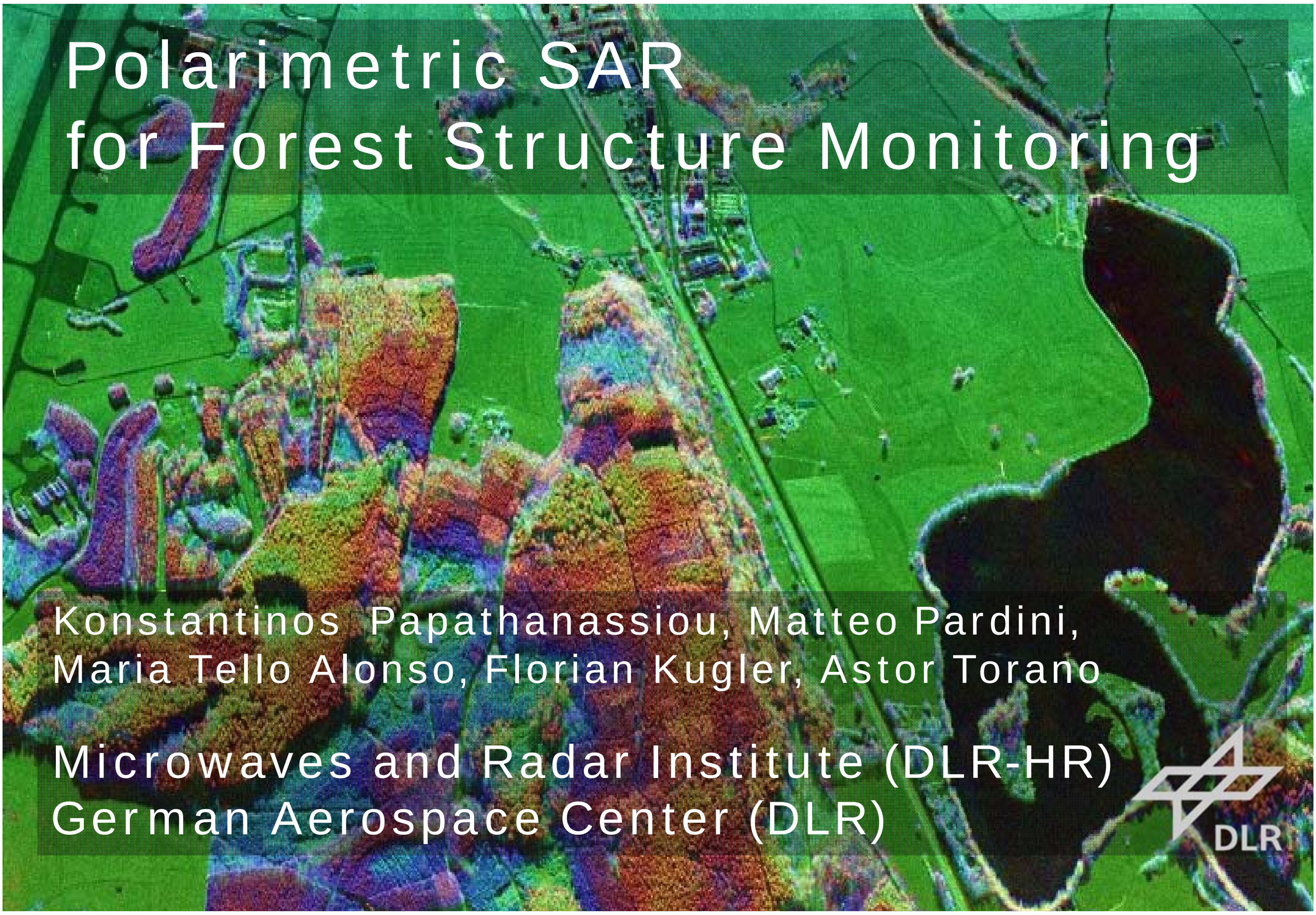
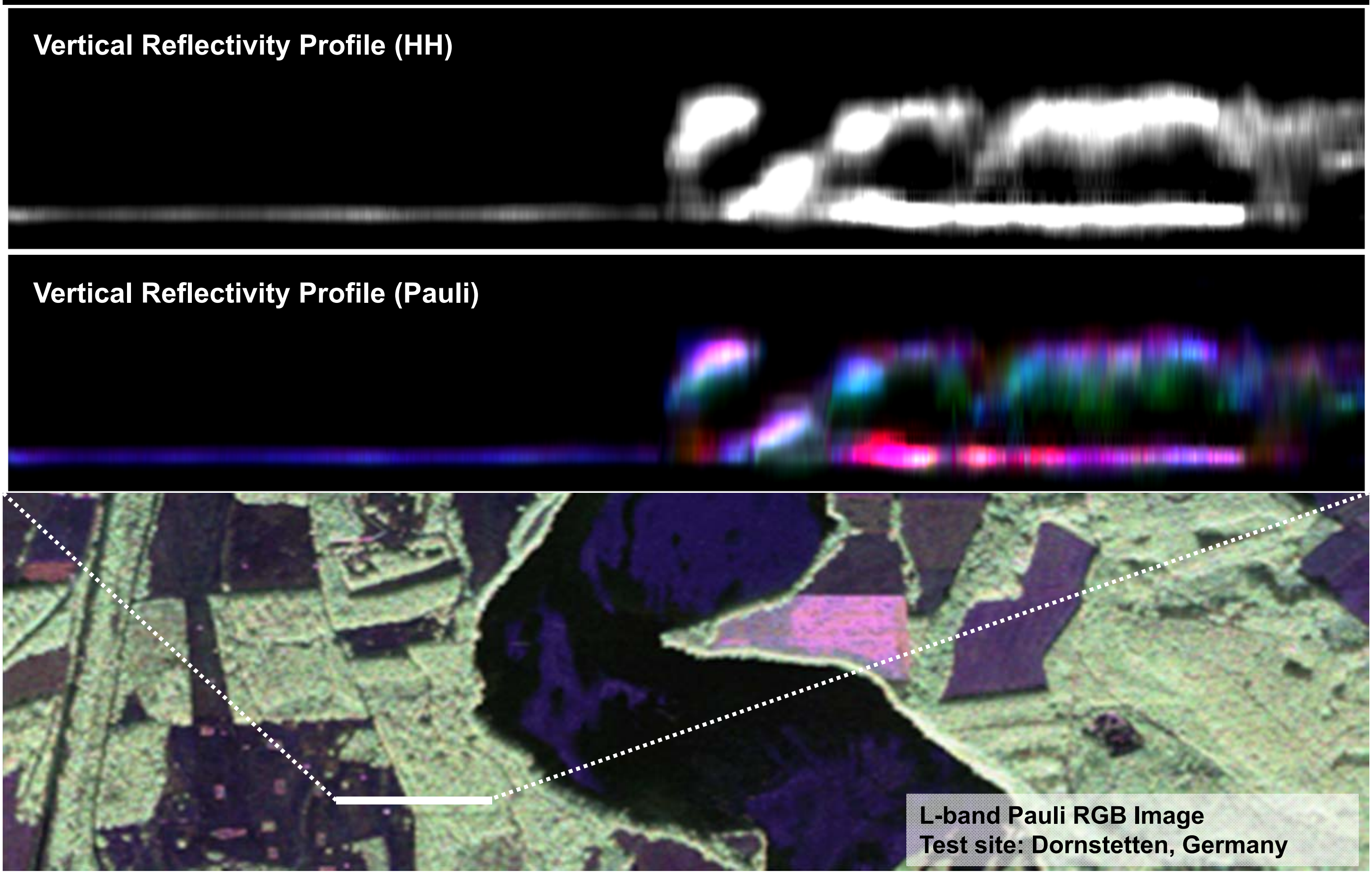
Polarimetric SAR for Forest Structure Monitoring



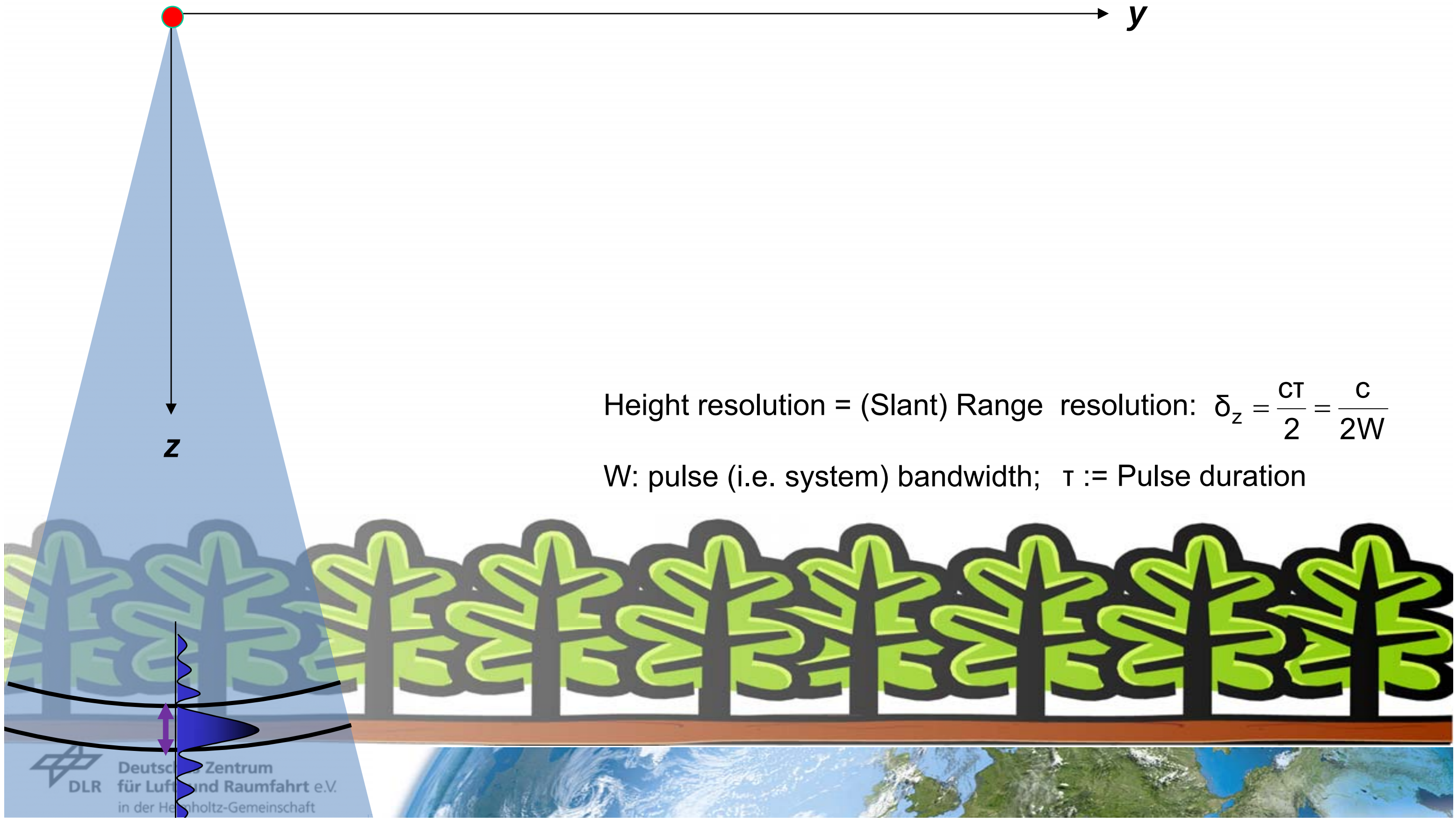
Konstantinos Papathanassiou, Matteo Pardini, Maria Tello Alonso, Florian Kugler, Astor Torano

Microwaves and Radar Institute (DLR-HR)
German Aerospace Center (DLR)

Penetration into Vegetation



Vertical Resolution: Nadir Looking Case



Height resolution = (Slant) Range resolution: $\delta_z = \frac{c\tau}{2} = \frac{c}{2W}$

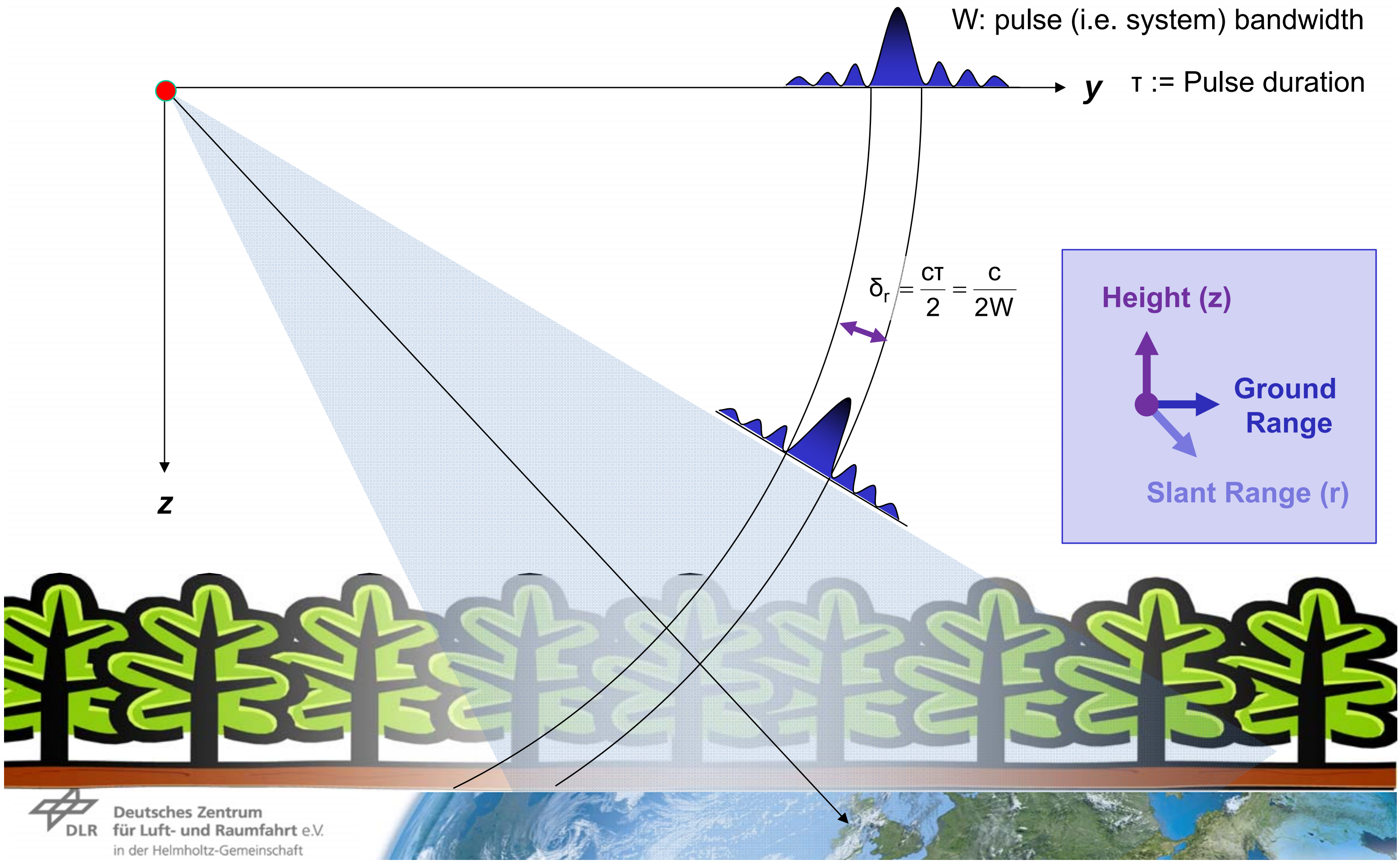
W: pulse (i.e. system) bandwidth; τ := Pulse duration

Vertical Resolution: Side Looking Case

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

W: pulse (i.e. system) bandwidth

τ := Pulse duration



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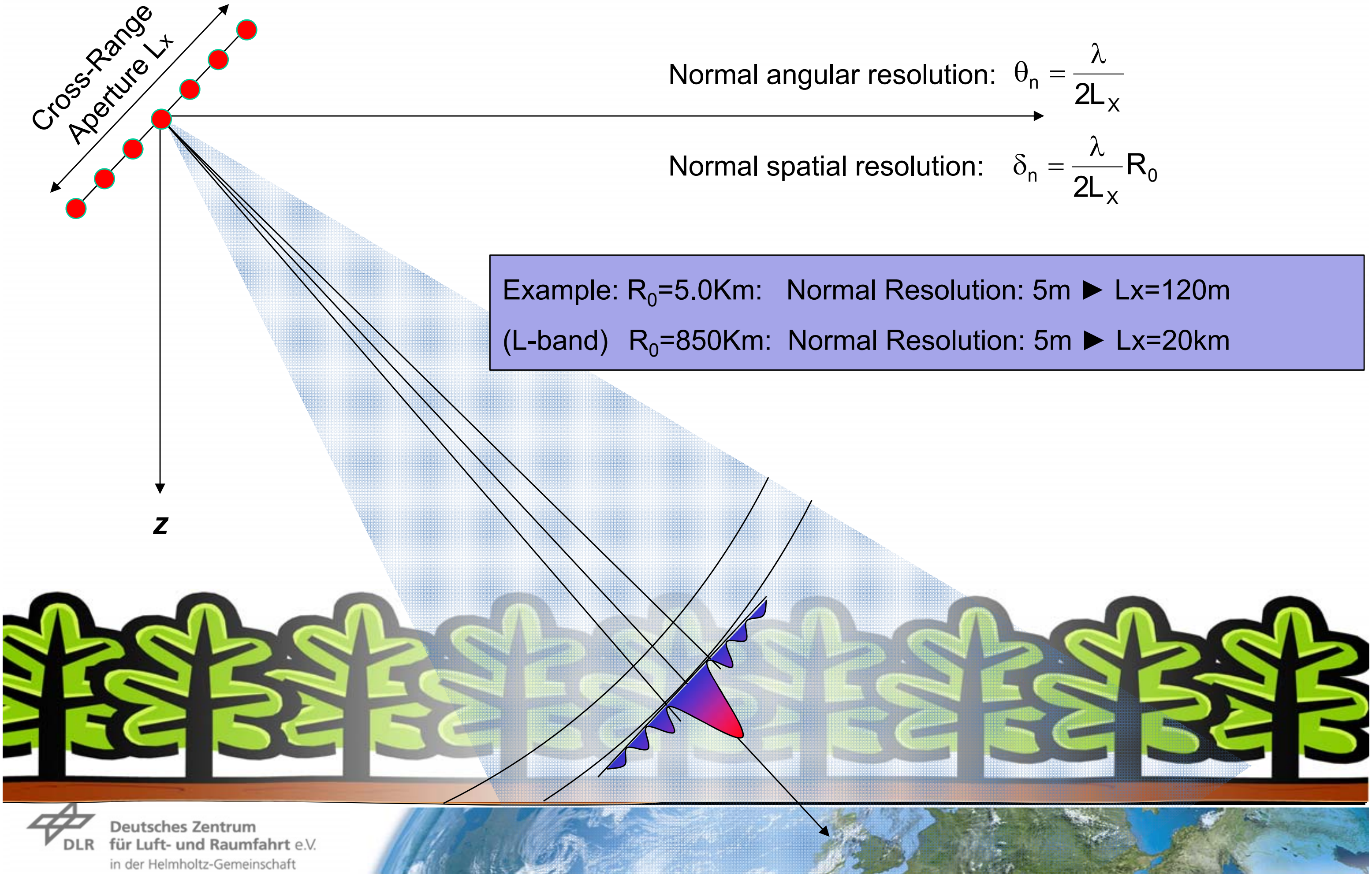
Vertical Resolution: SAR Tomography



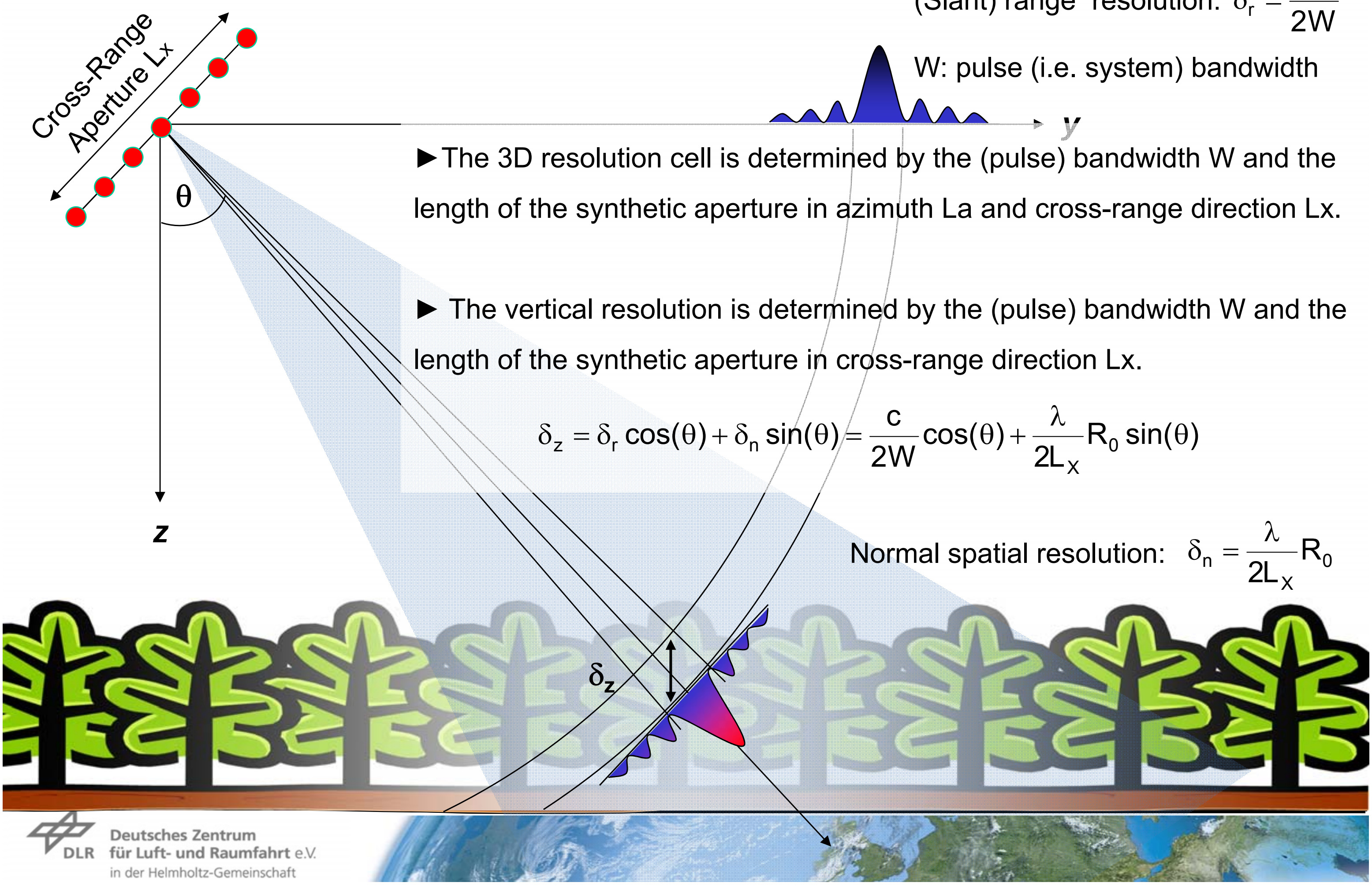
Normal angular resolution: $\theta_n = \frac{\lambda}{2L_X}$

Normal spatial resolution: $\delta_n = \frac{\lambda}{2L_X} R_0$

Example: R_0=5.0Km: Normal Resolution: 5m ► Lx=120m

(L-band) R_0=850Km: Normal Resolution: 5m ► Lx=20km

Vertical Resolution



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

W: pulse (i.e. system) bandwidth

► The 3D resolution cell is determined by the (pulse) bandwidth W and the length of the synthetic aperture in azimuth La and cross-range direction Lx.

► The vertical resolution is determined by the (pulse) bandwidth W and the length of the synthetic aperture in cross-range direction Lx.

$$\delta_z = \delta_r \cos(\theta) + \delta_n \sin(\theta) = \frac{c}{2W}\cos(\theta) + \frac{\lambda}{2L_X} R_0 \sin(\theta)$$

Normal spatial resolution: $\delta_n = \frac{\lambda}{2L_X} R_0$

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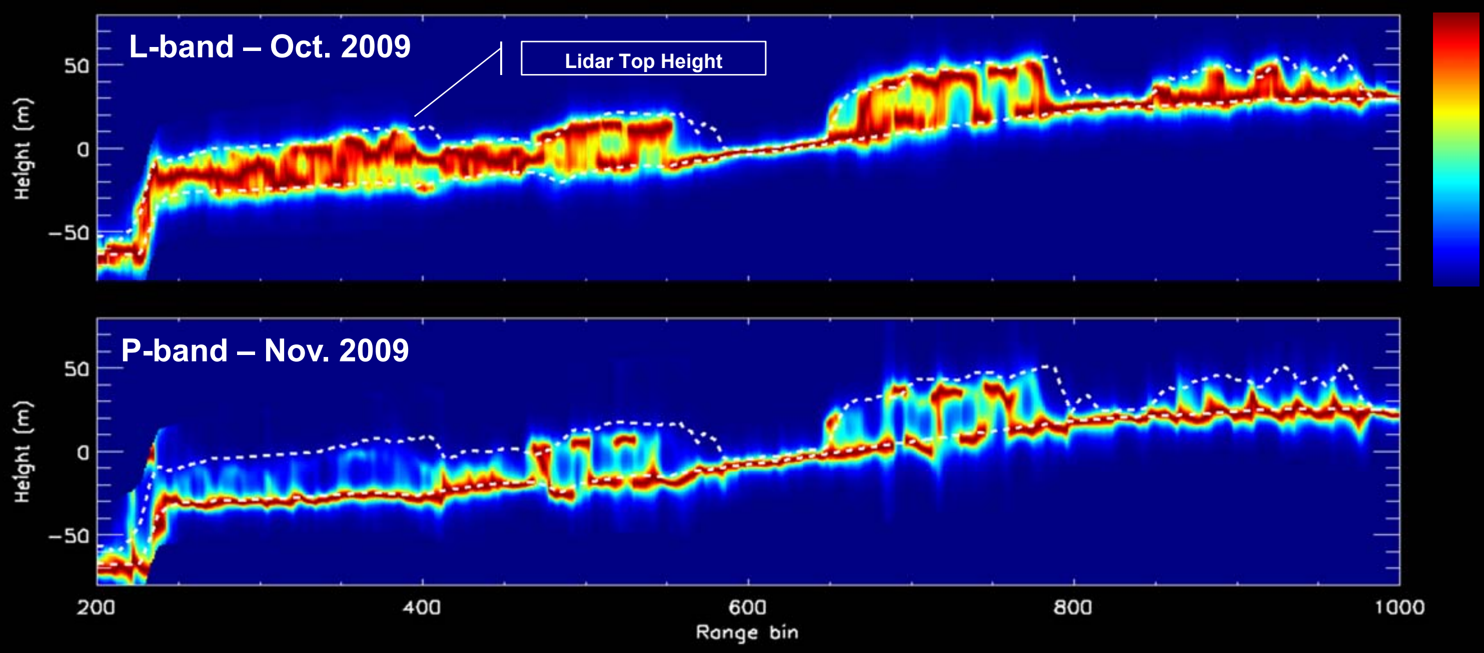
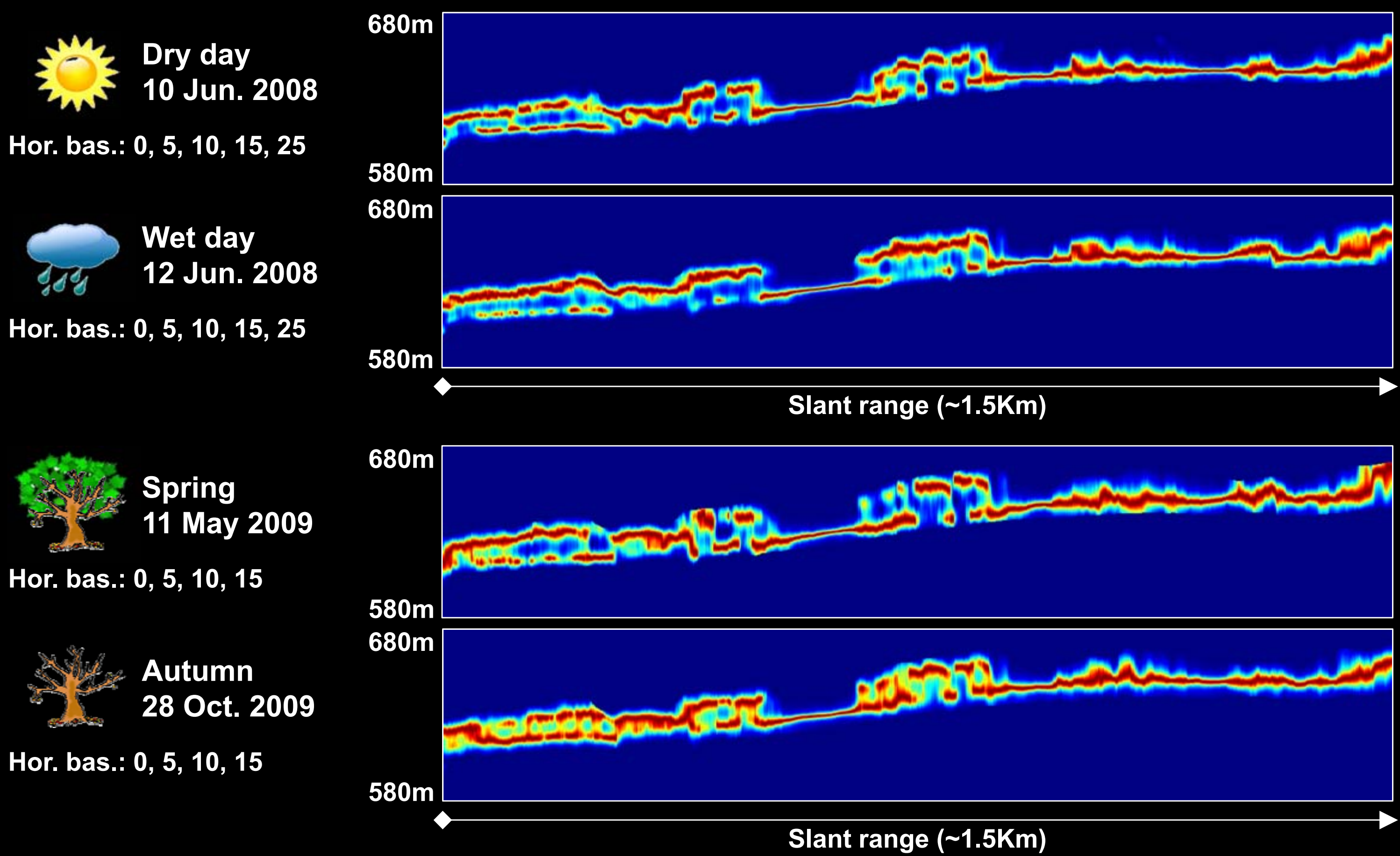
Forest Vertical Reflectivity: L- vs P-band

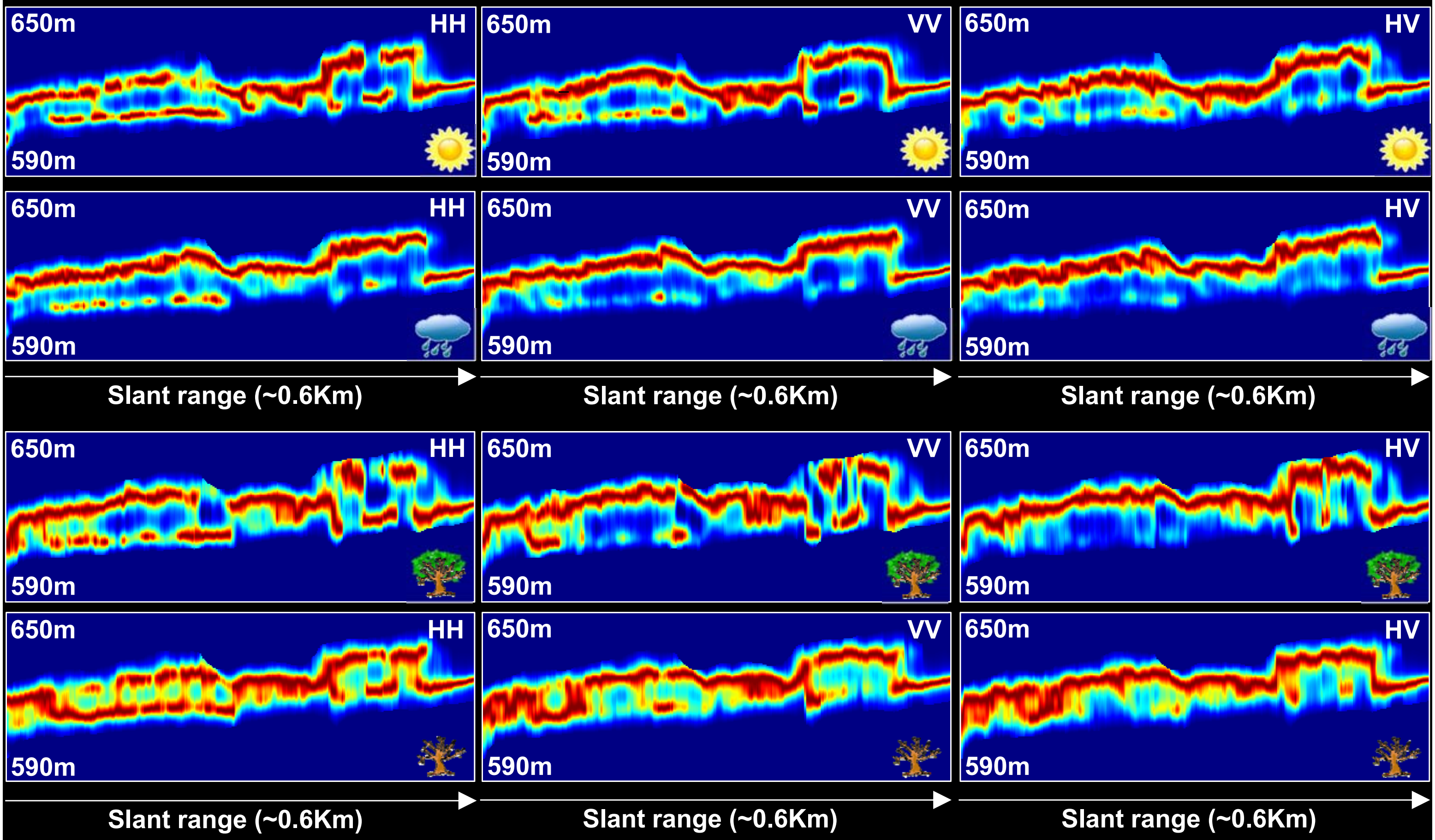


Traunstein Site, 5 tracks, E-SAR, Capon, HH-Polarisation

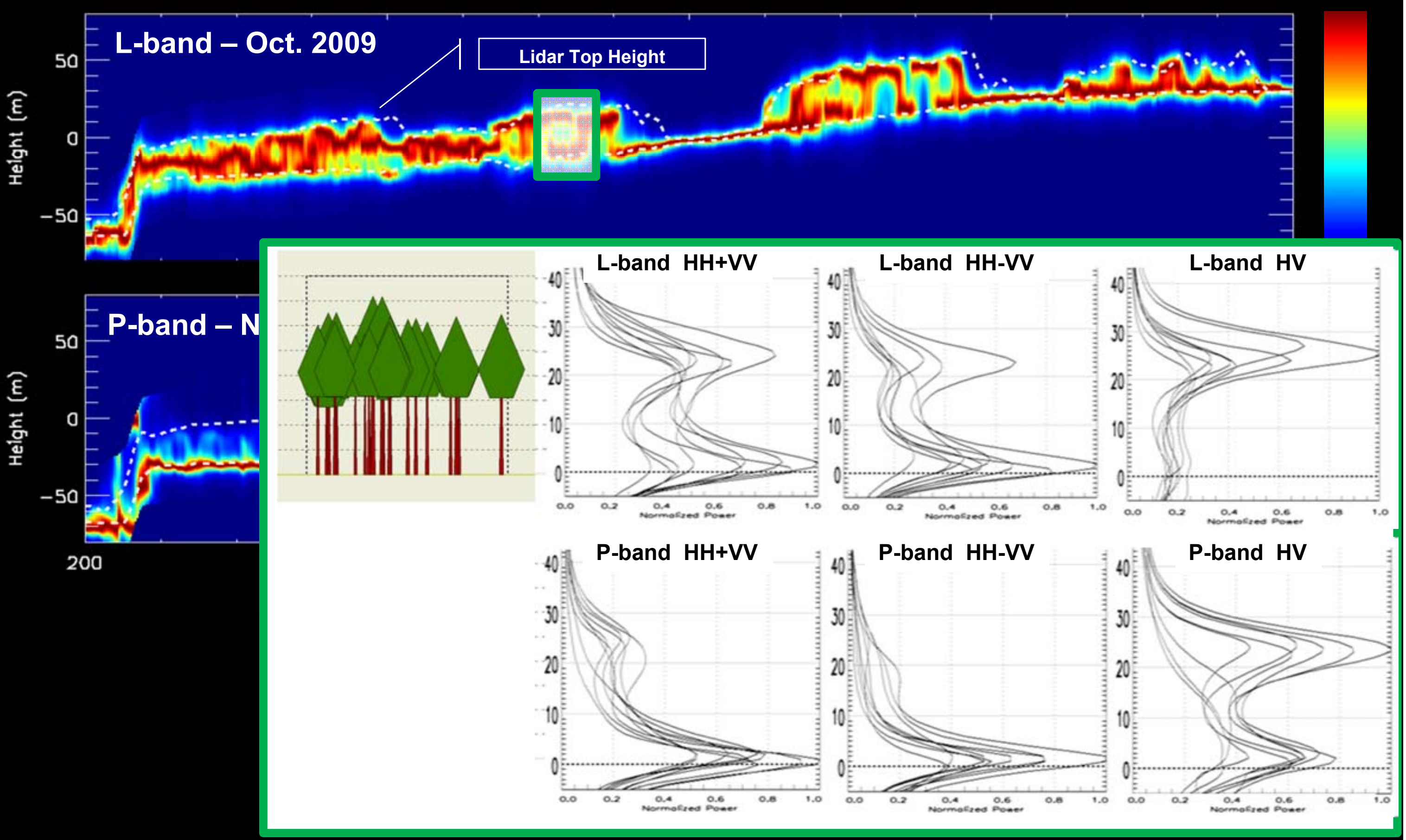
Data Sets & Tomogram Examples (Capon, ABF) – HH



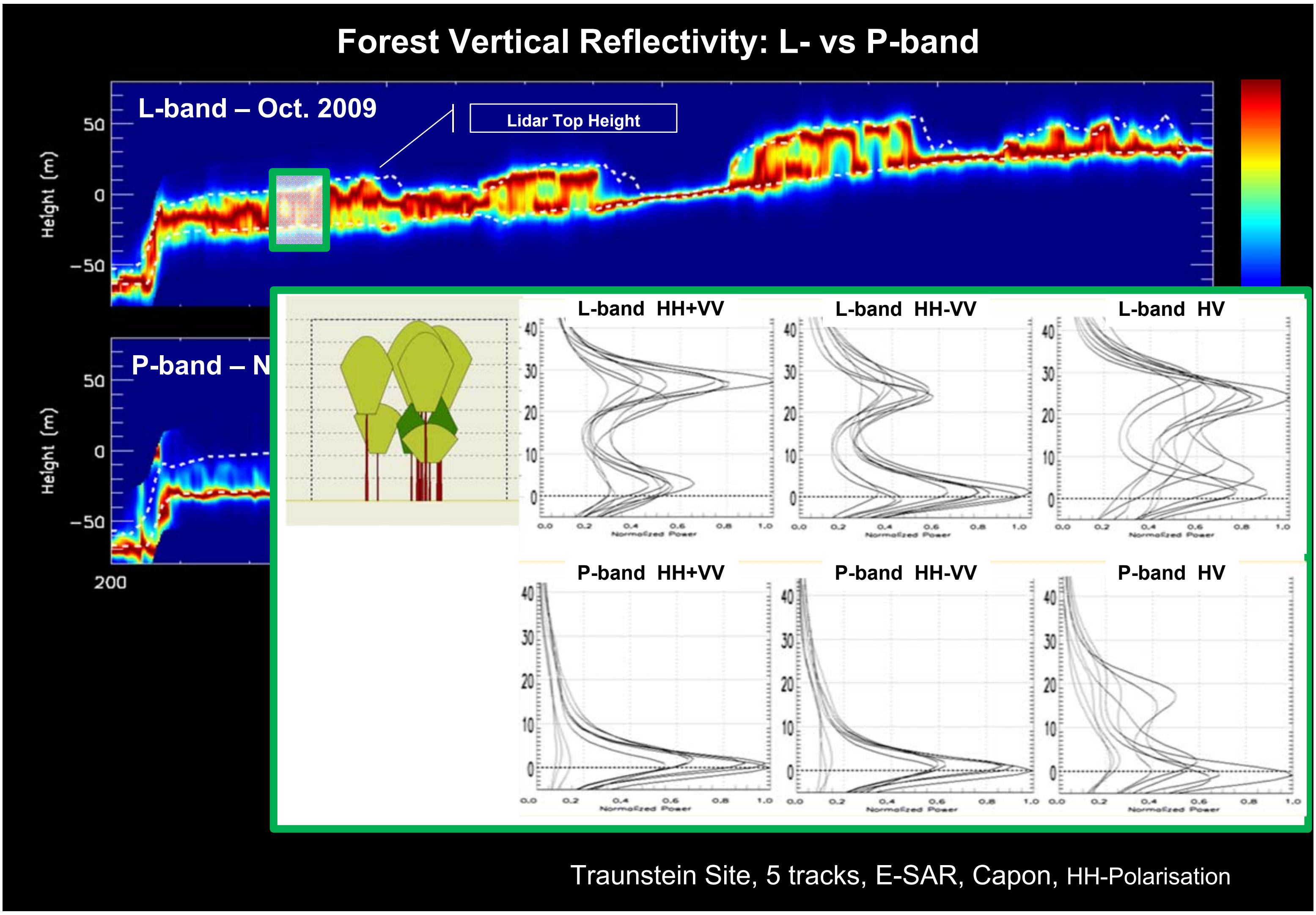
Tomogram Examples (Capon, ABF) – HH, VV, HV



Forest Vertical Reflectivity: L- vs P-band



Traunstein Site, 5 tracks, E-SAR, Capon, HH-Polarisation



SAR Interferometry for Volume Structure

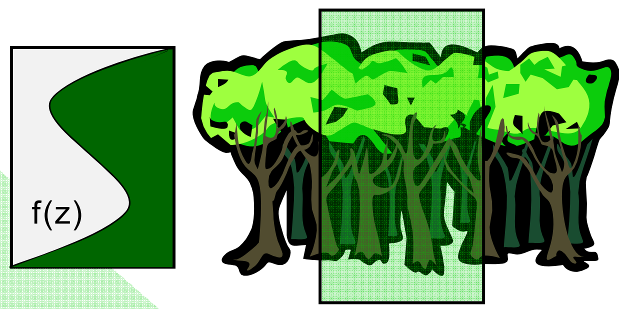
S_1 S_2

Interferometric Coherence

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

Volume Coherence

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



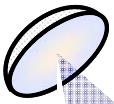
$f(z)$ … vertical reflectivity function

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

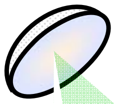
$$\tilde{\gamma} = \tilde{\gamma}_{Temporal}\ \gamma_{SNR}\ \tilde{\gamma}_{Vol}$$

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

SAR Interferometry for Volume Structure



S_1 S_2

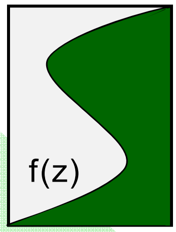


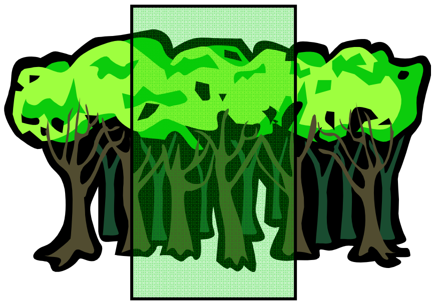
Interferometric Coherence

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

Volume Coherence

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





$f(z)$ … vertical reflectivity function

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

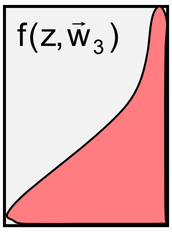
$$\tilde{\gamma} = \tilde{\gamma}_{Temporal} \; \gamma_{SNR} \; \tilde{\gamma}_{Vol}$$

- $\tilde{\gamma}_{Temporal}$ … temporal decorrelation
- γ_{SNR} … additive noise decorrelation
- $\tilde{\gamma}_{Volume}$ … 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 κ_z, i.e. at different spatial baselines.

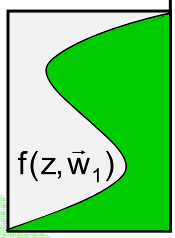
Polarisation 3 ($\underline{w_3}$):

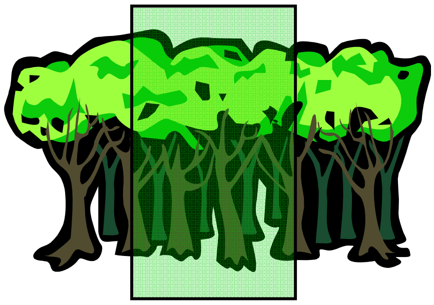
$$\tilde{\gamma}_{Vol}(f(z,\vec{w}_3)) = e^{ik_z z_0} \frac{\int_0^{h_v} f(z,\vec{w}_3)\, e^{ik_z z} dz}{\int_0^{h_v} f(z,\vec{w}_3)\, dz}$$



Polarisation 1 ($\underline{w_1}$):

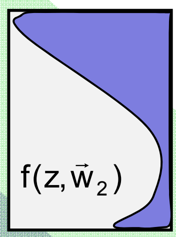
$$\tilde{\gamma}_{Vol}(f(z,\vec{w}_1)) = e^{ik_z z_0} \frac{\int_0^{h_v} f(z,\vec{w}_1)\, e^{ik_z z} dz}{\int_0^{h_v} f(z,\vec{w}_1)\, dz}$$





Polarisation 2 ($\underline{w_2}$):

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



$f(z,\vec{w})$ …vertical reflectivity function

Polarimetric SAR Interferometry

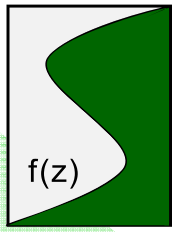
By changing the polarisation the contrast between the individual components consisting the vertical reflectivity f(z) of a (volume) scatterer changes.

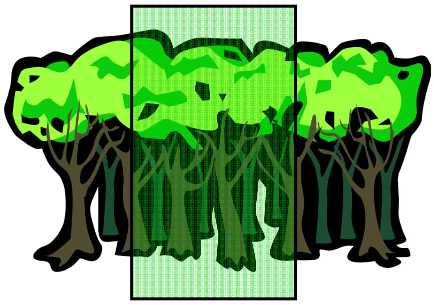
Interferometric Coherence

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

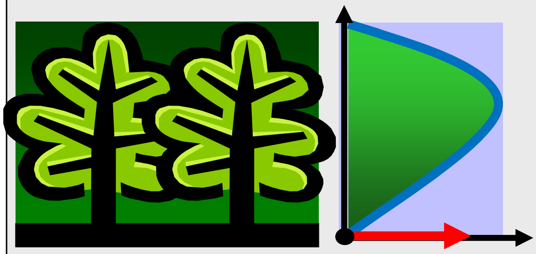
Volume Coherence

$$\tilde{\gamma}_{Vol}(f(z),k_z)=e^{ik_z z_o}\frac{\int_o^{h_V} f(z)\ e^{ik_z z}dz}{\int_o^{h_V} f(z)\ dz}$$





2 Layer Inversion Model



Volume Layer Ground Layer

$$f(z)=m_V f_V(z)+m_G\delta(z-z_0)$$

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

$f_V(z)$ … volume reflectivity function

Volume Coherence

$$\tilde{\gamma}_V=\frac{I}{I_0}\quad \begin{cases} I=\int_0^{h_V}\exp(i\kappa_z z')f_V(z')dz' & m(\vec{w})=\dfrac{m_G(\vec{w})}{m_V(\vec{w})I_0} \\ I_0=\int_0^{h_V}f_V(z')dz' & \kappa_z=\dfrac{\kappa\Delta\theta}{\sin(\theta_0)} \end{cases}$$

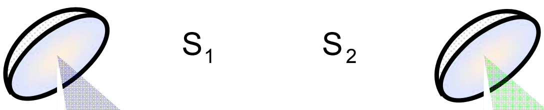
$f_V(z)$ parameterised with N param

Volume Height h_V

Topography φ_0

G/V Ratio $m(\vec{w})$

3+N Unknowns

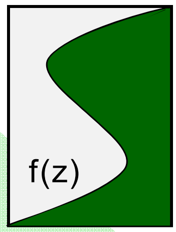


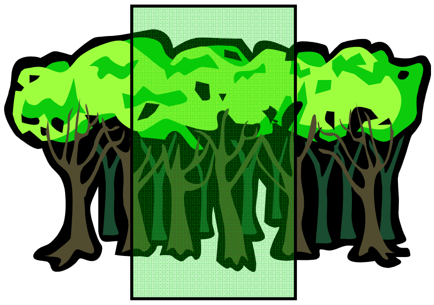
Interferometric Coherence

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

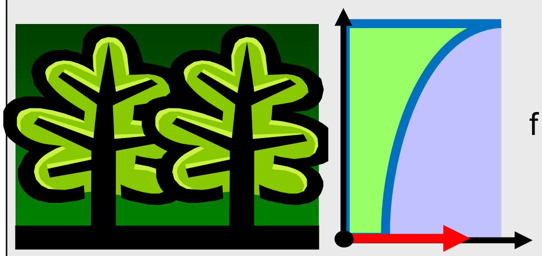
Volume Coherence

$$\tilde{\gamma}_{Vol}(f(z),k_z)=e^{ik_z z_o}\frac{\int_o^{h_V} f(z)\ e^{ik_z z}dz}{\int_o^{h_V} f(z)\ dz}$$





2 Layer Inversion Model



Volume Layer Ground Layer

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

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

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

Volume Coherence

$$\tilde{\gamma}_V=\frac{I}{I_0}\quad \begin{cases} I=\int_0^{h_V}\exp(i\kappa_z z')\ m_V\exp\left(\dfrac{2\ \sigma\ z'}{\cos\theta_0}\right)dz' & m(\vec{w})=\dfrac{m_G(\vec{w})}{m_V(\vec{w})I_0} \\ I_0=\int_0^{h_V}m_V\exp\left(\dfrac{2\ \sigma\ z'}{\cos\theta_0}\right)dz' & \kappa_z=\dfrac{\kappa\Delta\theta}{\sin(\theta_0)} \end{cases}$$

$\sigma(z)=\sigma$ "Volume Extinction"

Volume Height h_V

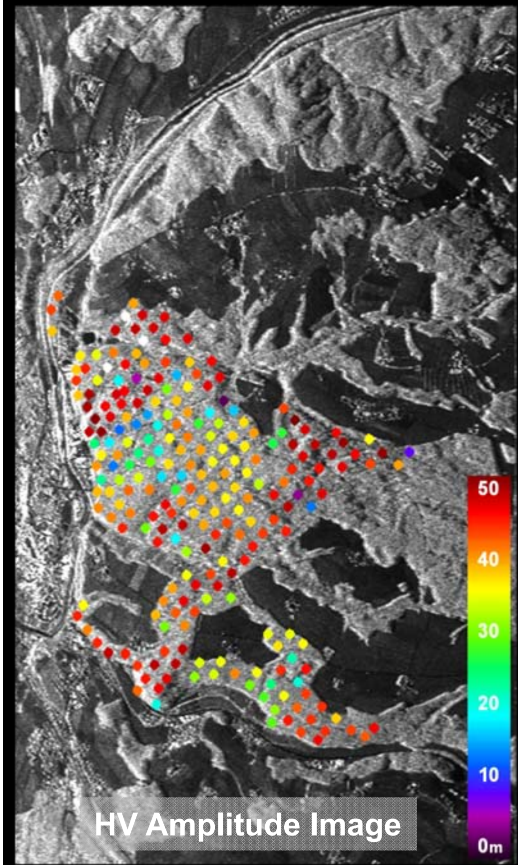
Topography φ_0

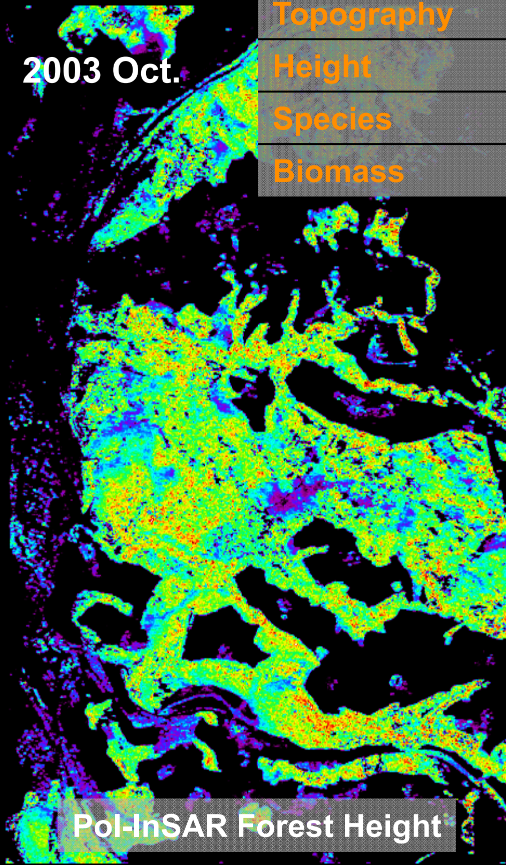
G/V Ratio $m(\vec{w})$

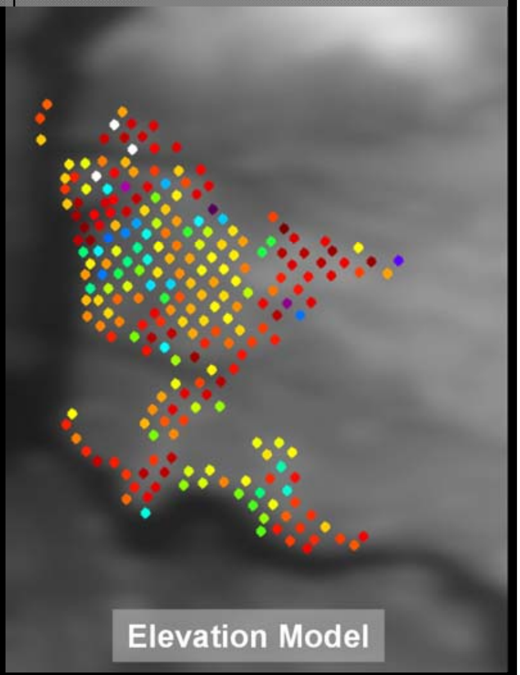
4 Unknowns

Traunstein Test Site

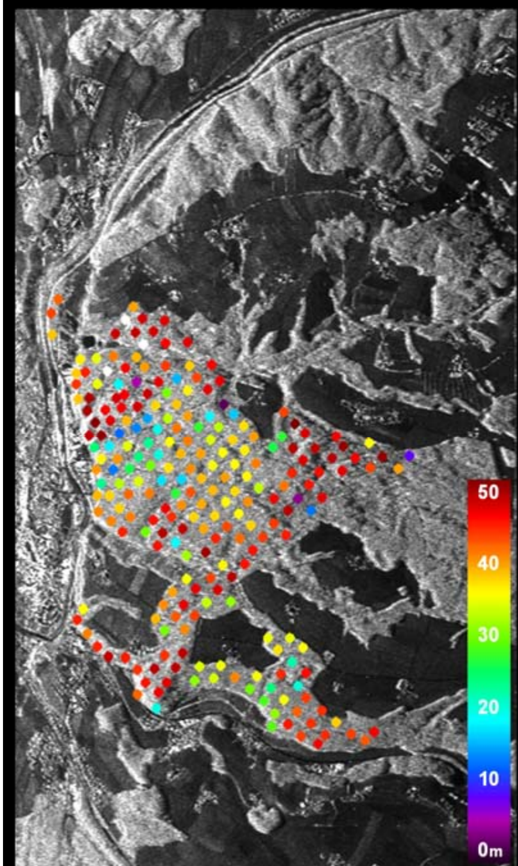
Forest type	Temperate
Topography	Moderate slopes
Height	25 ~ 35m
Species	N. Spruce, E. Beech, White Fir
Biomass	40 ~ 450 t/ha

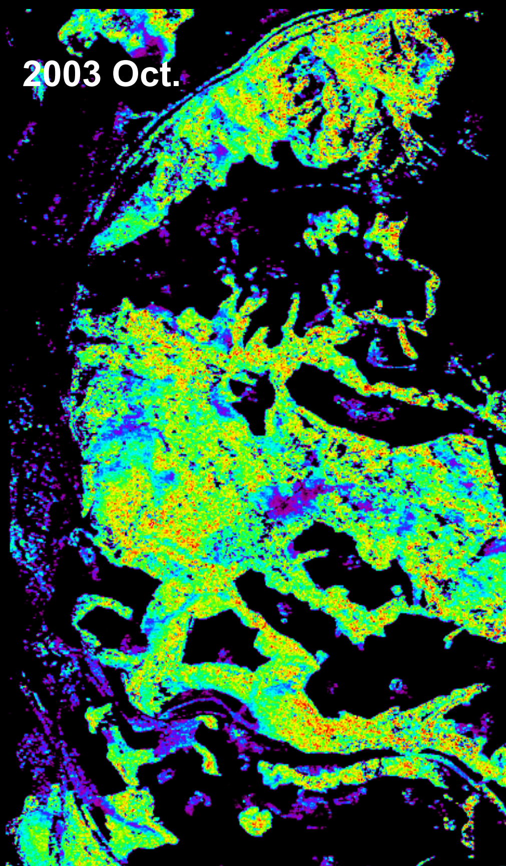


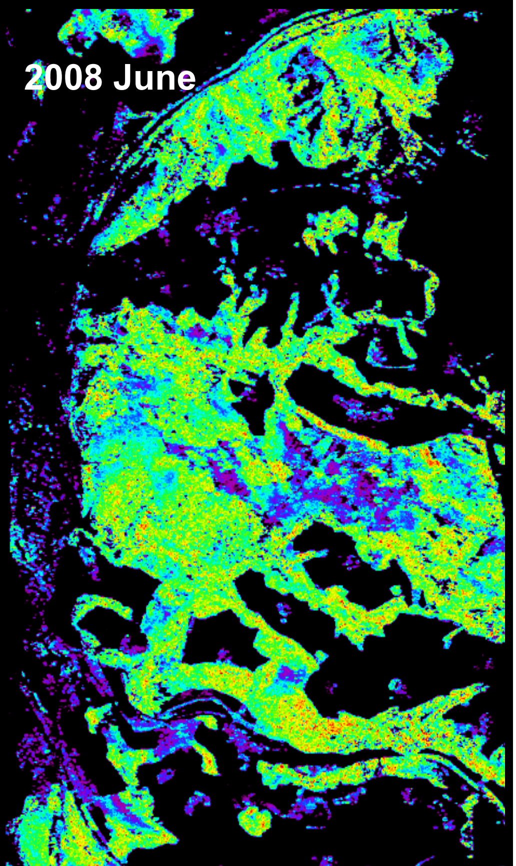


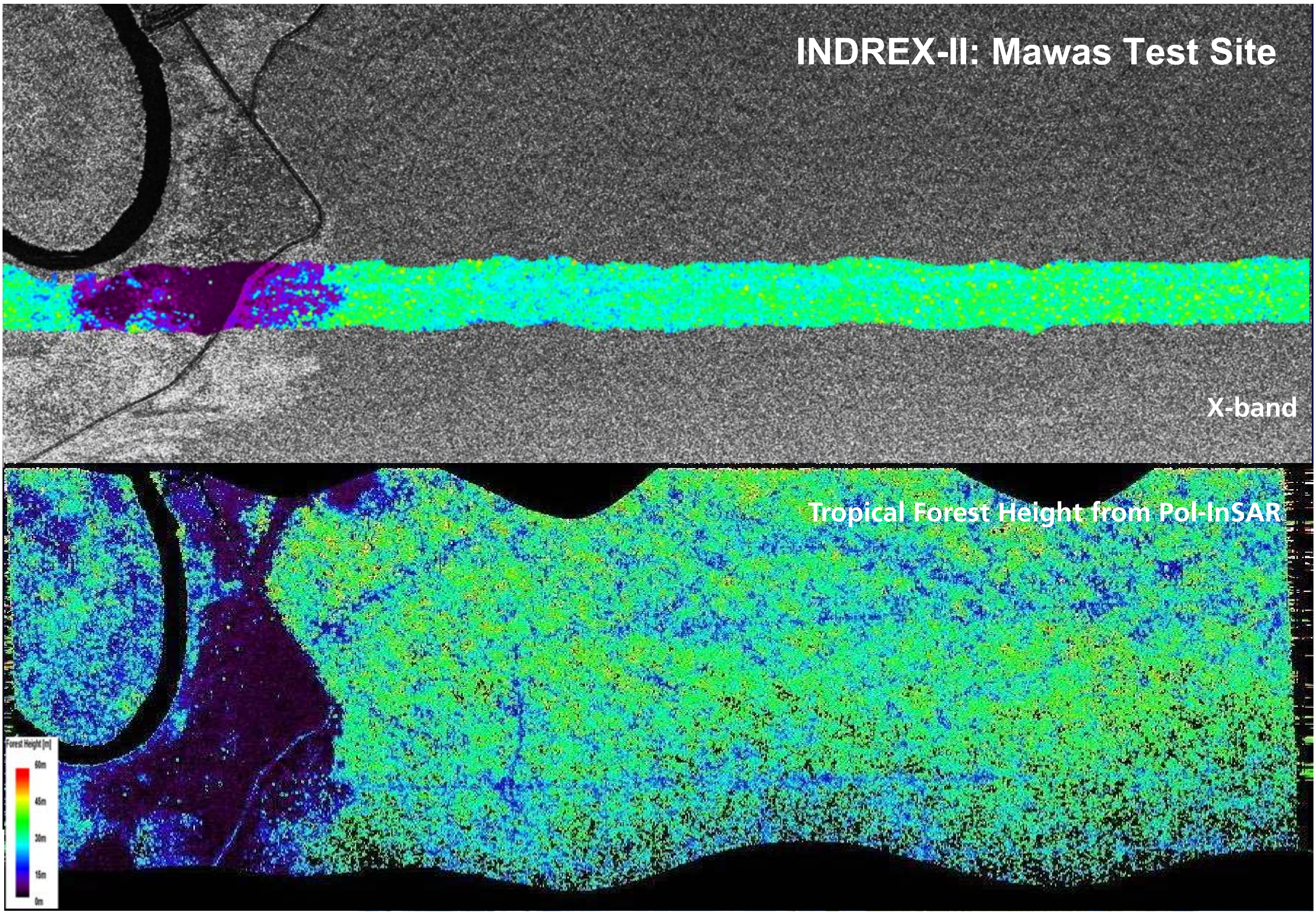


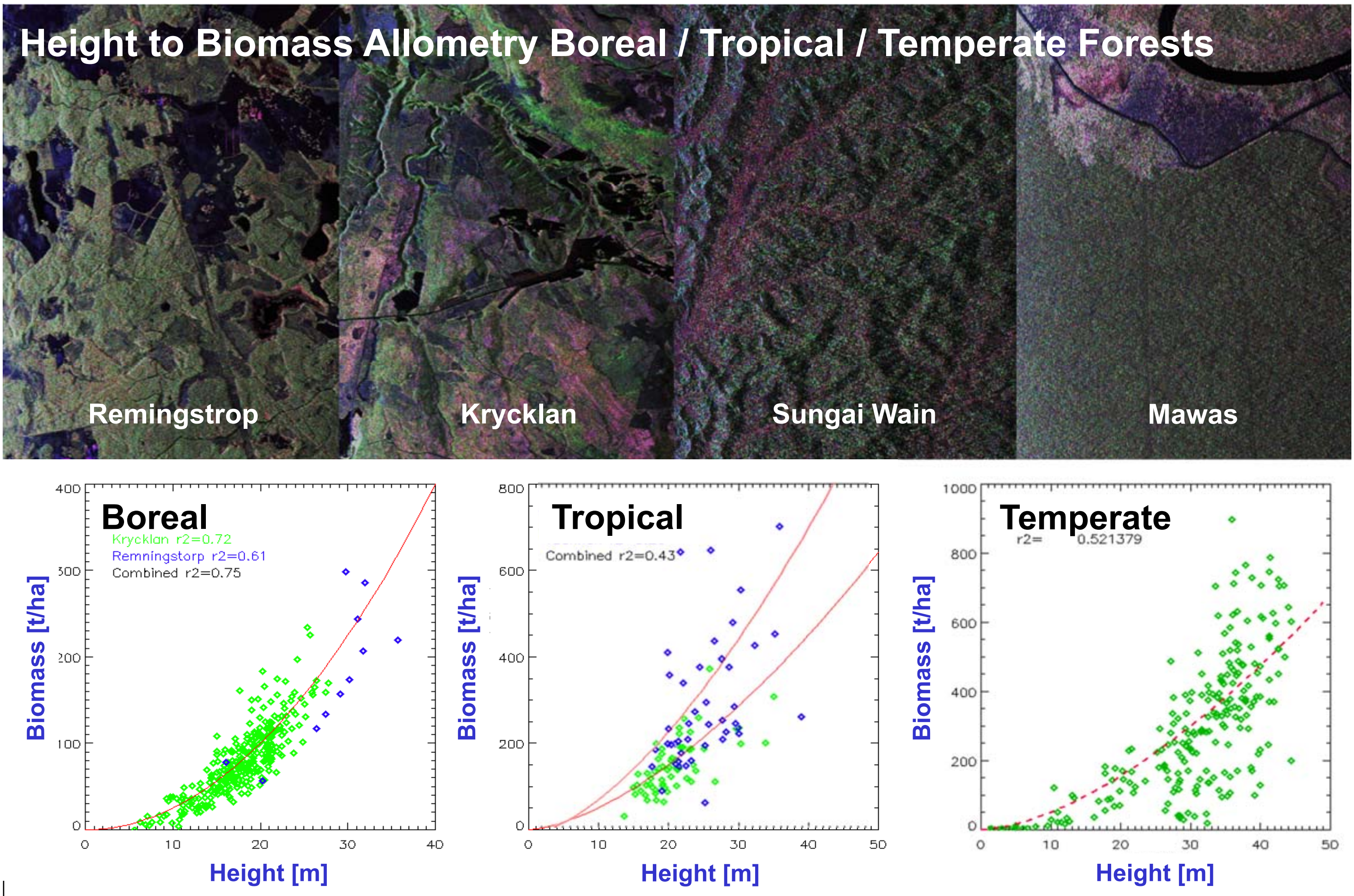
Traunstein Test Site



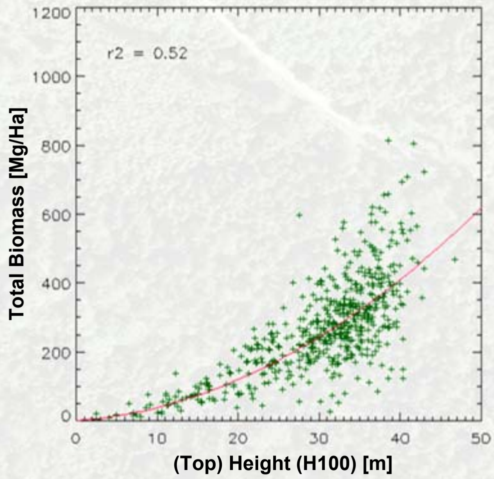





INDREX-II: Mawas Test Site
X-band
Tropical Forest Height from Pol-InSAR

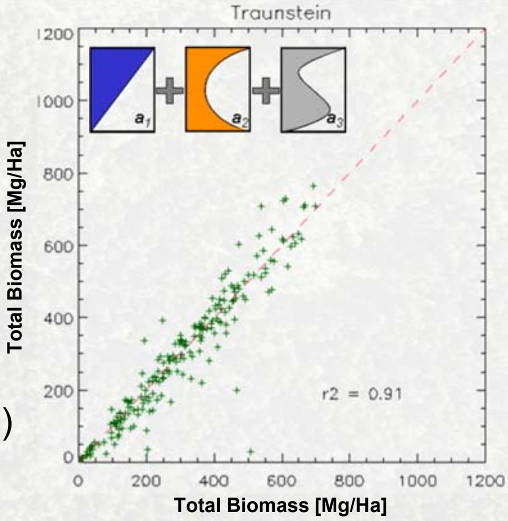

Height to Biomass Allometry Boreal / Tropical / Temperate Forests
Remingstrop
Krycklan
Sungai Wain
Mawas
Boreal
Krycklan r2=0.72
Remningstorp r2=0.61
Combined r2=0.75
Biomass [t/ha]
Height [m]
Tropical
Combined r2=0.43
Biomass [t/ha]
Height [m]
Temperate
r2= 0.521379
Biomass [t/ha]
Height [m]

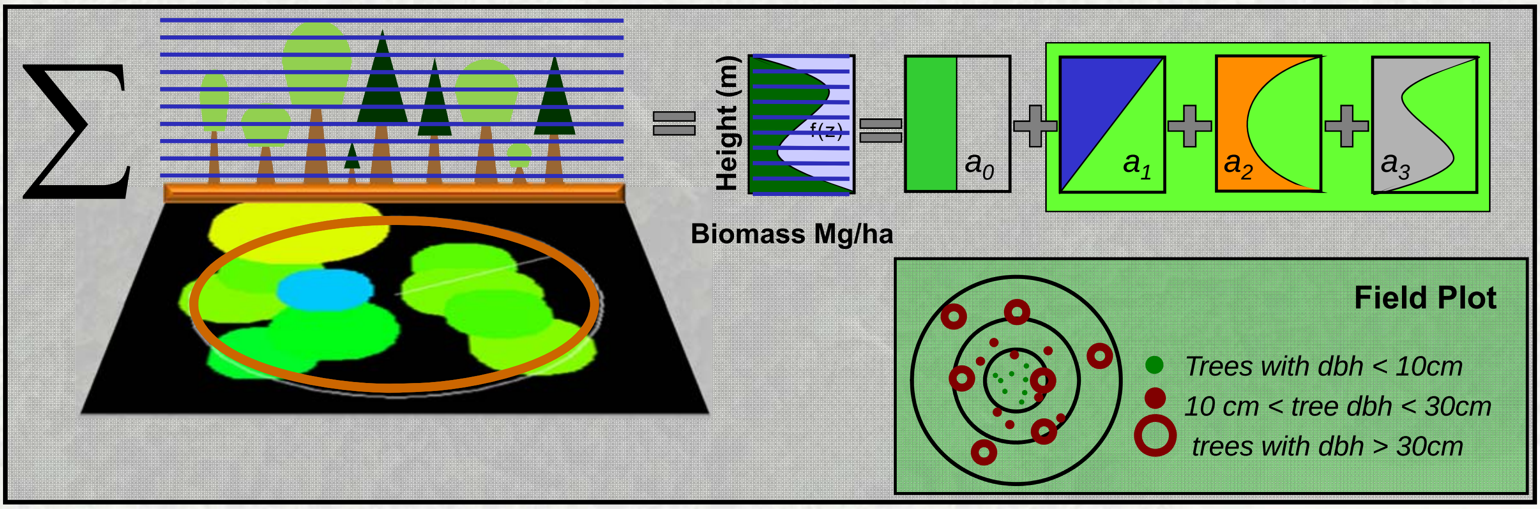
Structure-to-Biomass Allometry



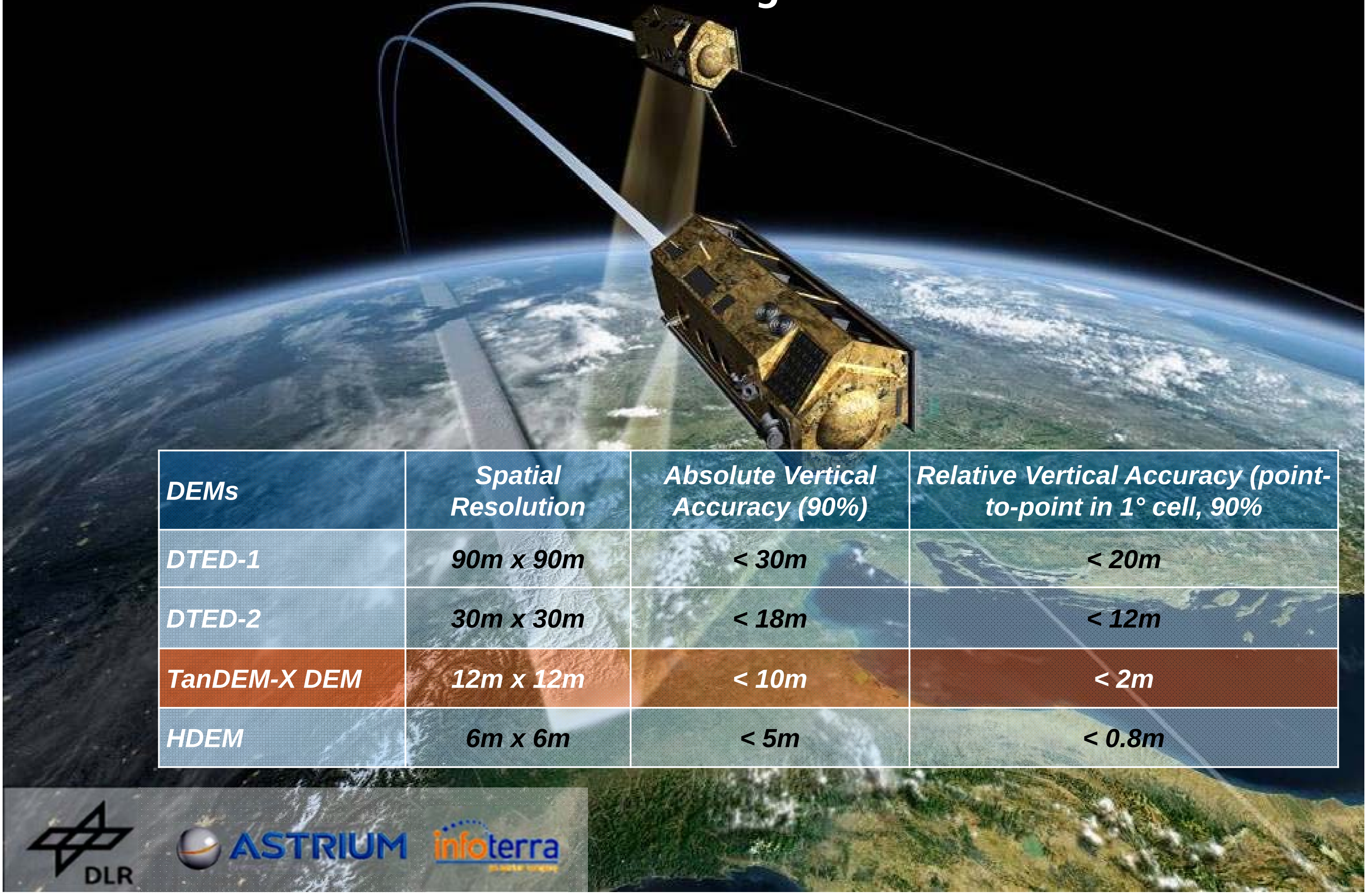
$$B = Ia * 1.66\,H^{1.50}$$

$$B = 3.11 * \sum_{i=0}^{H}\sum_{j=1}^{3} a_j * P_j(z_i)$$





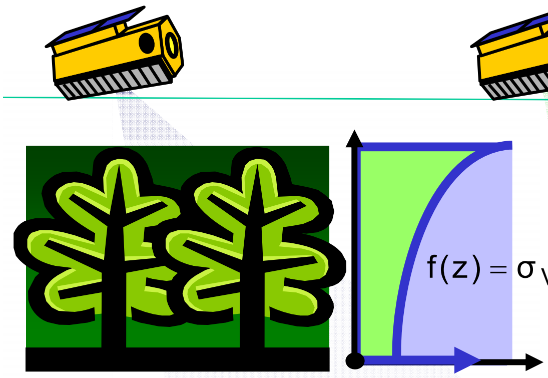
TanDEM-X: TerraSAR-X Add-on for Digital Elevation Measurements



DEMs	Spatial Resolution	Absolute Vertical Accuracy (90%)	Relative Vertical Accuracy (point-to-point in 1° cell, 90%
DTED-1	90m x 90m	< 30m	< 20m
DTED-2	30m x 30m	< 18m	< 12m
TanDEM-X DEM	12m x 12m	< 10m	< 2m
HDEM	6m x 6m	< 5m	< 0.8m

DLR ASTRIUM infoterra

Dual-Pol: 2 Layer Scattering Model



$$f(z) = \sigma_{V0} \exp\left(\frac{2\sigma z}{\cos\theta_0}\right) + m'_G \delta(z - z_0) \;\Rightarrow\; \tilde{\gamma}(\vec{w}) = \exp(i\varphi_0)\frac{\tilde{\gamma}_V + m(\vec{w})}{1 + m(\vec{w})}$$

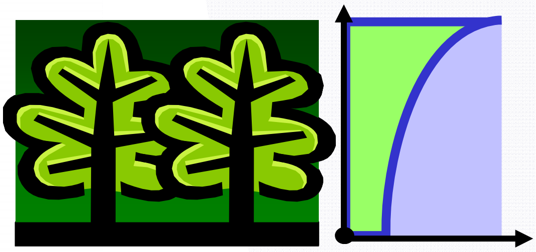
Volume Height h_V **Extinction** σ

Topography ϕ_0 **G/V Ratio** $m(\vec{w})$

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

G/V Ratio: $m(\vec{w}) = \frac{m_G(\vec{w})}{m_V(\vec{w}) I_0}$ **Vertical Wavenumber:** $\kappa_z = \frac{\kappa\Delta\theta}{\sin(\theta_0)}$

Single-Pol: 1 Layer Scattering Model

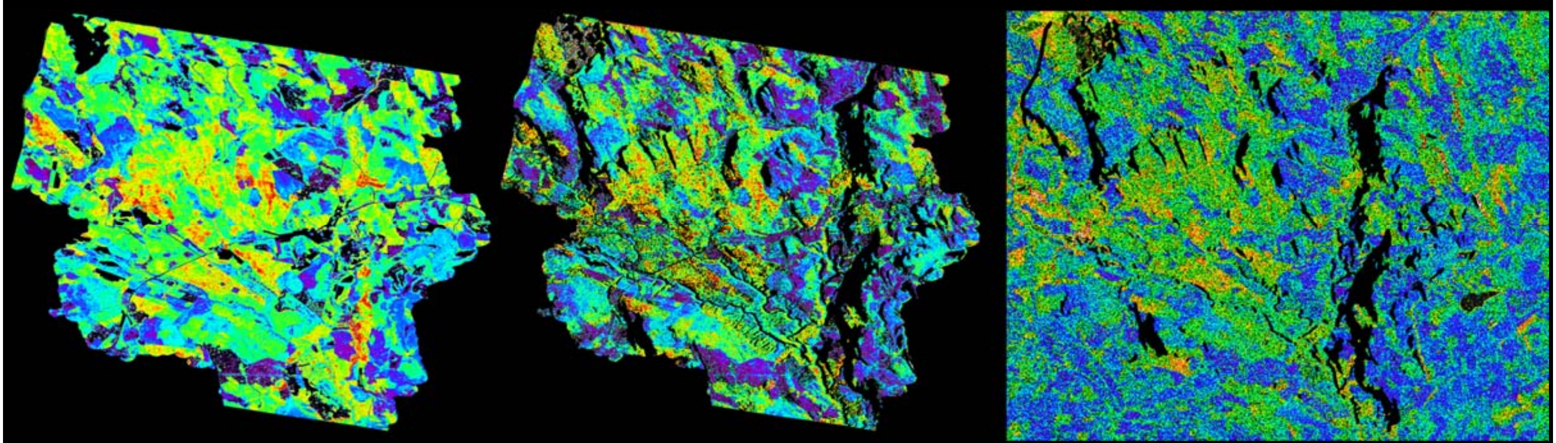


$$f(z) = \sigma_{V0} \exp\left(\frac{2\sigma z}{\cos\theta_0}\right) \;\Rightarrow\; \tilde{\gamma}(\vec{w}) = \exp(i\phi_0)\tilde{\gamma}_V$$

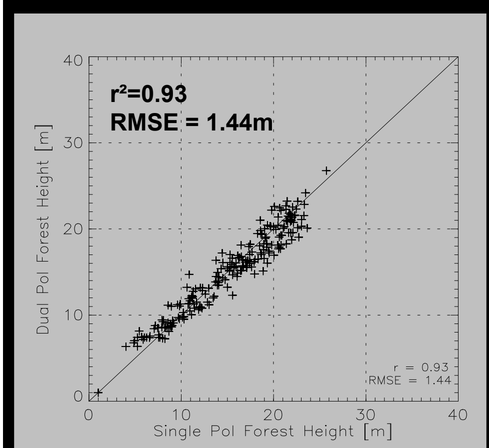
Topography ϕ_0 ◄ **DEM**

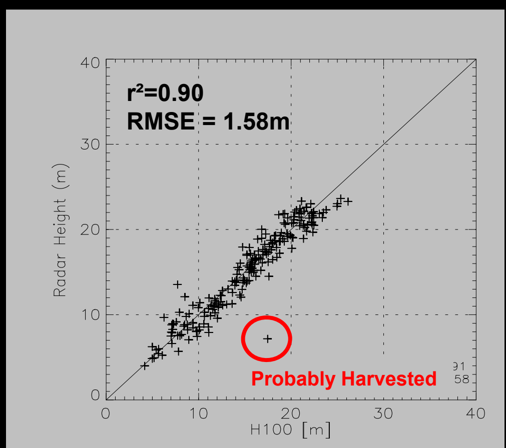
Volume Height h_V **Extinction** σ

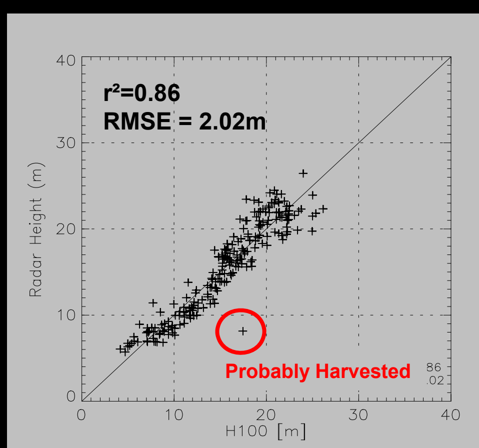
Test Site: Krycklan, Sweden



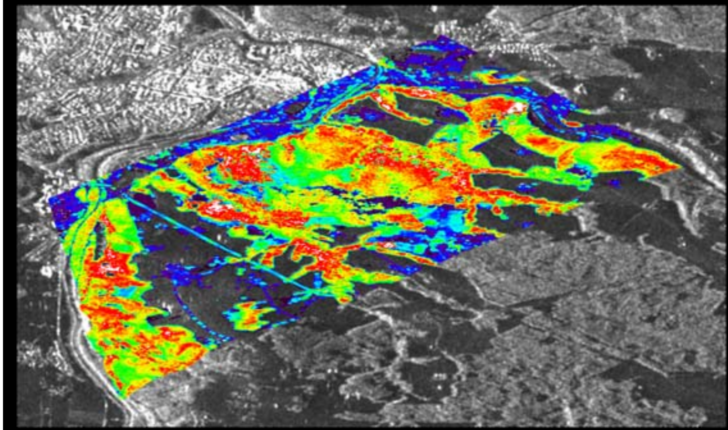
Lidar H100 **Single-Pol + DEM H100** **Dual-Pol H100**





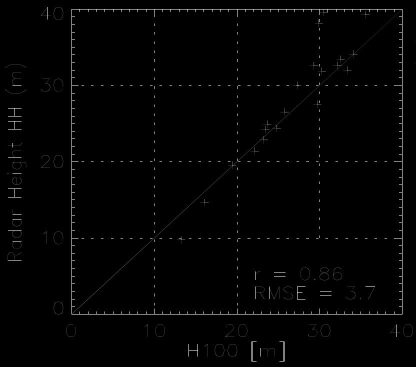


Test Site: Traunstein, Germany

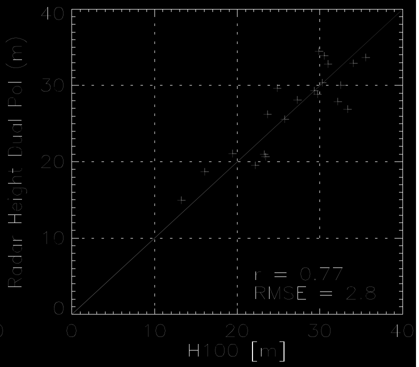


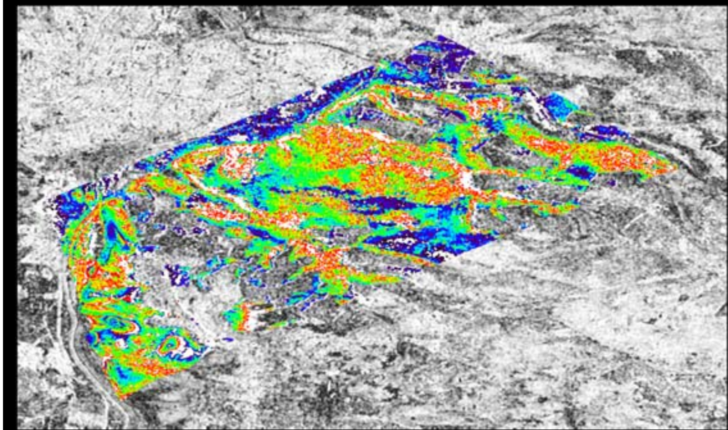
Lidar H100

Single-Pol (HH) + DEM

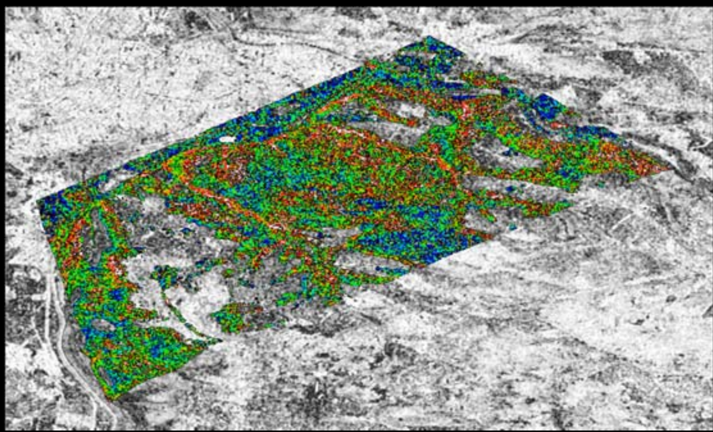


Dual-Pol

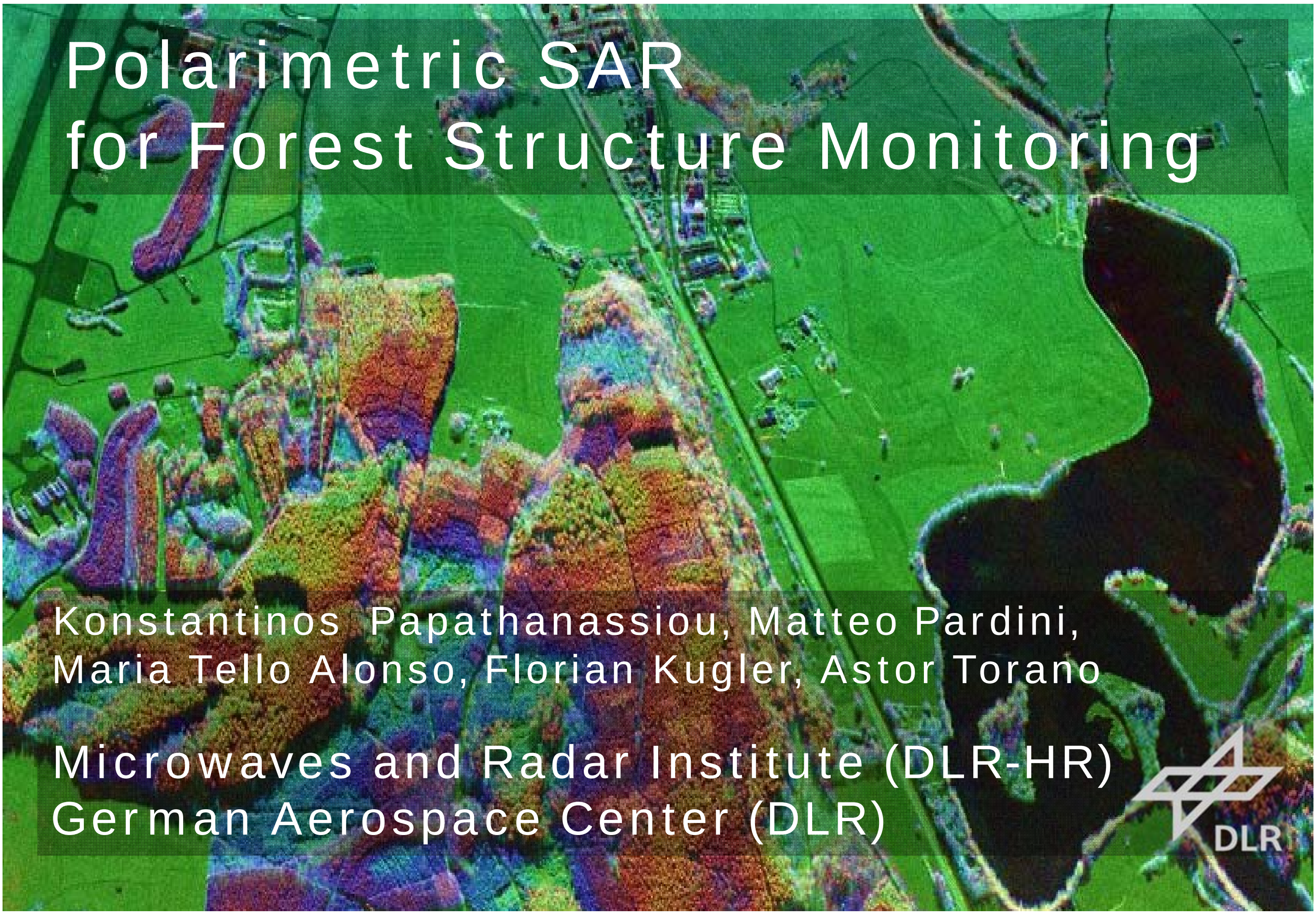




Single-Pol (HH) + DEM H100



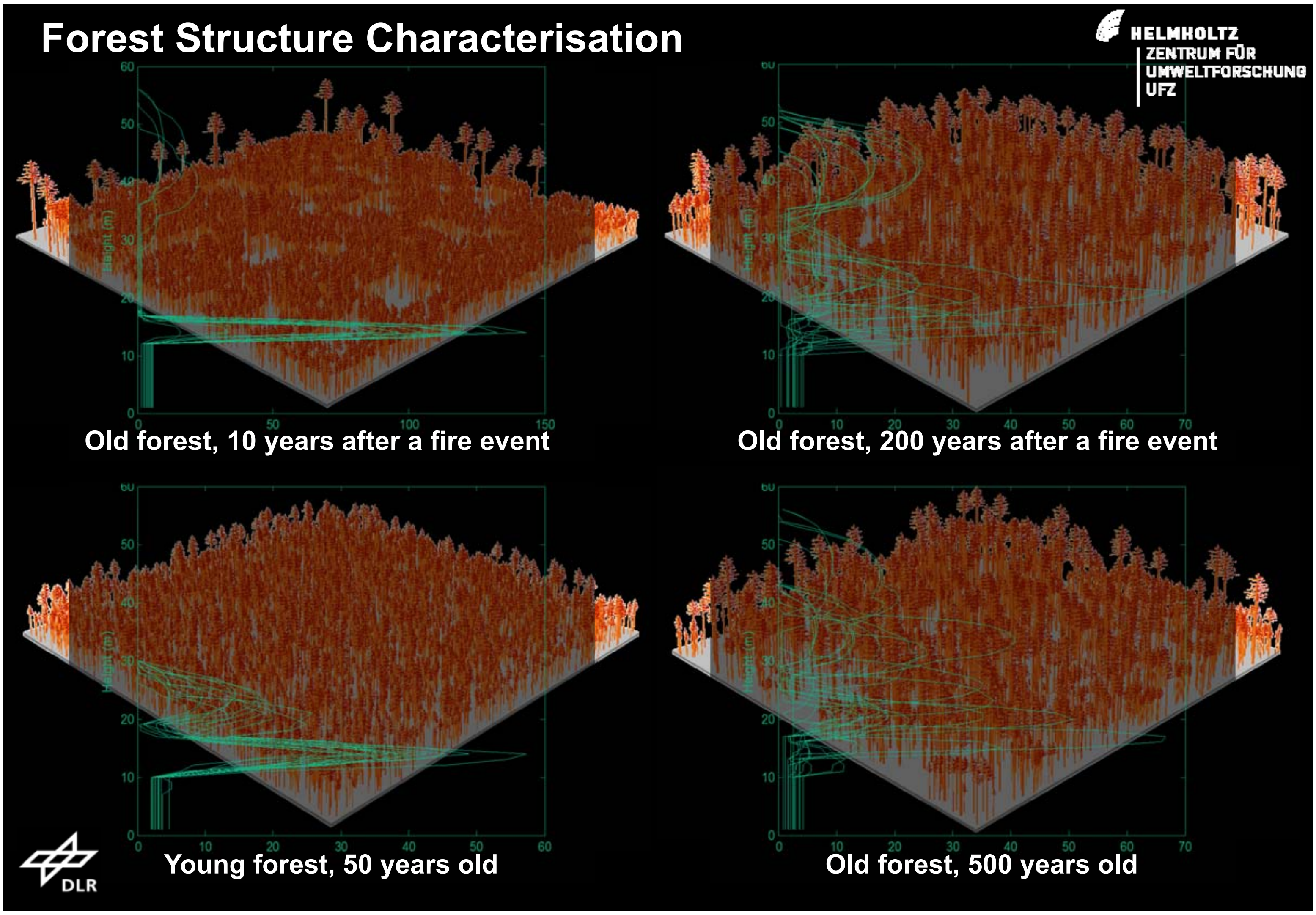
Dual-Pol H100

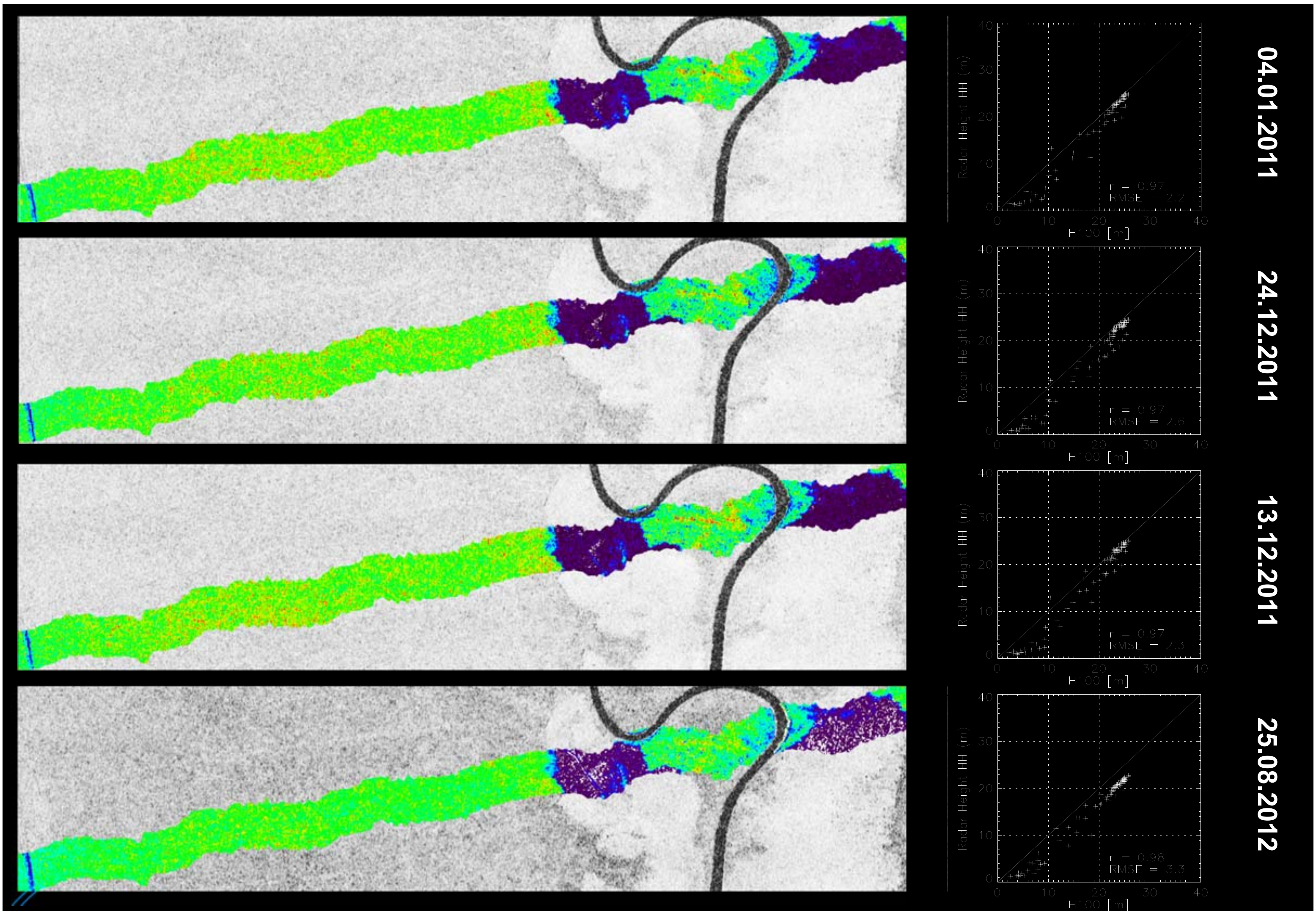


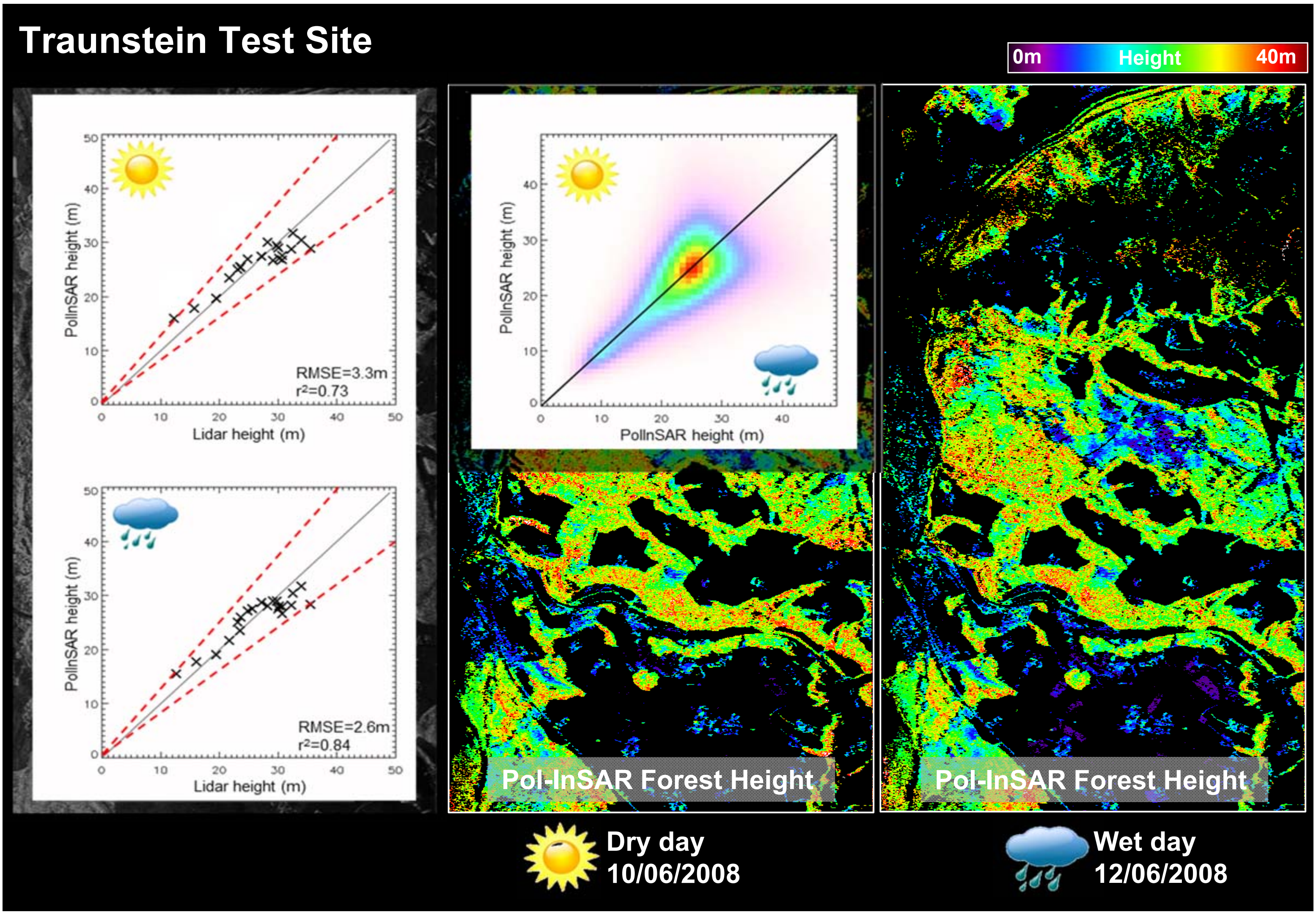
Polarimetric SAR for Forest Structure Monitoring

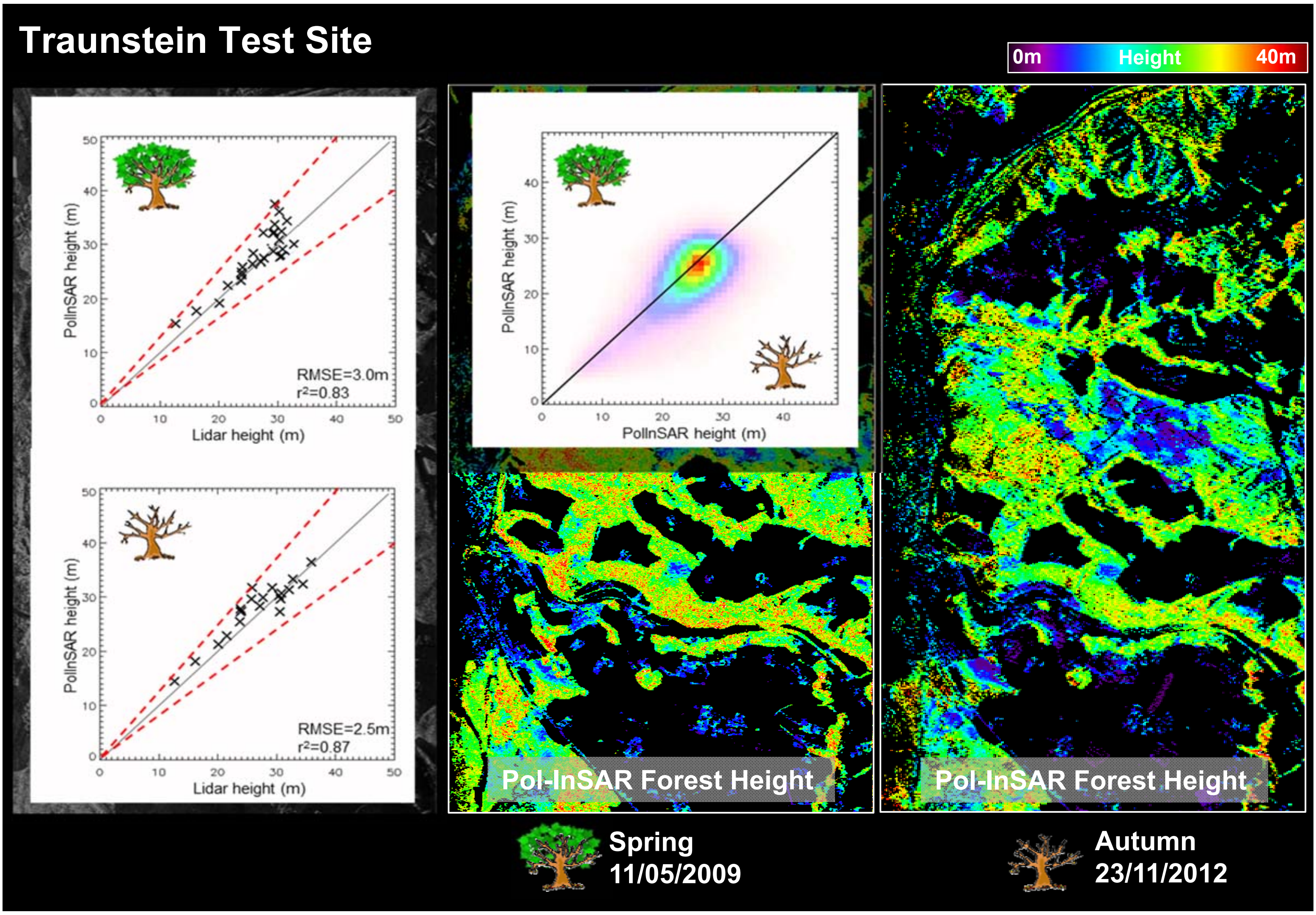
Konstantinos Papathanassiou, Matteo Pardini, Maria Tello Alonso, Florian Kugler, Astor Torano

Microwaves and Radar Institute (DLR-HR)
German Aerospace Center (DLR)


Forest Structure Characterisation
HELMHOLTZ
ZENTRUM FÜR
UMWELTFORSCHUNG
UFZ
Old forest, 10 years after a fire event
Old forest, 200 years after a fire event
Young forest, 50 years old
Old forest, 500 years old
DLR


04.01.2011
24.12.2011
13.12.2011
25.08.2012


Traunstein Test Site
0m
Height
40m
PolInSAR height (m)
Lidar height (m)
RMSE=3.3m
r²=0.73
RMSE=2.6m
r²=0.84
PolInSAR height (m)
Pol-InSAR Forest Height
Pol-InSAR Forest Height
Dry day
10/06/2008
Wet day
12/06/2008

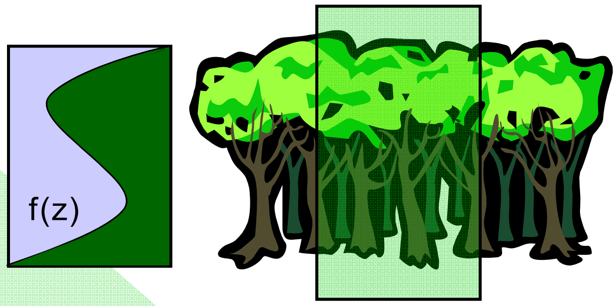

Traunstein Test Site
0m
Height
40m
PolInSAR height (m)
Lidar height (m)
RMSE=3.0m
r²=0.83
RMSE=2.5m
r²=0.87
PolInSAR height (m)
Pol-InSAR Forest Height
Pol-InSAR Forest Height
Spring
11/05/2009
Autumn
23/11/2012

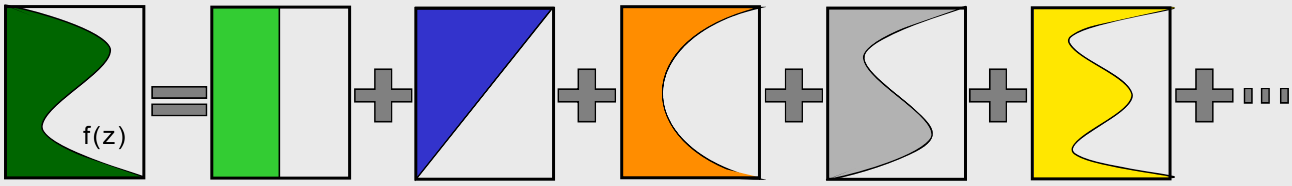
Polarimetric Coherence Tomography

f(z) … vertical reflectivity function

Volume Coherence

$$\tilde{\gamma}_{Vol}(f(z)) = e^{ik_z z_o} \frac{\int_o^{h_v} f(z)\, e^{ik_z z} dz}{\int_o^{h_v} f(z)\, dz}$$





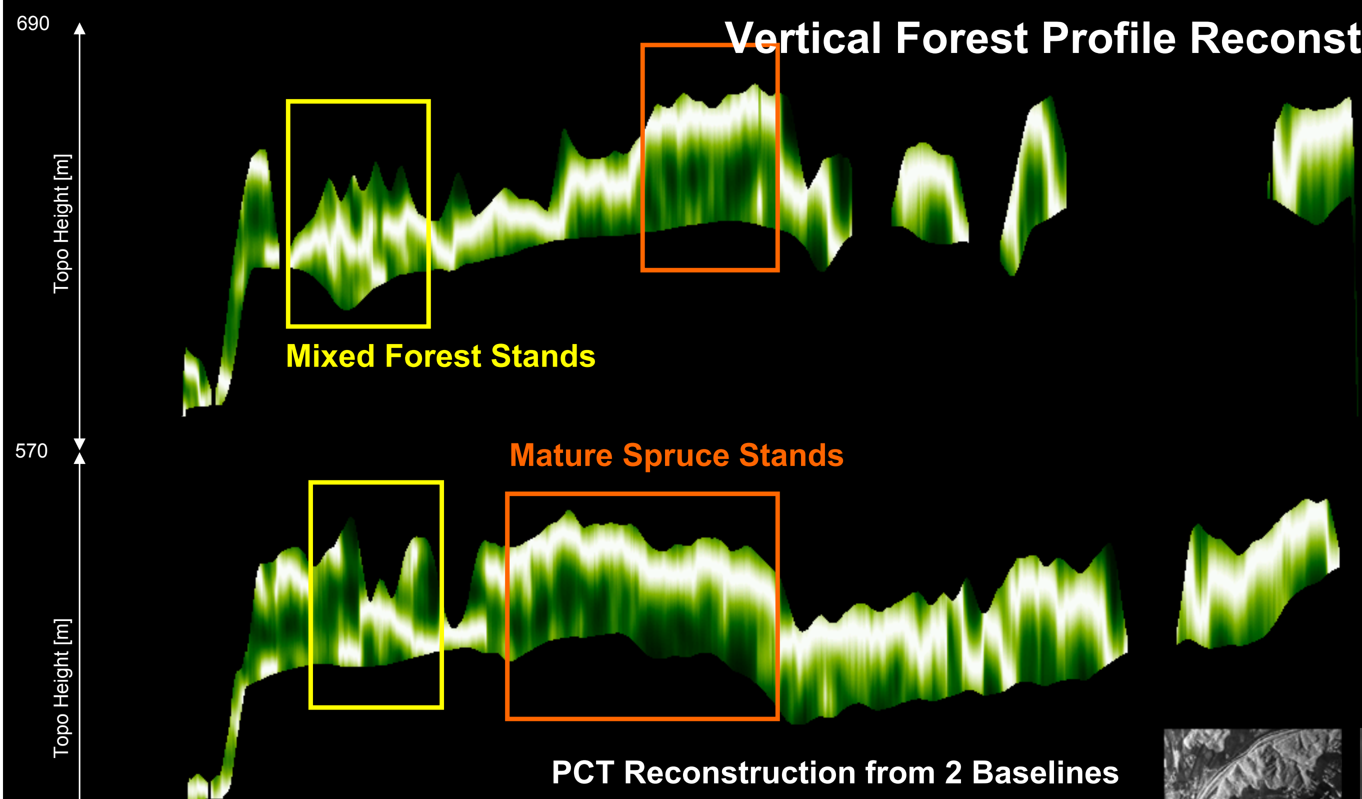
$$\tilde{\gamma}_{Vol}(f(z)) = e^{ik_z z_o} \frac{\int_o^{h_v} f(z)\, e^{ik_z z} dz}{\int_o^{h_v} f(z)\, dz}$$

$$\int_0^{h_v} f(z)\, e^{ik_z z} dz = \frac{h_v}{2} e^{i\frac{k_z h_v}{2}} \int_{-1}^{1} (1+f(z'))\, e^{i\frac{k_z h_v}{2} z'} dz'$$

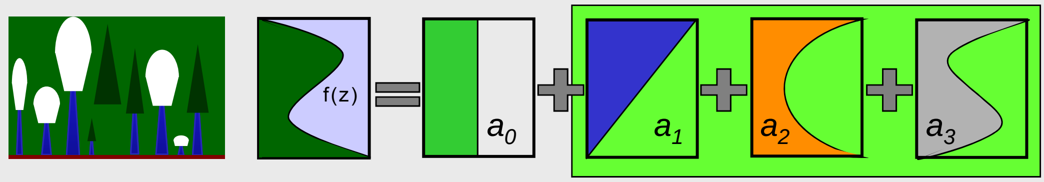
$$\int_0^{h_v} f(z)\, dz = \frac{h_v}{2} \int_{-1}^{1} (1+f(z'))\, dz'$$

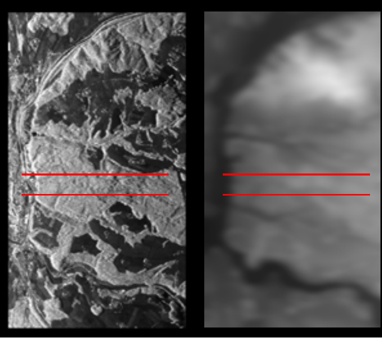
Fourier Legendre Series: $f(z') = \sum_n a_n P_n(z')$ **where** $a_n = \frac{2n+1}{2} \int_{-1}^{1} f(z') P_n(z') dz'$

Vertical Forest Profile Reconstruction



PCT Reconstruction from 2 Baselines





Test site: Traunstein, Germany, L-band @ HV Polarisation