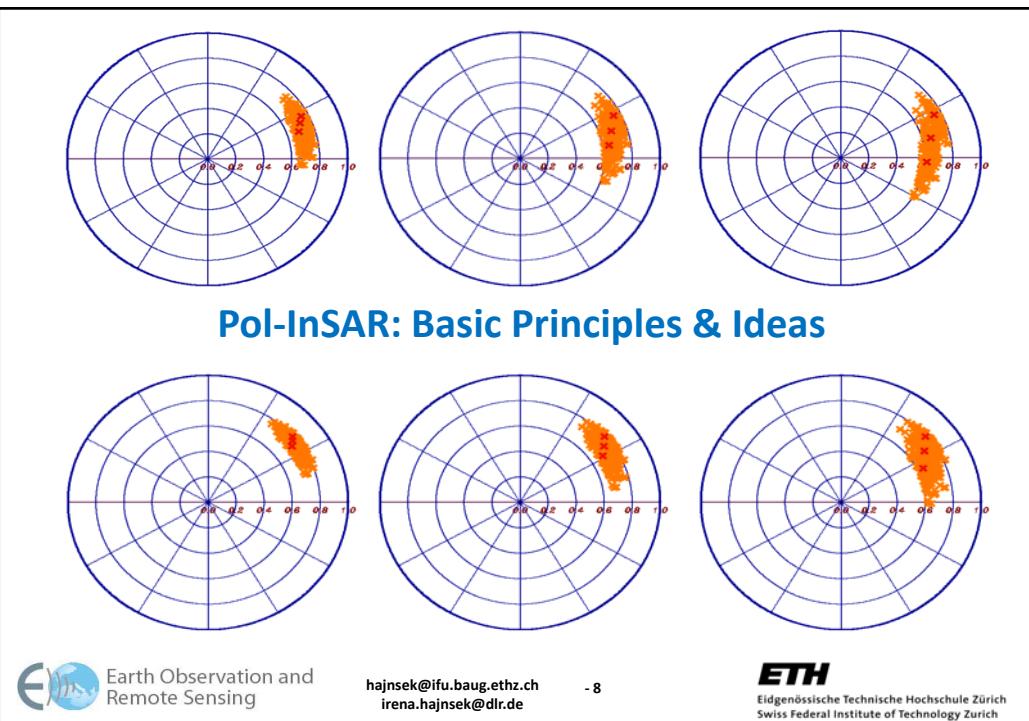
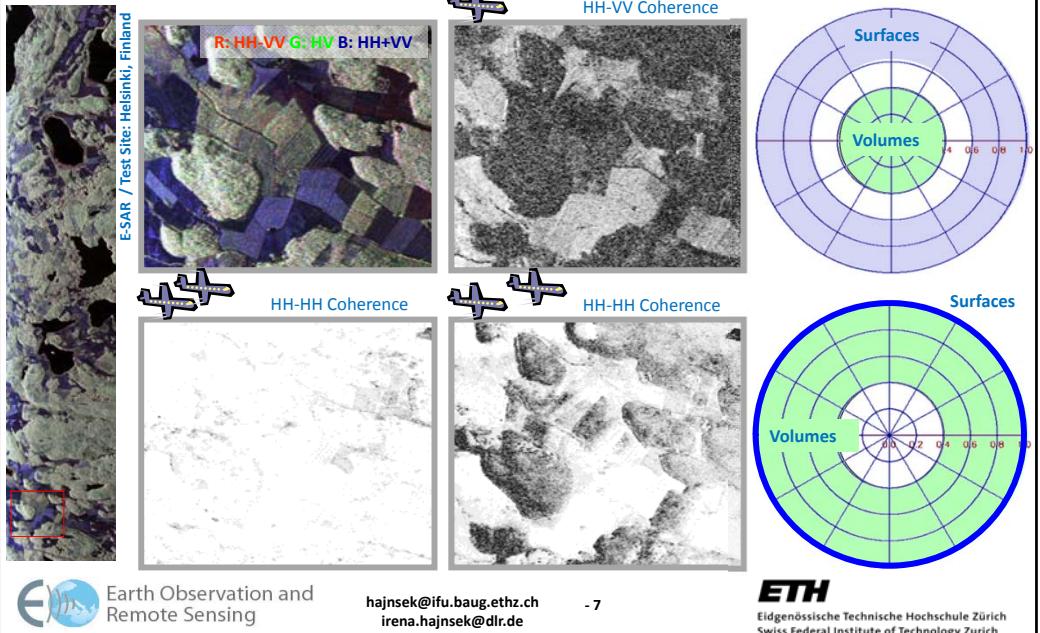
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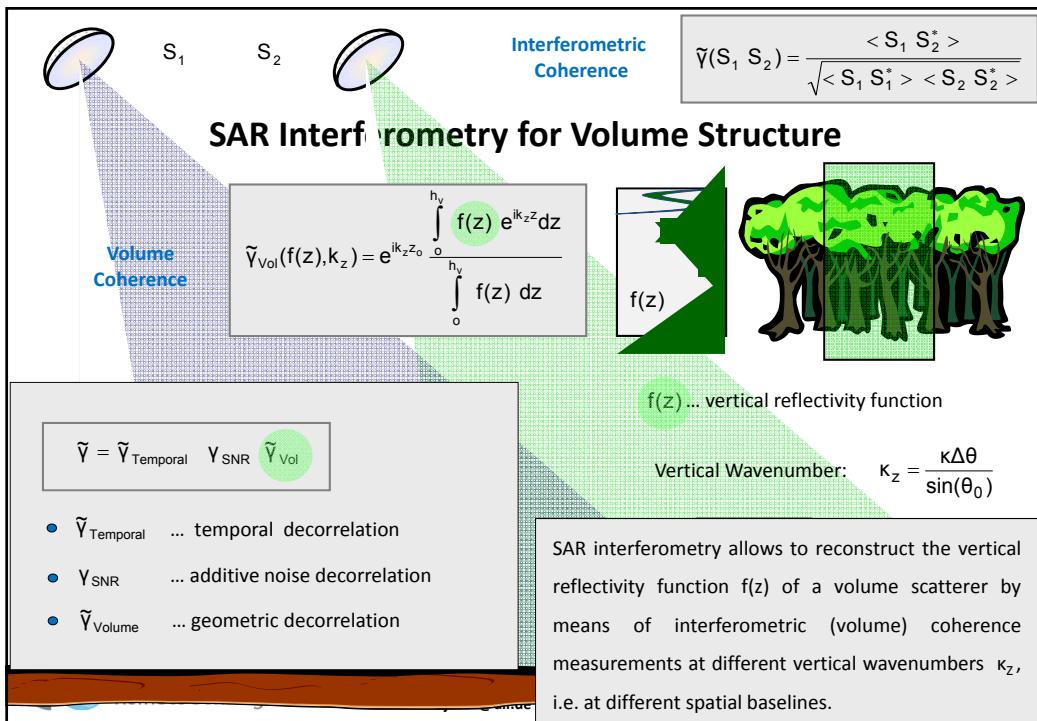
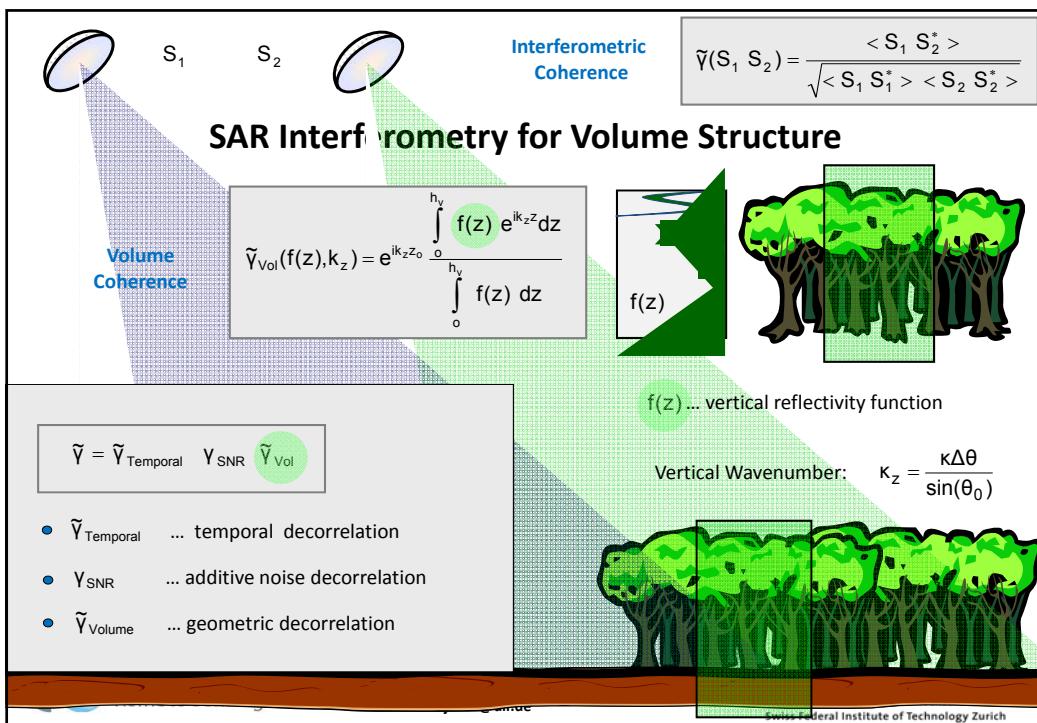


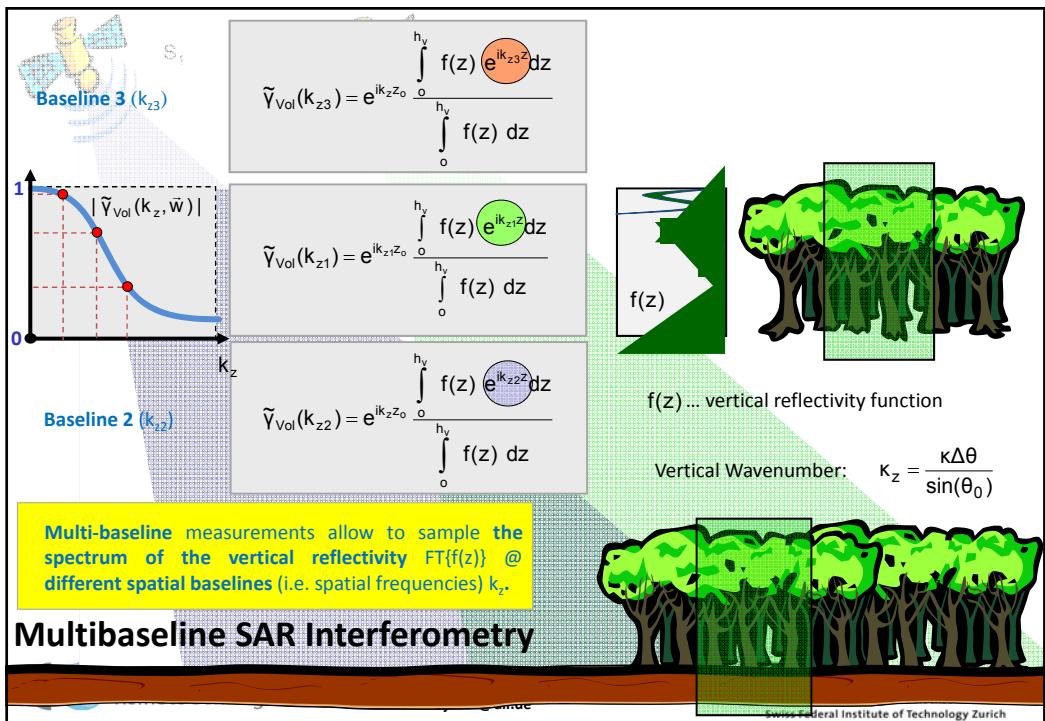
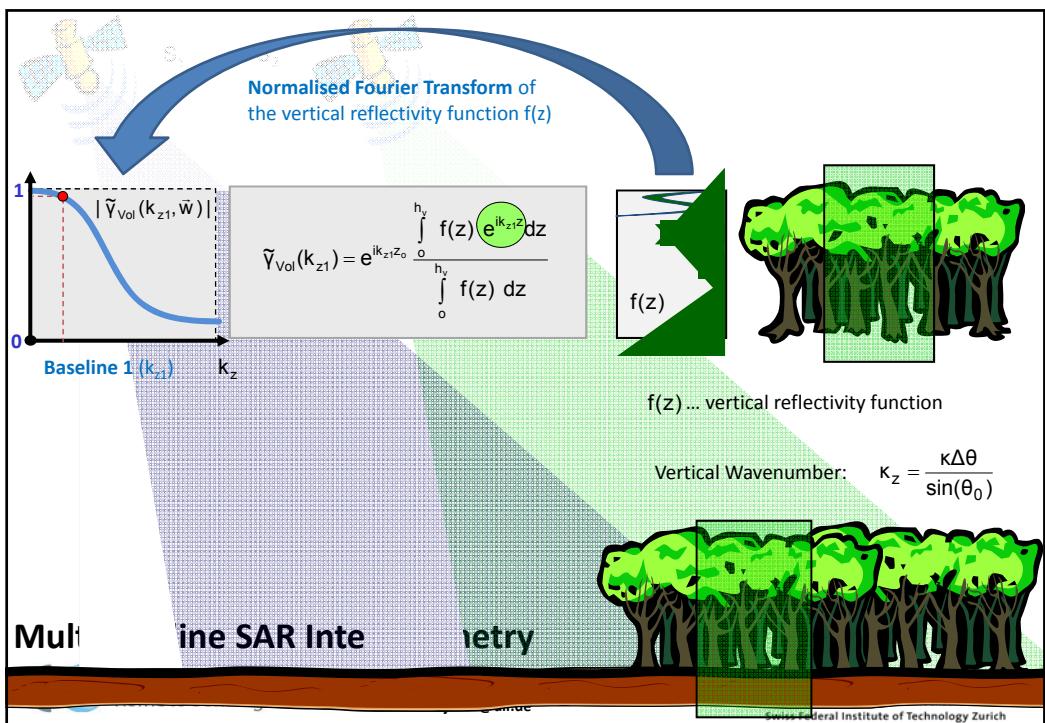
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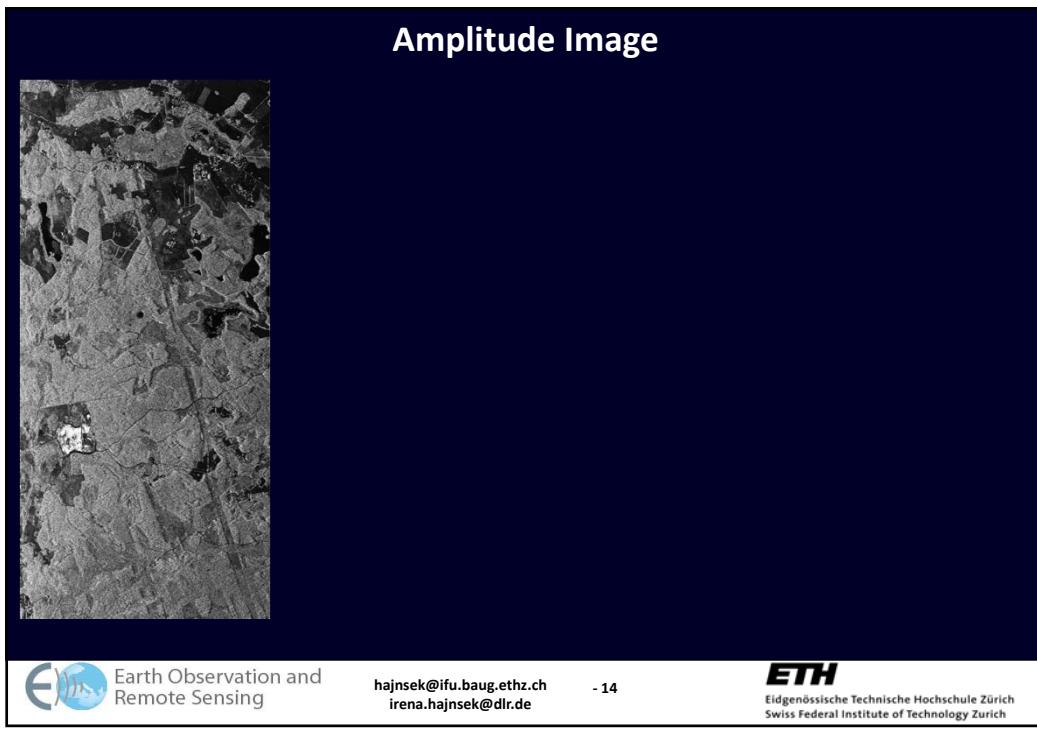
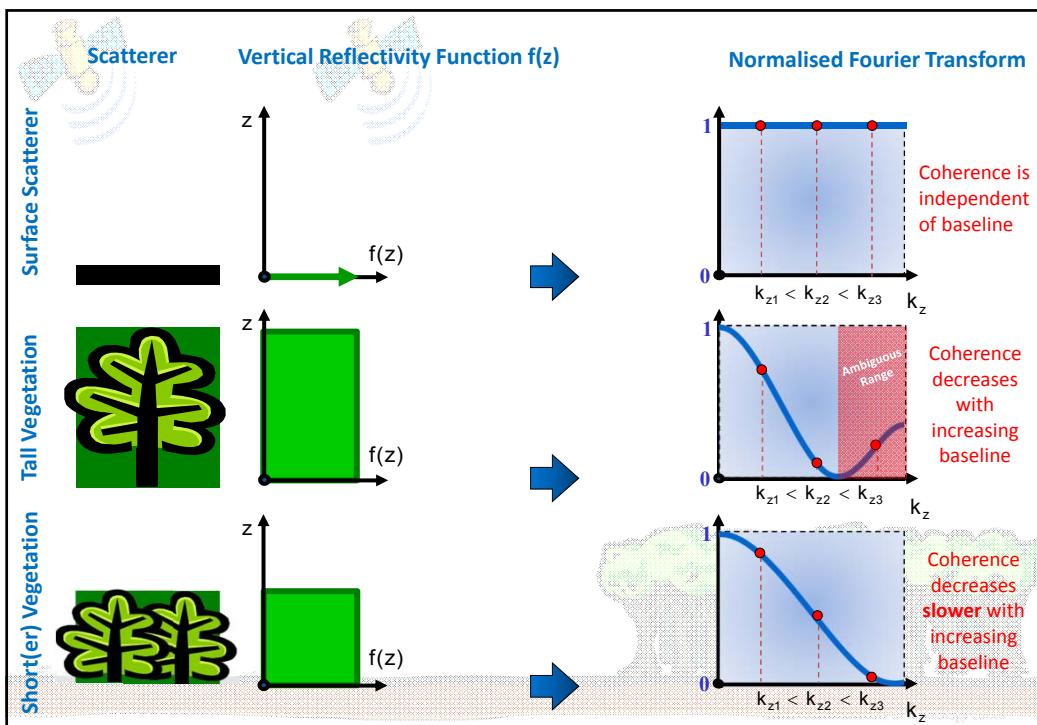


Why is Interferometry important for Volume Scatterers?

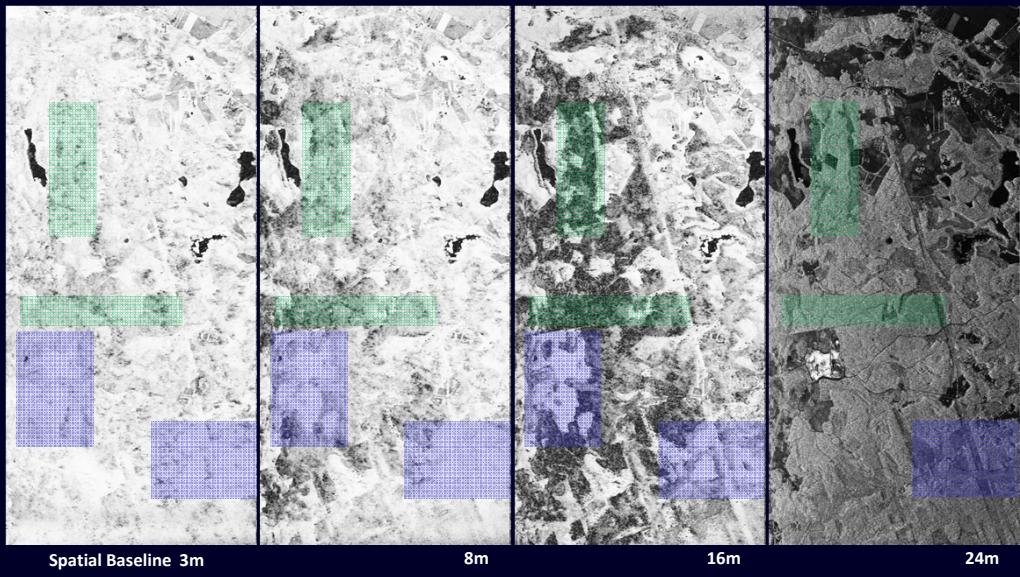








Interferometric Coherence: Volume Decorrelation



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Polarimetric SAR Interferometry

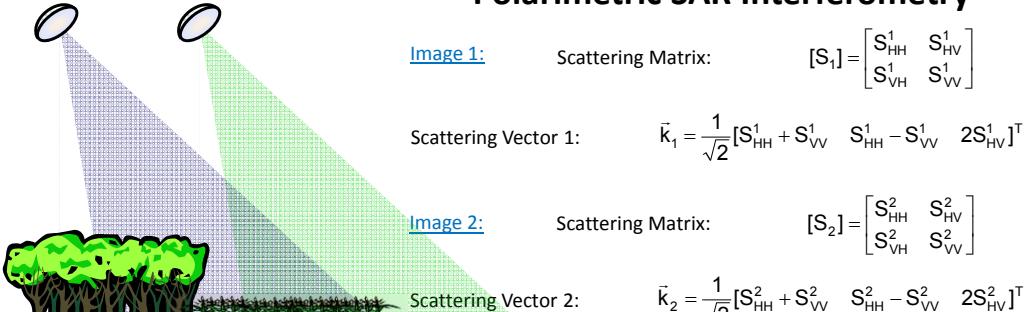
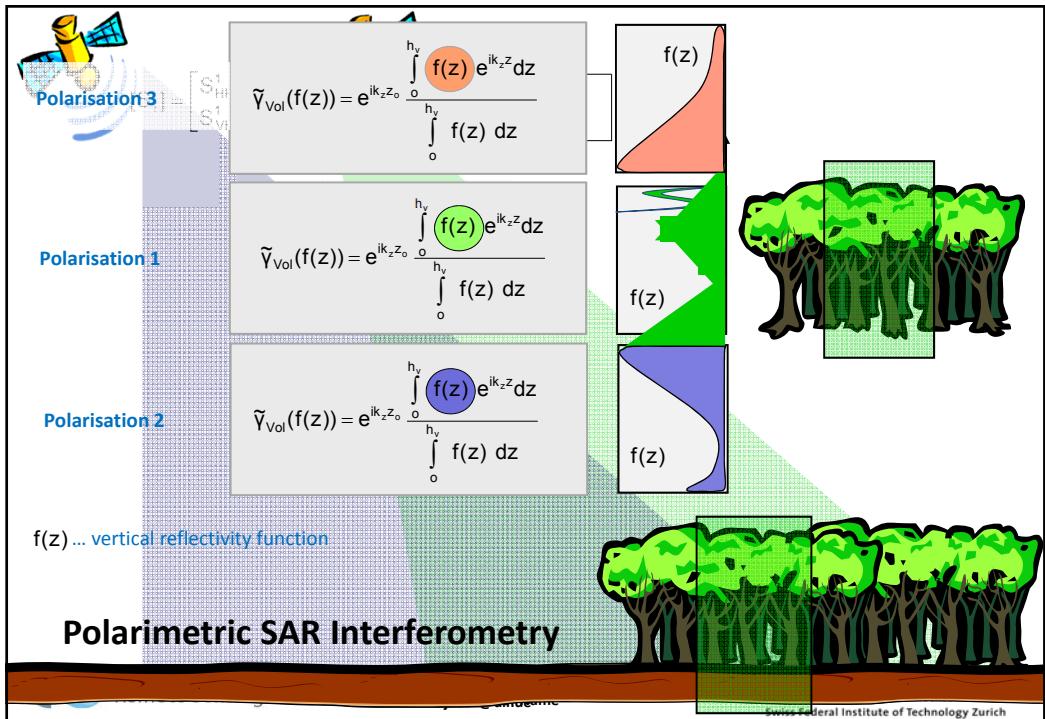
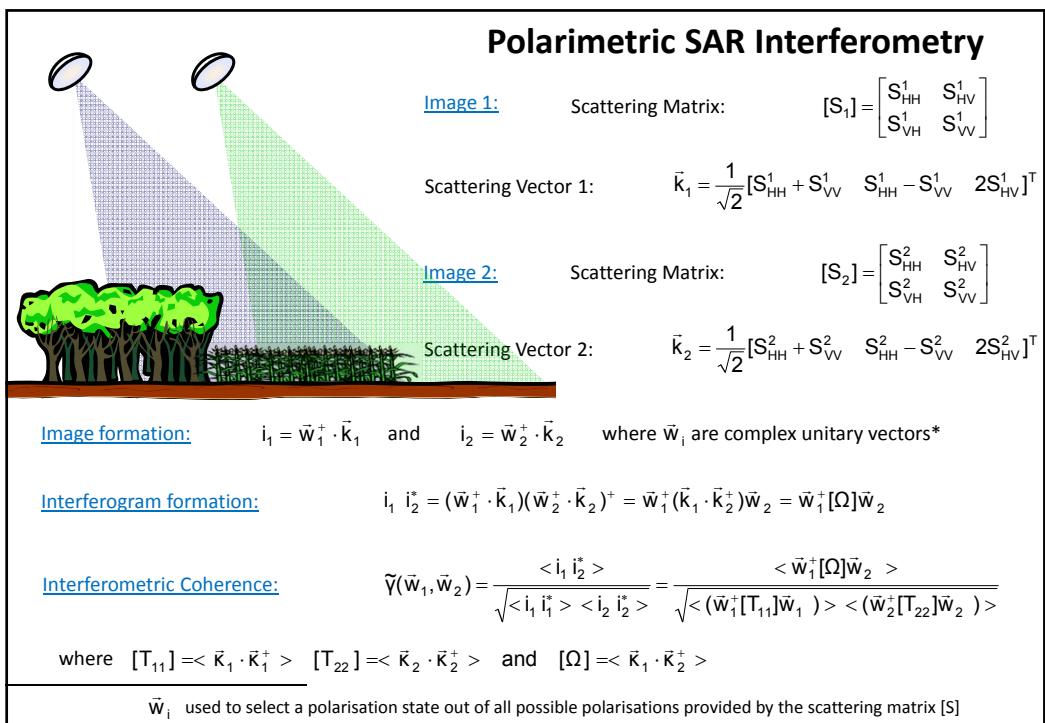


Image formation: $i_1 = \vec{w}_1^+ \cdot \vec{k}_1$ and $i_2 = \vec{w}_2^+ \cdot \vec{k}_2$... projection of the scattering vector on a (complex) unitary vector \vec{w}_i

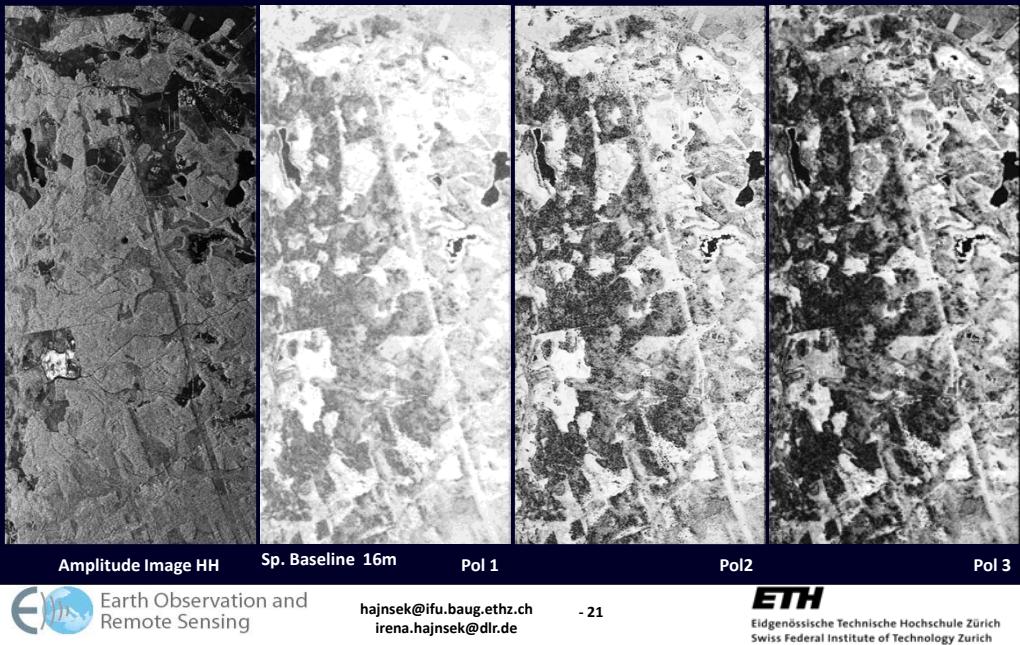
\vec{w}_i used to select a given polarisation out of all possible polarisations provided by the scattering matrix [S]

Example: $S_{HH} + S_{VV}$ image: $\vec{w} = [1 \ 0 \ 0]^T \rightarrow i = \vec{w}^+ \cdot \vec{k}_j = \frac{1}{\sqrt{2}} (S_{HH}^j + S_{VV}^j)$

S_{HH} image: $\vec{w}_1 = [1/\sqrt{2} \ 1/\sqrt{2} \ 0]^T \rightarrow i_j = \vec{w}_1^+ \cdot \vec{k}_j = S_{HH}^j$



Interferometric Coherence: Volume Decorrelation

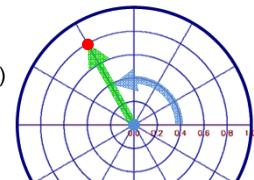


Geometrical Representation

Interferometric Coherence: $\tilde{\gamma}(\vec{w}_i, \vec{w}_i) = |\tilde{\gamma}(\vec{w}_i, \vec{w}_i)| \exp(i \operatorname{Arg}\{\tilde{\gamma}(\vec{w}_i, \vec{w}_i)\})$

Radius Angle

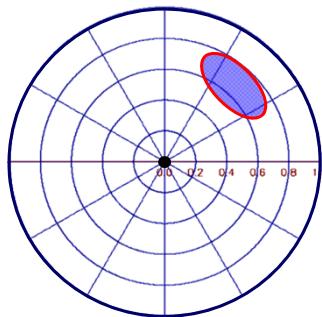
► can be represented by a single point on the unit circle



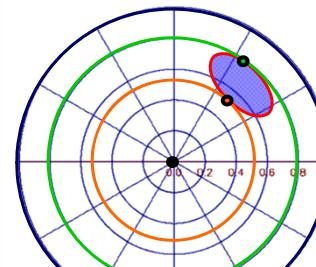
Coherence Region:

$$\tilde{\gamma}(\vec{w}_i, \vec{w}_i) \quad \forall \quad \vec{w}_i = \begin{bmatrix} \cos \alpha \exp(i\varphi_1) \\ \sin \alpha \cos \beta \exp(i\varphi_2) \\ \sin \alpha \sin \beta \exp(i\varphi_3) \end{bmatrix} \quad 0 \leq \alpha \leq \frac{\pi}{2} \quad -\pi \leq \beta \leq \pi \quad \in C$$

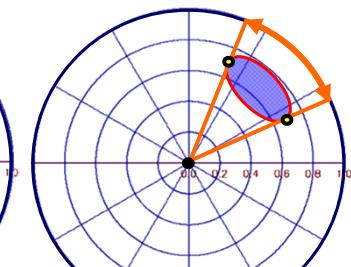
Shape and size depend on acquisition parameters and the structure of the underlying scatterer.



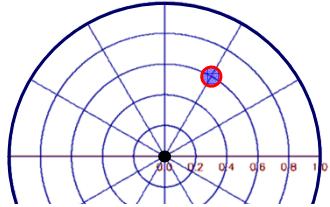
Max./ Min. Interferometric Coherence
as function of the polarisation used
to form the interferogram



Max. Phase Difference between
interferograms formed at different
polarisations



Coherence Region Interpretation

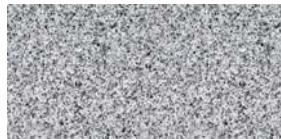


Point Like Coherence Region

i.e. InSAR Coherence and Phase are independent of polarisation.

Pol-InSAR does not provide any additional information compared to InSAR !!!

(Random) Volume scattering



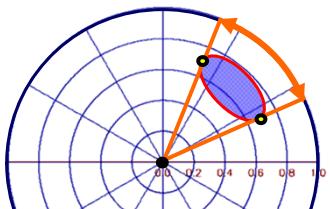
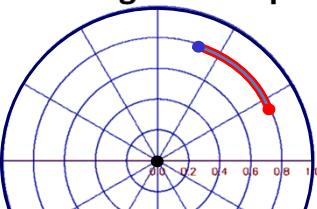
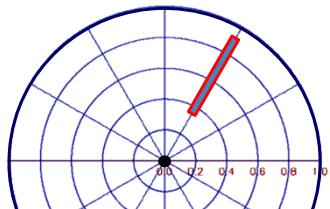
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Coherence Region Interpretation



Radial Coherence Region

i.e. InSAR Coherence changes with polarisation but not the location of the phase center.

Radial Coherence Region

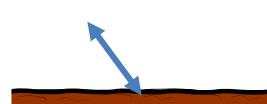
i.e. InSAR Phase changes, but not the InSAR coherence with polarisation

Elliptical Coherence Region

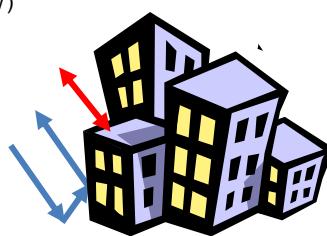
i.e. InSAR Coherence and Phase changes with polarisation.

Surface Scattering

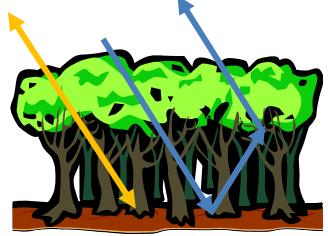
$$\tilde{\gamma}(\vec{w}) = \gamma_{\text{SNR}}(\vec{w}) \quad \tilde{\gamma}_{\text{Vol}} = \gamma_{\text{SNR}}(\vec{w})$$



(Polarised) Coherent scatterers at different heights



(Depolarising) Scatterers at different heights

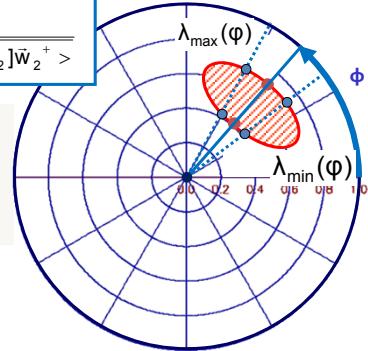


Coherence Region (CR)

Interferometric Coherence: $\tilde{\gamma}(\bar{w}_1, \bar{w}_2) = \frac{<\bar{w}_1[\Omega]\bar{w}_2^+>}{\sqrt{<\bar{w}_1[T_{11}]\bar{w}_1^+><\bar{w}_2[T_{22}]\bar{w}_2^+>}}$

The boundary of the coherence region can be reconstructed by estimating for each angle ϕ the max (λ_1) and min (λ_2) coherences:

Optimisation Problem ($\bar{w}_1 = \bar{w}_2$): $[T]^{-1}[\Omega_\phi] \bar{w} = \lambda \bar{w}$



where $[T] = \frac{1}{2}([T_{11}] + [T_{22}]), \lambda = -(\lambda_1 + \lambda_2^*) \quad [\Omega_\phi] = \frac{1}{2}(\exp(i\phi)[\Omega] + \exp(-i\phi)[\Omega]^+)$

and $[T_{11}] := <\vec{k}_1 \cdot \vec{k}_1^+> \quad [T_{22}] := <\vec{k}_2 \cdot \vec{k}_2^+> \quad [\Omega] := <\vec{k}_1 \cdot \vec{k}_2^+>$

Coherence Region: $\forall \phi \rightarrow \lambda_{\max}, \lambda_{\min}$ that have to be connected to provide the boundary of the CR

Shape and size are characterised by the acquisition and scattering parameters



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Structure Parameters & Applications

Forest

- Forest Height
- Forest (Vertical) Structure
- Forest Biomass
- Underlying Topography



- Forest Ecology
- Forest Management
- Ecosystem Modeling
- Climate Change

Agriculture

- Underlying Soil Moisture
- Moisture of Vegetation Layer
- Height of Vegetation Layer
- Soil Roughness



- Farming Management
- Ecosystem Modeling
- Water Cycle / CC
- Desertification

Snow & Ice

- Ice Layer Structure
- Penetration Depth (Ice)
- Snow Layer Thickness
- Snow Water Equivalent



- Ecosystem Change
- Water Cycle
- Water Management



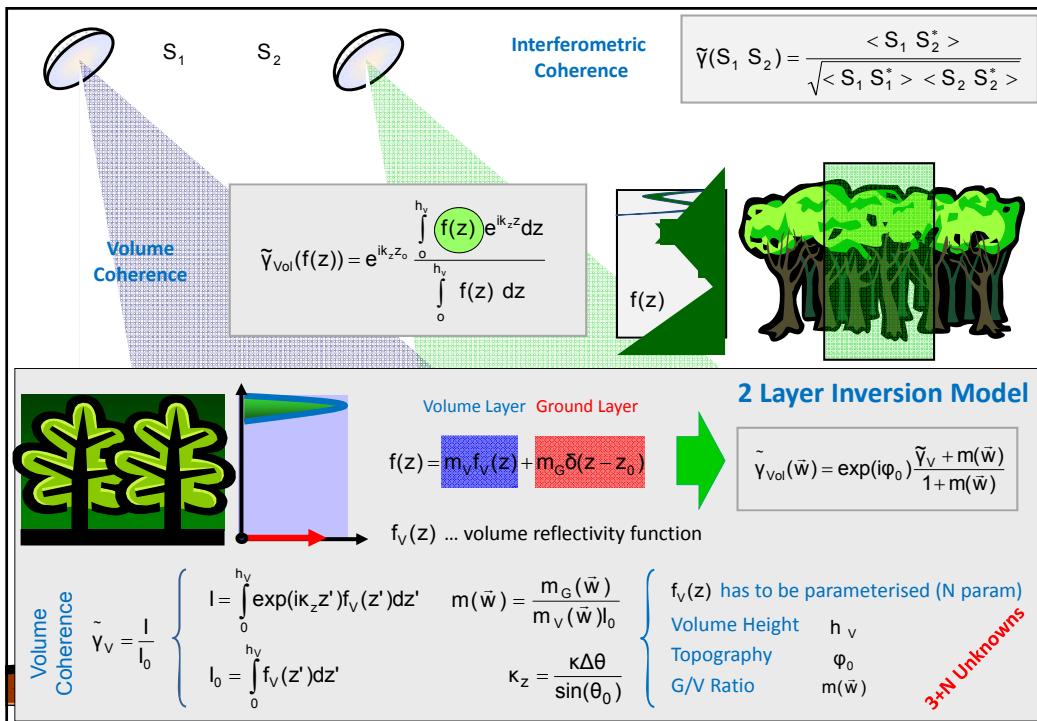
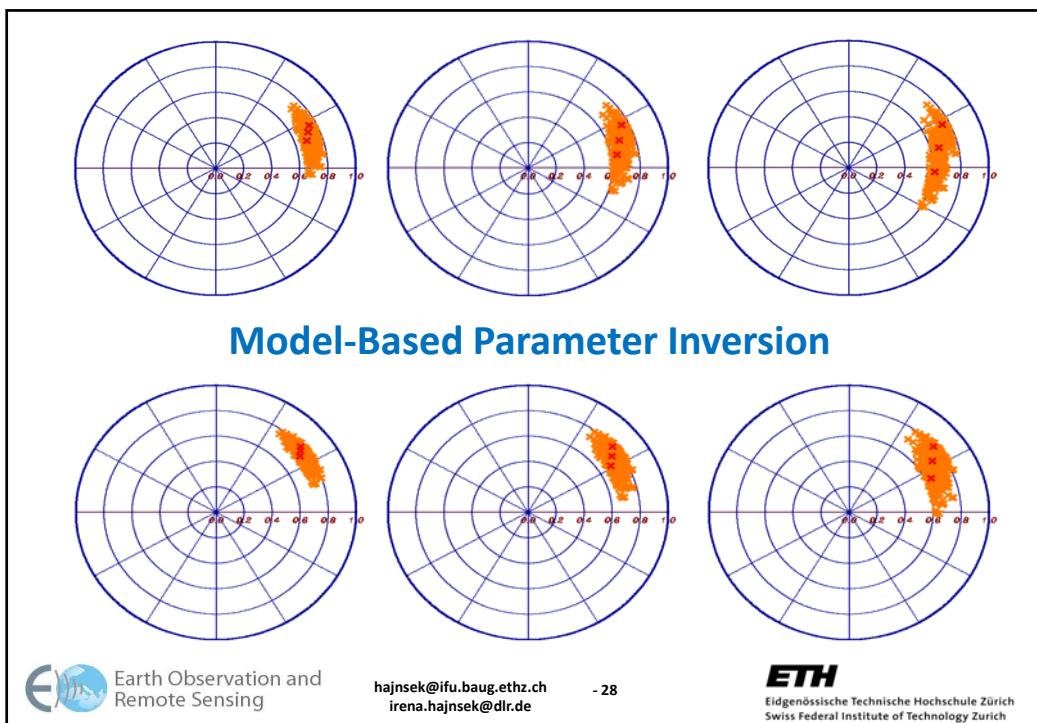
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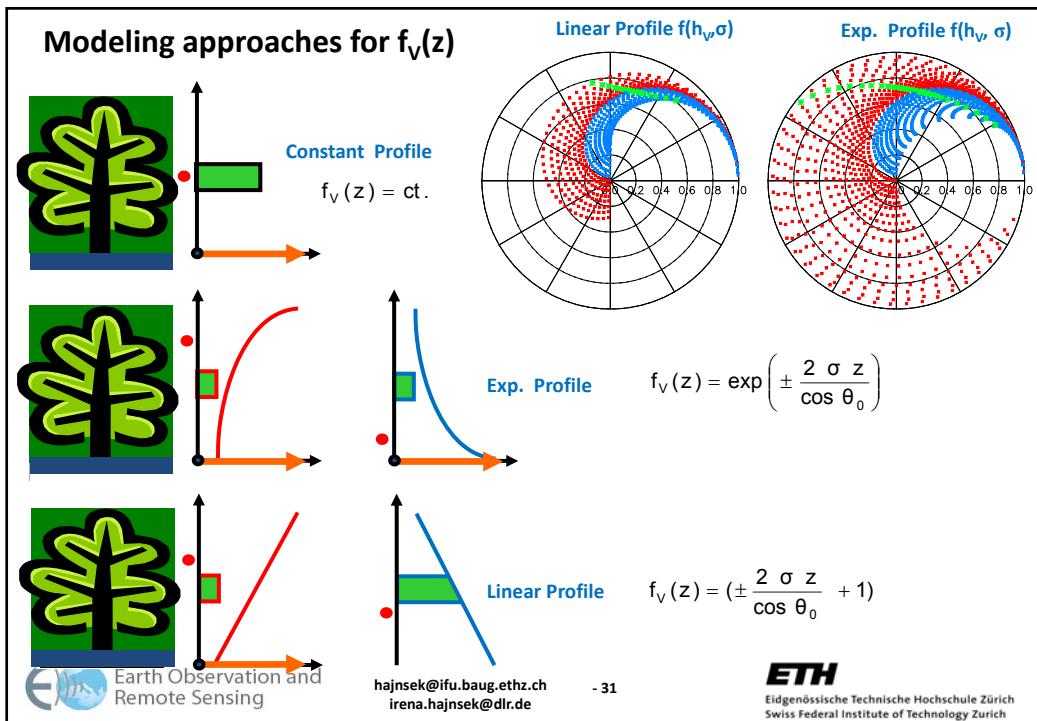
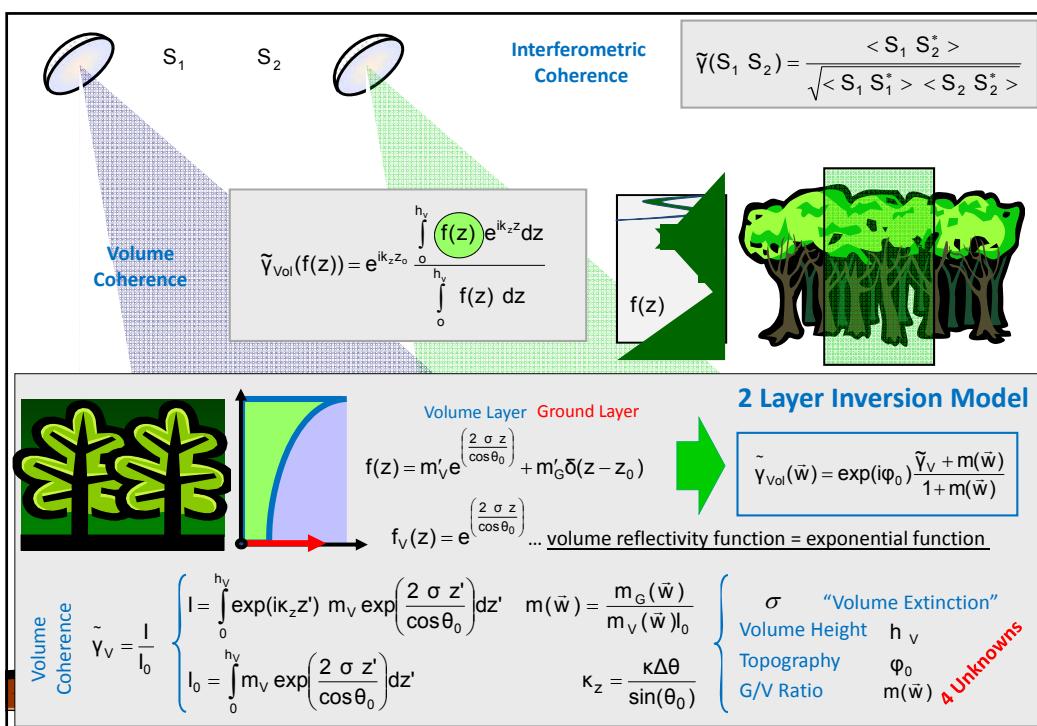
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Polarimetric Behaviour: Random vs. Oriented Volume

Random Volume: The vertical reflectivity function is independent of polarisation (or each polarisation sees the same volume vertical reflectivity $f_v(z)$)

$$f_v := f_v(z) \mapsto \gamma_v(k_z)$$

Oriented Volume: The vertical reflectivity function changes with polarisation (or each polarisation sees a different volume vertical reflectivity $f_v(z)$)

$$f_v := f_v(z, \bar{w}) \mapsto \gamma_v(k_z, \bar{w})$$

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Polarimetric Behaviour: 3-dim vs 2-dim Ground Scatterer

3-dim ground scatterer: A ground scattering component is visible in all polarisations (or there is no polarisation that "switches-off" the ground)

$$\forall \bar{w} \quad m(\bar{w}) \neq 0$$

2-dim ground scatterer: There is (at least) one polarisation in which the ground disappears

$$\exists \bar{w} \mapsto m(\bar{w}) = 0$$

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$$\exists \bar{w}_x \mapsto m(\bar{w}_x) = 0$$

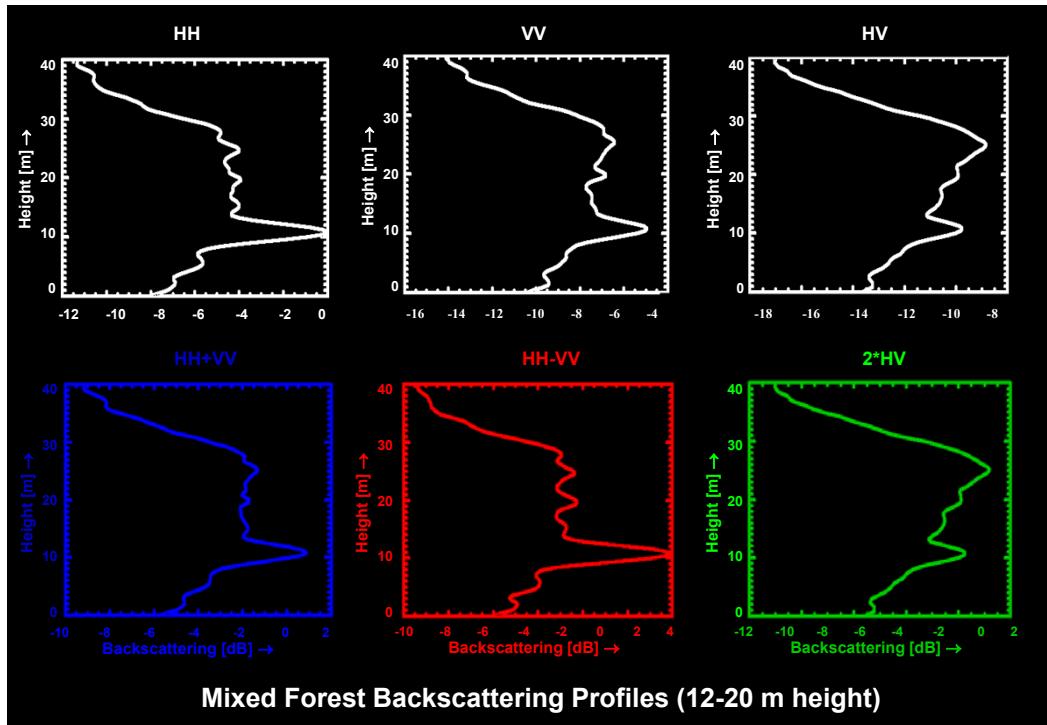
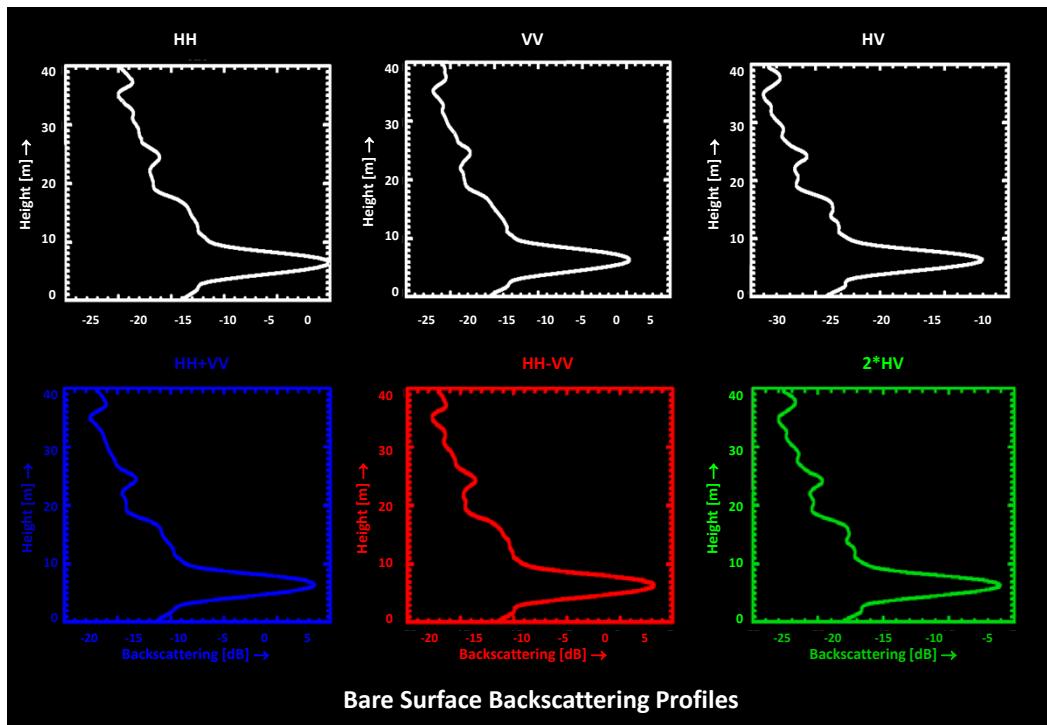
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RVoG Scattering Model: Geometrical Interpretation

Interferometric Coherence:
(2 Layer Random Volume)

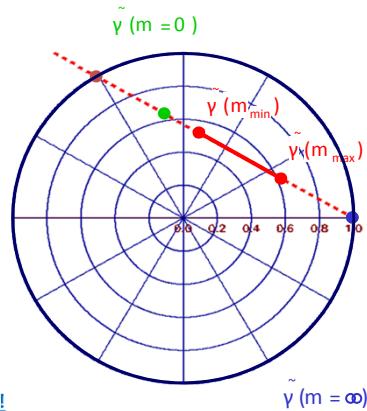
$$\tilde{\gamma}(\bar{w}) = \exp(i\phi_0) \frac{\tilde{\gamma}_V + m(\bar{w})}{1 + m(\bar{w})}$$

$$\tilde{\gamma}(\bar{w}) = \exp(i\phi_0) \left[\tilde{\gamma}_V + \frac{m(\bar{w})}{1 + m(\bar{w})} (1 - \tilde{\gamma}_V) \right]$$

$$\tilde{\gamma}(\bar{w}) = \exp(i\phi_0) [B + X(\bar{w}) A]$$

Equation of a straight line in the complex plane ►

The coherence region of the RVoG model is a line segment !!!



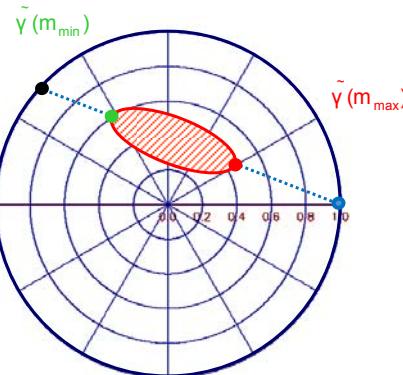
- The ends of the segment correspond to the coherences given by the max / min G-V Ratio: $\tilde{\gamma}(m_{\max})$ and $\tilde{\gamma}(m_{\min})$
- One of the line-unit circle intersection points correspond to the "Ground only" point, i.e. $\tilde{\gamma}(m=\infty) = \exp(i\phi_0)$
- The second line-unit circle intersection points is non-physical
- The "Volume only" point (i.e. $\tilde{\gamma}(m(\bar{w})=0) = \exp(i\phi_0)\tilde{\gamma}_V$) lies on the line but (in general) not on the coherence region segment

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RVoG Solution on the Unit Circle



1. Estimation of the Coherence Region (CR);
2. Line fit through the extreme points of the CR
 $\tilde{\gamma}(m_{\min})$ and $\tilde{\gamma}(m_{\max})$
3. Estimation of the line-circle intersection point that corresponds to the underlying ground, i.e.:
 $\tilde{\gamma}(m = \infty) = \exp(i\phi_0)$



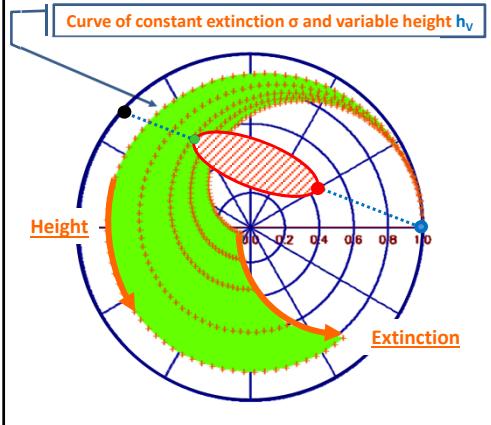
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RVoG Solution on the Unit Circle



$$\tilde{\gamma}(m=0) = \exp(i\phi_0) \frac{\int_0^{h_v} \exp(i\kappa_z z') \exp\left(\frac{2\sigma}{\cos\theta_0} z'\right) dz'}{\int_0^{h_v} \exp\left(\frac{2\sigma}{\cos\theta_0} z'\right) dz'}$$

4. From the underlying ground point $\tilde{\gamma} = \exp(i\phi_0)$ a Volume Height–Extinction Look-Up Table (LUT) is initialised that provides at every intersection with the line a solution couple (h_v, σ)

There is no unique solution of the RVoG model in the context of a single baseline !!!

5. Regularisation: Assuming a 2-dim ground, i.e. $\tilde{\gamma}(m_{min}) = \tilde{\gamma}(m=0)$ leads to a unique (h_v, σ) solution through the intersection of $\tilde{\gamma}(m_{min})$ with the LUT



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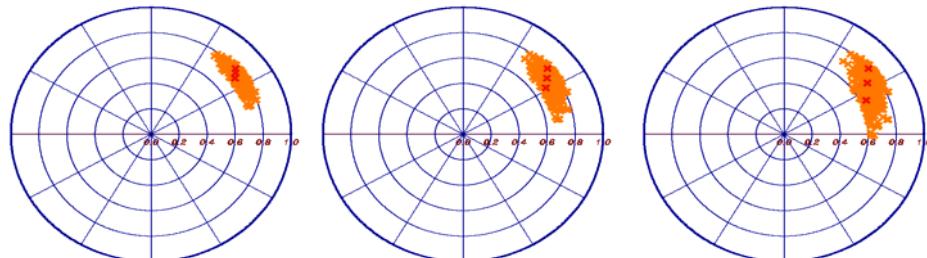
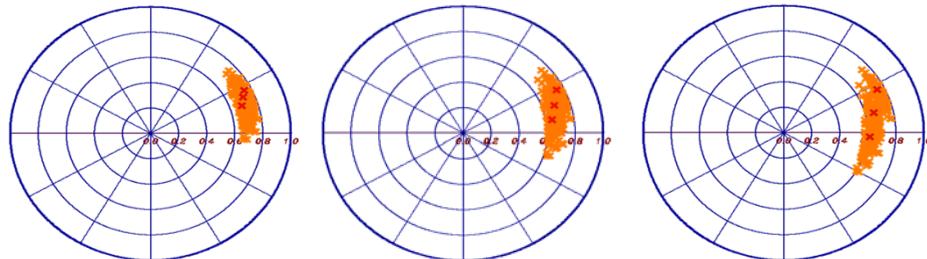
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RVoG Inversion: Validation



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Snow & Ice

- Ice Layer Structure
- Penetration Depth (Ice)
- Snow Layer Thickness
- Snow Water Equivalent

- Ecosystem Change
- Water Cycle
- Water Management



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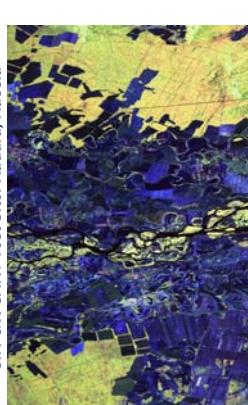
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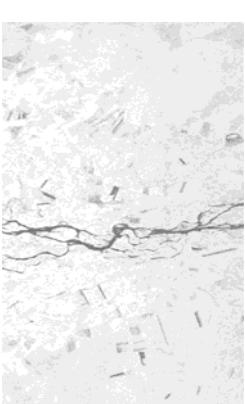
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Forest: The beginning of Pol-InSAR

SIR-C/X-SAR / Test Site: Kudara, Russia



L-band / Pauli RGB



1994: SIR-C / X-SAR acquires the first POL-InSAR data set
1996: First publication on Pol-InSAR.
1998: First Pol-InSAR forest height estimation.



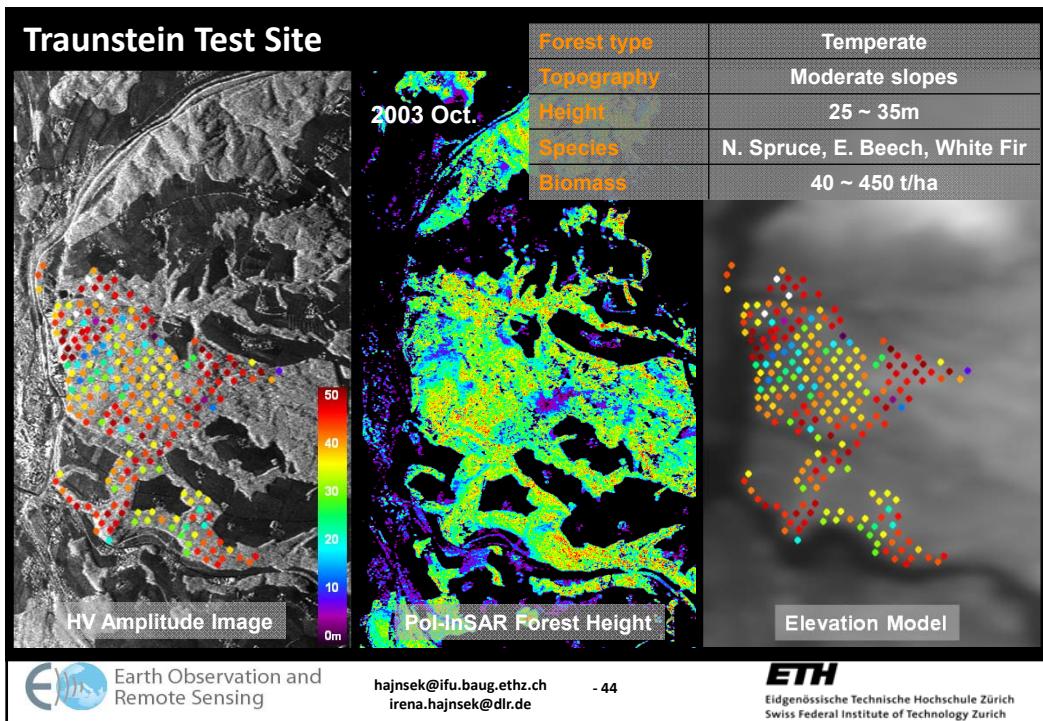
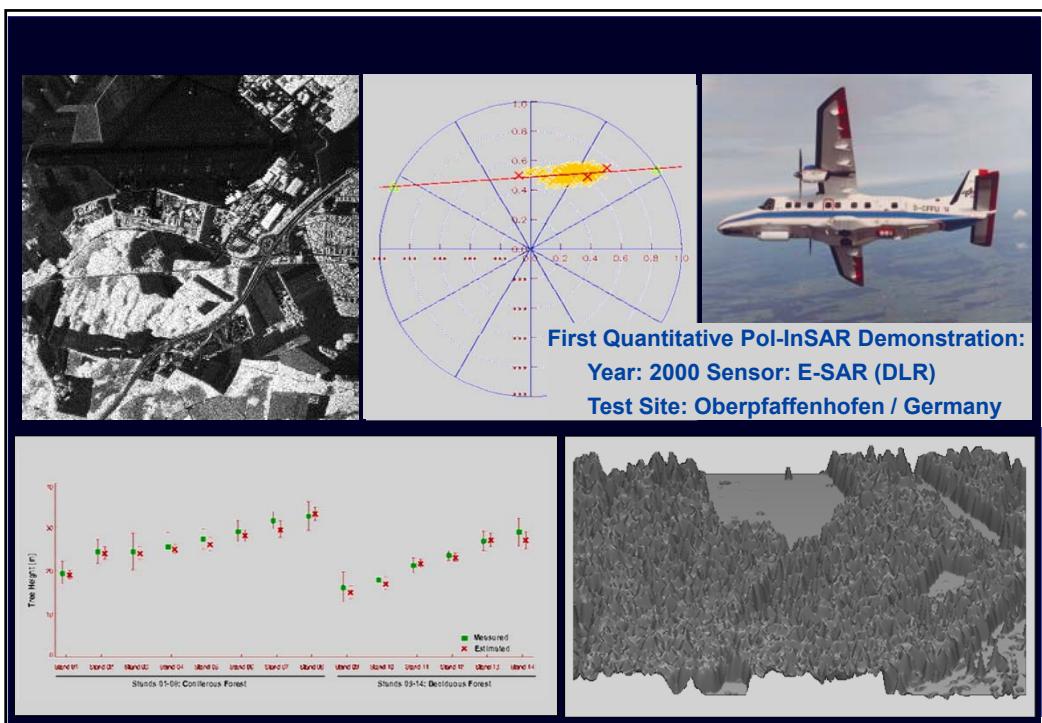
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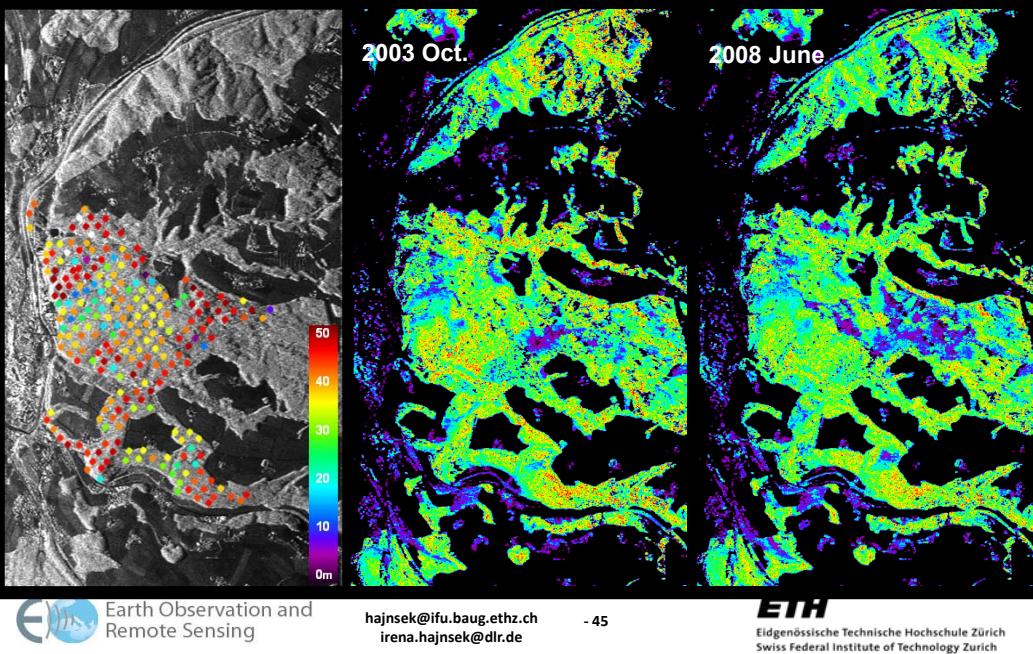
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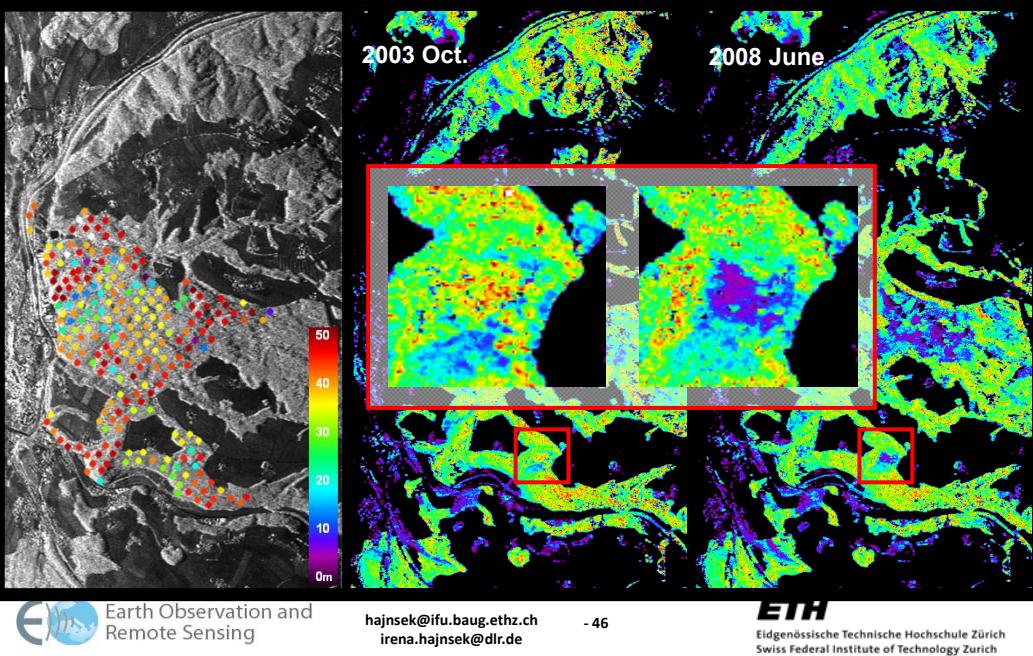
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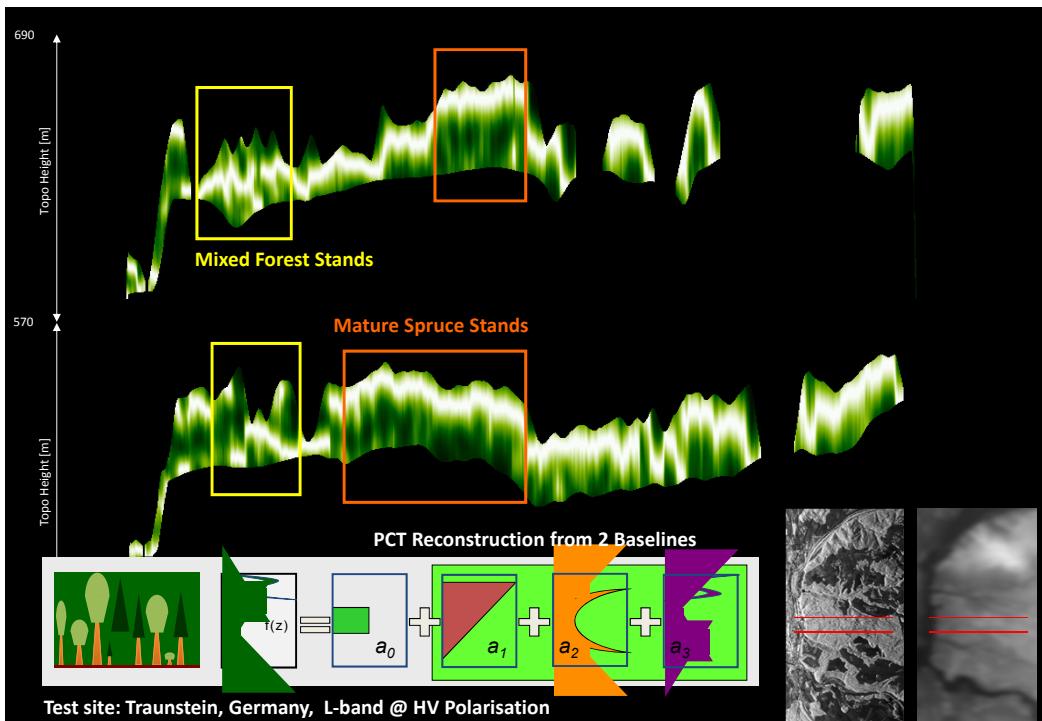
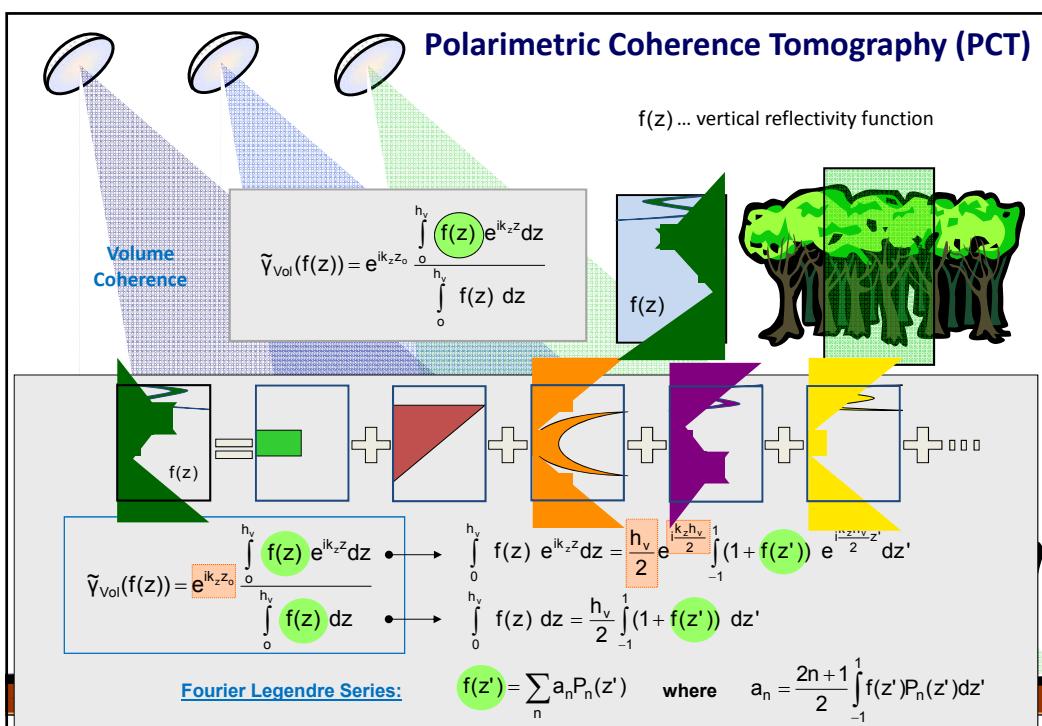


Traunstein Test Site



Traunstein Test Site





Agriculture Pol-InSAR Applications

Pol-SAR

Pol-InSAR

Bare Surfaces: Isolated Scattering Center

- Low Entropy scatterers -> High polarimetric coherence
- The interferometric coherence is baseline independent

Vegetated Surfaces: Volume Scatterers

- High Entropy scatterers -> Low polarimetric coherence
- The interferometric coherence depends on the baseline

Forest vs Agricultural Vegetation	Impact
Orientation effects in the vegetation layer	Anisotropic Propagation
Thinner / shorter vegetation layer	Increased importance of ground scattering
Short crop / plant phenological cycle	Short spatial / large temporal baseline
Variety of crop / plant structure	Abstract modelling

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Agriculture Vegetation @ Alling/Germany 2000

Test Site: Kuettinghoffen, Switzerland

SAR Image @ L-band 3-D Height Map E-SAR / Test Site: Alling, Germany

Interferometric Coherence:

$$\tilde{\gamma}(\bar{w}) = \exp(i\phi_0) \frac{\tilde{Y}_V(\bar{w}) + m(\bar{w})}{1 + m(\bar{w})}$$

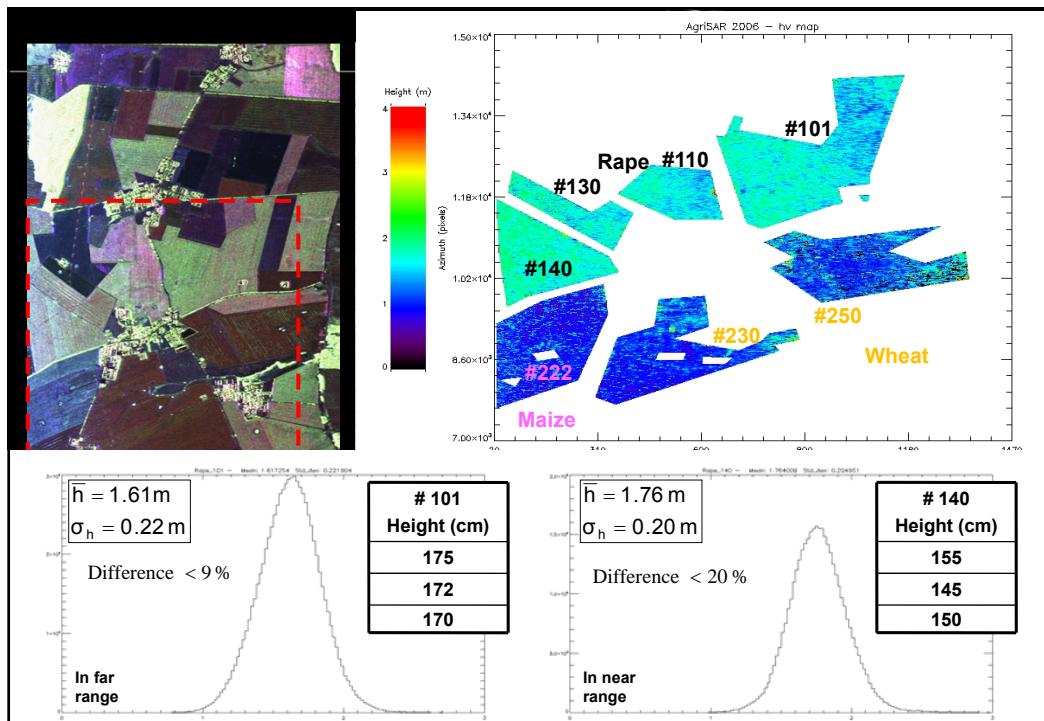
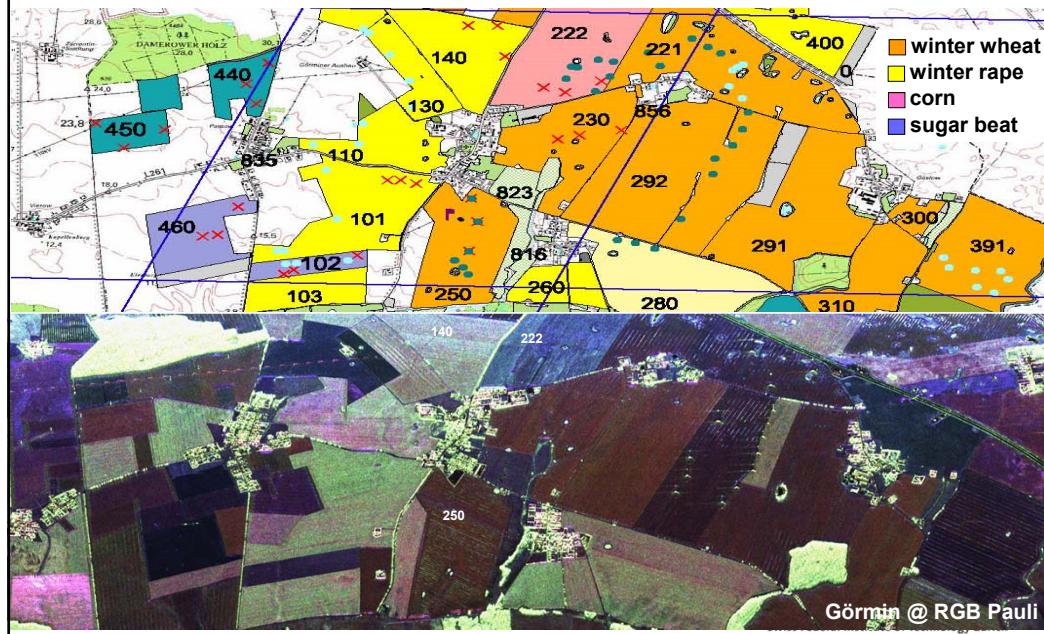
$$\tilde{Y}_V(\bar{w}) = \frac{I}{I_0} \quad I = \int_0^{h_V} \exp(i\kappa_z z') \exp\left(\frac{2 \sigma(\bar{w}) z'}{\cos\theta_0}\right) dz'$$

$$I_0 = \int_0^{h_V} \exp\left(\frac{2 \sigma(\bar{w}) z'}{\cos\theta_0}\right) dz'$$

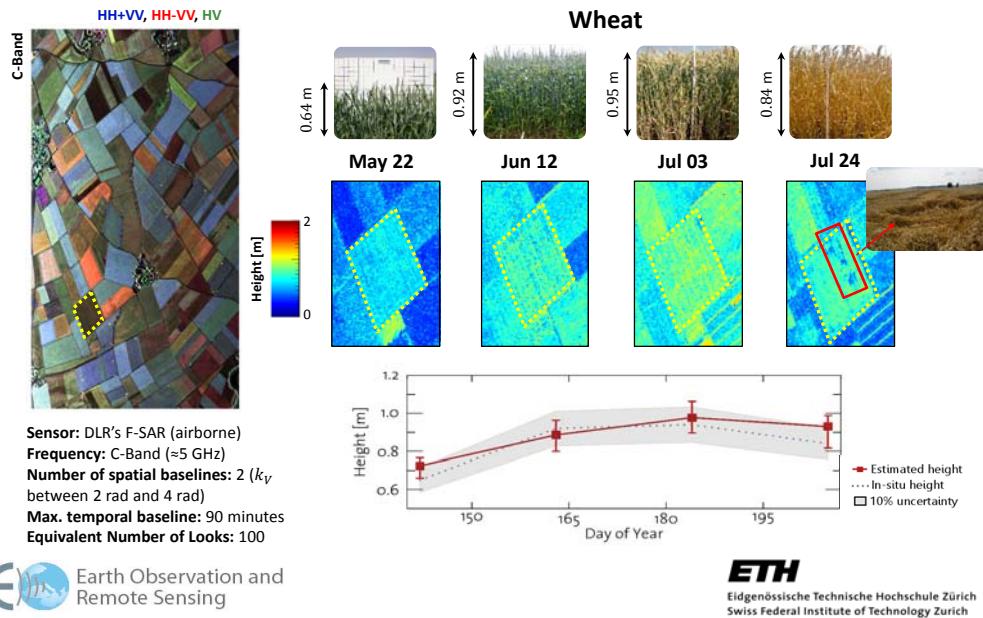
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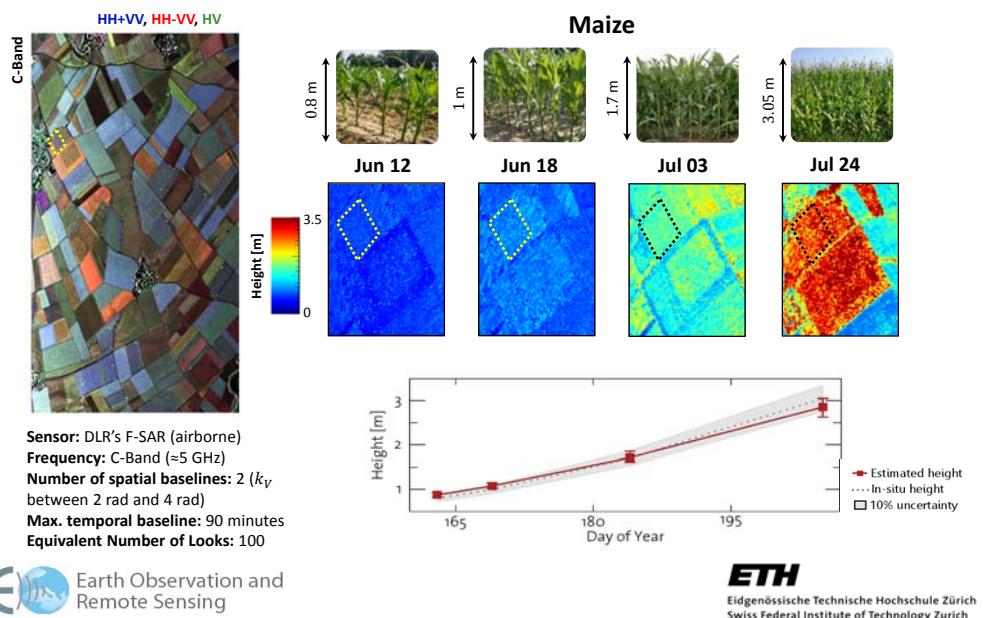
AGRISAR @ L-band in April 2006



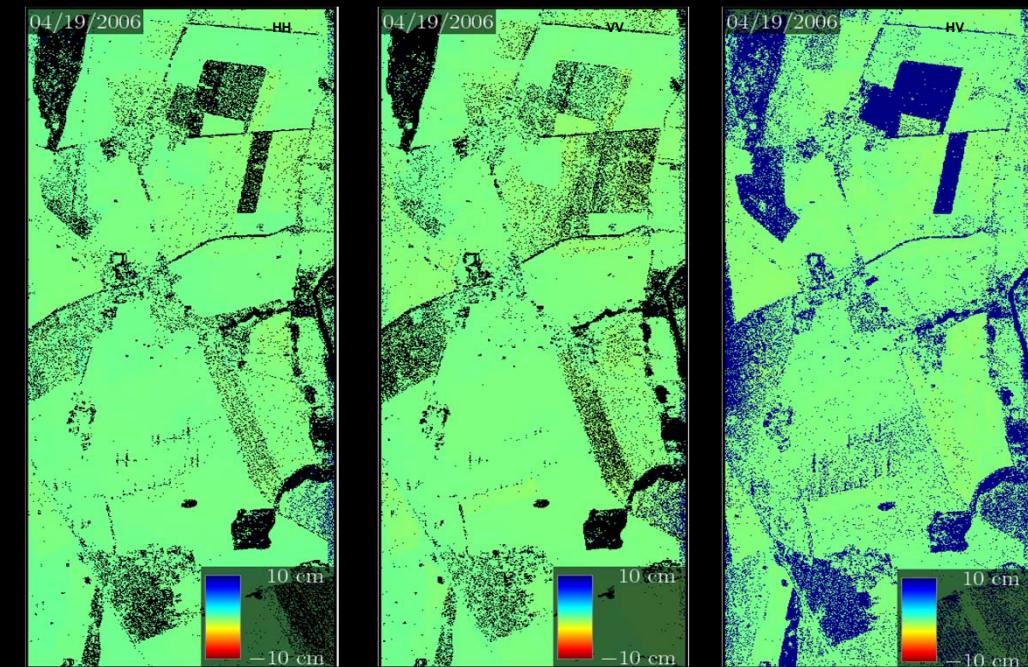
CROP-EX 2014: Crop height estimation from Pol-InSAR data



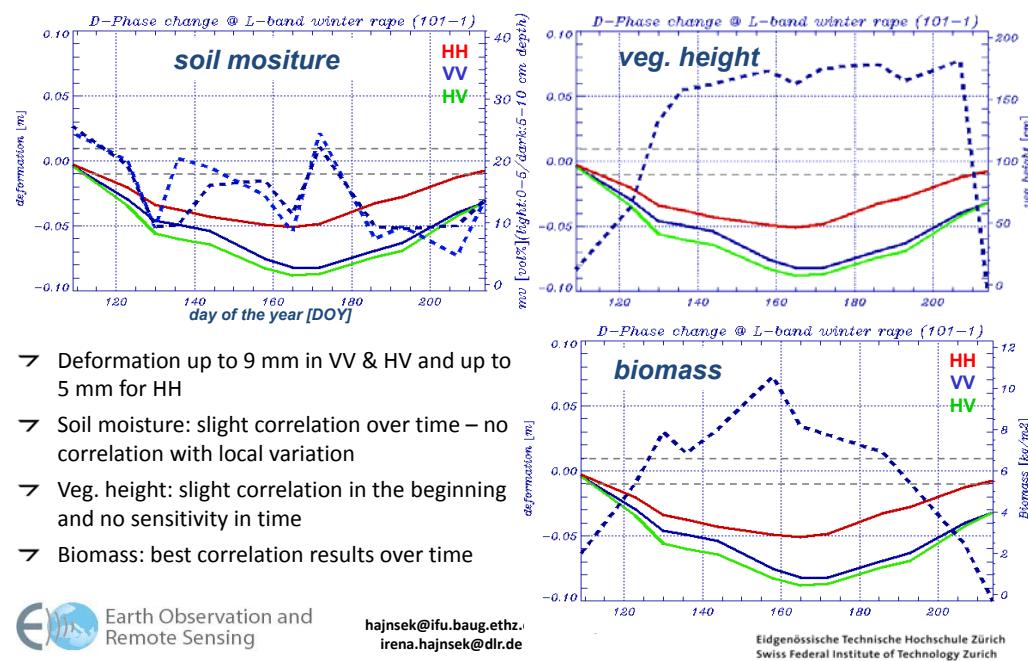
CROP-EX 2014: Crop height estimation from Pol-InSAR data



D-InSAR Soil Mapping @ different Polarisation and L-band



Deformation Change in Time @ Winter Rape (101-1)



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Structure Parameters & Applications

Forest

- Forest Height
- Forest (Vertical) Structure
- Forest Biomass
- Underlying Topography

- 
- Forest Ecology
 - Forest Management
 - Ecosystem Modeling
 - Climate Change

Agriculture

- Underlying Soil Moisture
- Moisture of Vegetation Layer
- Height of Vegetation Layer
- Soil Roughness

- 
- Farming Management
 - Ecosystem Modeling
 - Water Cycle / CC
 - Desertification

Snow & Ice

- Ice Layer Structure
- Penetration Depth (Ice)
- Snow Layer Thickness
- Snow Water Equivalent

- 
- Ecosystem Change
 - Water Cycle
 - Water Management



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Snow

First Pol-InSAR Snow Experiment in Austria 2004

*E-SAR: Kuehtai / Austria 2004
Cooperation with University of Innsbruck*



Campaign
Objectives:

Investigation of
Pol-InSAR for snow
characterisation

Snow appears as a Volume Scatterer @ L-band

L-band / HH Image

X-band DEM

HH-HH Coherence
L-band / Baseline 1

HH-HH Coherence
L-band / Baseline 2



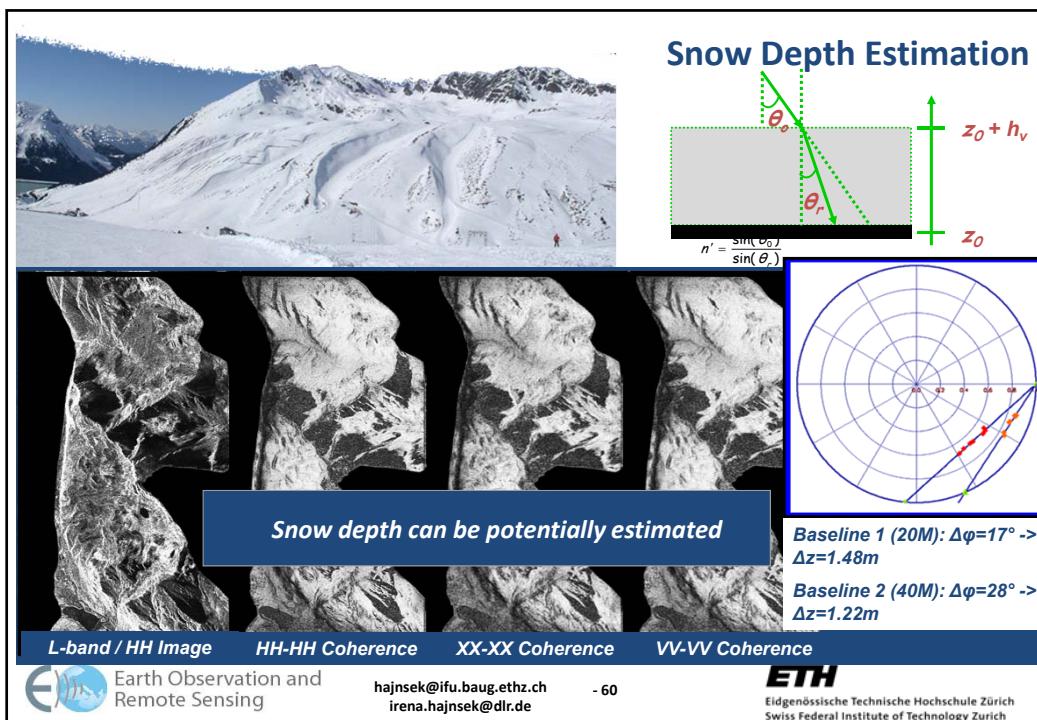
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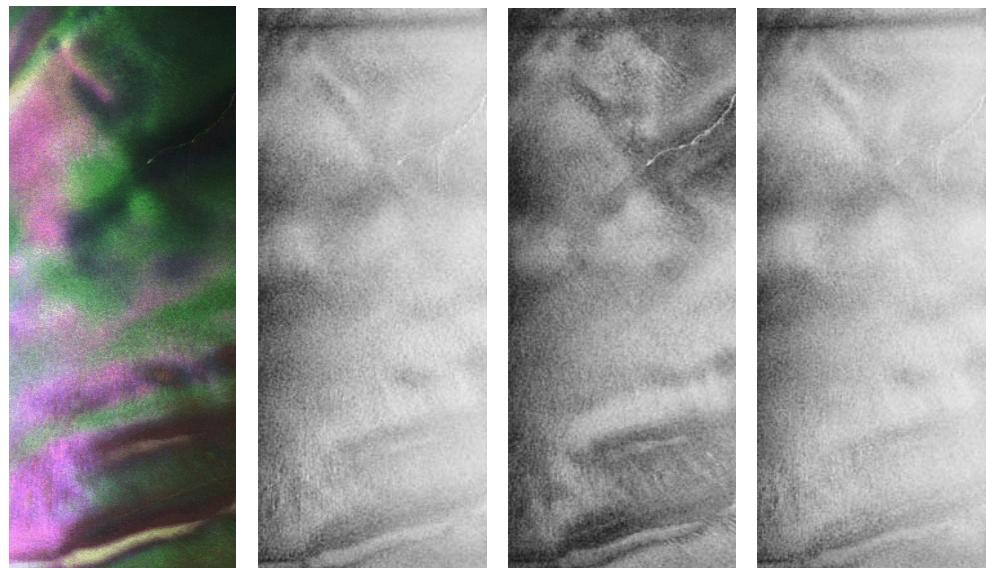
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Austfonna: 2 Flight Tracks (~10km) @ CryoSAT



ICESAR Campaign 2007: InSAR Coherences

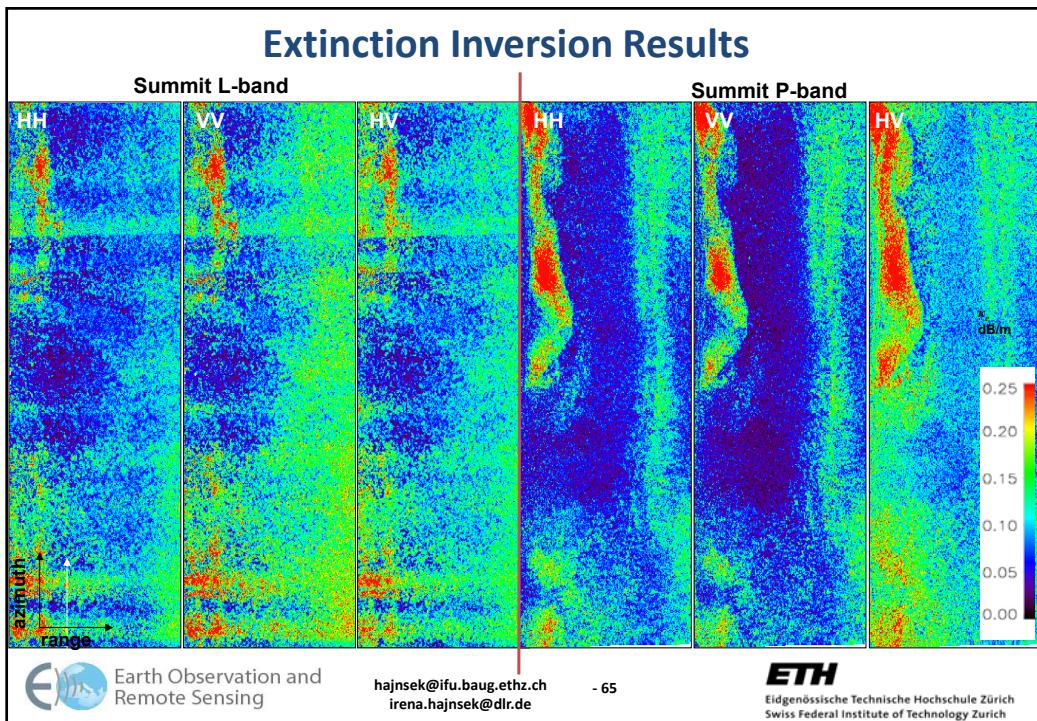
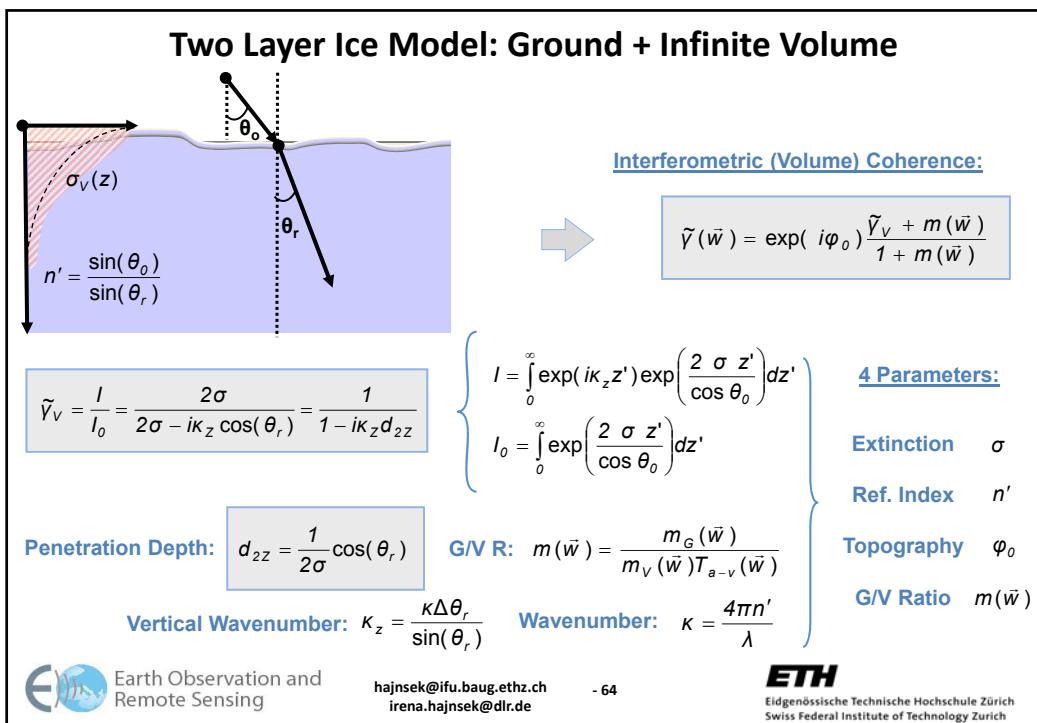


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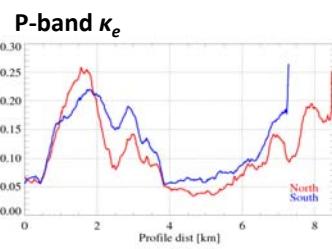
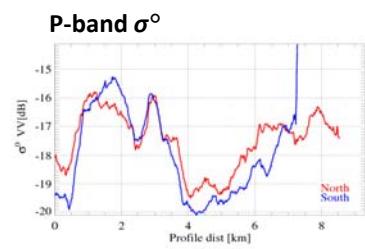
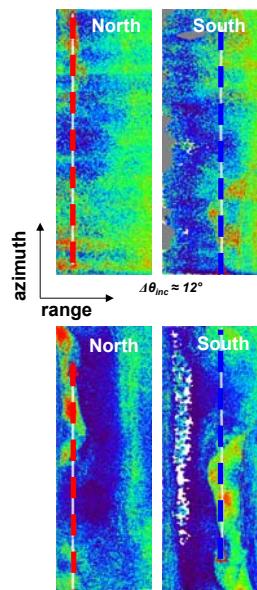
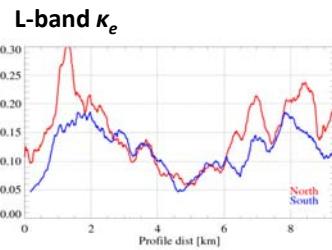
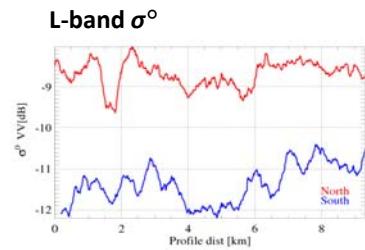
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Extinction Inversion Stability



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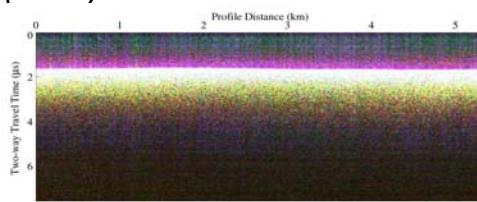
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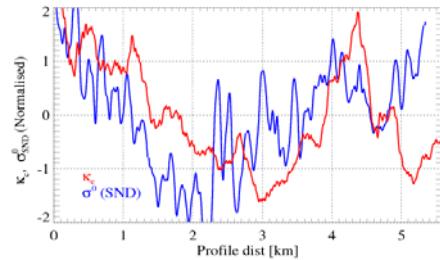
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First Validations of the Estimated Extinction Parameter

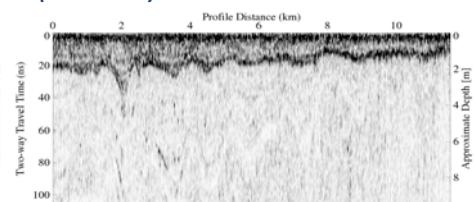
**P-band Sounder vs. P-band Pol-InSAR
(Summit)**



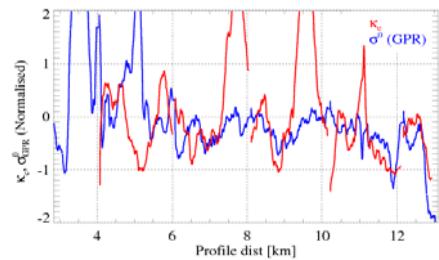
- σ^0_{SND} (sounder summed over depth)
- κ_e (P-band Pol-InSAR extinctions)



**GPR (800 MHz) vs. L-band Pol-InSAR
(Etonbreen)**



- σ^0_{GPR} (volume summed over depth)
- κ_e (L-band Pol-InSAR extinctions)



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