

Multi-baseline Polarimetric SAR Interferometry: Forest Applications

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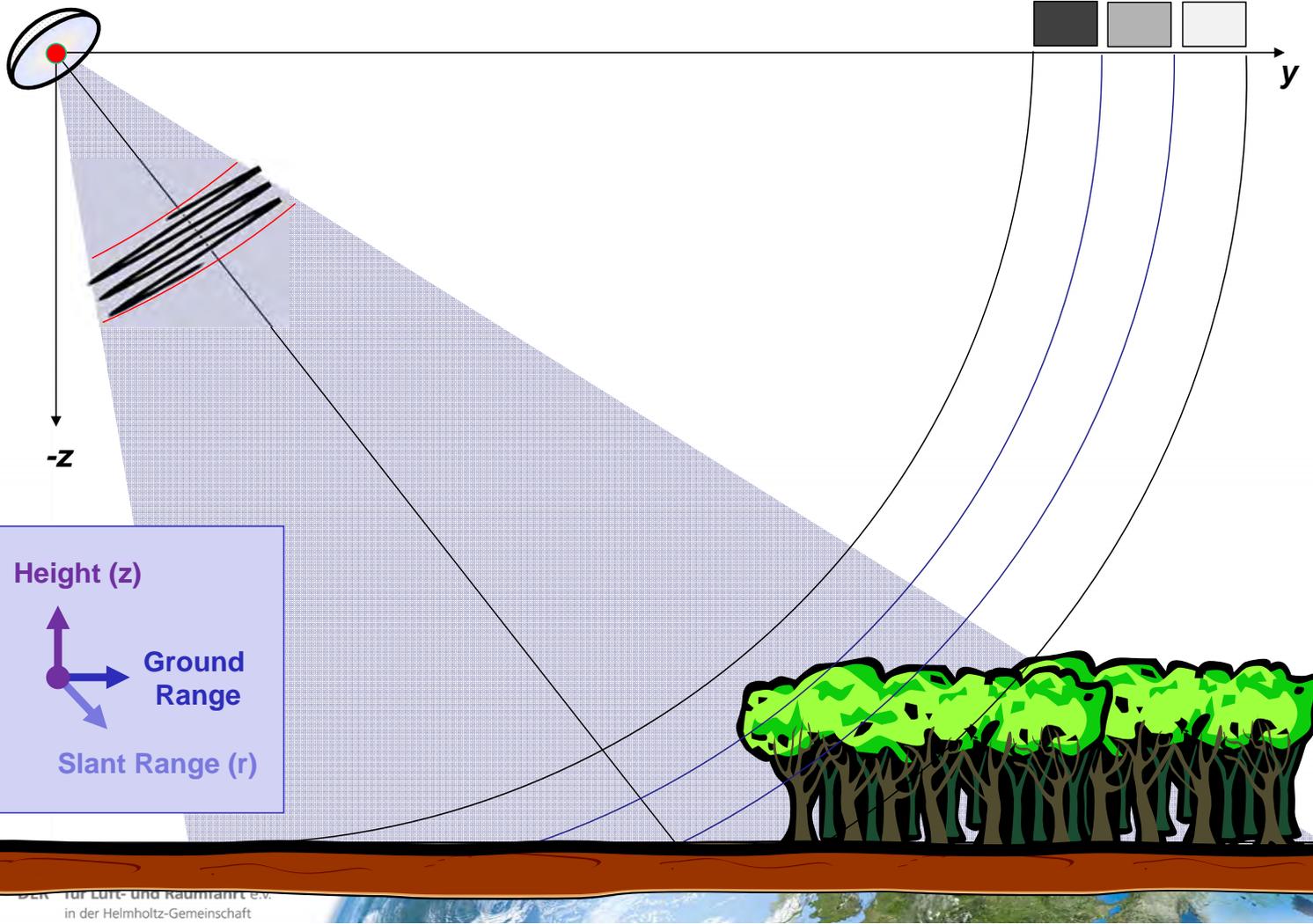


τ : Pulse duration

(Slant) range resolution: $\delta_r = \frac{c\tau}{2} = \frac{c}{2W}$

W: pulse (i.e. system) bandwidth

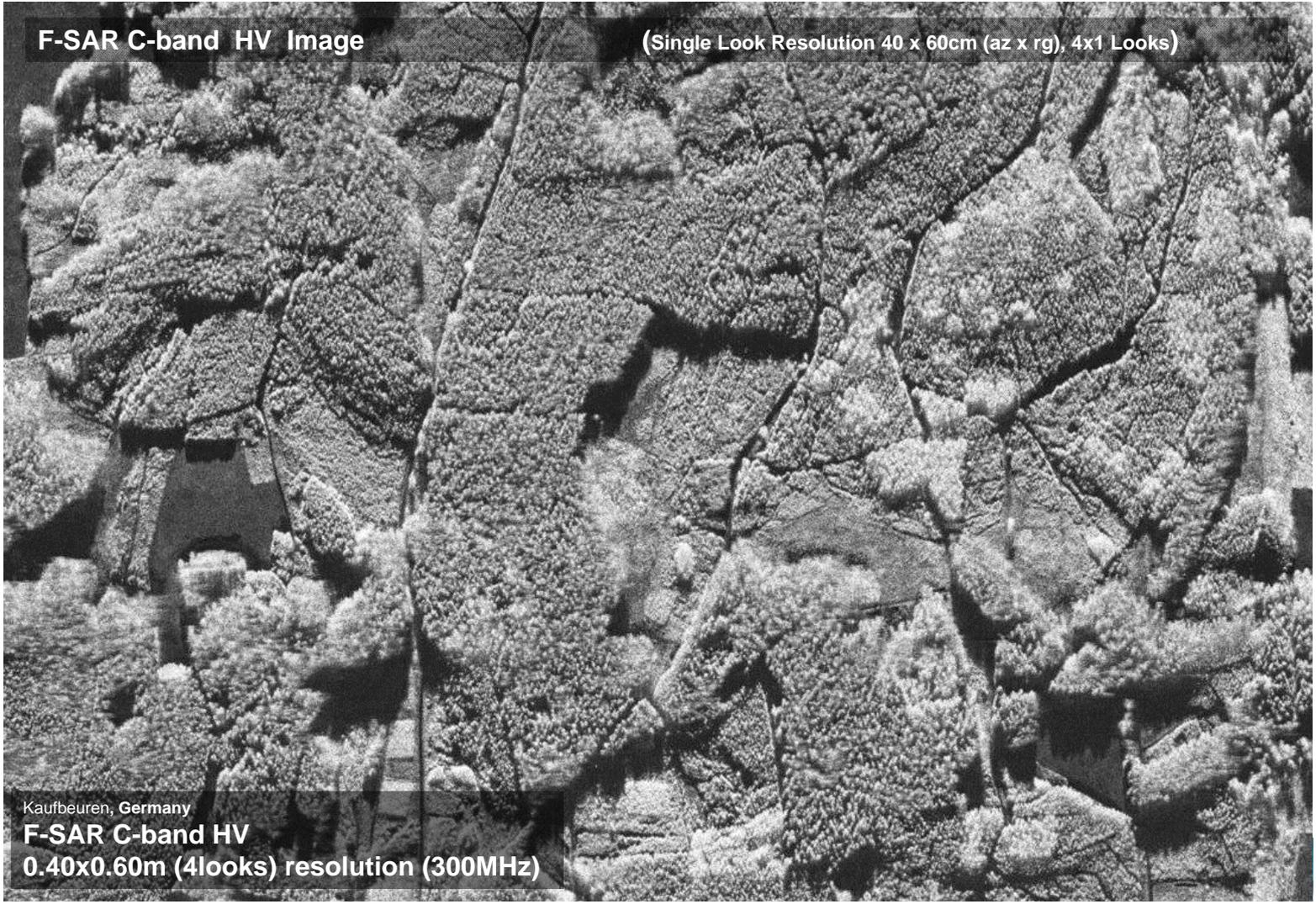




DLR - Institut für Luft- und Raumfahrt e.v.
in der Helmholtz-Gemeinschaft

F-SAR C-band HV Image

(Single Look Resolution 40 x 60cm (az x rg), 4x1 Looks)



Kaufbeuren, Germany
F-SAR C-band HV
0.40x0.60m (4looks) resolution (300MHz)



S₁

S₂

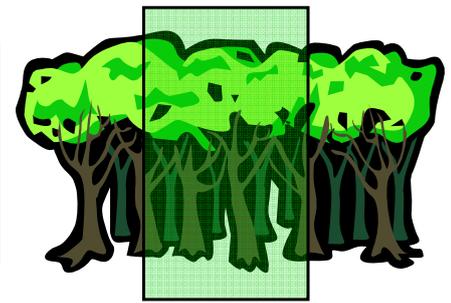
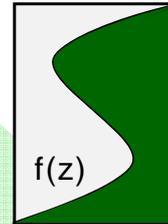
Interferometric Coherence

$$\tilde{\gamma}(S_1, S_2) = \frac{\langle S_1 S_2^* \rangle}{\sqrt{\langle S_1 S_1^* \rangle \langle S_2 S_2^* \rangle}}$$

SAR Interferometry for Volume Structure

Volume Coherence

$$\tilde{\gamma}_{\text{Vol}}(f(z), k_z) = \frac{e^{ik_z z_0} \int_0^{h_v} f(z) e^{ik_z z} dz}{\int_0^{h_v} f(z) dz}$$



f(z) ... vertical reflectivity function

Vertical Wavenumber: $k_z = \frac{\kappa \Delta \theta}{\sin(\theta_0)}$



$$\tilde{\gamma} = \tilde{\gamma}_{\text{Temporal}} \gamma_{\text{SNR}} \tilde{\gamma}_{\text{Vol}}$$

- $\tilde{\gamma}_{\text{Temporal}}$... temporal decorrelation
- γ_{SNR} ... additive noise decorrelation
- $\tilde{\gamma}_{\text{Volume}}$... geometric decorrelation



S₁

S₂

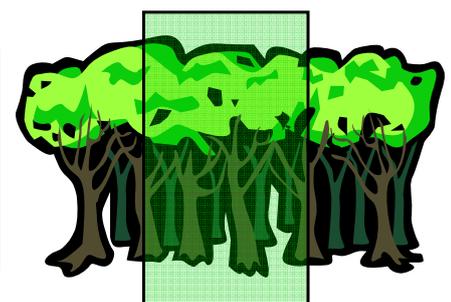
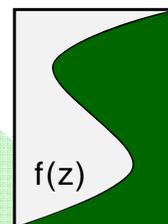
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f(z) ... vertical reflectivity function

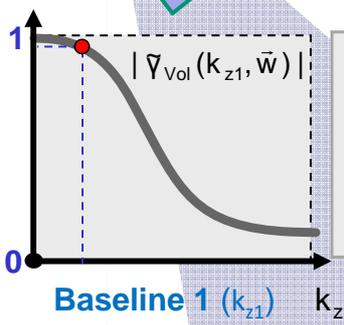
Vertical Wavenumber: $k_z = \frac{\kappa \Delta \theta}{\sin(\theta_0)}$

$$\tilde{\gamma} = \tilde{\gamma}_{\text{Temporal}} \gamma_{\text{SNR}} \tilde{\gamma}_{\text{Vol}}$$

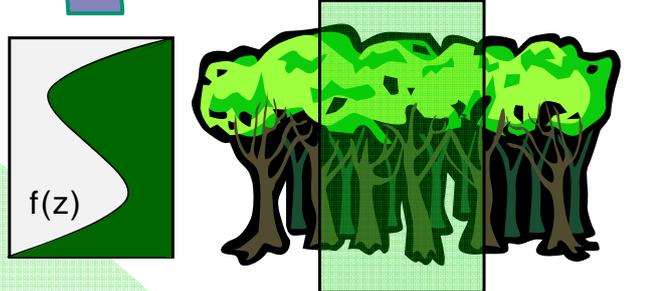
- $\tilde{\gamma}_{\text{Temporal}}$... temporal decorrelation
- γ_{SNR} ... additive noise decorrelation
- $\tilde{\gamma}_{\text{Volume}}$... geometric decorrelation

SAR interferometry allows to reconstruct the vertical reflectivity function f(z) of a volume scatterer by means of interferometric (volume) coherence measurements at different vertical wavenumbers k_z , i.e. at different spatial baselines.

Normalised Fourier Transform of the vertical reflectivity function $f(z)$



$$\tilde{V}_{Vol}(k_{z1}) = e^{ik_{z1}z_0} \frac{\int_0^{h_v} f(z) e^{ik_{z1}z} dz}{\int_0^{h_v} f(z) dz}$$



$f(z)$... vertical reflectivity function

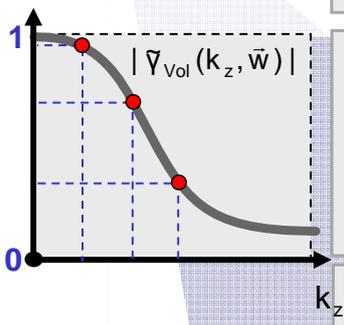
Vertical Wavenumber: $k_z = \frac{\kappa \Delta \theta}{\sin(\theta_0)}$

Multibaseline SAR Interferometry

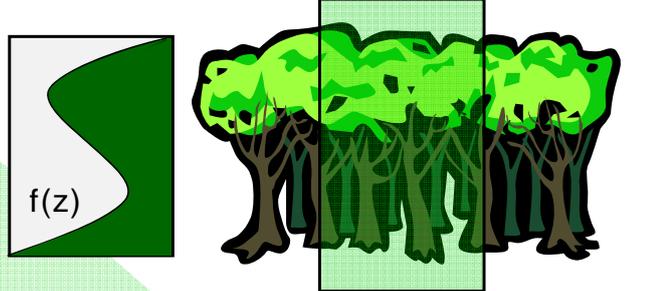


Baseline 3 (k_{z3})

$$\tilde{V}_{Vol}(k_{z3}) = e^{ik_{z3}z_0} \frac{\int_0^{h_v} f(z) e^{ik_{z3}z} dz}{\int_0^{h_v} f(z) dz}$$



$$\tilde{V}_{Vol}(k_{z1}) = e^{ik_{z1}z_0} \frac{\int_0^{h_v} f(z) e^{ik_{z1}z} dz}{\int_0^{h_v} f(z) dz}$$



$f(z)$... vertical reflectivity function

Vertical Wavenumber: $k_z = \frac{\kappa \Delta \theta}{\sin(\theta_0)}$

Baseline 2 (k_{z2})

$$\tilde{V}_{Vol}(k_{z2}) = e^{ik_{z2}z_0} \frac{\int_0^{h_v} f(z) e^{ik_{z2}z} dz}{\int_0^{h_v} f(z) dz}$$



Multibaseline SAR Interferometry

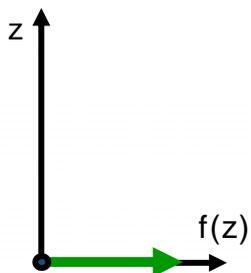
Multi-baseline measurements allow to sample the spectrum of the vertical reflectivity $FT\{f(z)\}$ @ different (spatial) frequencies (k_z).



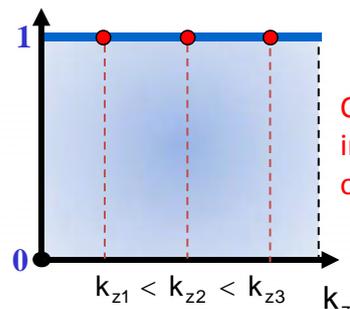
Vertical Reflectivity Function $f(z)$

InSAR Volume Coherence $|\tilde{\gamma}_{Vol}(k_z)|$

Surface Scatterer

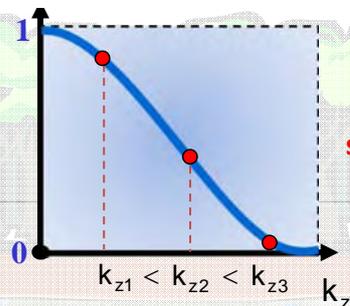
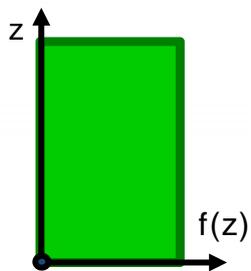


$$|\tilde{\gamma}_{Vol}(k_z)| = \frac{\left| \int_0^{h_v} f(z) e^{ik_z z} dz \right|}{\int_0^{h_v} f(z) dz}$$



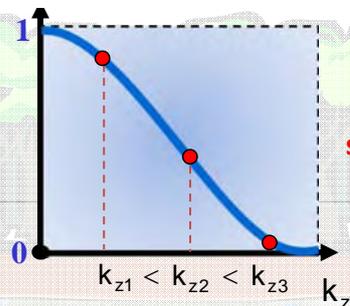
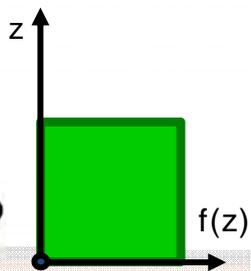
Coherence is independent of baseline

Tall Vegetation

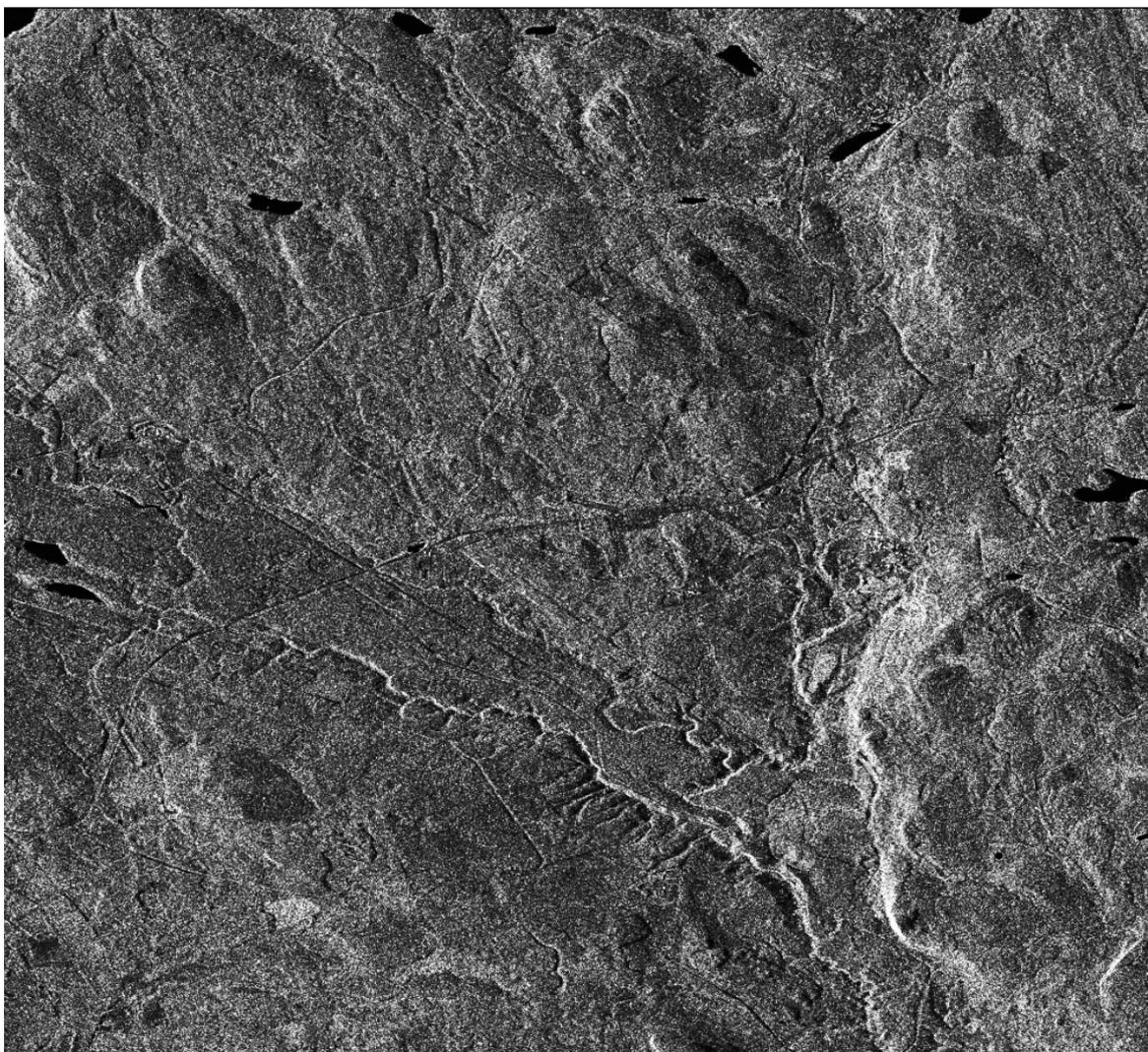


Coherence degrades slower with increasing baseline

Short Vegetation



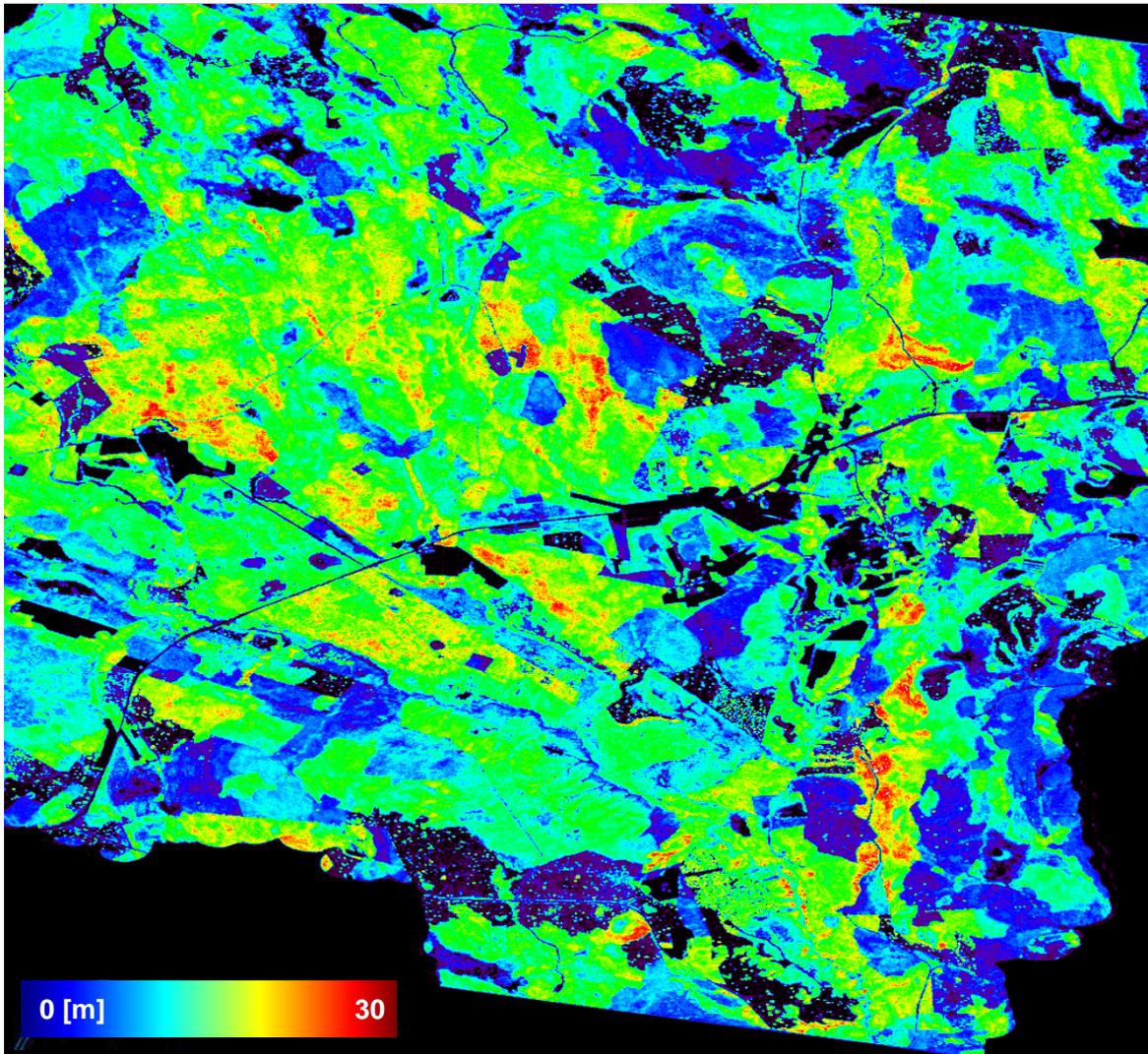
in der Helmholtz-Gemeinschaft



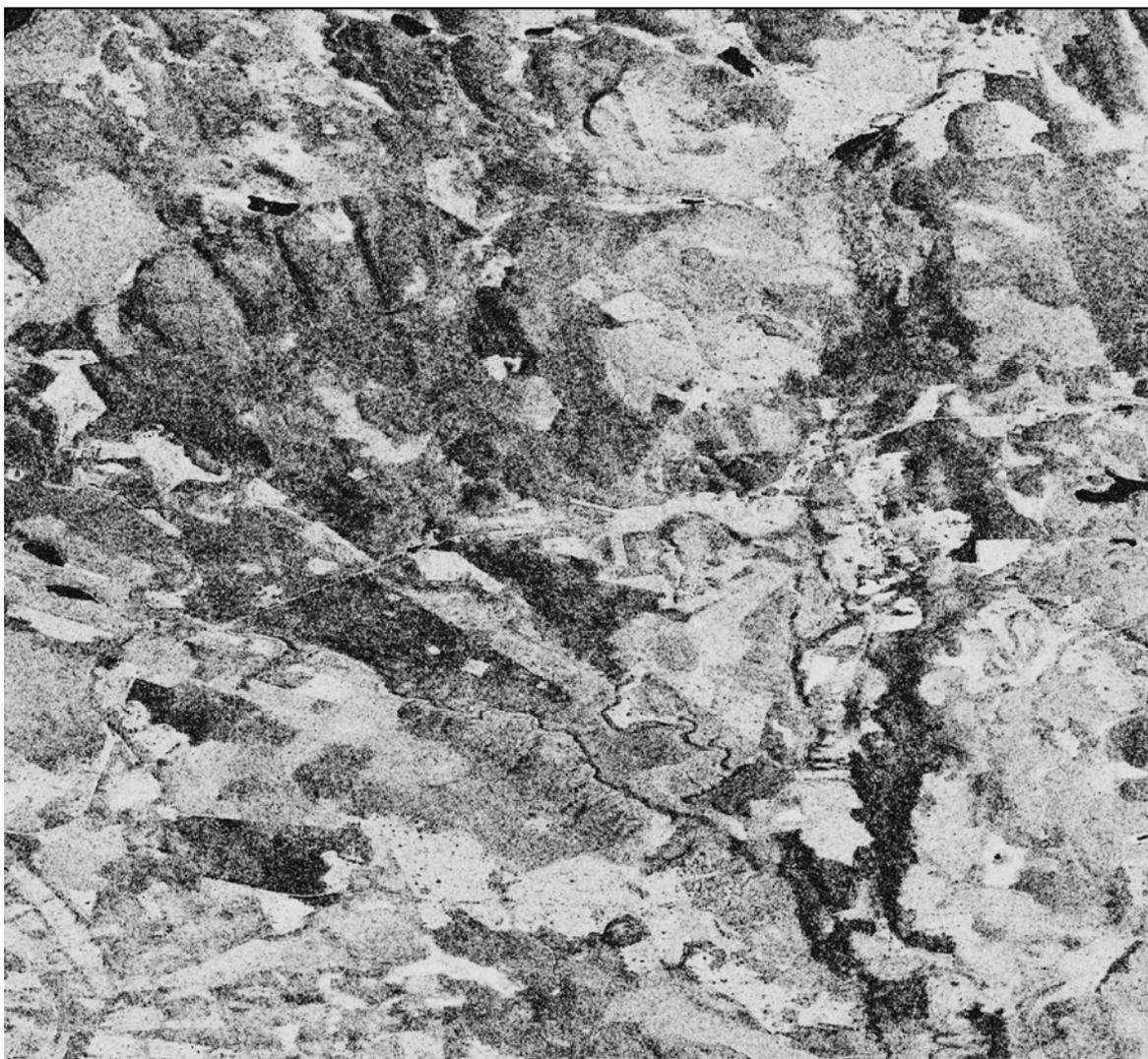
Test Site: Krycklan, Sweden



Test Site: Krycklan,
Sweden



Test Site: Krycklan,
Sweden



Scattering Amplitudes Images

HH

HV

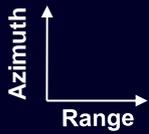


E-SAR / Test Site: Oberpfafenhoffen



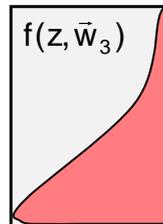
VH

VV



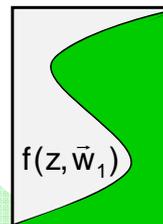
Polarisation 3 (\bar{w}_3):

$$\bar{\gamma}_{Vol}(f(z, \bar{w}_3)) = e^{ik_z z_0} \frac{\int_0^{h_v} f(z, \bar{w}_3) e^{ik_z z} dz}{\int_0^{h_v} f(z, \bar{w}_3) dz}$$



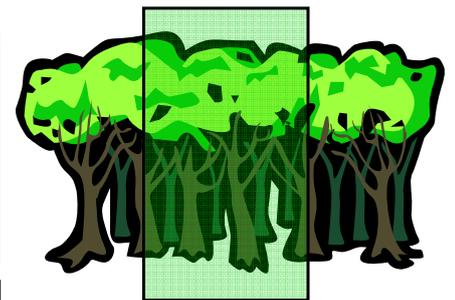
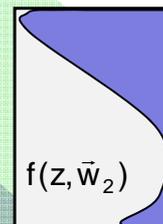
Polarisation 1 (\bar{w}_1):

$$\bar{\gamma}_{Vol}(f(z, \bar{w}_1)) = e^{ik_z z_0} \frac{\int_0^{h_v} f(z, \bar{w}_1) e^{ik_z z} dz}{\int_0^{h_v} f(z, \bar{w}_1) dz}$$



Polarisation 2 (\bar{w}_2):

$$\bar{\gamma}_{Vol}(f(z, \bar{w}_2)) = e^{ik_z z_0} \frac{\int_0^{h_v} f(z, \bar{w}_2) e^{ik_z z} dz}{\int_0^{h_v} f(z, \bar{w}_2) dz}$$



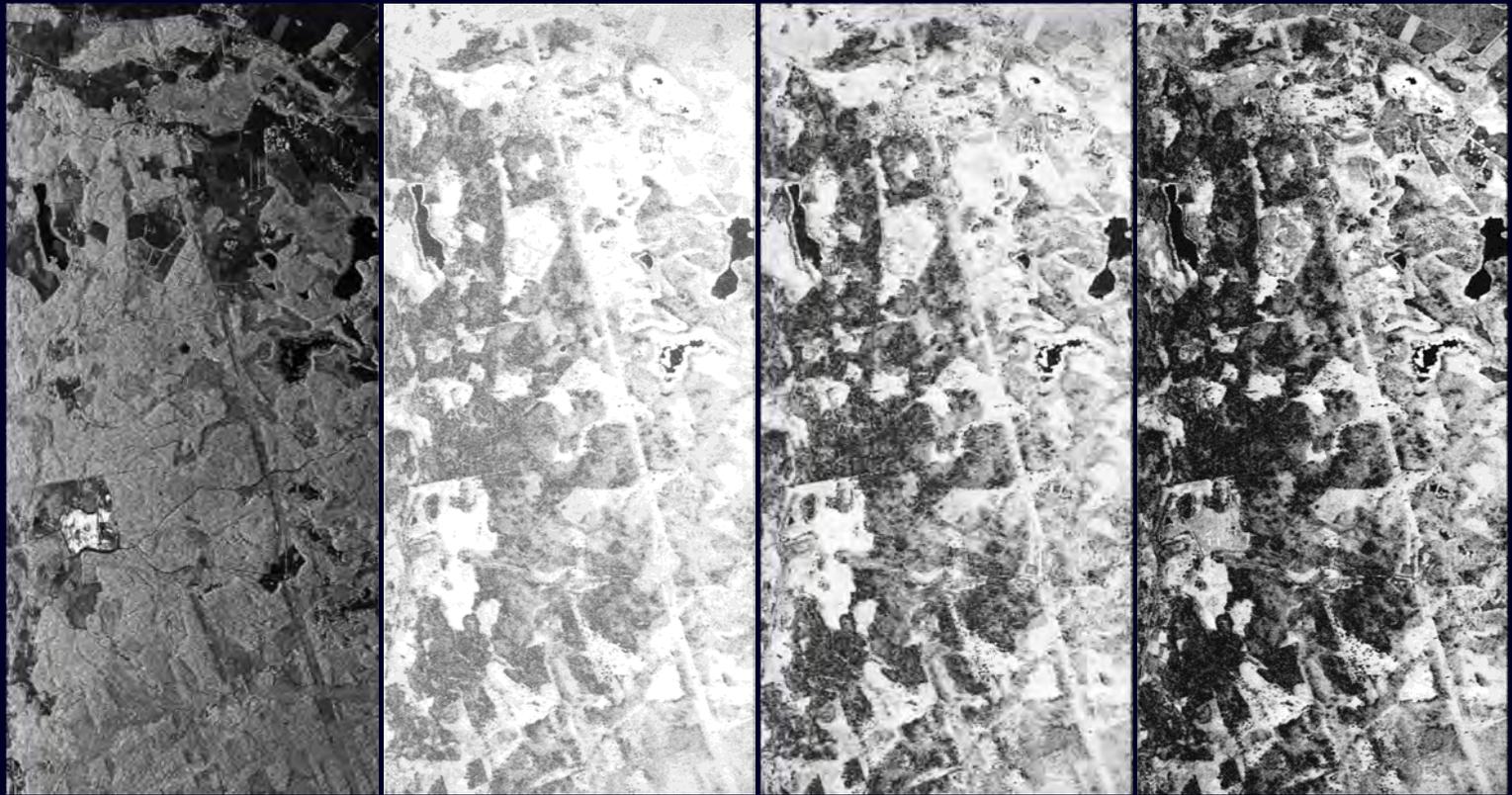
$f(z, \bar{w})$...vertical reflectivity function



Polarimetric SAR Interferometry

By changing the polarisation the contrast between the individual components consisting the vertical reflectivity $f(z)$ of a (volume) scatterer changes.

Interferometric Coherence: Volume Decorrelation



Amplitude Image HH

Sp. Baseline 16m Opt 1

HH

Opt 3



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



Pol-InSAR In Orbit

ALOS-2



RadarSAT 2



Sentinel 1a+1b



TerraSAR-X



TanDEM-X

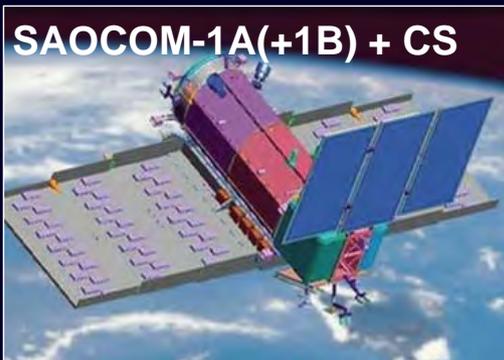


RISAT-1



Pol-InSAR In Orbit

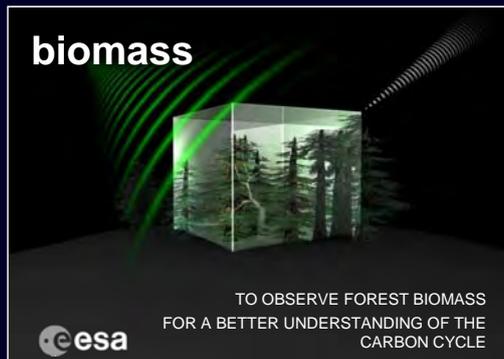
SAOCOM-1A(+1B) + CS



RadarSAT Constellation



biomass



Tandem-L



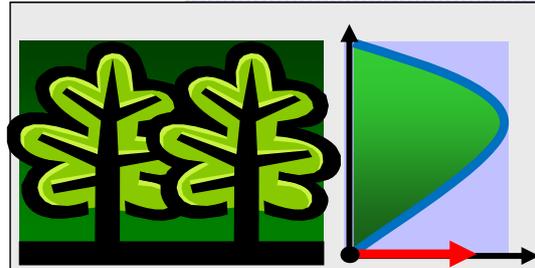
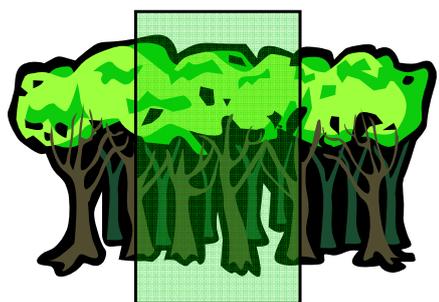
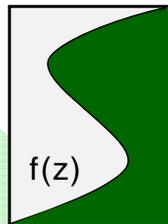


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Volume Coherence

$$\tilde{\gamma}_{Vol}(f(z)) = e^{ik_z z_0} \frac{\int_0^{h_v} f(z) e^{ik_z z} dz}{\int_0^{h_v} f(z) dz}$$



Volume Layer Ground Layer

$$f(z) = m_v f_v(z) + m_g \delta(z - z_0)$$

2 Layer Inversion Model

$$\tilde{\gamma}_{Vol}(\bar{w}) = \exp(i\varphi_0) \frac{\tilde{\gamma}_V + m(\bar{w})}{1 + m(\bar{w})}$$

$f_v(z)$... volume reflectivity function

Volume Coherence

$$\tilde{\gamma}_V = \frac{I}{I_0}$$

$$\left\{ \begin{aligned} I &= \int_0^{h_v} \exp(ik_z z') f_v(z') dz' \\ I_0 &= \int_0^{h_v} f_v(z') dz' \end{aligned} \right.$$

$$m(\bar{w}) = \frac{m_g(\bar{w})}{m_v(\bar{w}) I_0}$$

$$\kappa_z = \frac{\kappa \Delta \theta}{\sin(\theta_0)}$$

- $f_v(z)$ has to be parameterised (N param)
- Volume Height h_v
- Topography φ_0
- G/V Ratio $m(\bar{w})$

3+N Unknowns

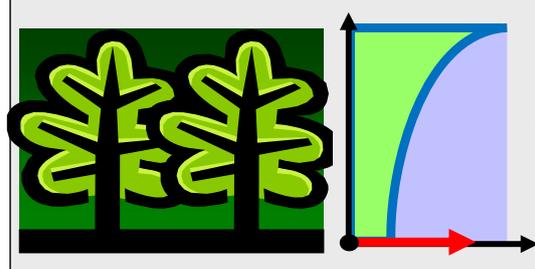
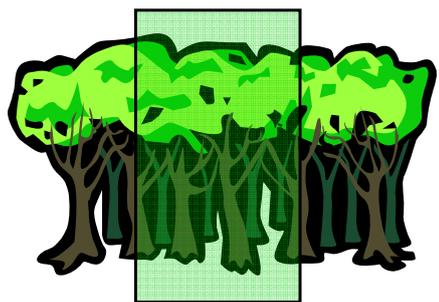
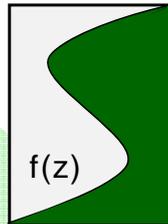


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$$f(z) = m'_v e^{\left(\frac{2 \sigma z}{\cos \theta_0}\right)} + m'_g \delta(z - z_0)$$

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$f_v(z) = e^{\left(\frac{2 \sigma z}{\cos \theta_0}\right)}$... volume reflectivity function = exponential function

Volume Coherence

$$\tilde{\gamma}_V = \frac{I}{I_0}$$

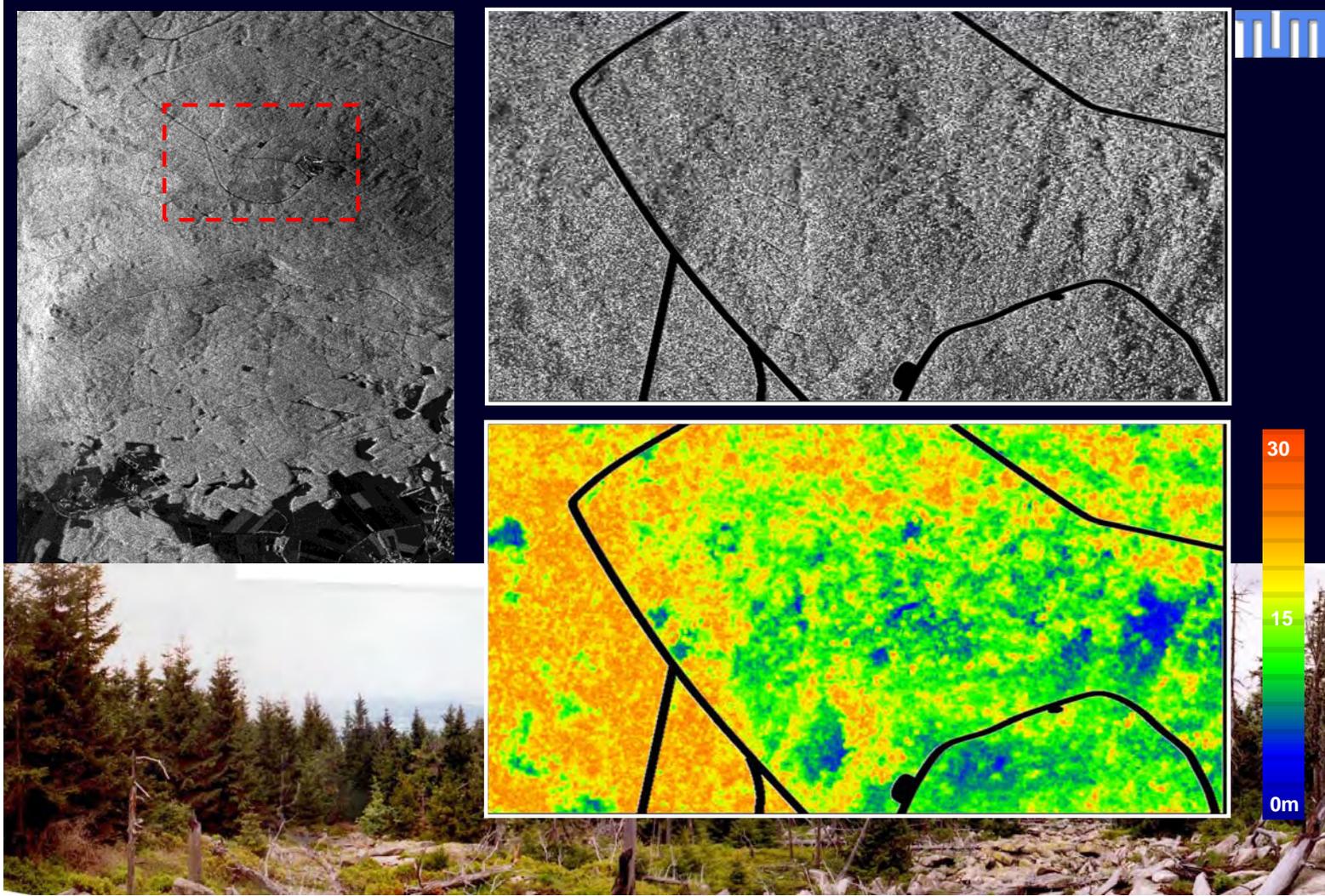
$$\left\{ \begin{aligned} I &= \int_0^{h_v} \exp(ik_z z') m_v \exp\left(\frac{2 \sigma z'}{\cos \theta_0}\right) dz' \\ I_0 &= \int_0^{h_v} m_v \exp\left(\frac{2 \sigma z'}{\cos \theta_0}\right) dz' \end{aligned} \right.$$

$$m(\bar{w}) = \frac{m_g(\bar{w})}{m_v(\bar{w}) I_0}$$

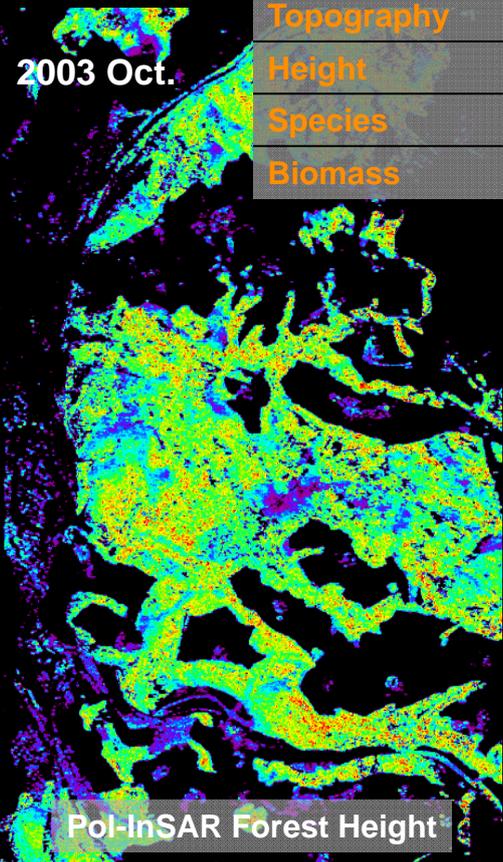
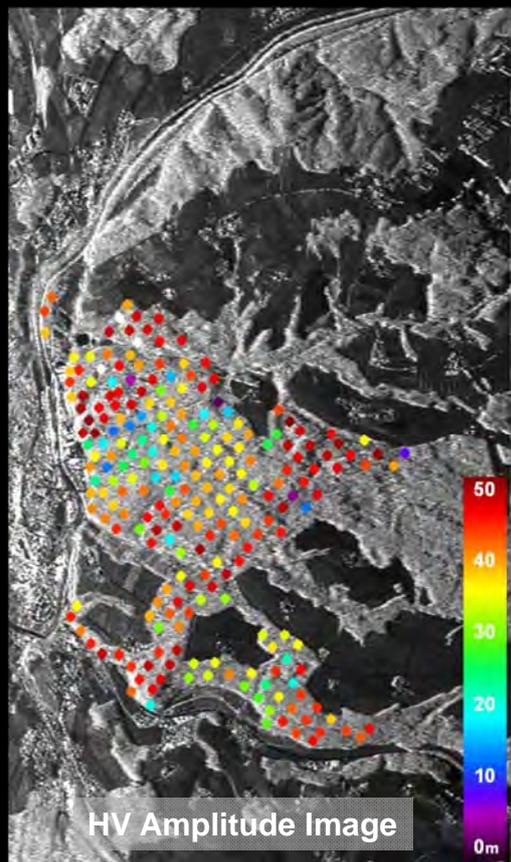
$$\kappa_z = \frac{\kappa \Delta \theta}{\sin(\theta_0)}$$

- $\sigma(z) = \sigma$ "Volume Extinction"
- Volume Height h_v
- Topography φ_0
- G/V Ratio $m(\bar{w})$

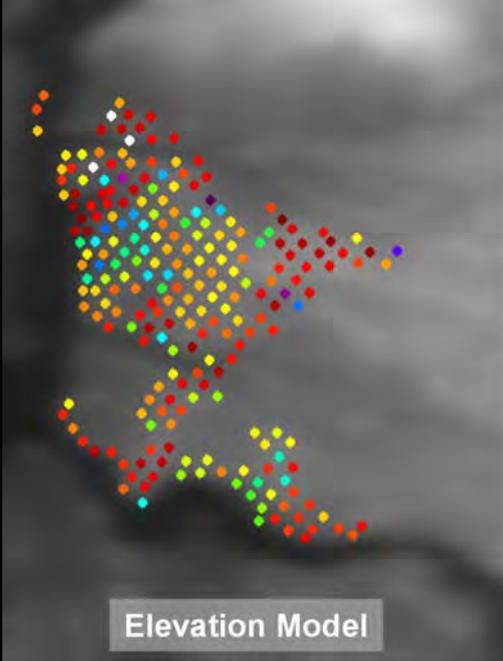
4 Unknowns



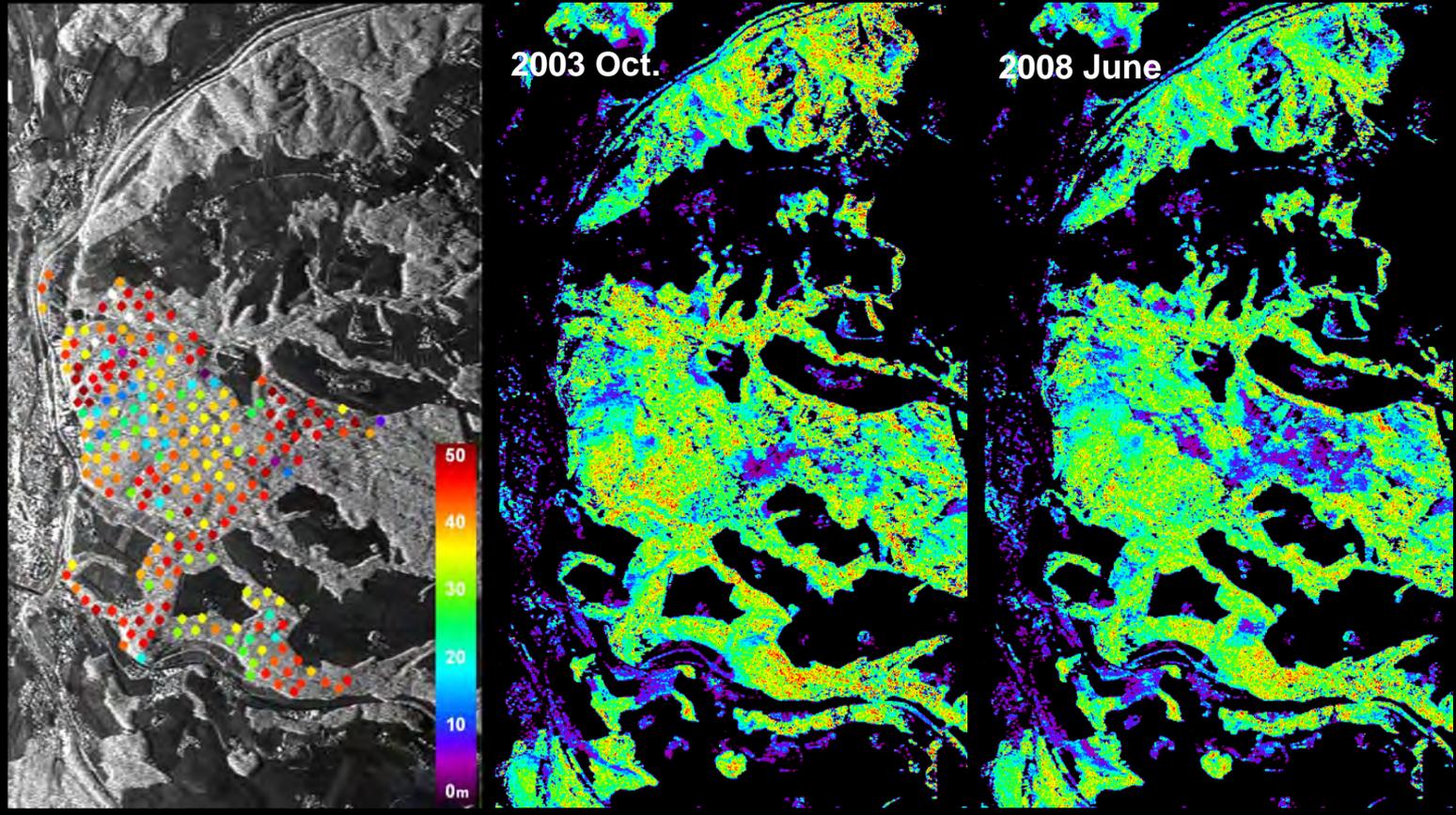
Traunstein Test Site



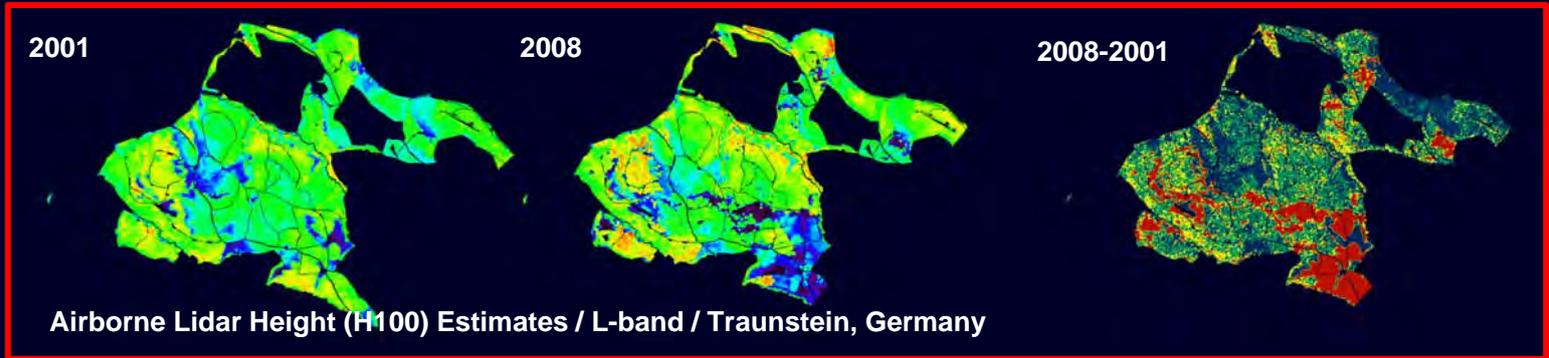
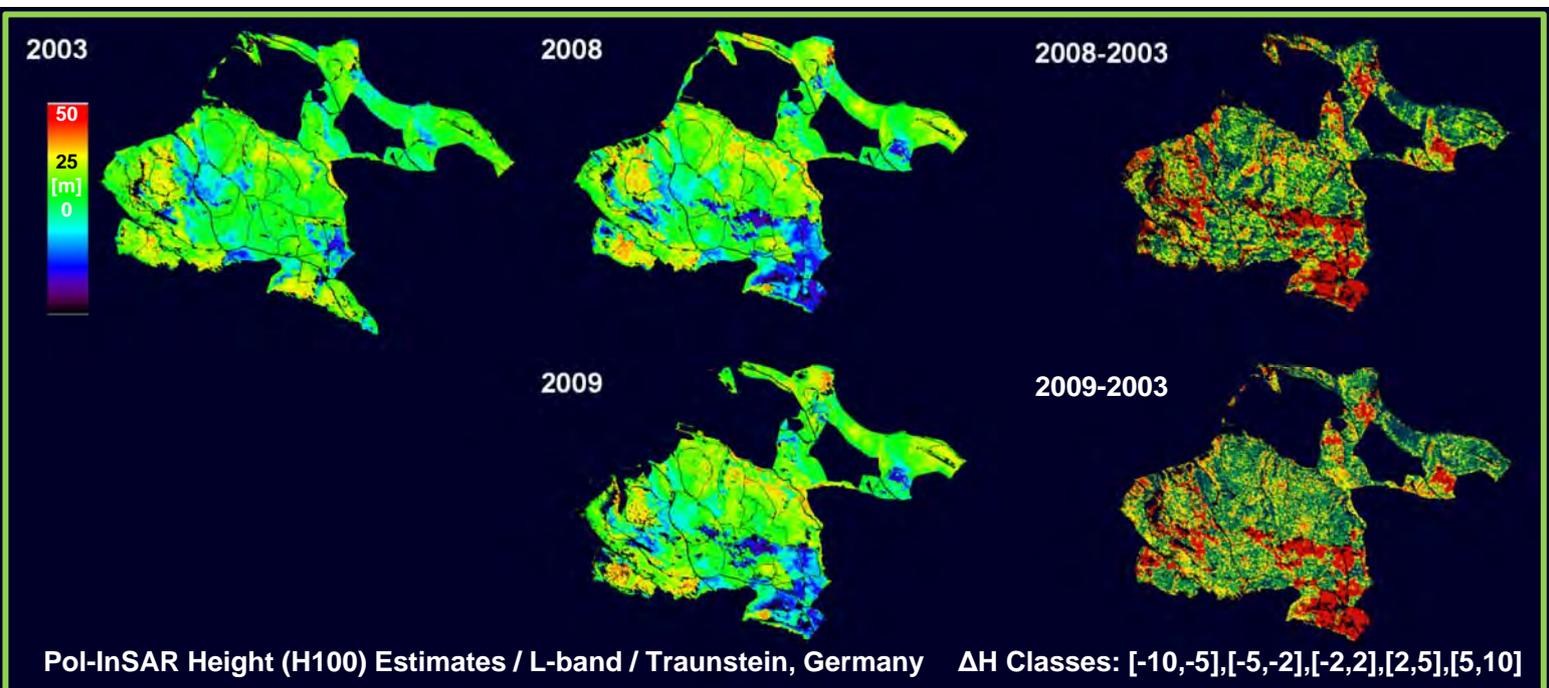
| | |
|--------------------|--------------------------------|
| Forest type | Temperate |
| Topography | Moderate slopes |
| Height | 25 ~ 35m |
| Species | N. Spruce, E. Beech, White Fir |
| Biomass | 40 ~ 450 t/ha |



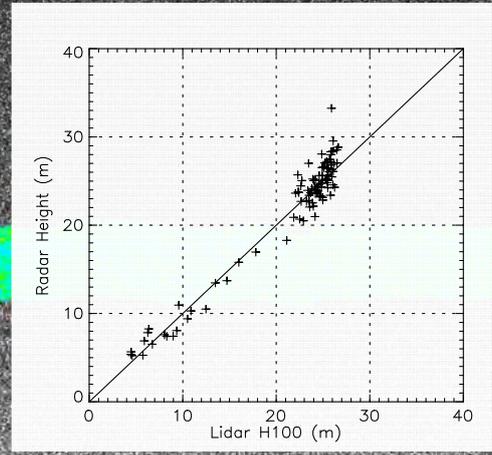
Traunstein Test Site



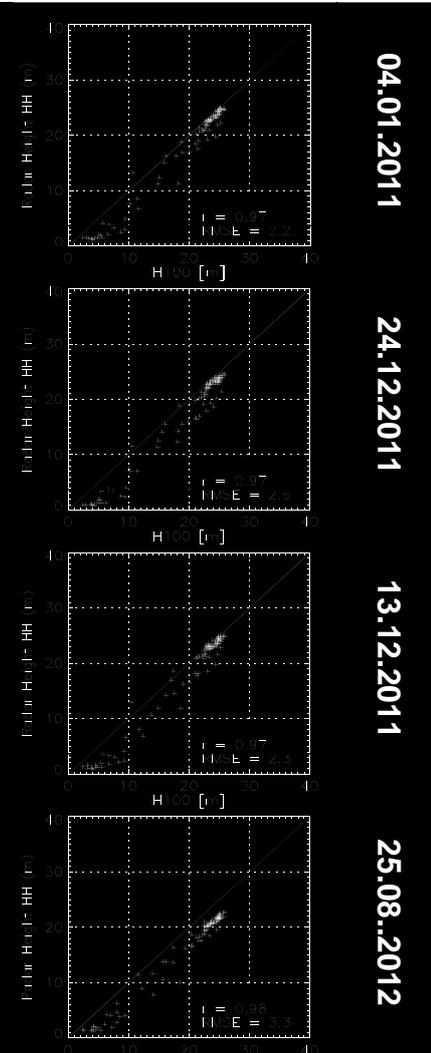
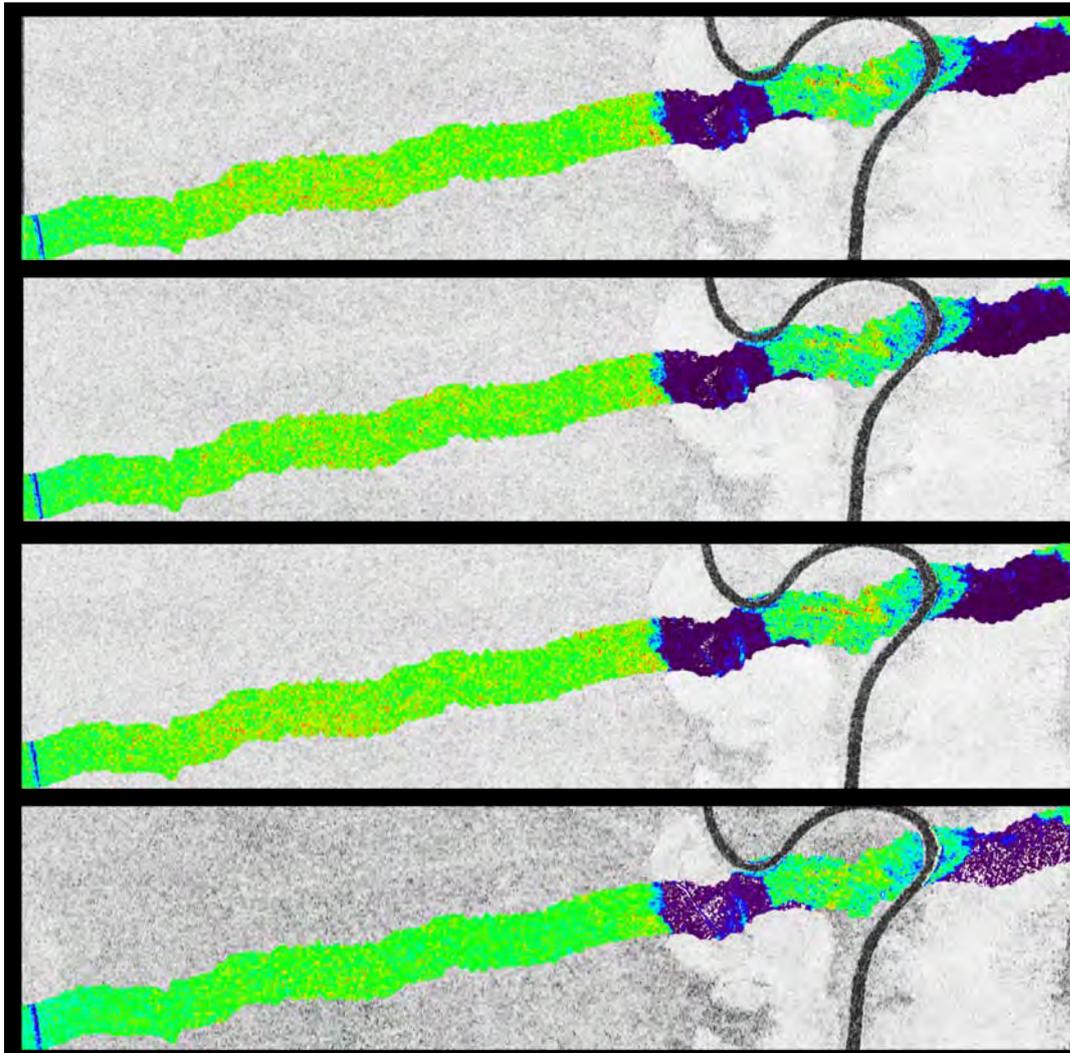
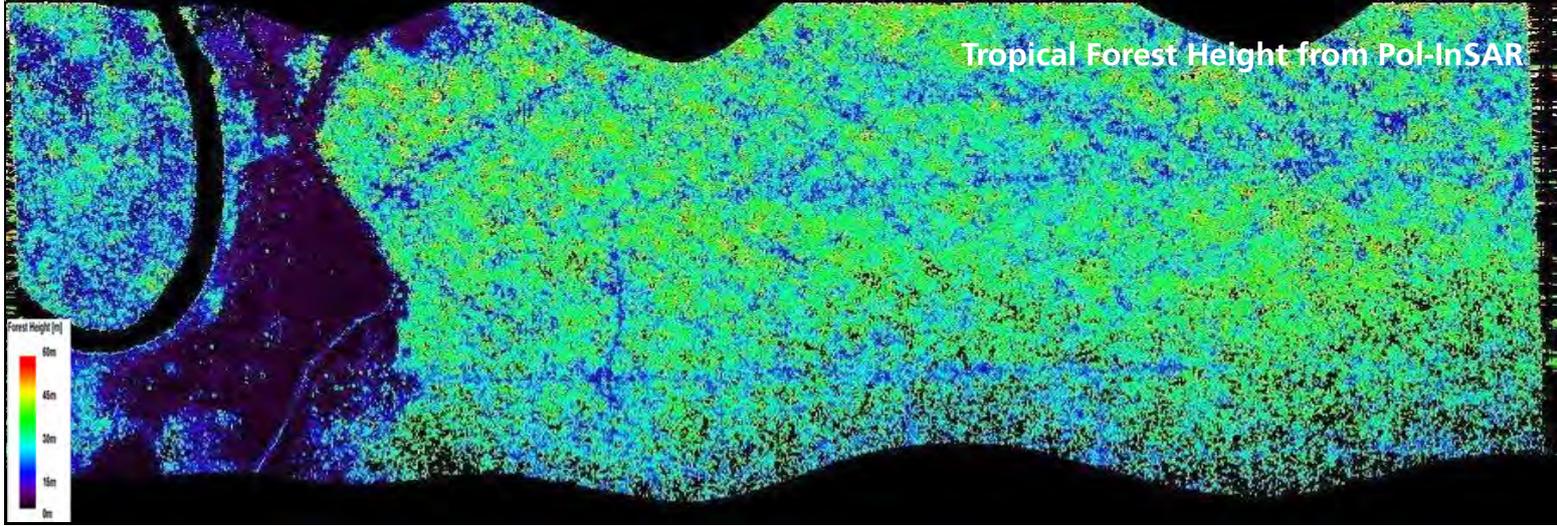

**Deutsches Zentrum
für Luft- und Raumfahrt e.V.**
 in der Helmholtz-Gemeinschaft



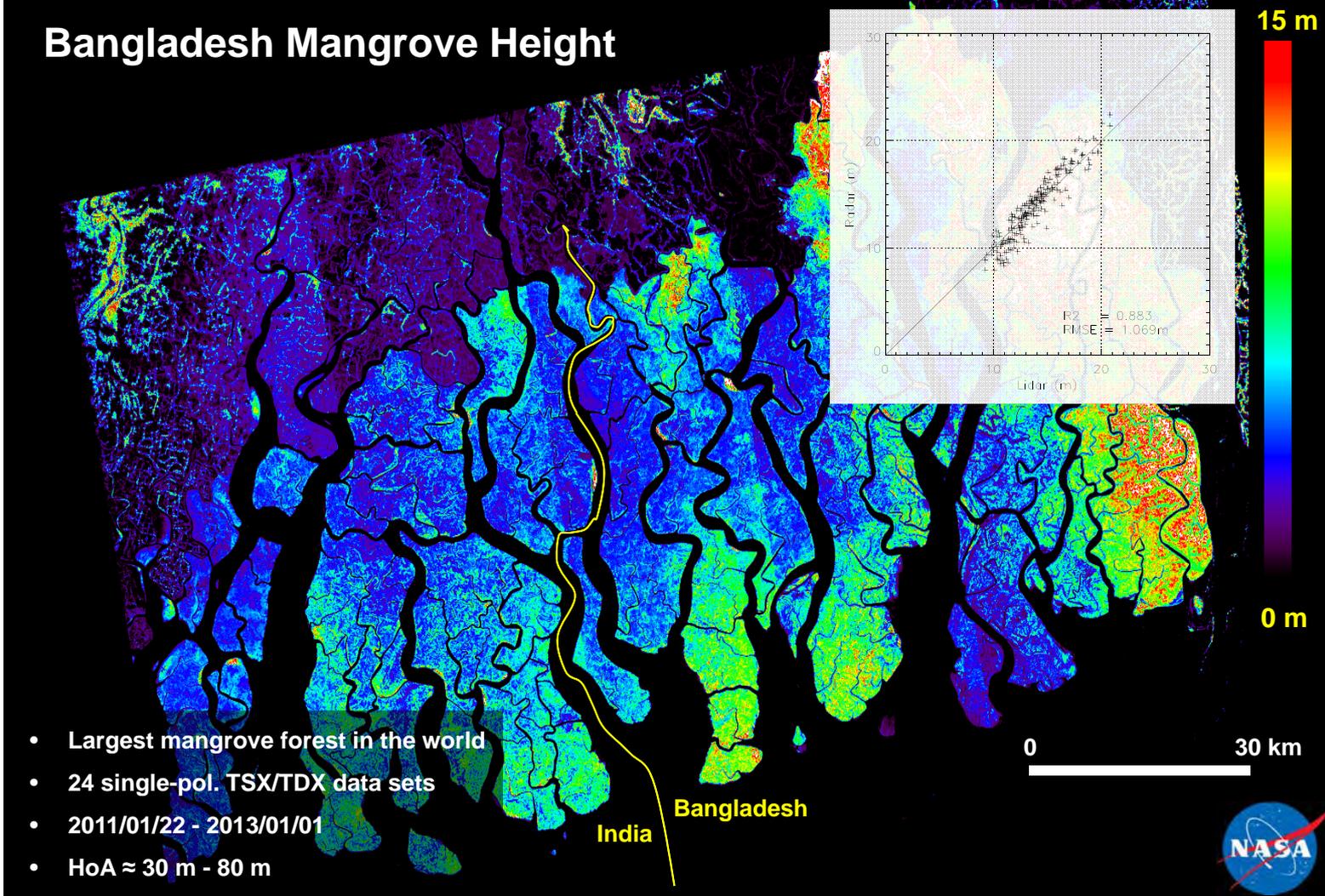
INDREX-II: Mawas Test Site



Tropical Forest Height from Pol-InSAR



Bangladesh Mangrove Height



- Largest mangrove forest in the world
- 24 single-pol. TSX/TDX data sets
- 2011/01/22 - 2013/01/01
- HoA \approx 30 m - 80 m

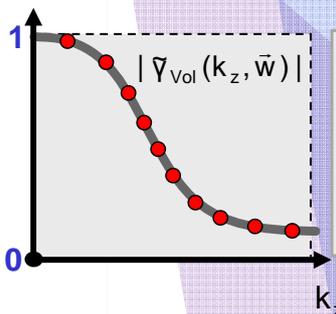
India Bangladesh



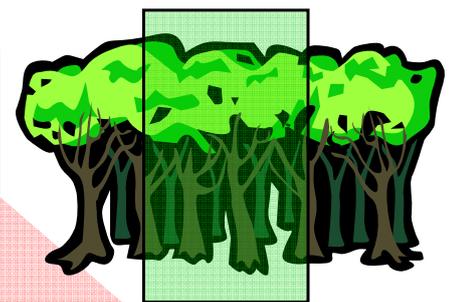
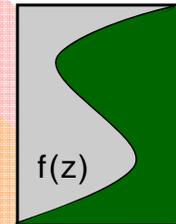
SAR Tomography



$f(z)$... vertical reflectivity function

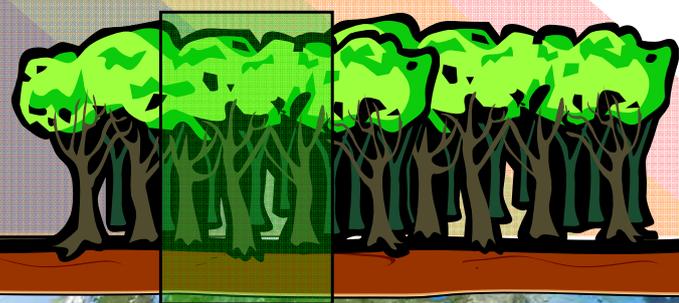


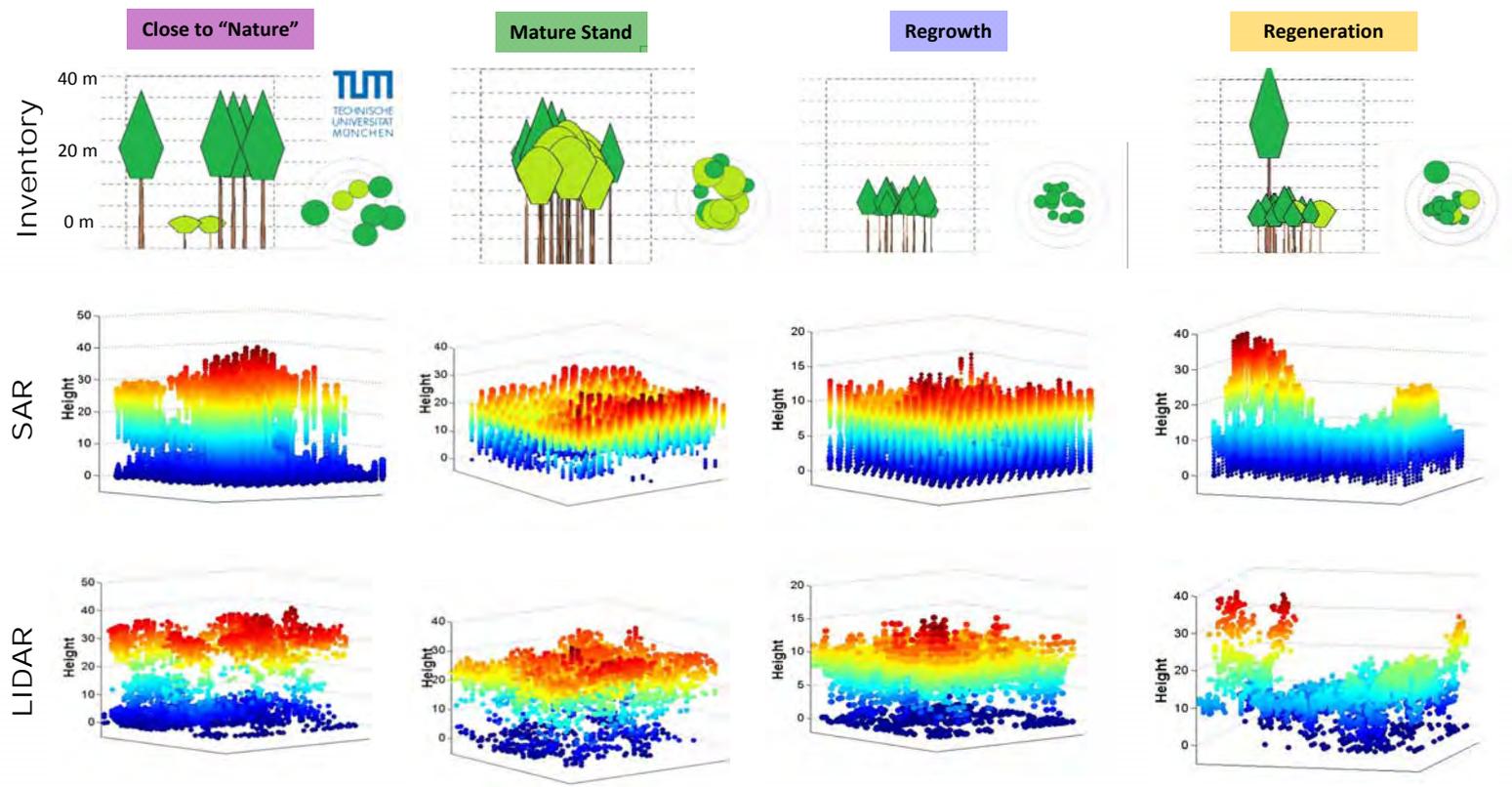
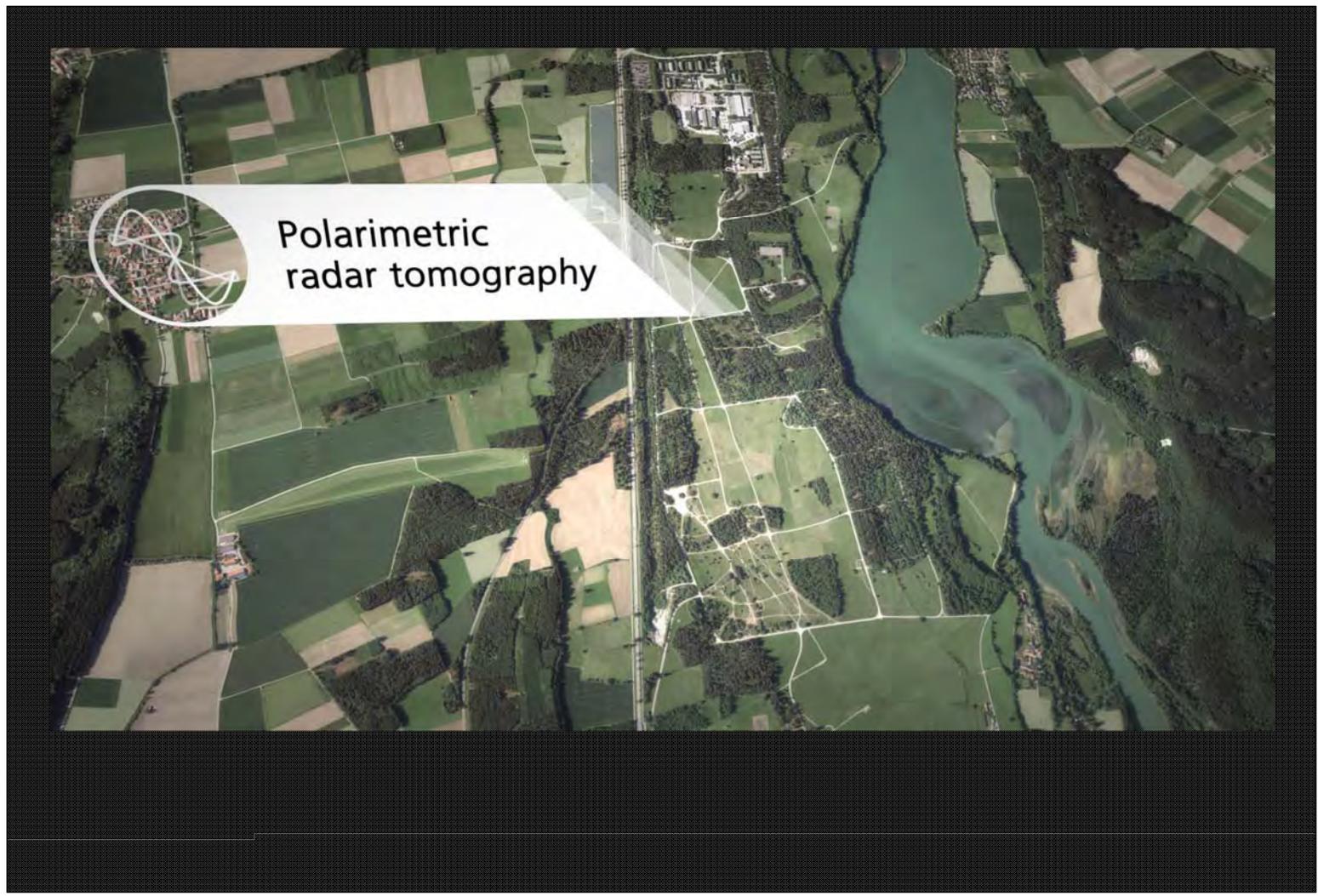
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$f(z)$... vertical reflectivity function

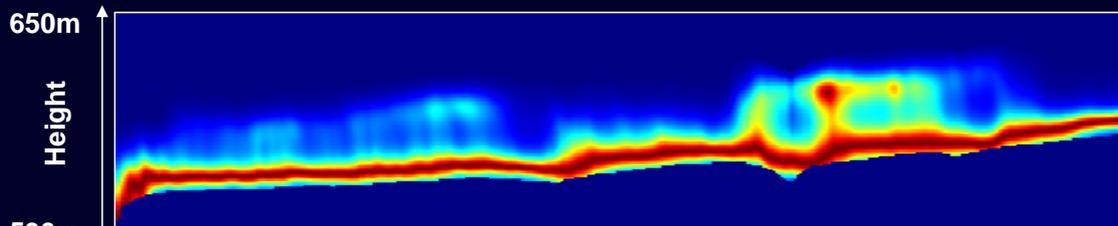
Vertical Wavenumber: $k_z = \frac{\kappa \Delta \theta}{\sin(\theta_0)}$



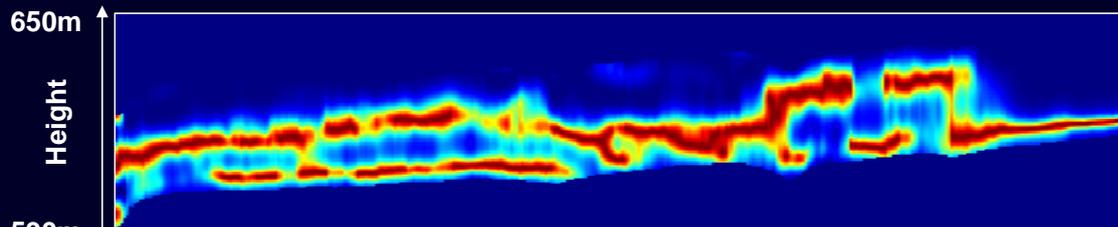




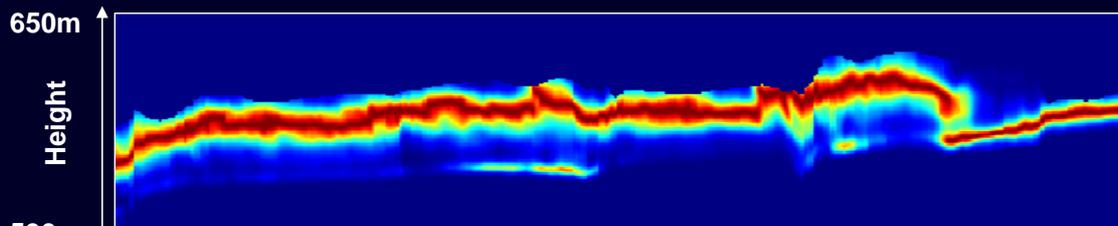
P-band



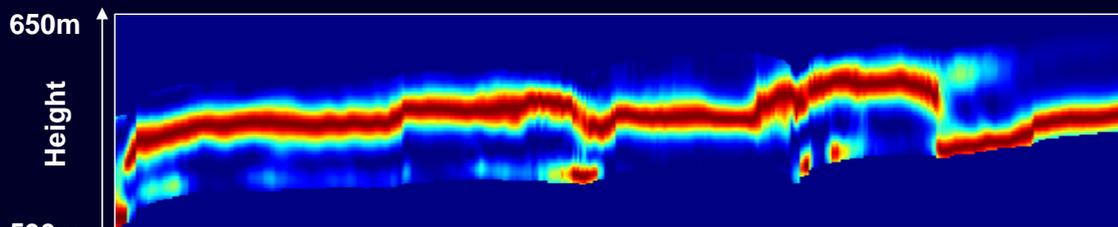
L-band



S-band

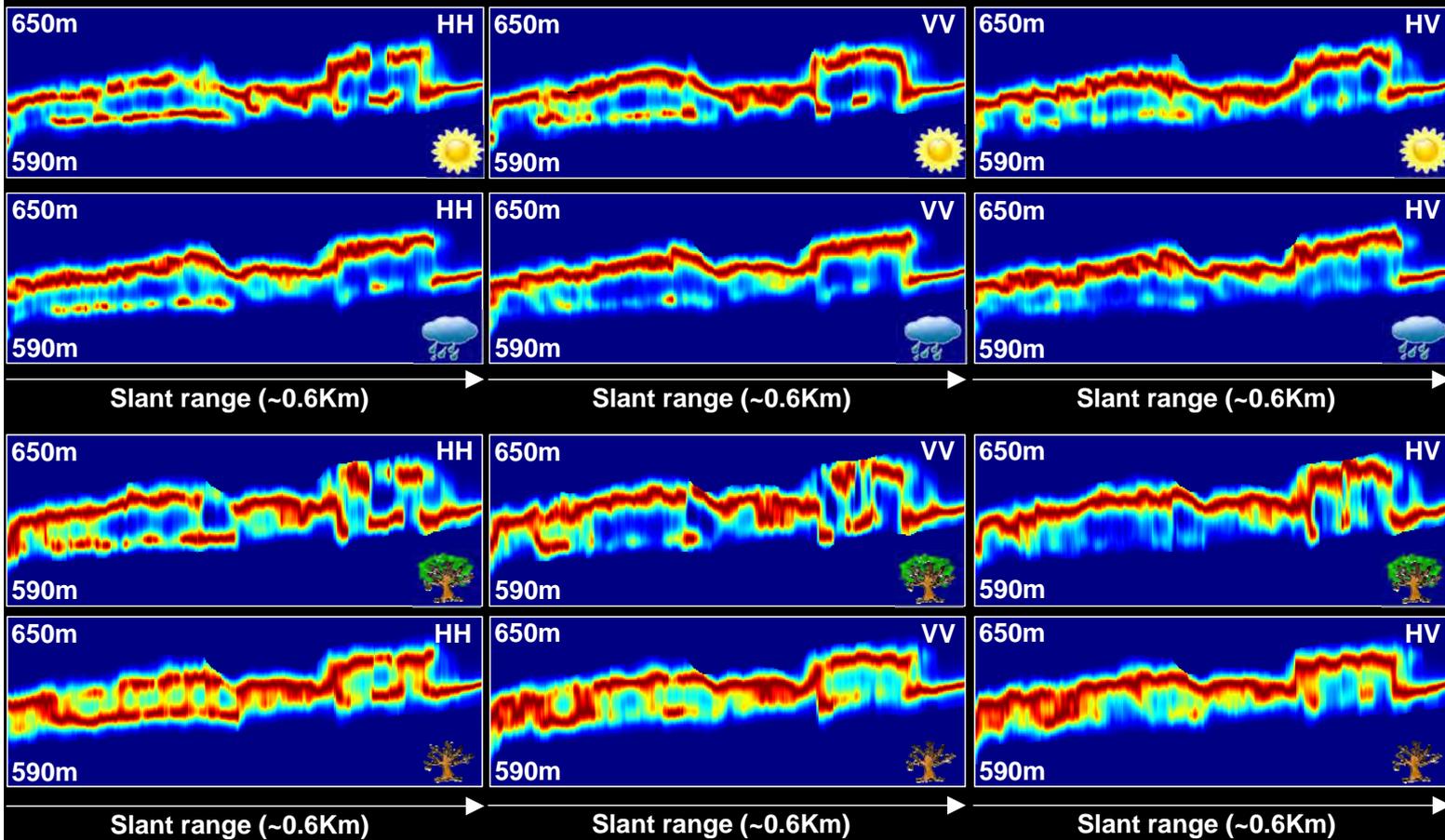


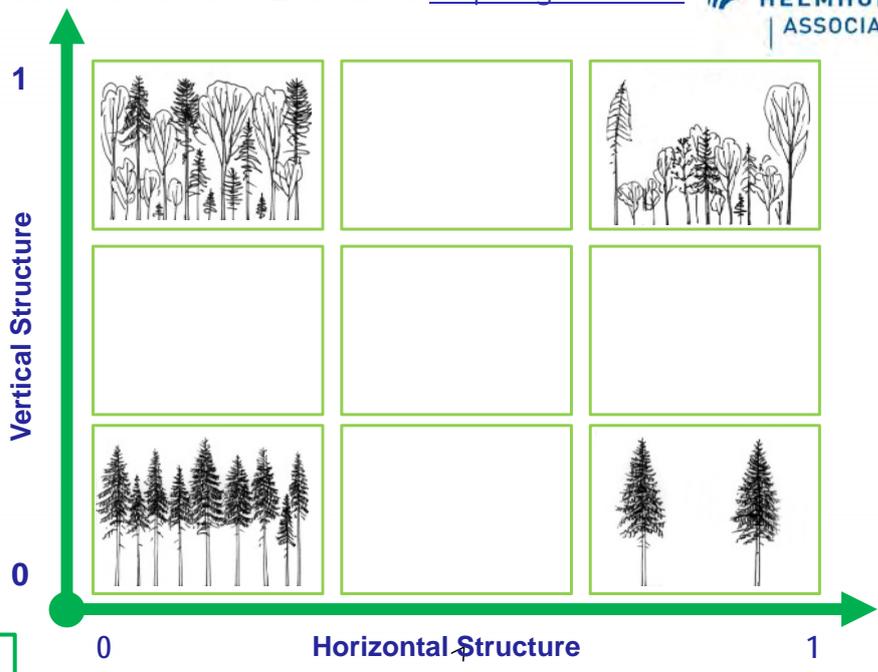
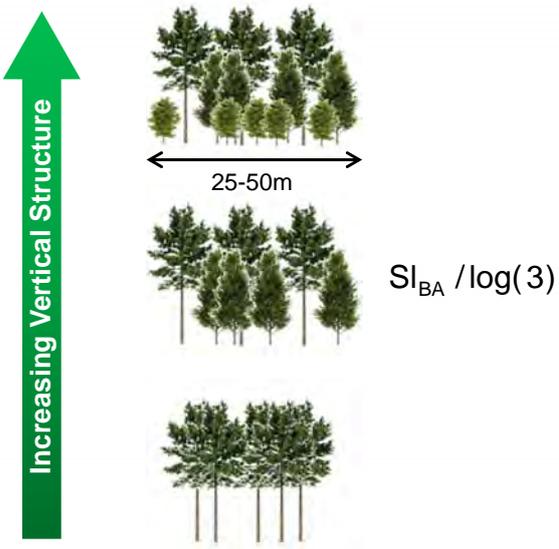
X-band



Slant range (0.6Km)

Temporal variations at L-band (Capon)



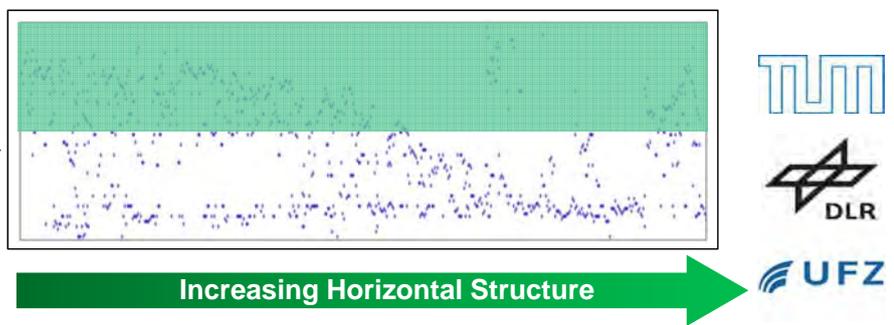
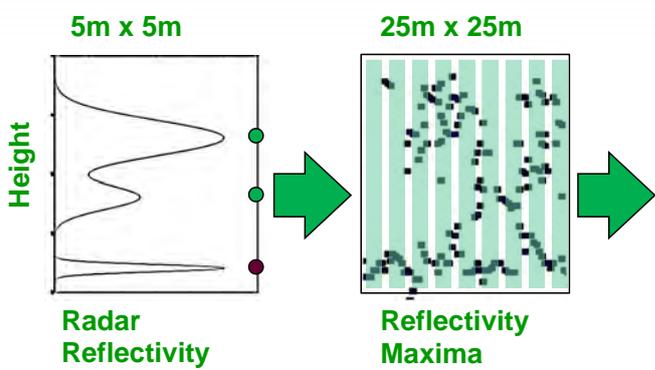
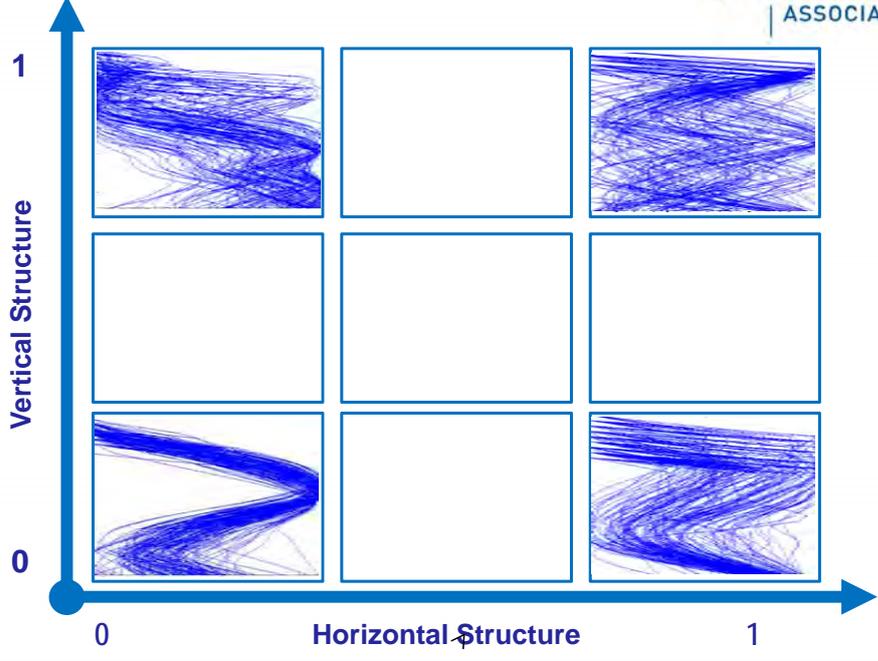
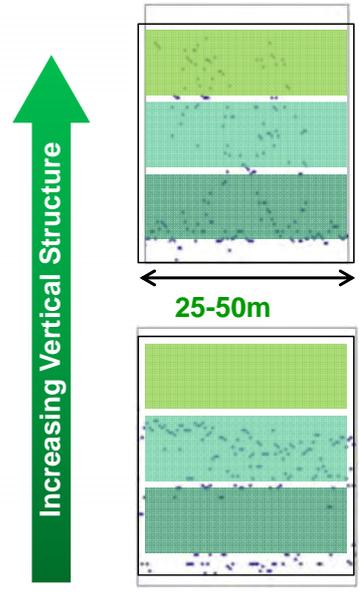
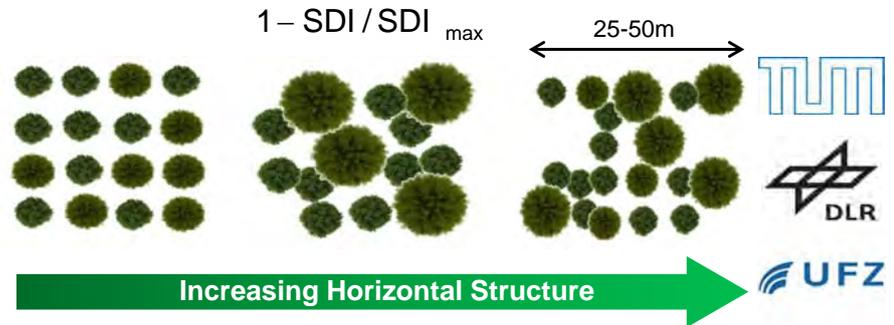


Species Profile Index (Pretzsch 2002)

$$SI_{BA} := - \sum_{i=1}^N p_i \ln(p_i) / \log(3) \quad p_i := \frac{ba_i}{ba_{tot}}$$

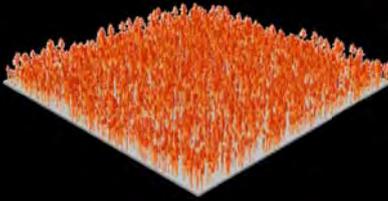
Stand Density Index (Reineke 1933)

$$SDI := N h a^{-1} \left(\frac{25}{dg} \right)^{-1.605} \quad \text{ba: basal area}$$

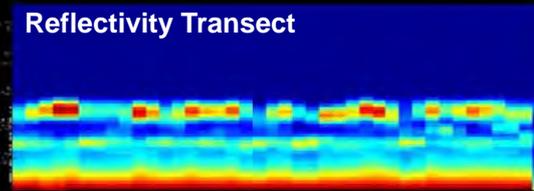


Forest Structure Characterisation

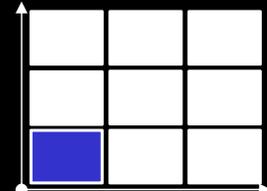
► Young forest, 50 years old



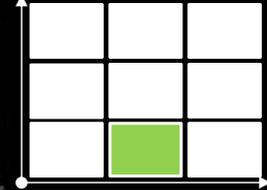
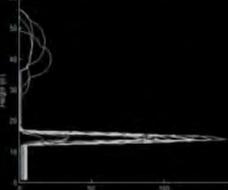
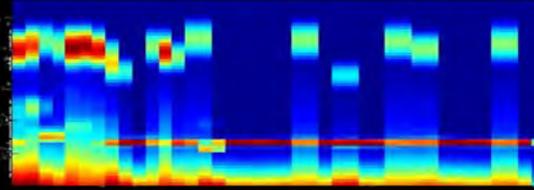
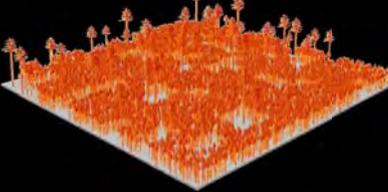
Reflectivity Transect



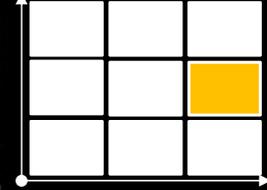
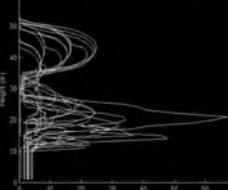
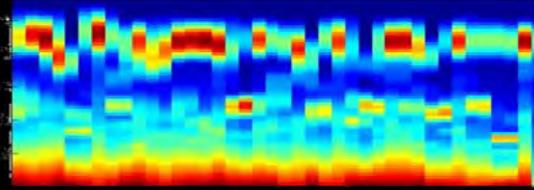
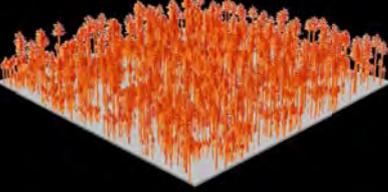
Reflectivity Profiles



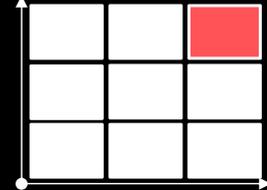
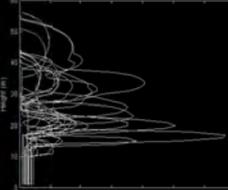
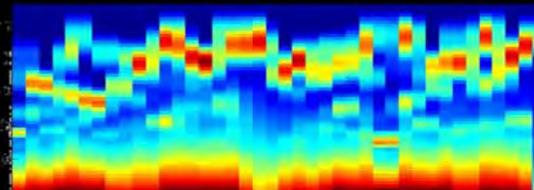
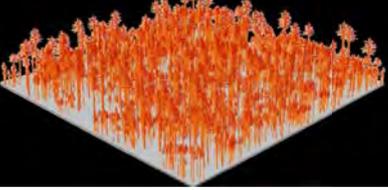
► Old forest, 10 years after a fire event



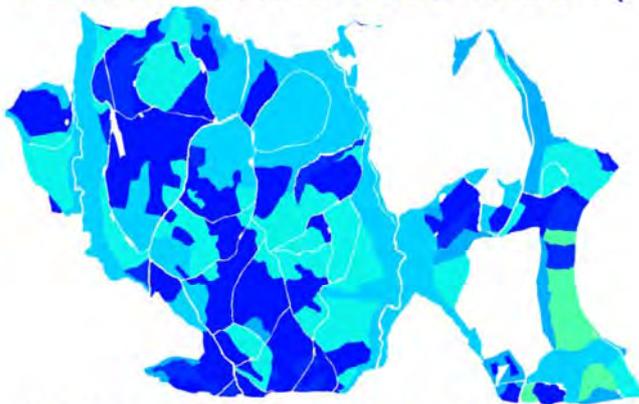
► Old forest, 200 years after a fire event



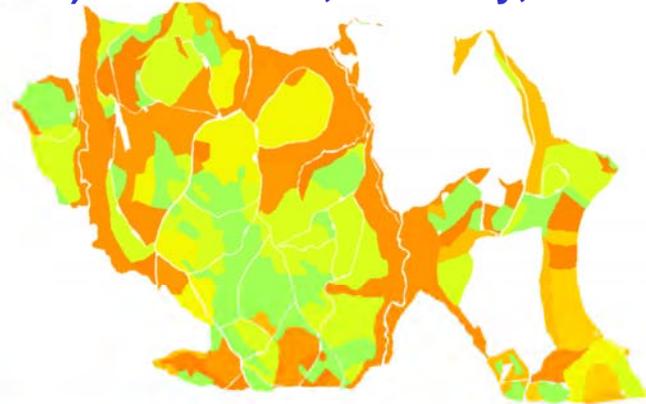
► Old forest, 500 years old



Forest Structure Classification (25x25 m): Traunstein, Germany, 2008



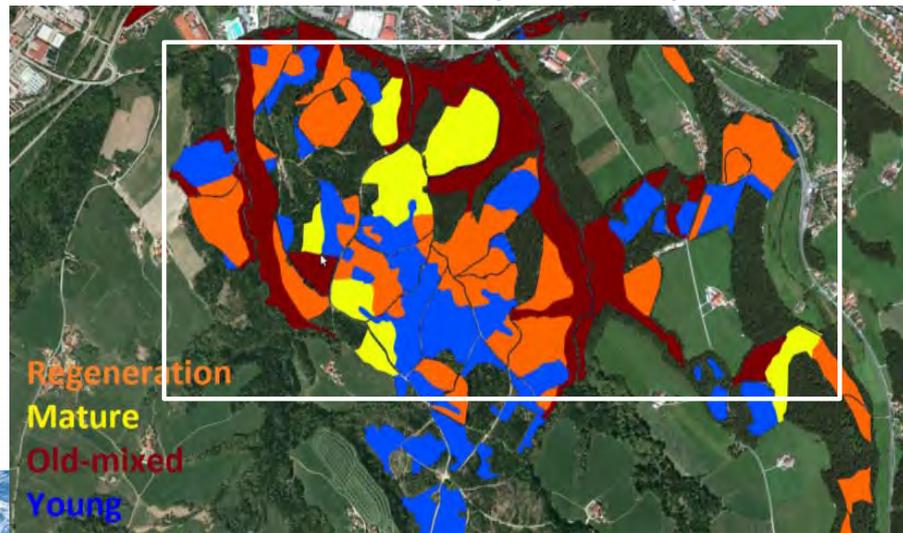
Horizontal structure (Radar 2008)



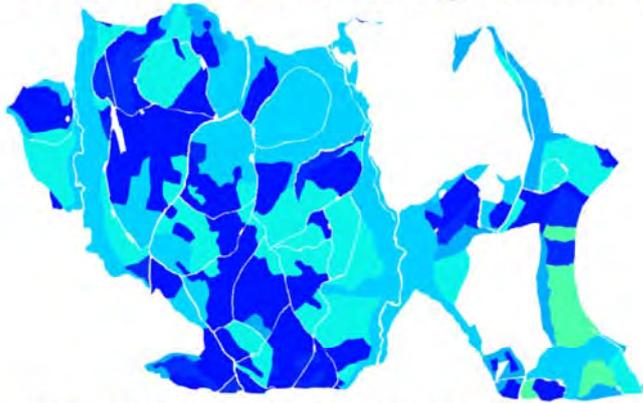
Vertical structure CM (Radar 2008)



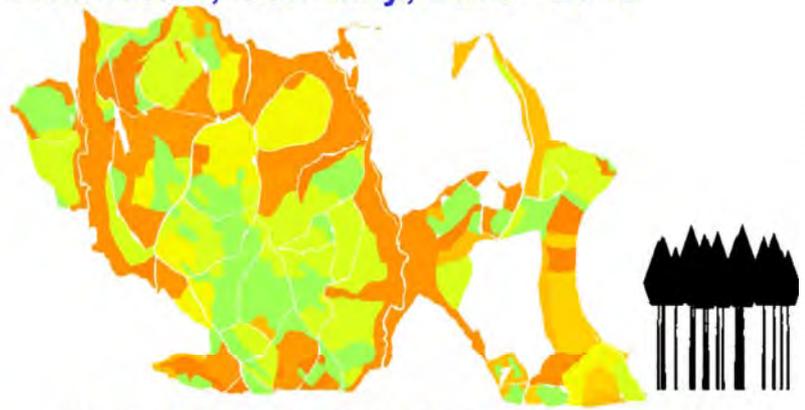
- Regeneration forest
- Plenter forest
- Mature forest
- Young forest



Forest Structure Change (25x25 m): Traunstein, Germany, 2008 - 2012



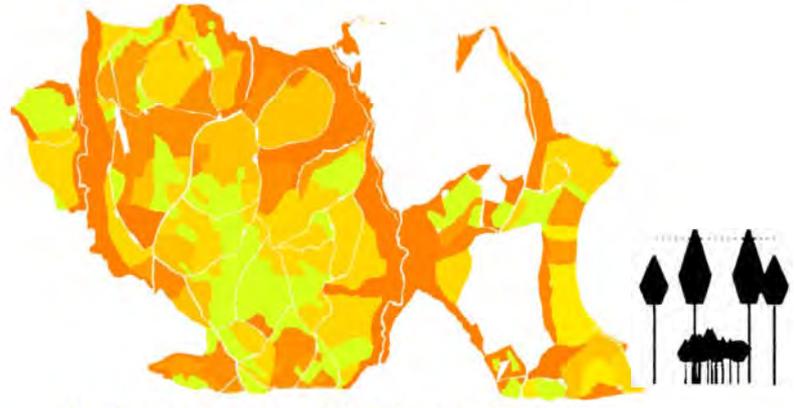
Horizontal structure (Radar 2008)



Vertical structure CM (Radar 2008)



Horizontal structure (Radar 2012)

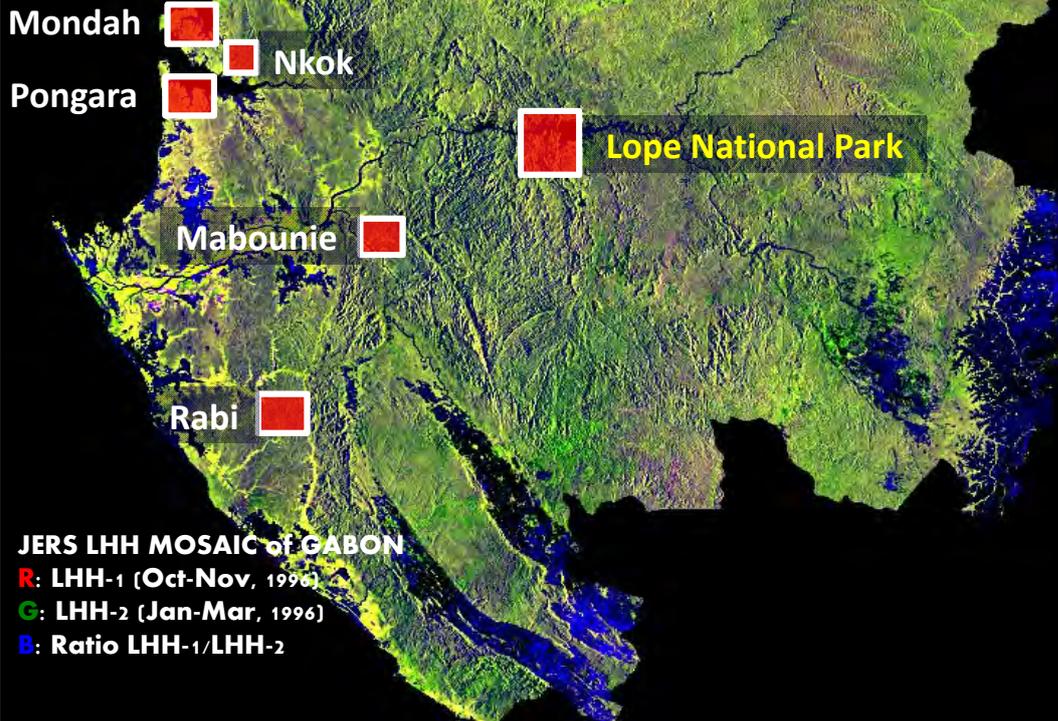


Vertical structure CM (Radar 2012)

 Deutsches Zentrum für Luft- und Raumfahrt e.V. in der Helmholtz-Gemeinschaft



AfriSAR 2016



Objectives

Tandem-L:

Development & validation of algorithms for forest structure characterisation @ L-band

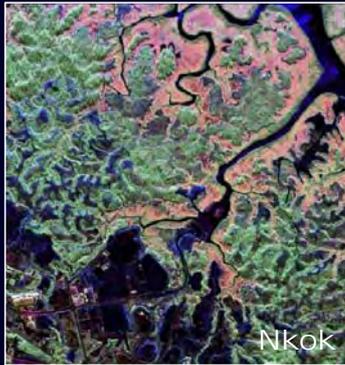
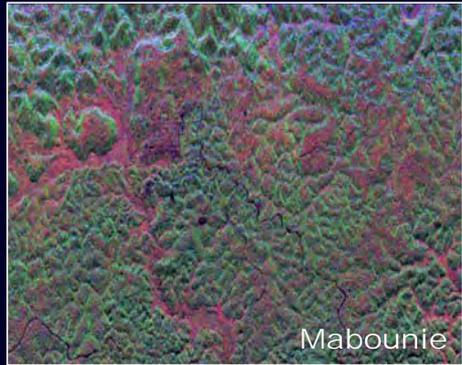
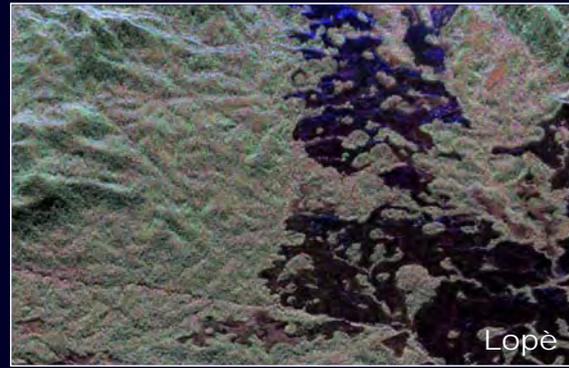
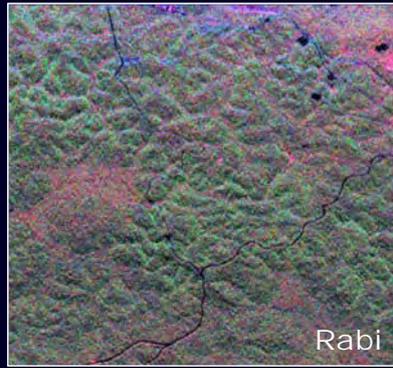
GEDI

Development & validation of methodology for combining TD-X and GEDI measurements

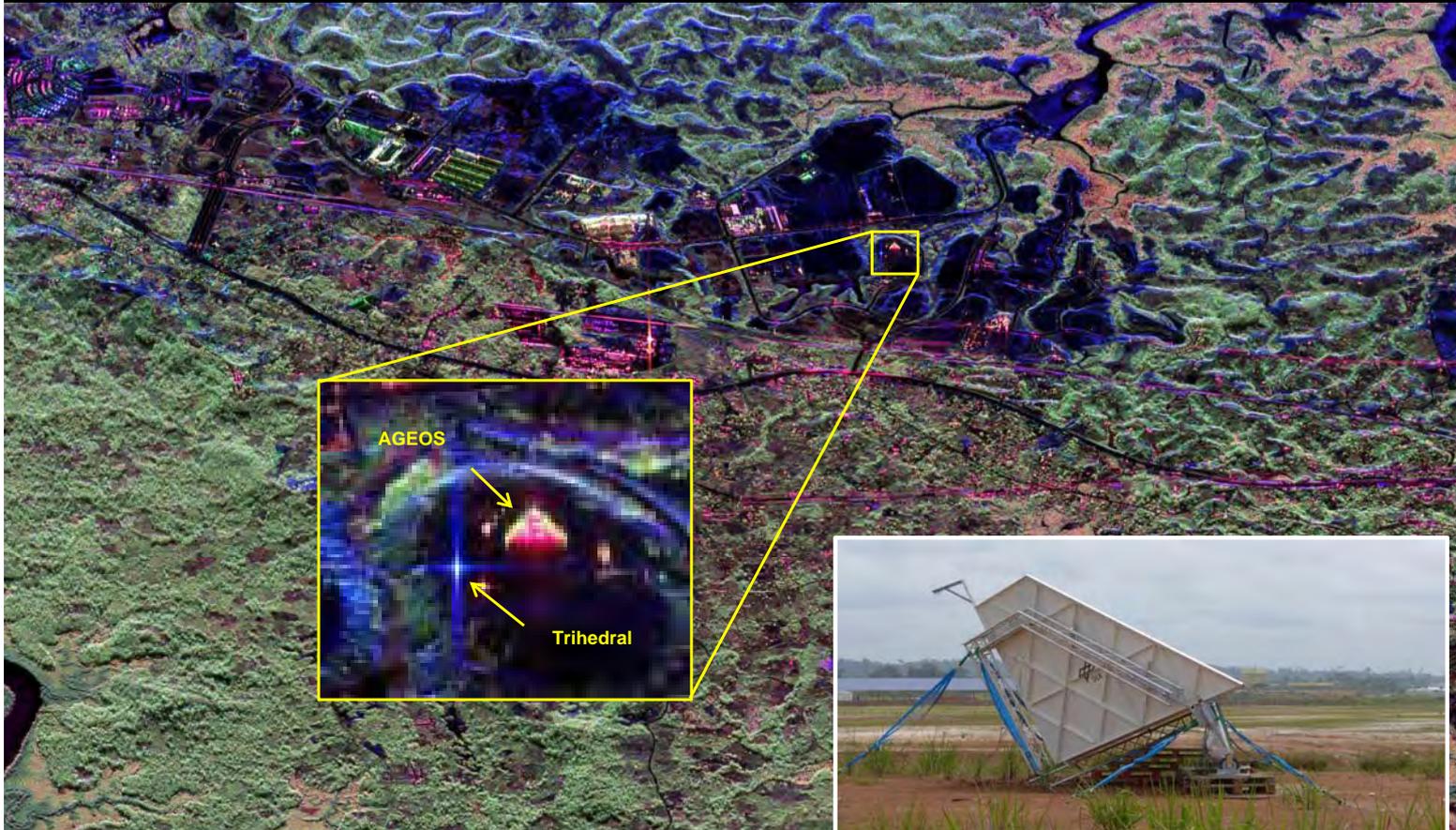
BIOMASS

Establishment & validation of a common framework for PoISAR, Po-InSAR and TomoSAR measurements to support Biomass estimation @ P-band



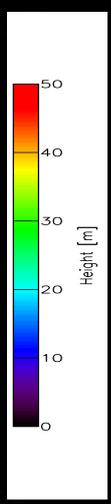
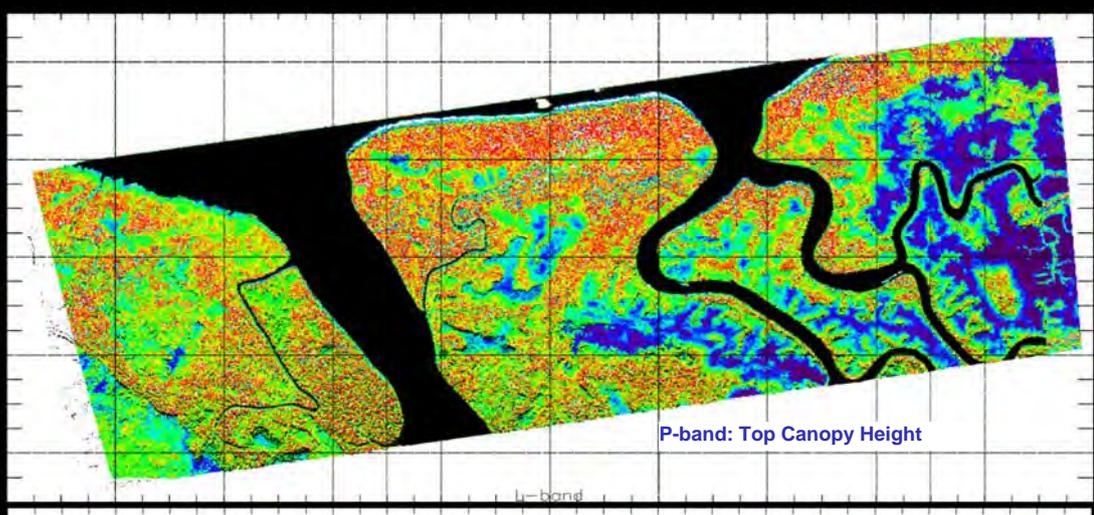


Nkok

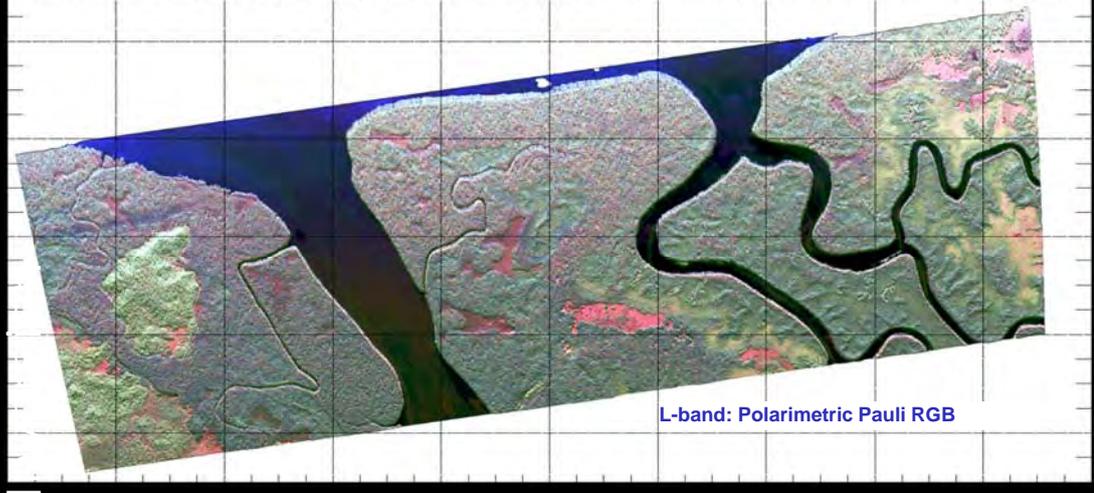


F-SAR L-Band, 100 MHz, Pauli (HH-VV,HV) Trihedral reflector deployed at Nkok near Libreville, on the premises of AGEOS

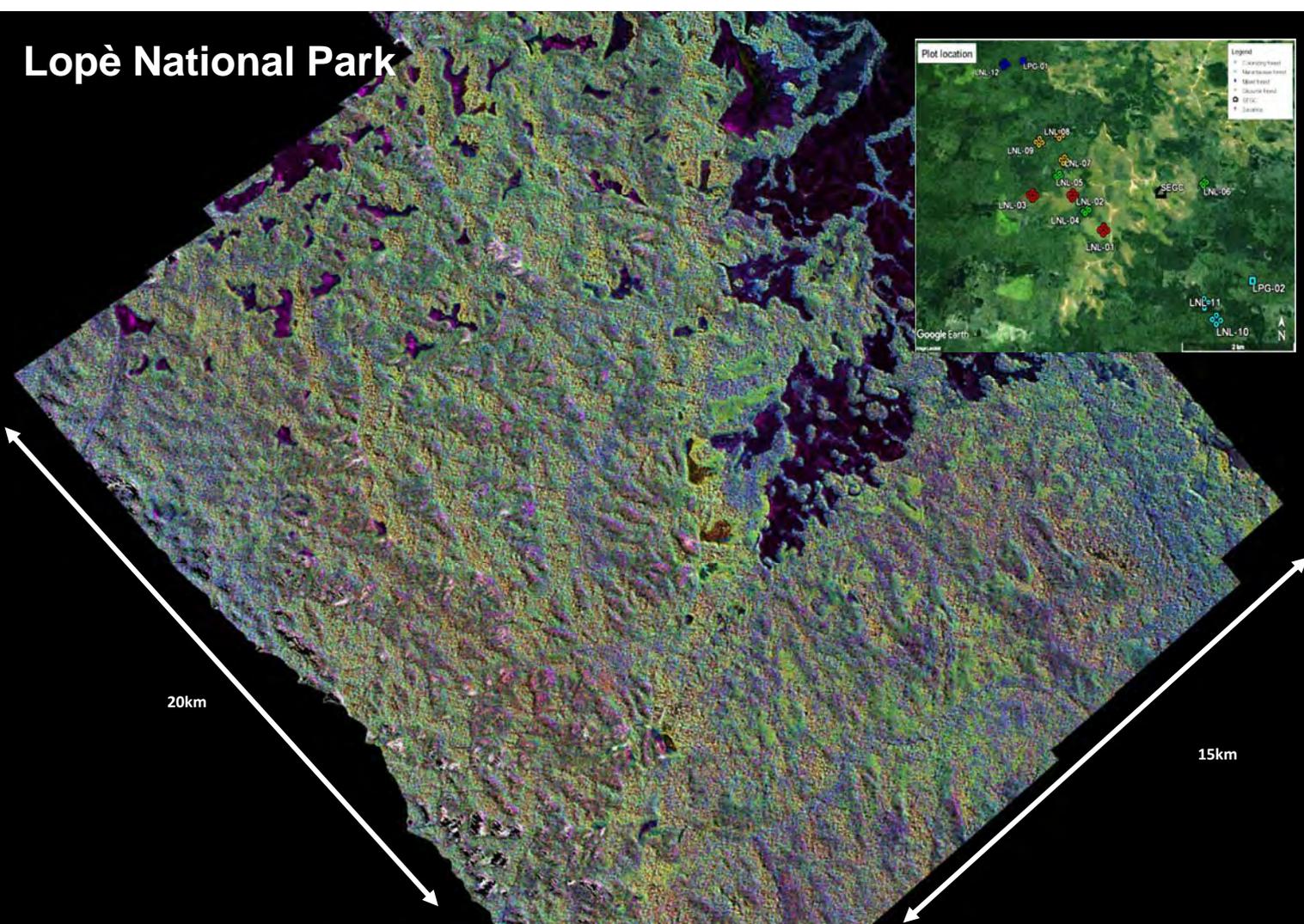
AfrisAR Pol-InSAR Forest Height



Pongara



Lopè National Park



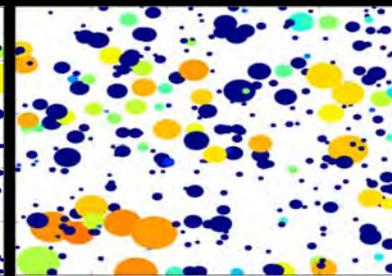
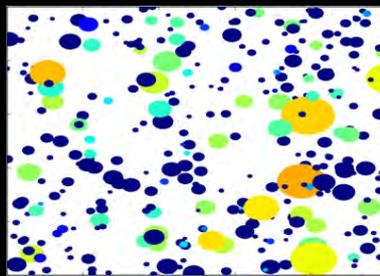
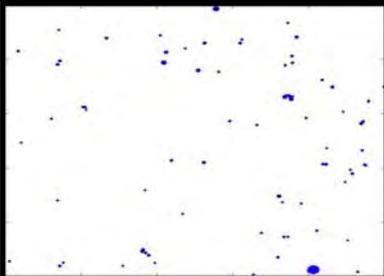
AfriSAR

Savanna

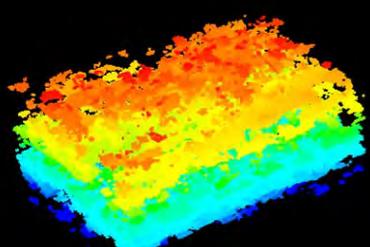
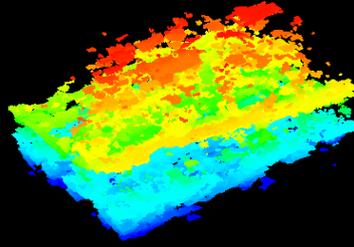
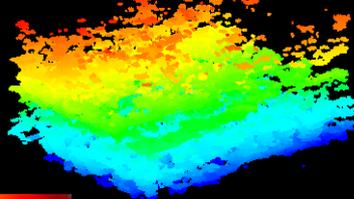
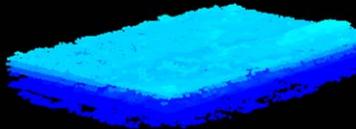
Colonizing forest

Okoumé forest

Marantaceae



Local maxima of reflectivity profiles



0 [m] 60

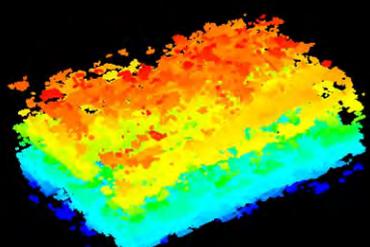
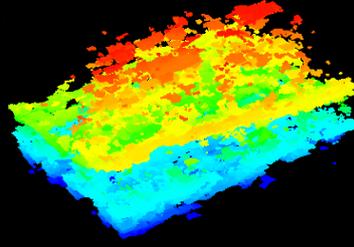
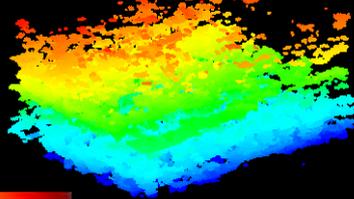
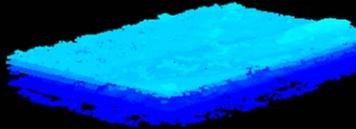
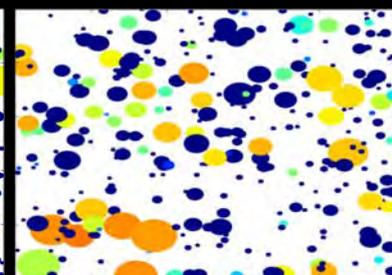
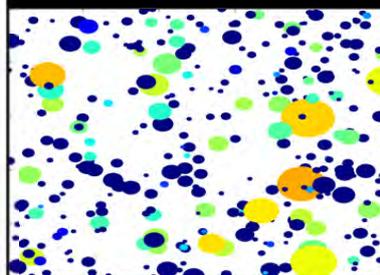
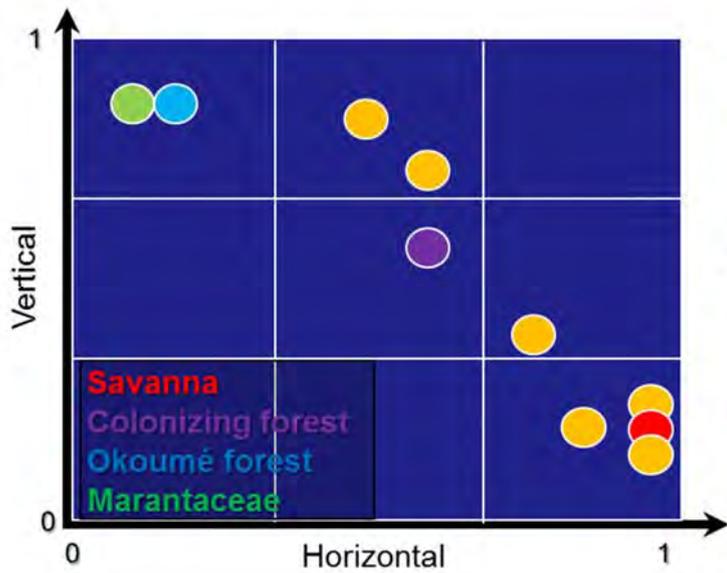
AfriSAR

Savanna

Colonizing forest

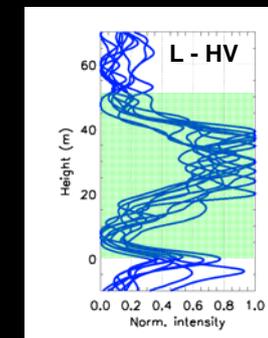
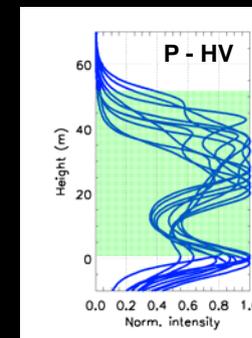
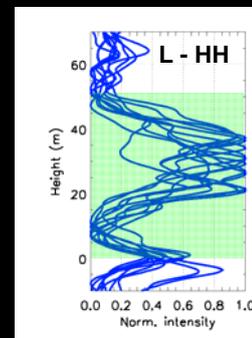
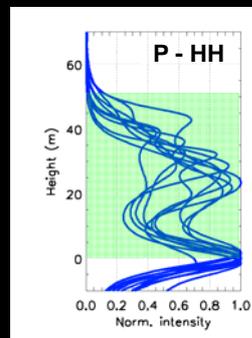
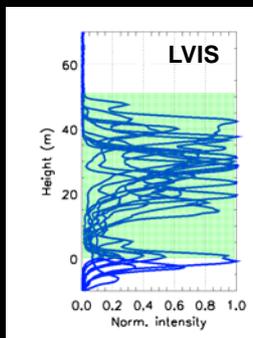
Okoumé forest

Marantaceae

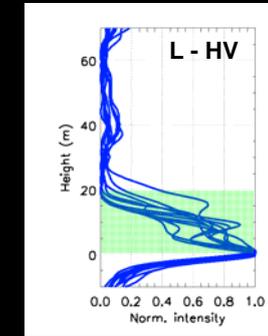
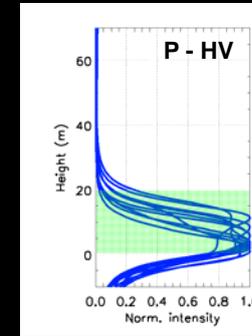
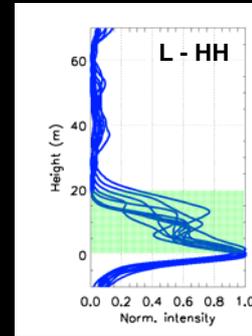
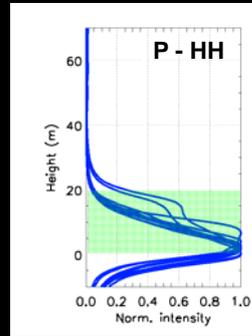
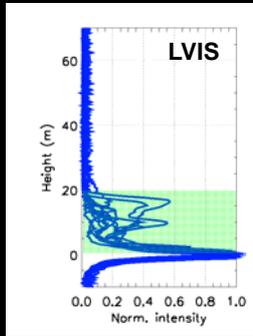


0 [m] 60

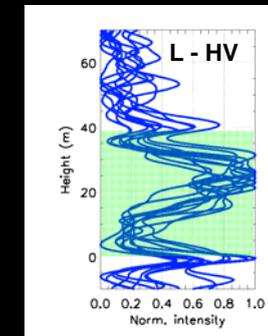
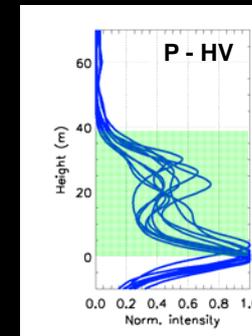
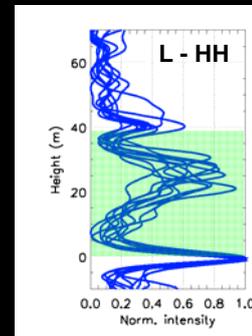
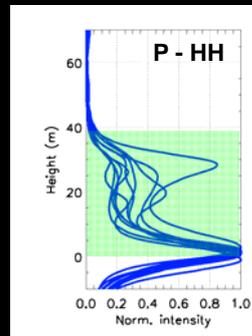
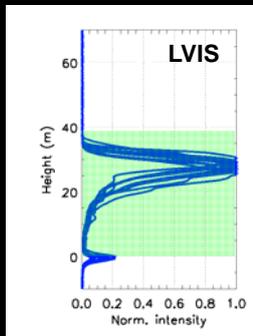
LNL-10 (MAR1)



LNL-05 (COL2)



LNL-08 (OKO2)



Multi-baseline Polarimetric SAR Interferometry: Forest Applications

Konstantinos P. Papathanassiou

German Aerospace Center (DLR)
Microwaves and Radar Institute (DLR-HR)
Pol-InSAR Research Group

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