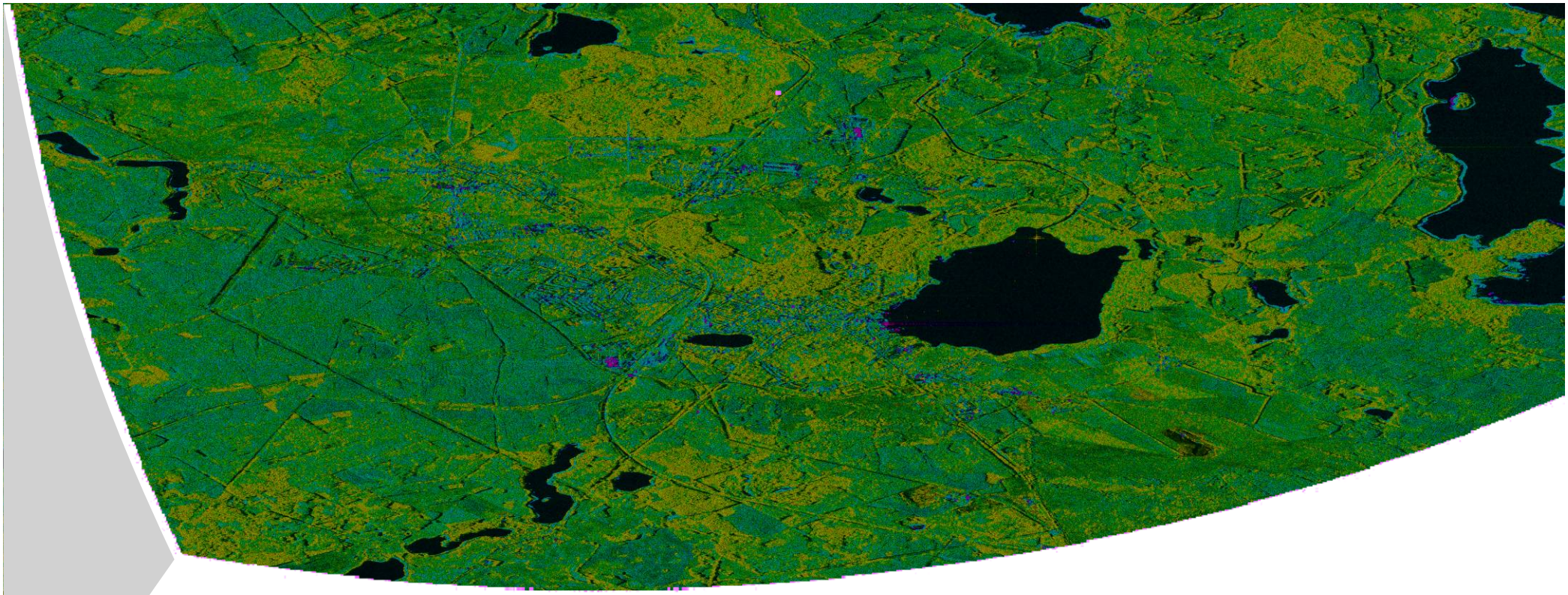


Polarimetric SAR Interferometry (Pol-InSAR)

for Structural Forest Parameter Estimation

K. Papathanassiou, F. Kugler, A. Torano Caioya, M. Padrini, S-L. Lee & I. Hajnsek

German Aerospace Center (DLR)

Microwaves and Radar Institute (DLR-HR)

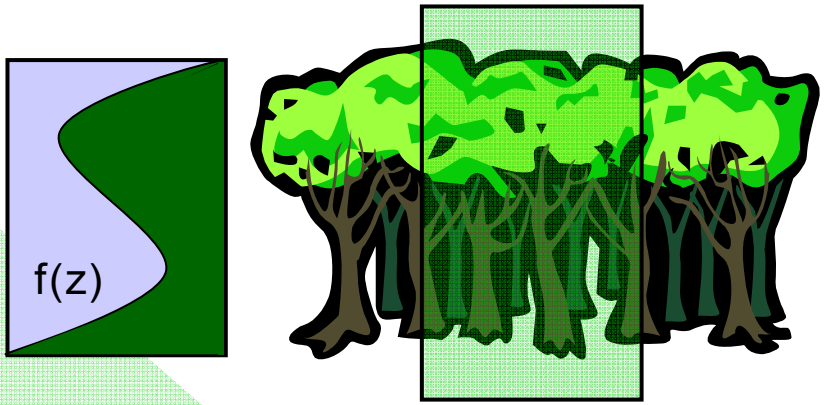
Interferometric Coherence

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

SAR Interferometry for Volume Structure

Volume Coherence

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

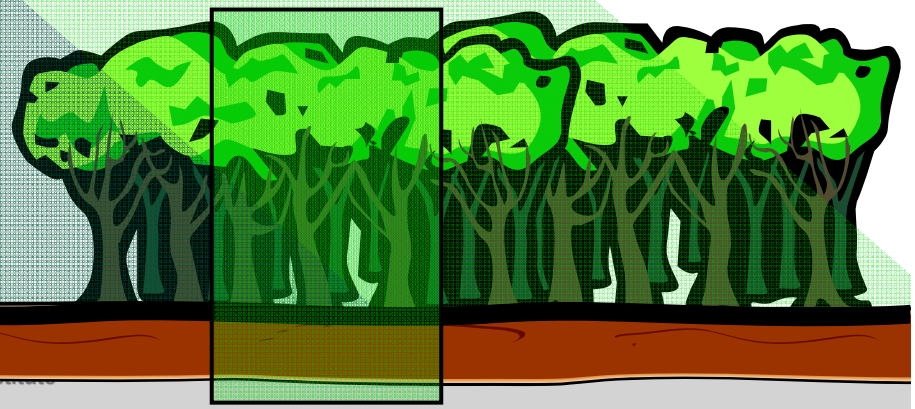


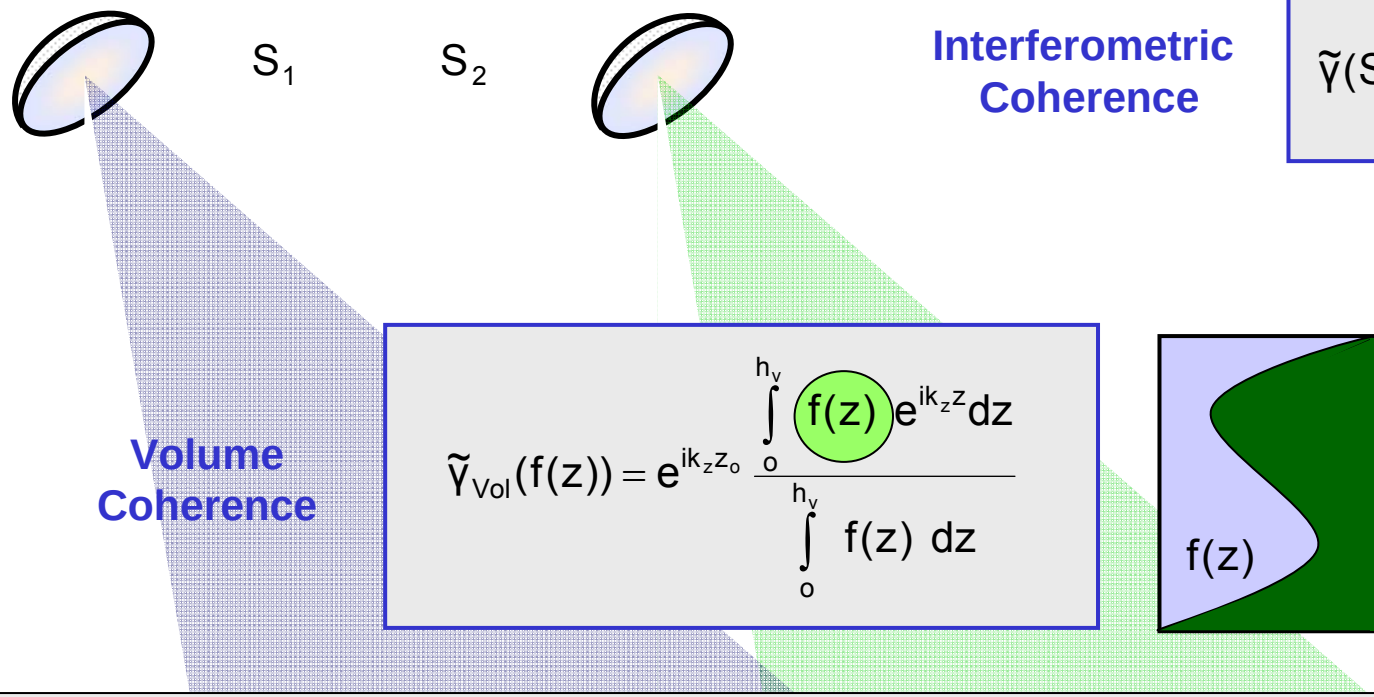
f(z) … vertical reflectivity function

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

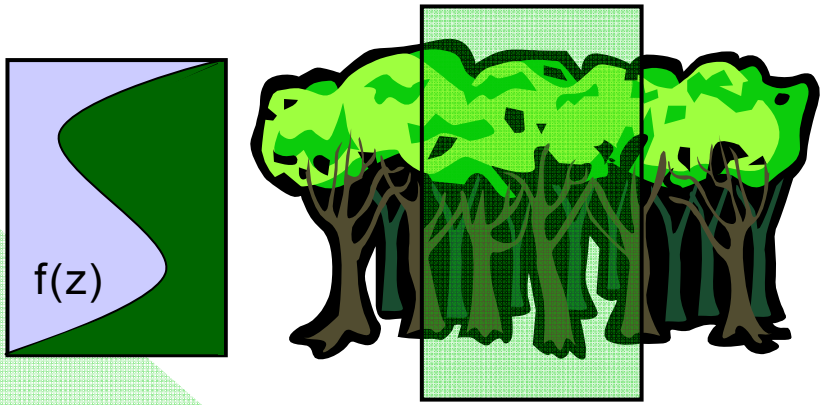




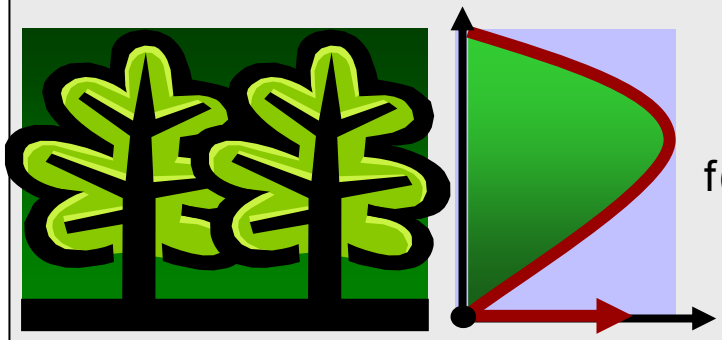
Interferometric Coherence

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

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



2 Layer Inversion Model



$$f(z) = f_0 e^{\left(\frac{2\ \sigma(z)\ z}{\cos\theta_0}\right)} + m'_G \delta(z - z_0)$$

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

Volume Coherence

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

$$I = \int_0^{h_V} \exp(i\kappa_z z') \exp\left(\frac{2\ \sigma(z)\ z'}{\cos\theta_0}\right) dz'$$

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

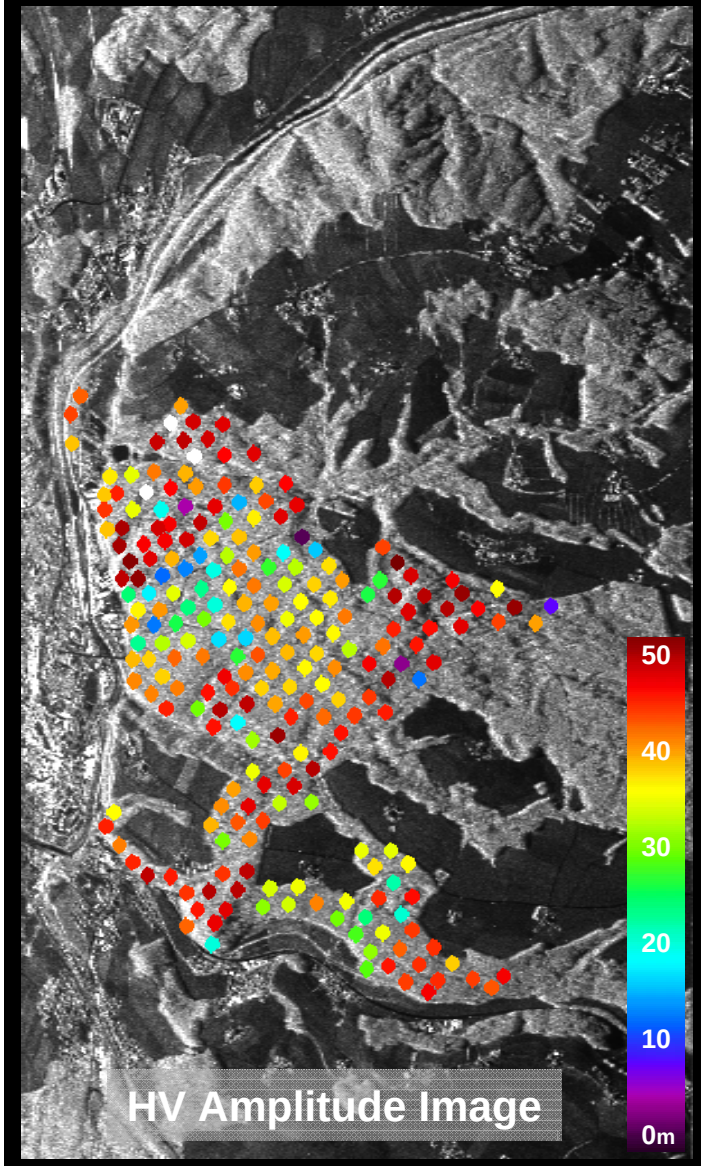
$$m(\vec{w}) = \frac{m_G(\vec{w})}{m_V(\vec{w}) I_0}$$

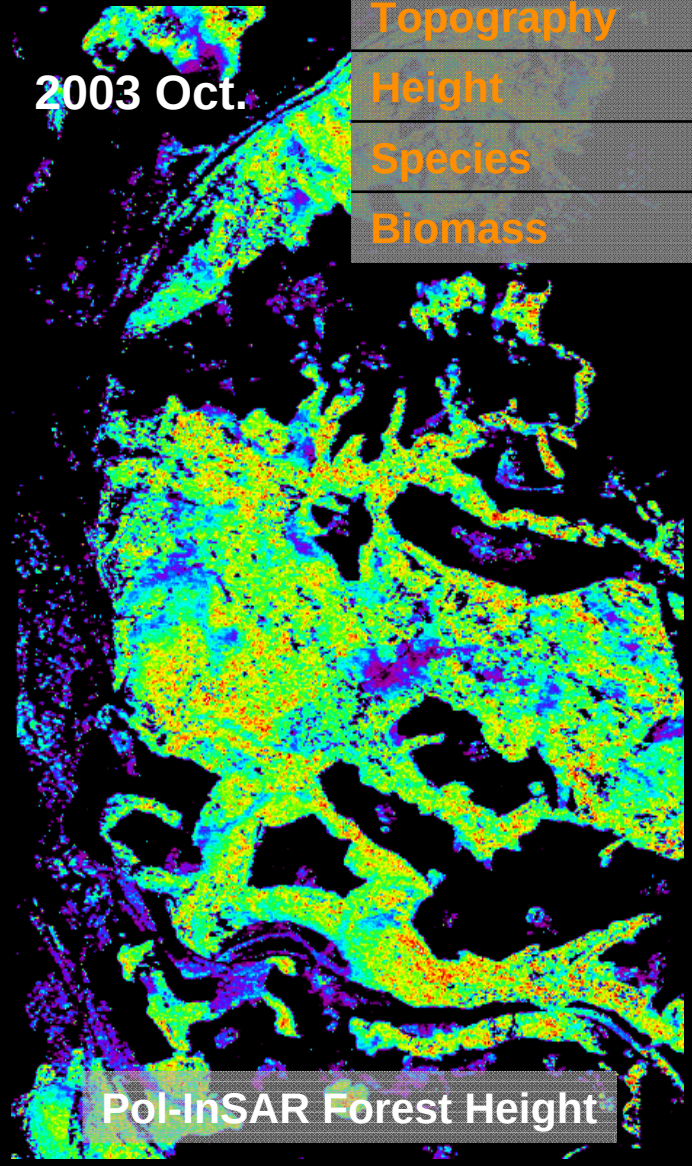
$$\kappa_z = \frac{\kappa \Delta\theta}{\sin(\theta_0)}$$

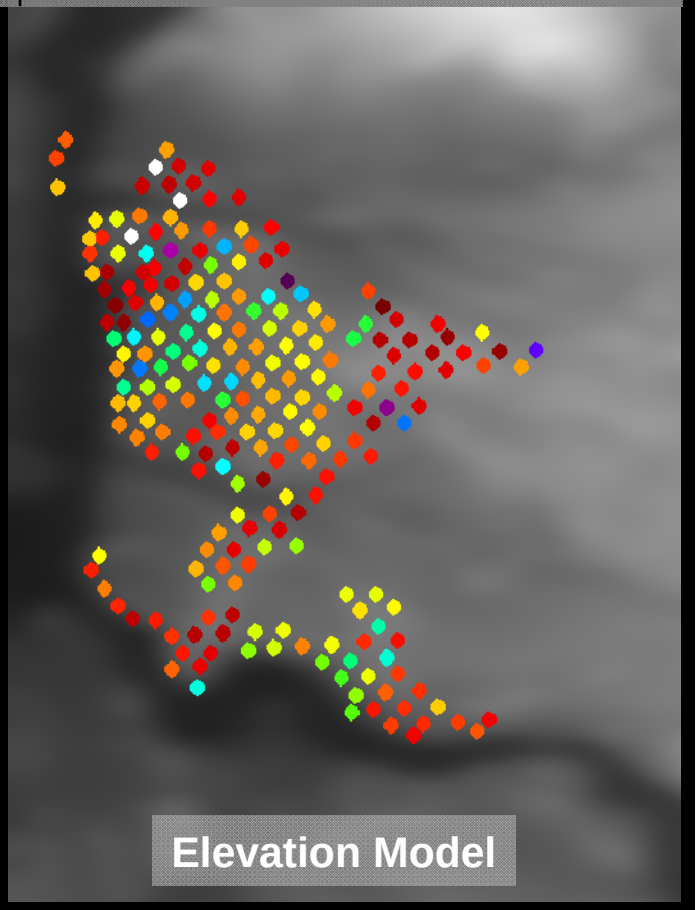
- $\sigma(z)$ has to be parameterised
- Volume Height h_V
- Topography φ_0
- G/V Ratio $m(\vec{w})$

Traunstein Test Site

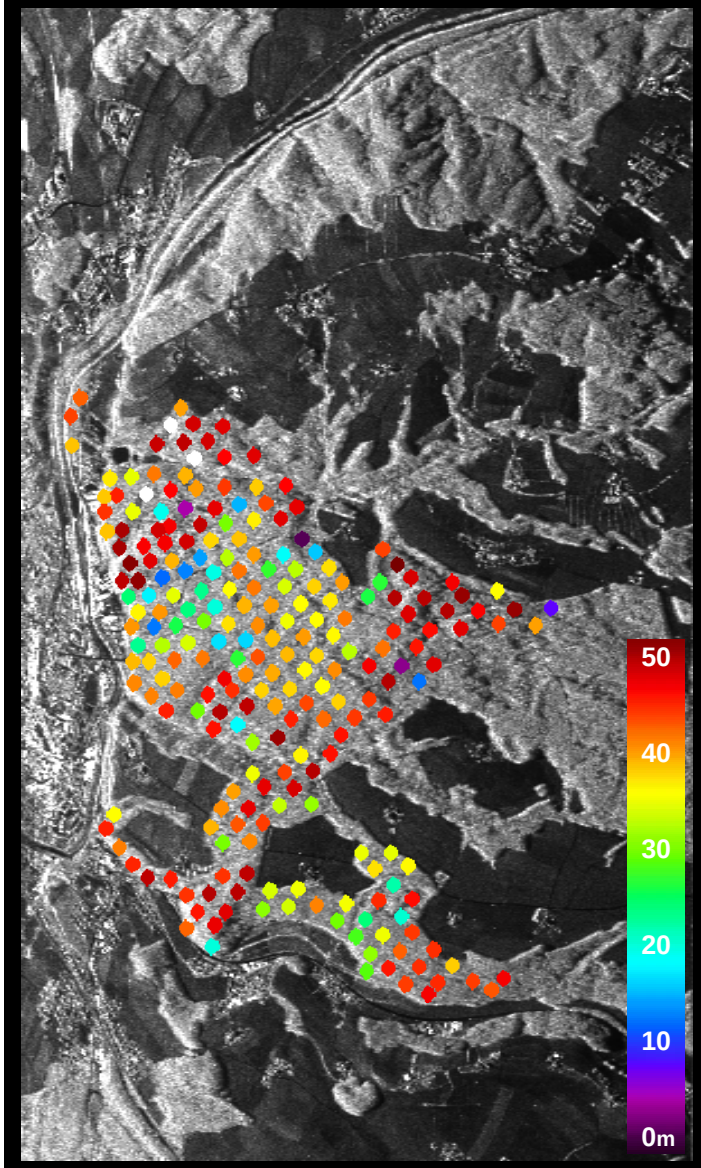
Forest type	Temperate
Topography	Moderate slopes
Height	25 ~ 35m
Species	N. Spruce, E. Beech, White Fir
Biomass	40 ~ 450 t/ha

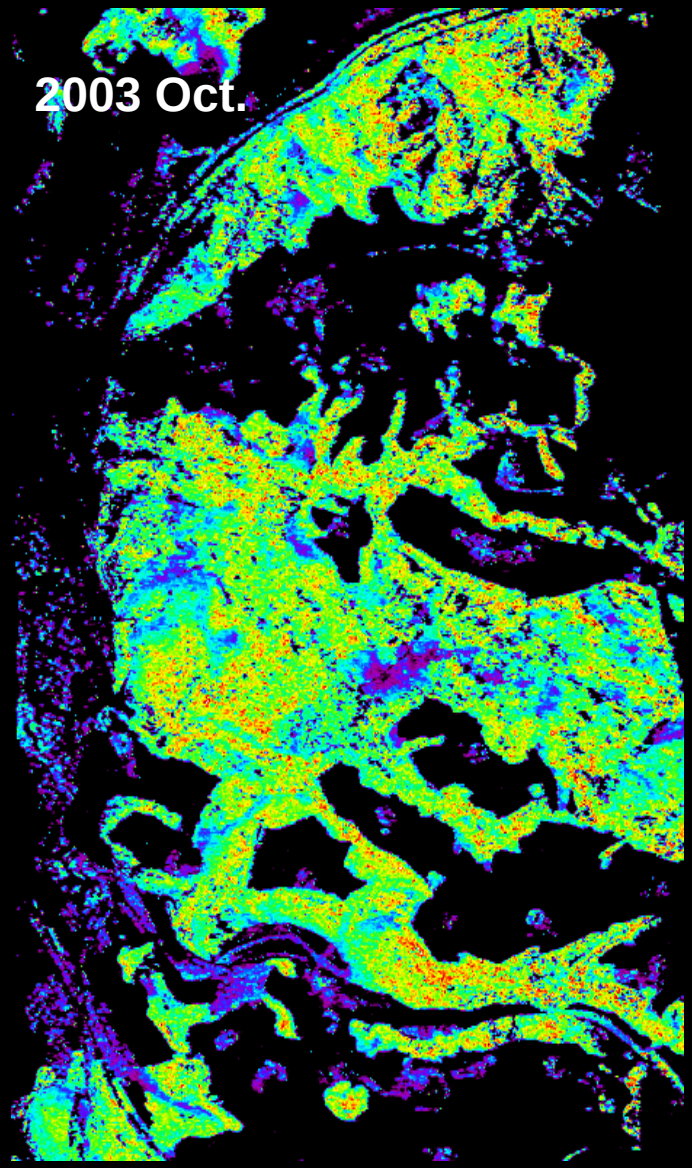


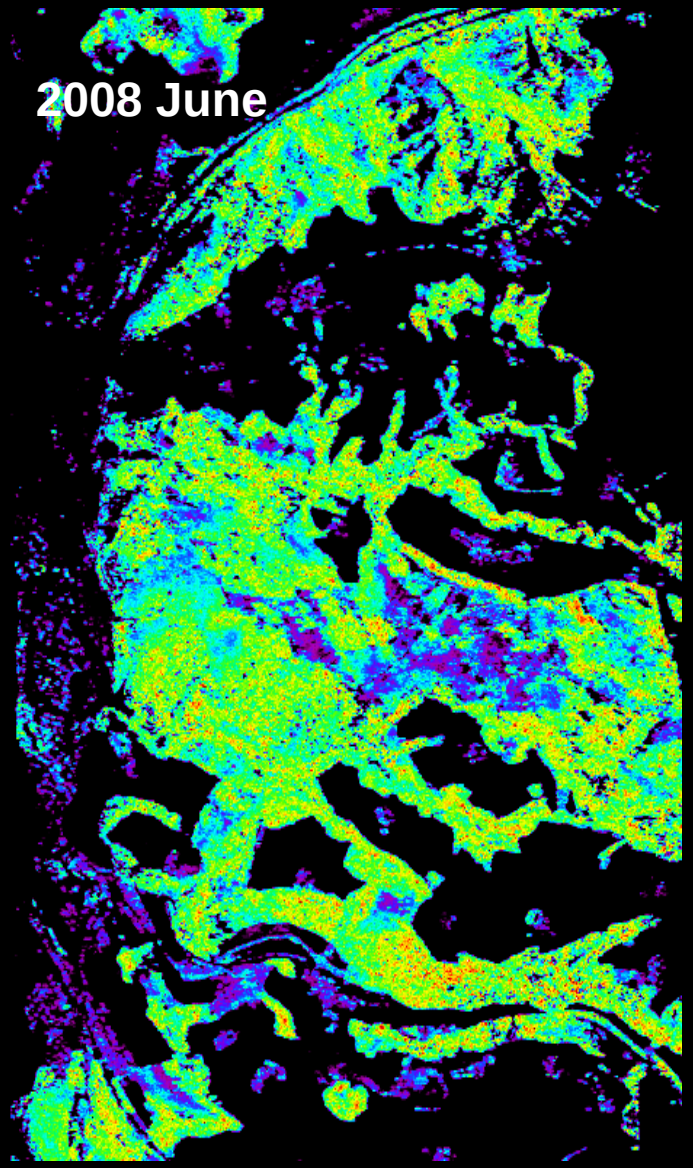




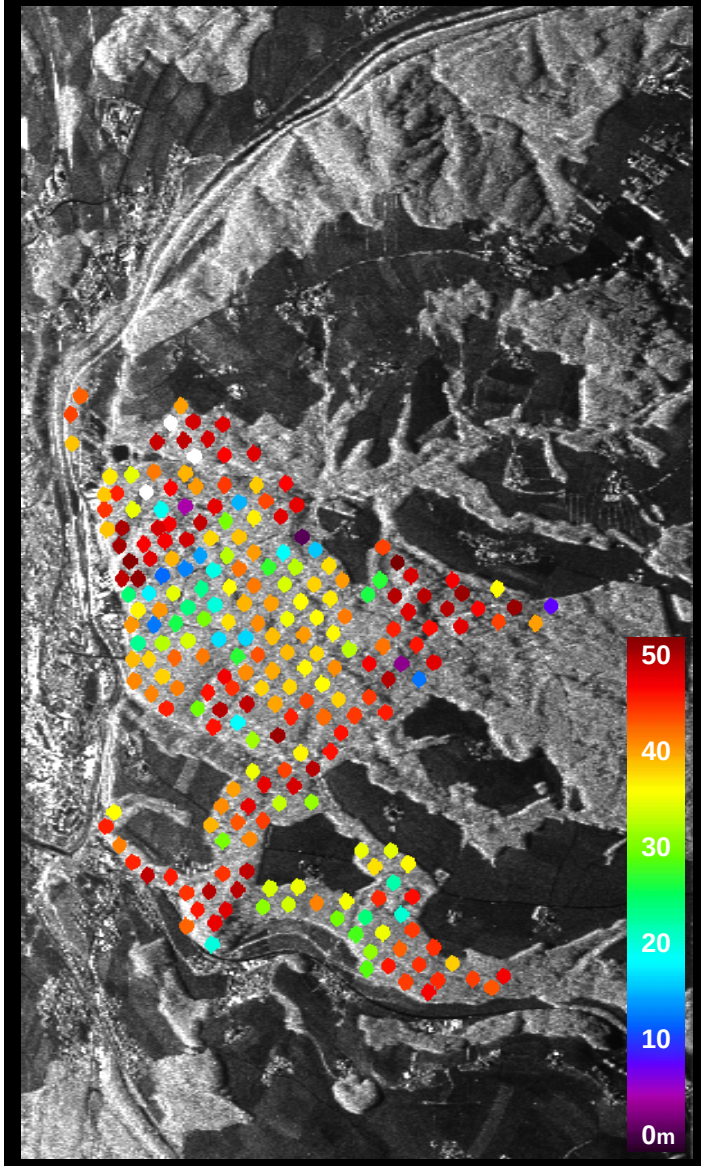
Traunstein Test Site

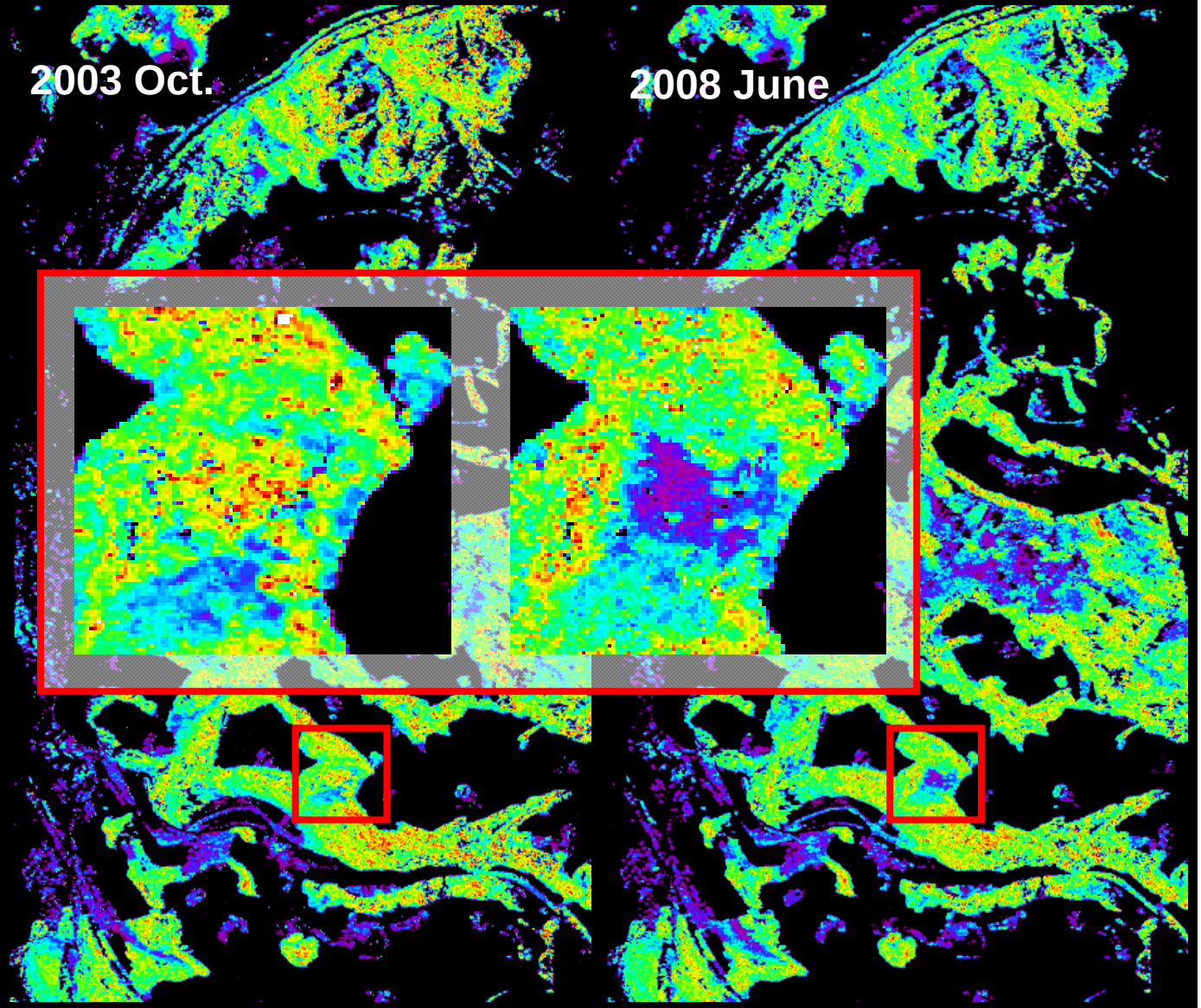




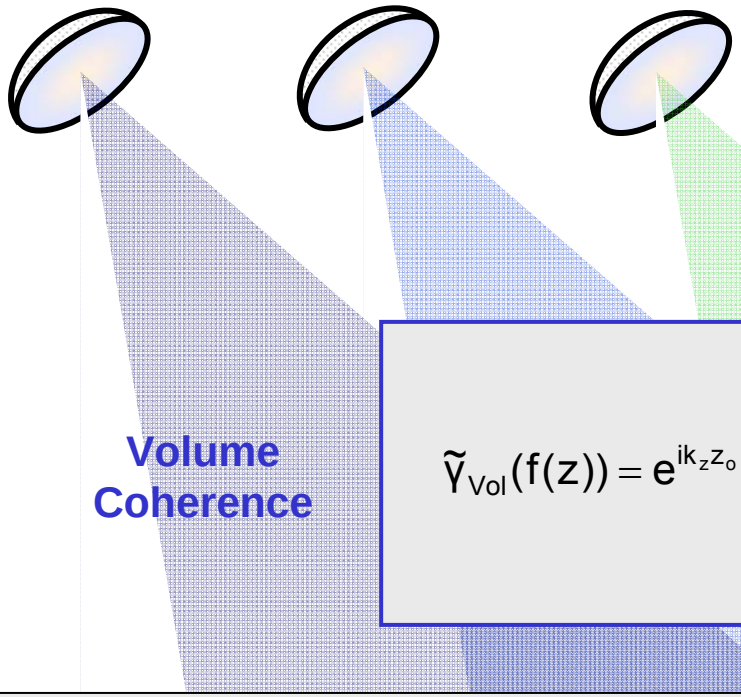


Traunstein Test Site





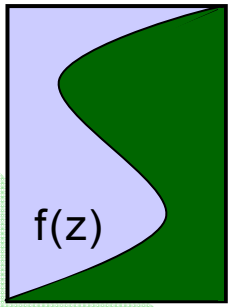
Polarimetric Coherence Tomography

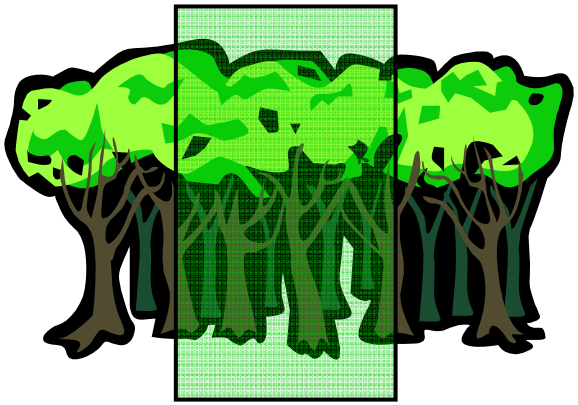


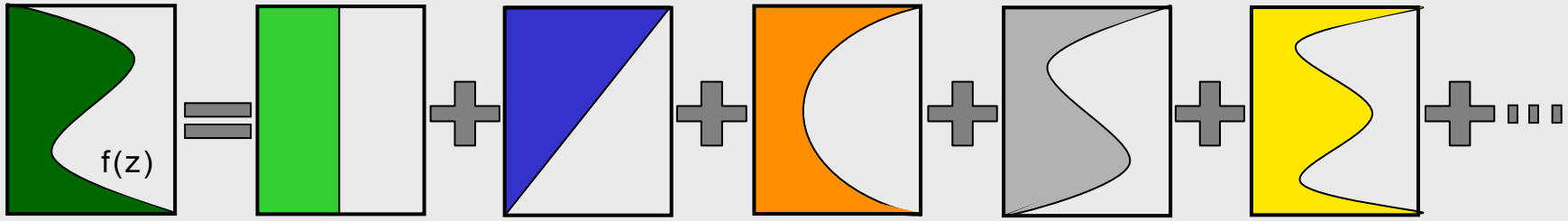
f(z) … vertical reflectivity function

Volume Coherence

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







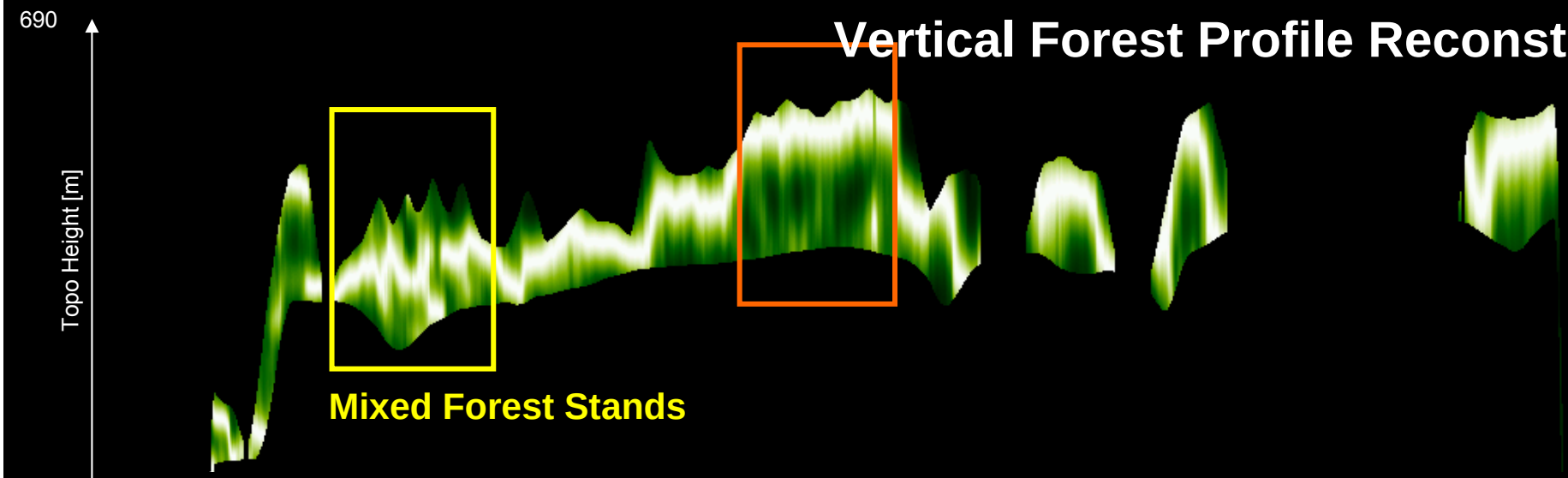
$$\tilde{\gamma}_{Vol}(f(z)) = e^{ik_z z_o} \frac{\int_o^{h_v} f(z)\, e^{ik_z z} dz}{\int_o^{h_v} f(z)\, dz}$$

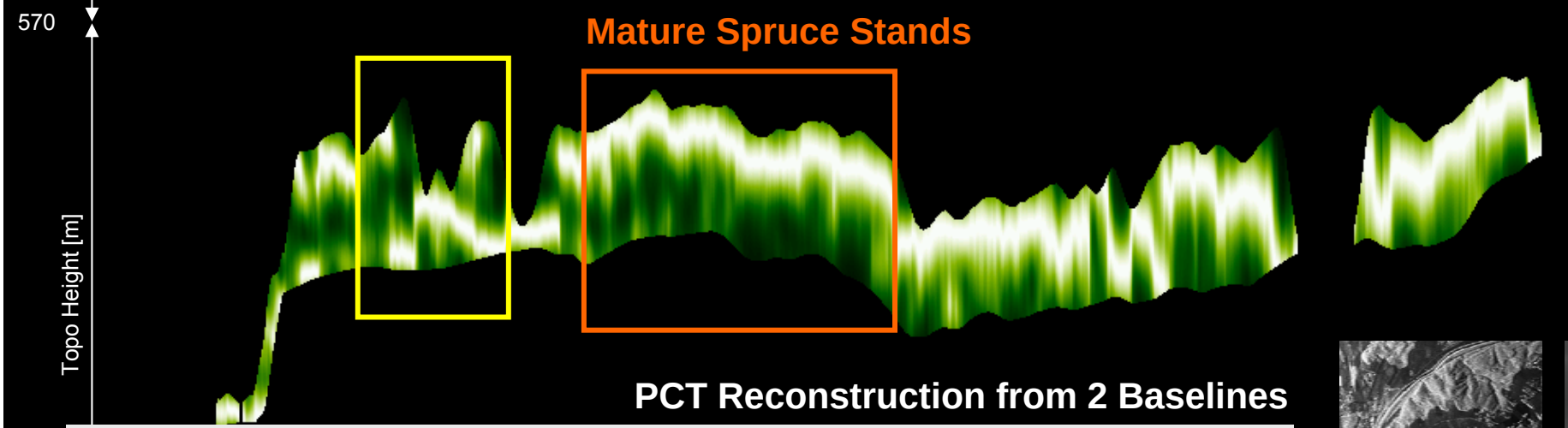
$$\int_0^{h_v} f(z)\, e^{ik_z z} dz = \frac{h_v}{2} e^{i\frac{k_z h_v}{2}} \int_{-1}^{1} (1 + f(z'))\, e^{i\frac{k_z h_v}{2} z'} dz'$$

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

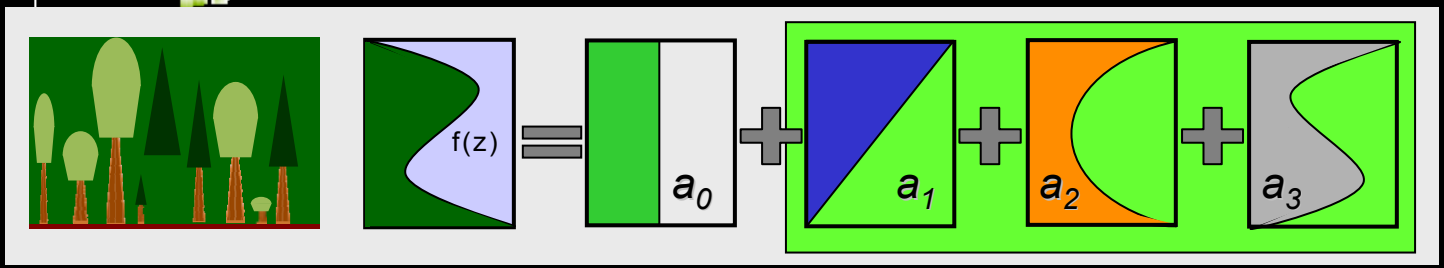
Fourier Legendre Series: $f(z') = \sum_n a_n P_n(z')$ **where** $a_n = \frac{2n+1}{2} \int_{-1}^{1} f(z') P_n(z') dz'$

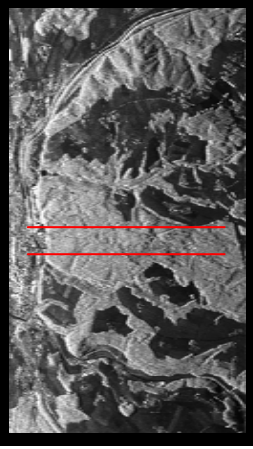
Vertical Forest Profile Reconstruction

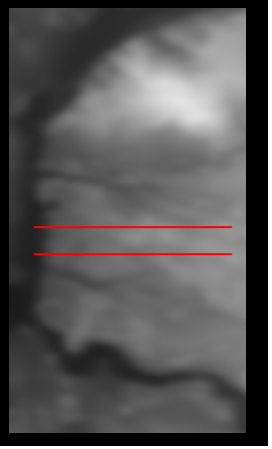




PCT Reconstruction from 2 Baselines

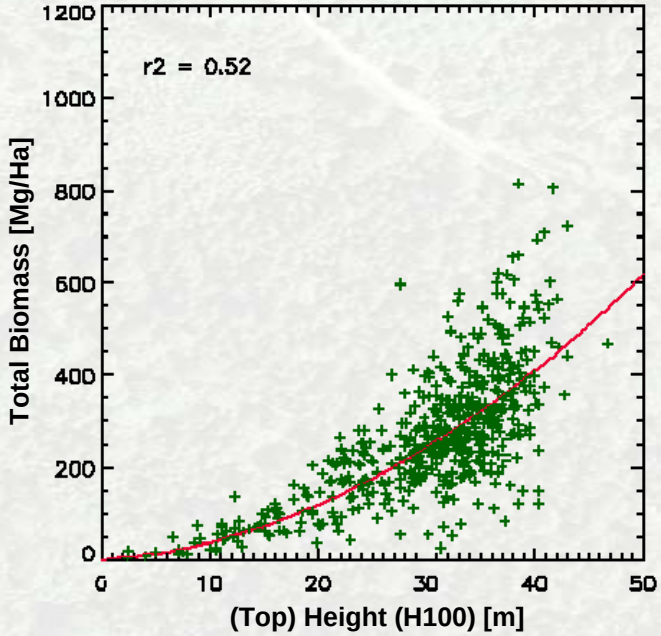






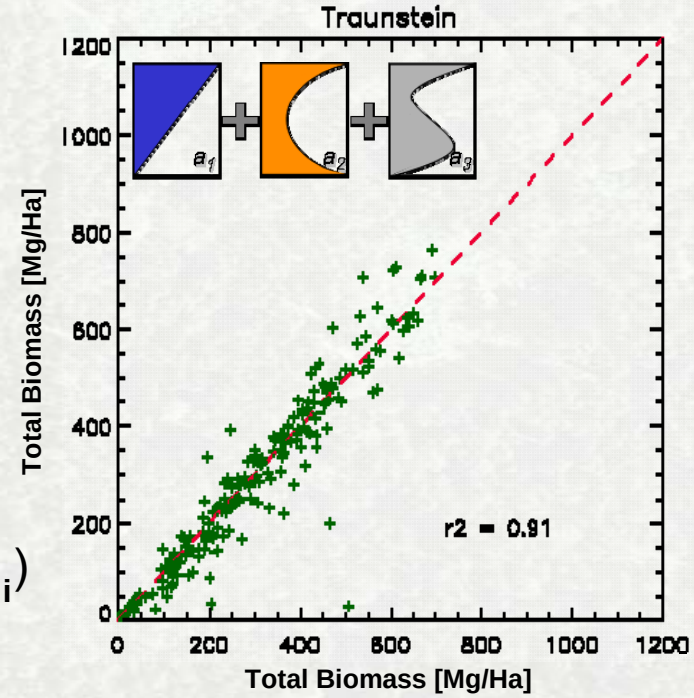
Test site: Traunstein, Germany, L-band @ HV Polarisation

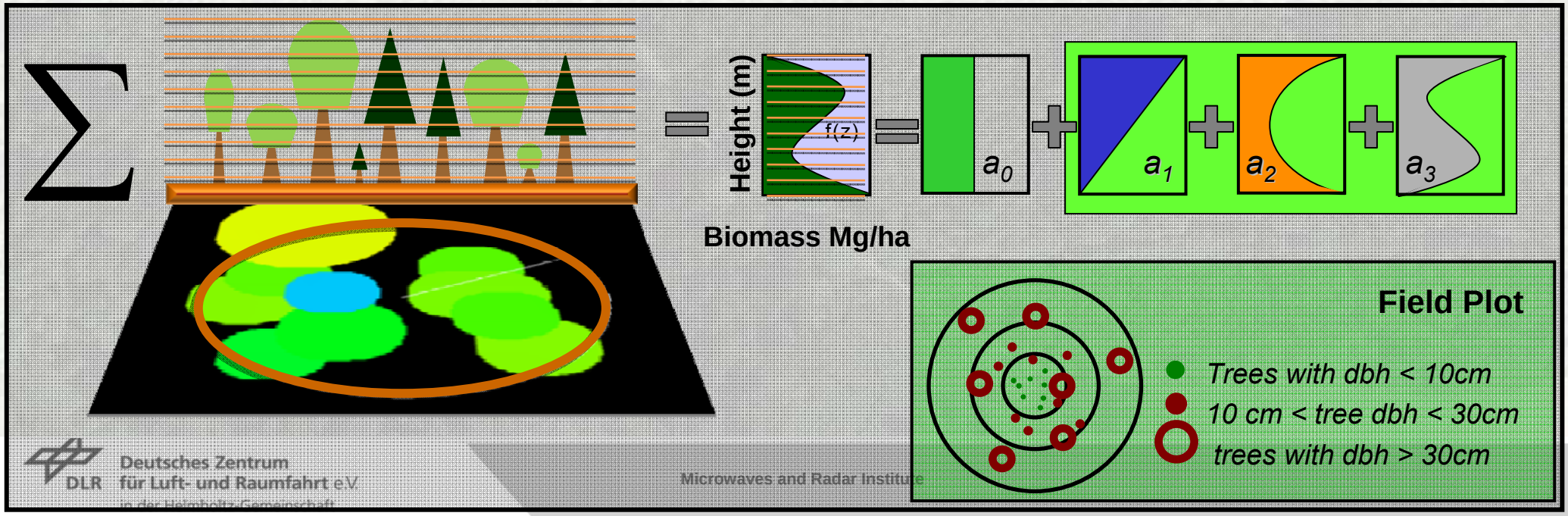
Structure-to-Biomass Allometry



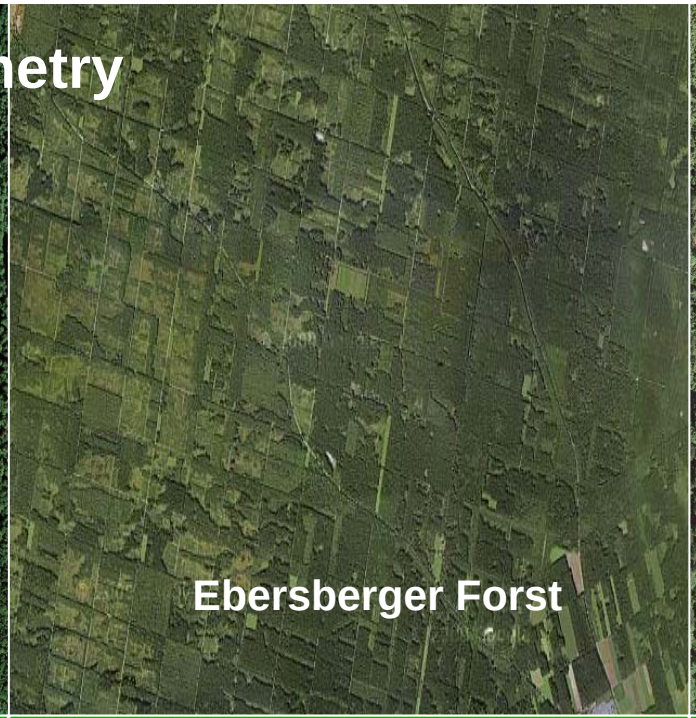
$$B = la * 1.66\, H^{1.50}$$

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





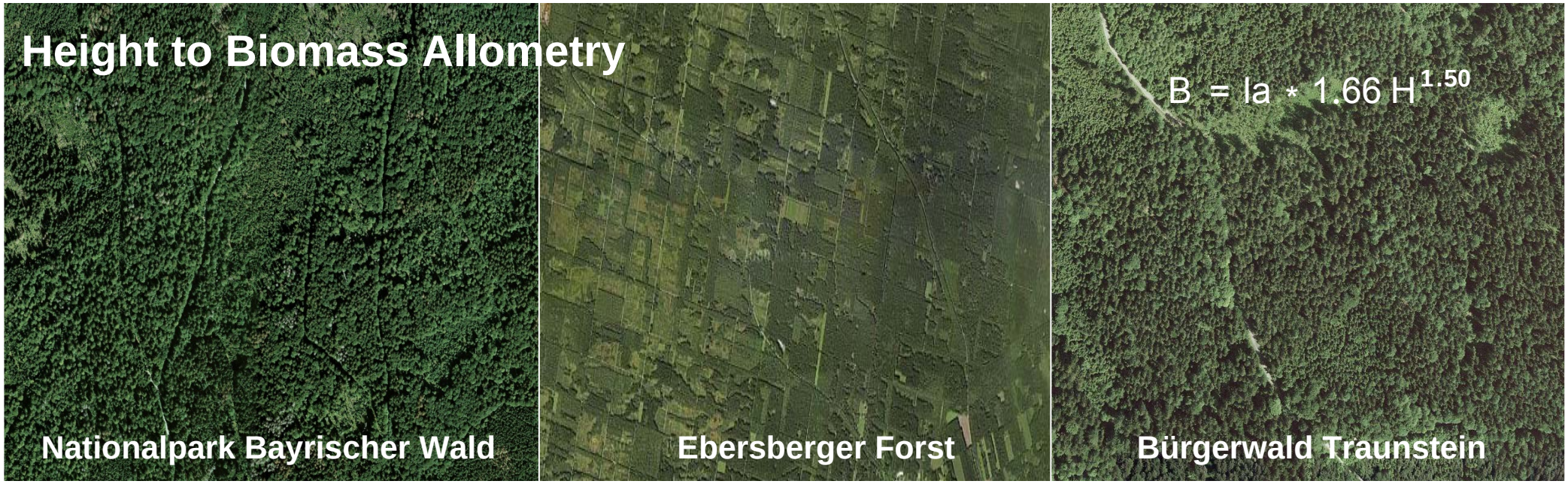
Height to Biomass Allometry

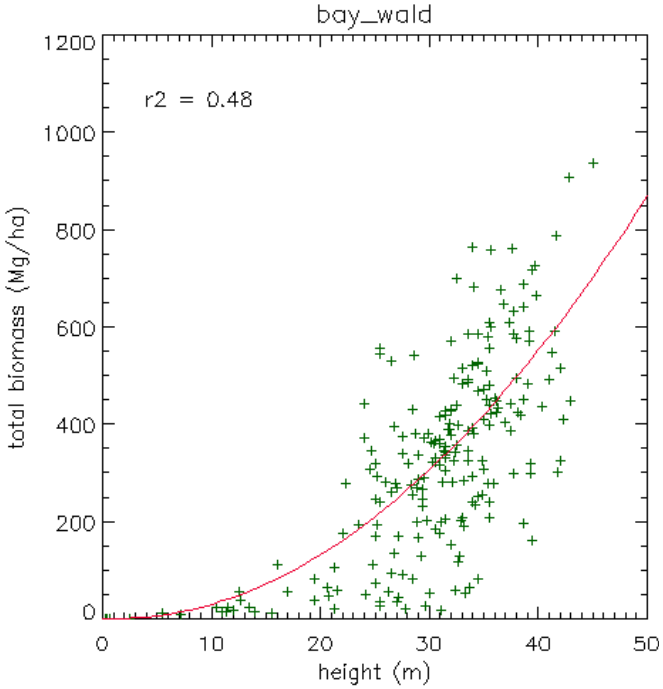


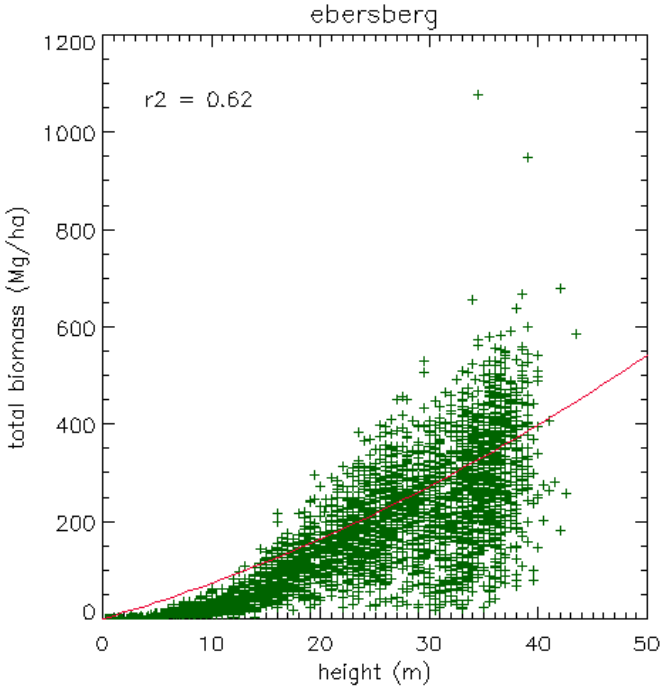
Natural development since 1972	Intensely managed	“Close to Nature”
Montane spruce forest > 1100m asl.		Temperate managed forest
<u>Submontane mixed forest</u>		
Floodplain spruce forest < 600m asl		
	Single species (Spruce)	N. Spruce, E. Beech, White Fir
Height Range (H100): 5 - 45m	Height Range (H100): 5 - 40m	Height Range (H100): 10 - 40m
Biomass Range: 40 ~ 450 t/ha	Biomass Range: 40 ~ 350 t/ha	Biomass Range: 40 ~ 450 t/ha
Steep Slopes	Flat Terrain	Moderate Slopes

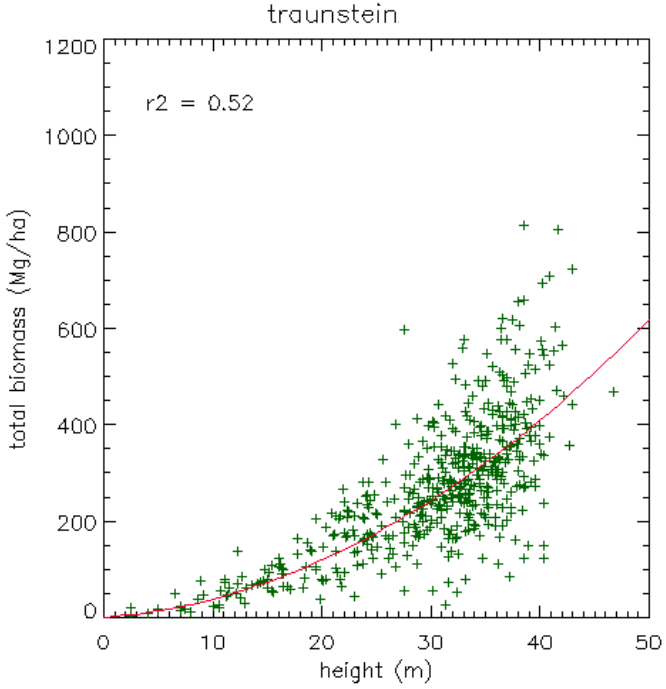
Height to Biomass Allometry

$$B = la * 1.66\ H^{1.50}$$

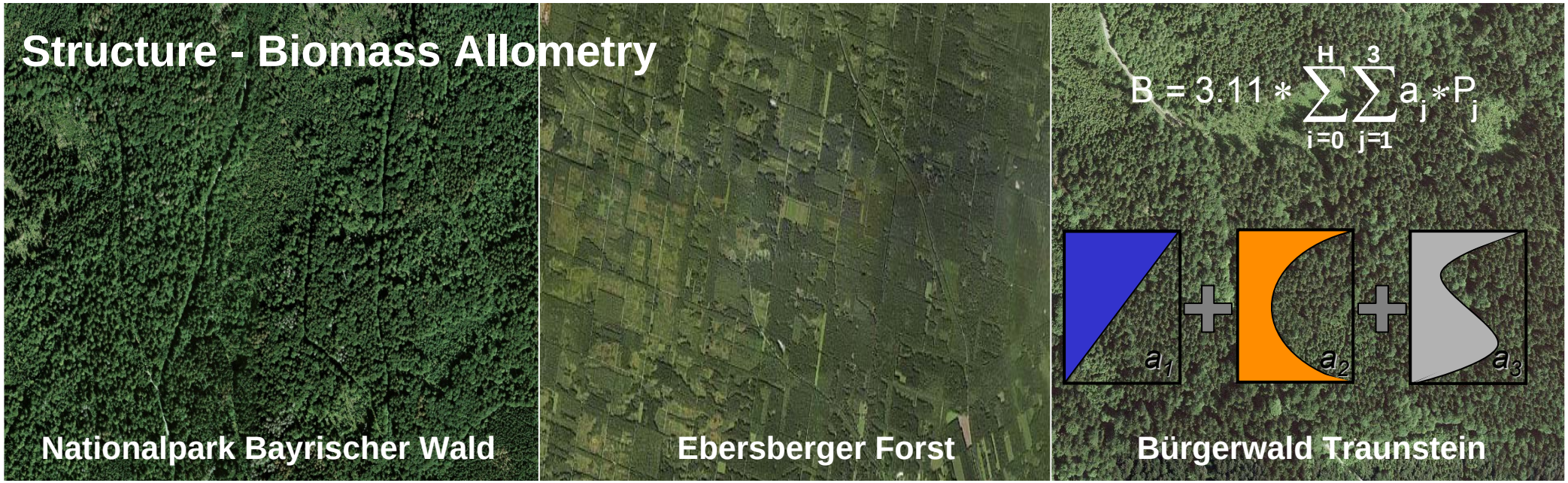


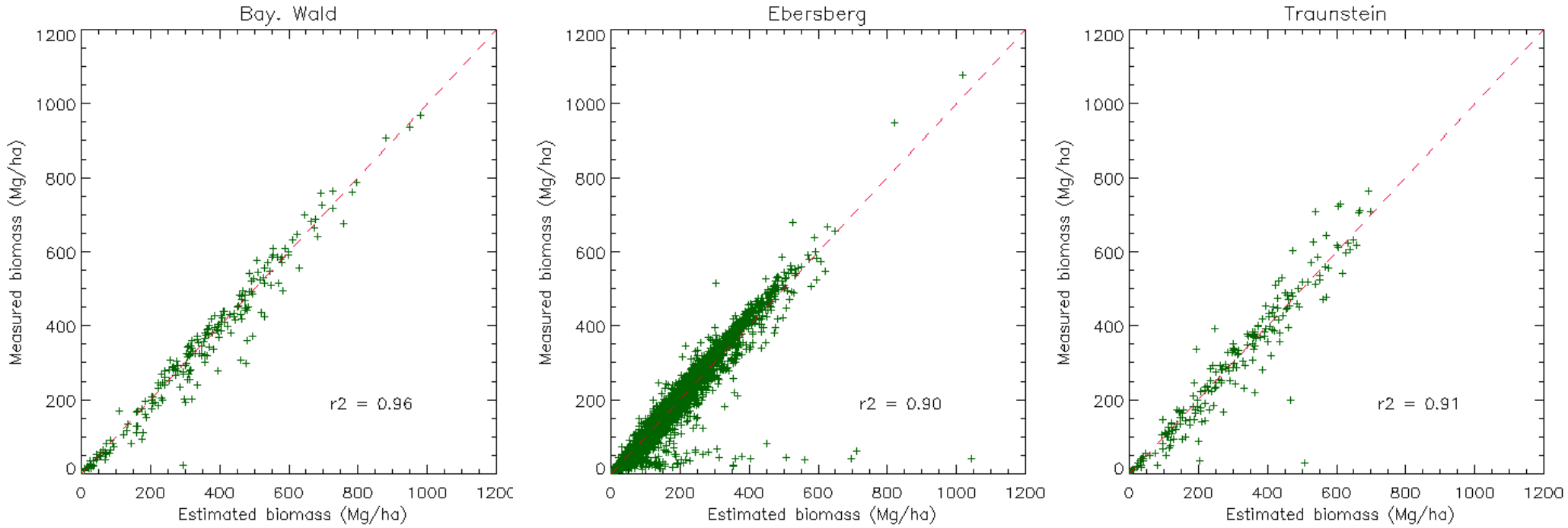






Structure - Biomass Allometry

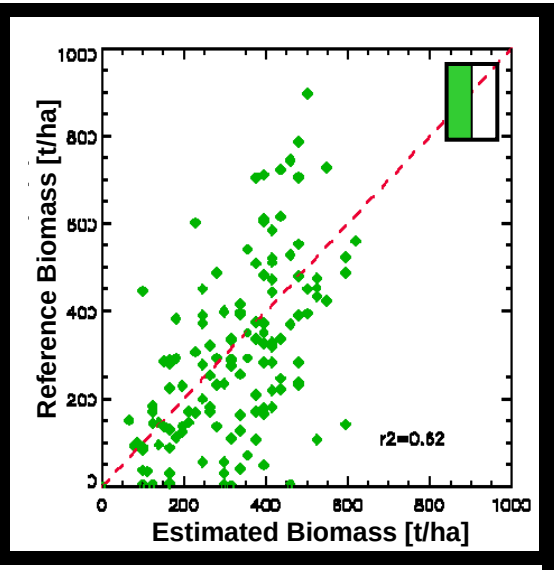


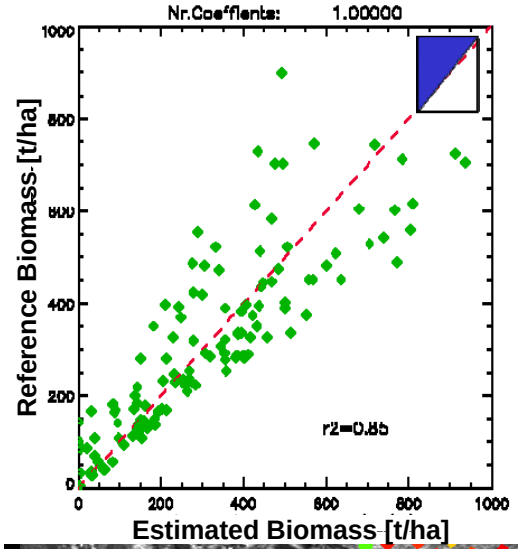


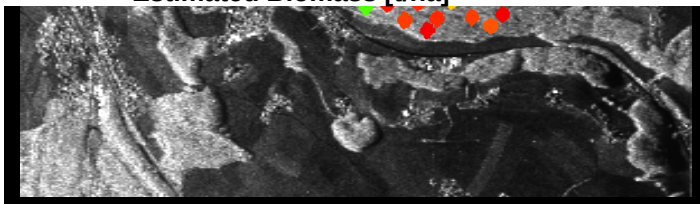
Three Legendre polynomials explain the 92% of the total biomass !!!

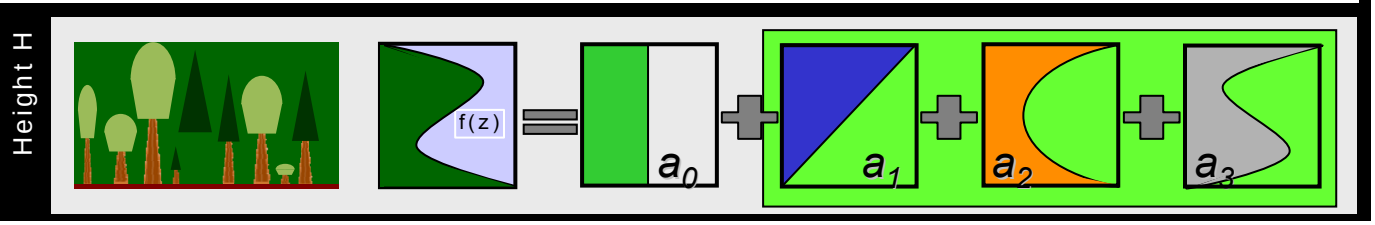
Traunstein Test Site

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

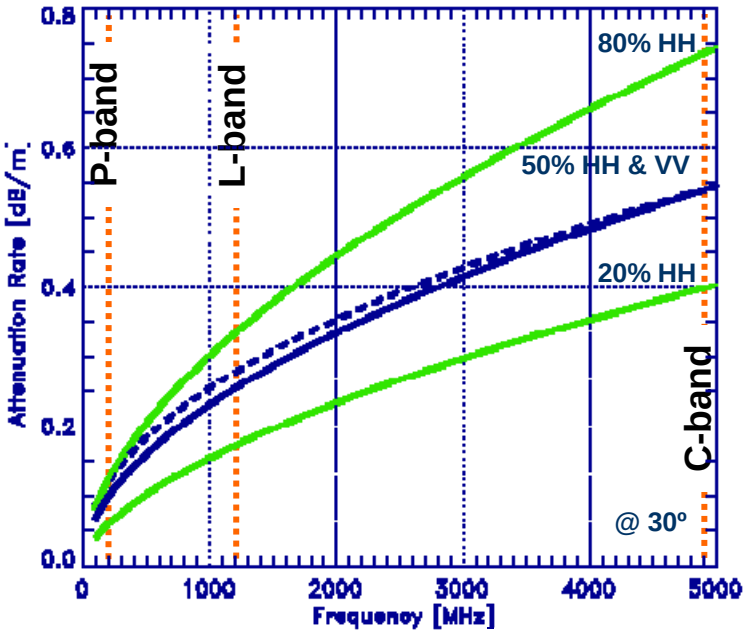






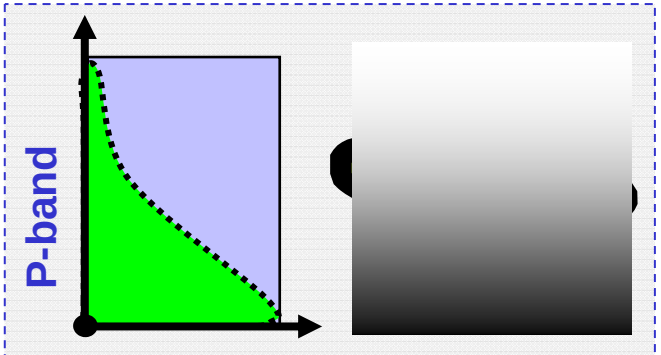


Frequency Dependency

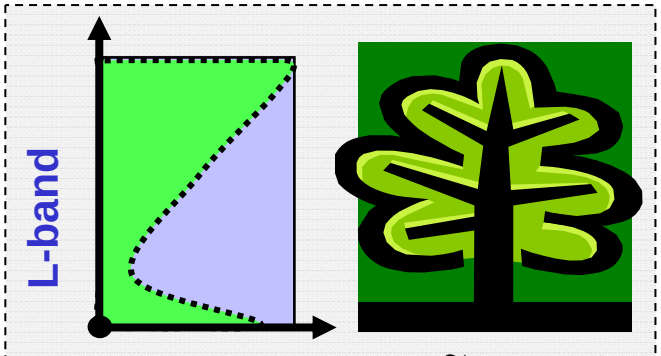


With degreasing frequency:

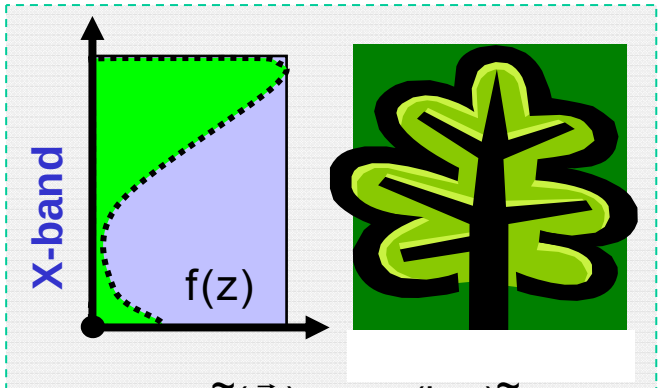
- The attenuation through the vegetation degreases;
- The relative importance of the volume decreases;
- The relative importance of the ground increases;
- The effective scatterers and their distribution changes.



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

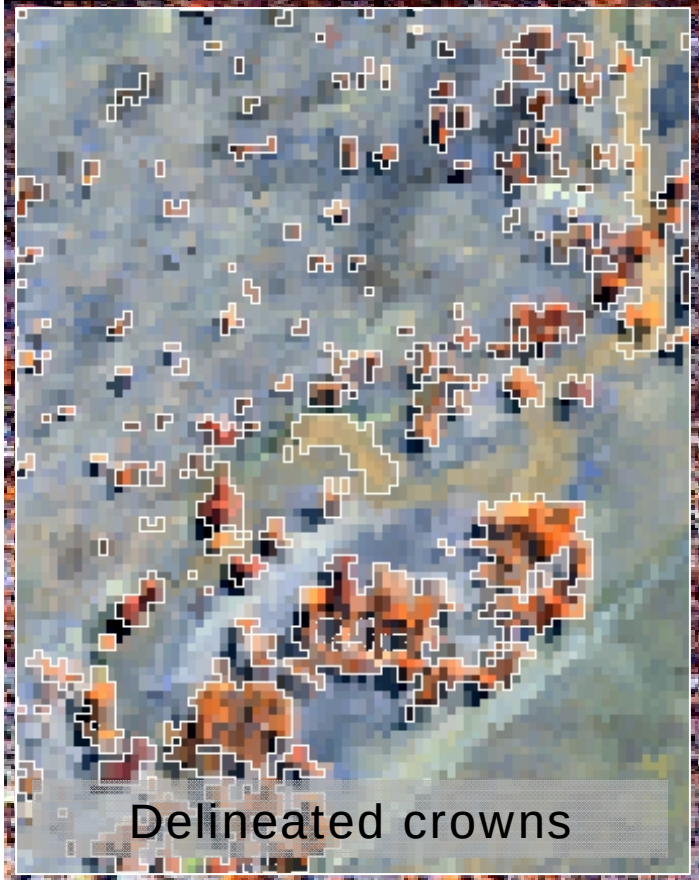


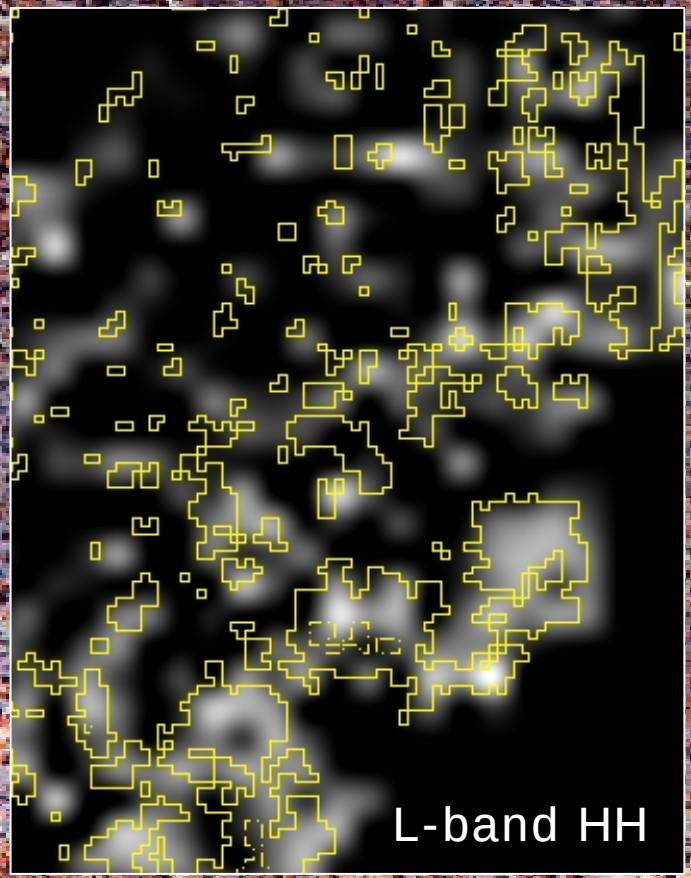
$$\tilde{\gamma}(\vec{w}) = \exp(i\varphi_0)\frac{\tilde{\gamma}_V + m(\vec{w})}{1 + m(\vec{w})}$$

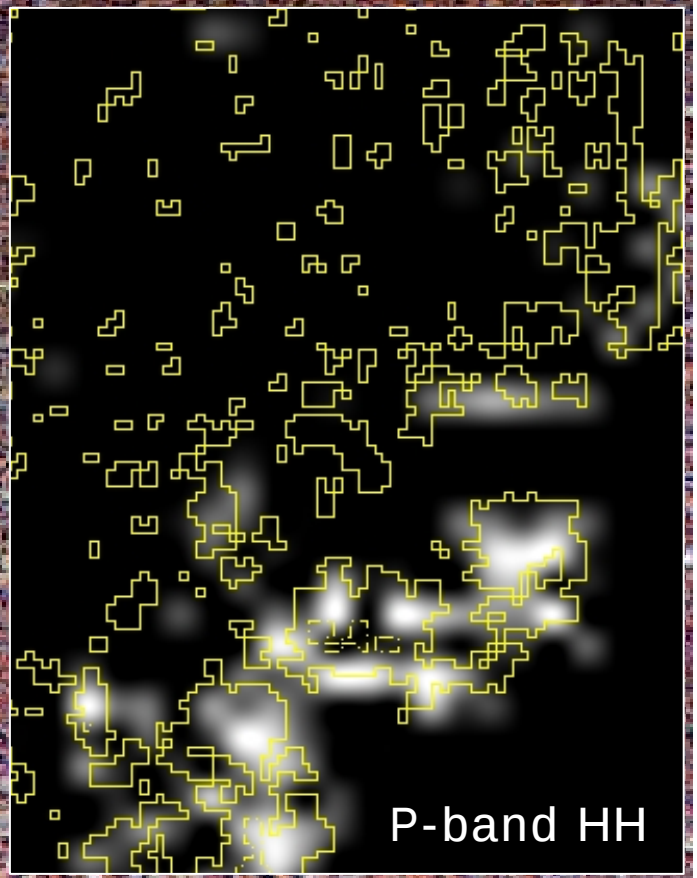


$$\tilde{\gamma}(\vec{w}) = \exp(i\varphi_0)\tilde{\gamma}_V$$

L.Bessette, S.Ayasli "Ultra Wide Band P-3 and Carabas II Foliage Attenuation and Backscatter Analysis", Proceedings of IEEE Radar Conference, 2001.

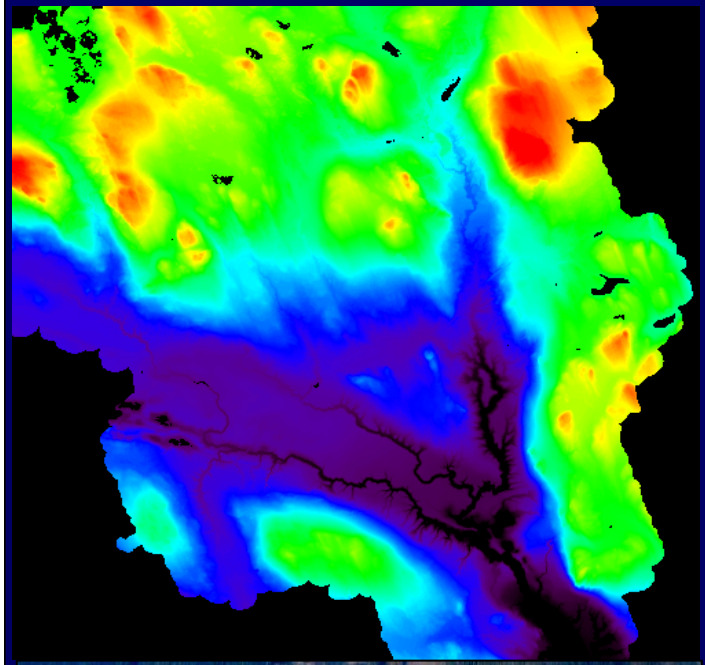


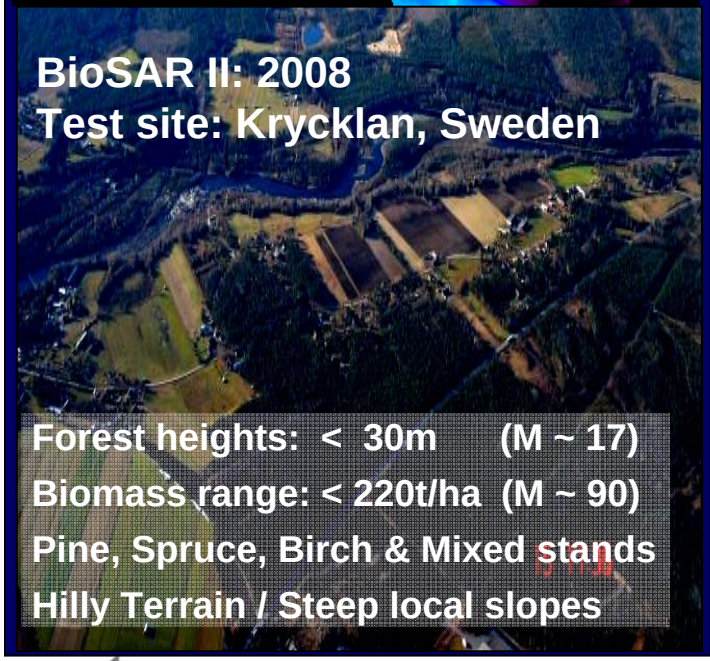


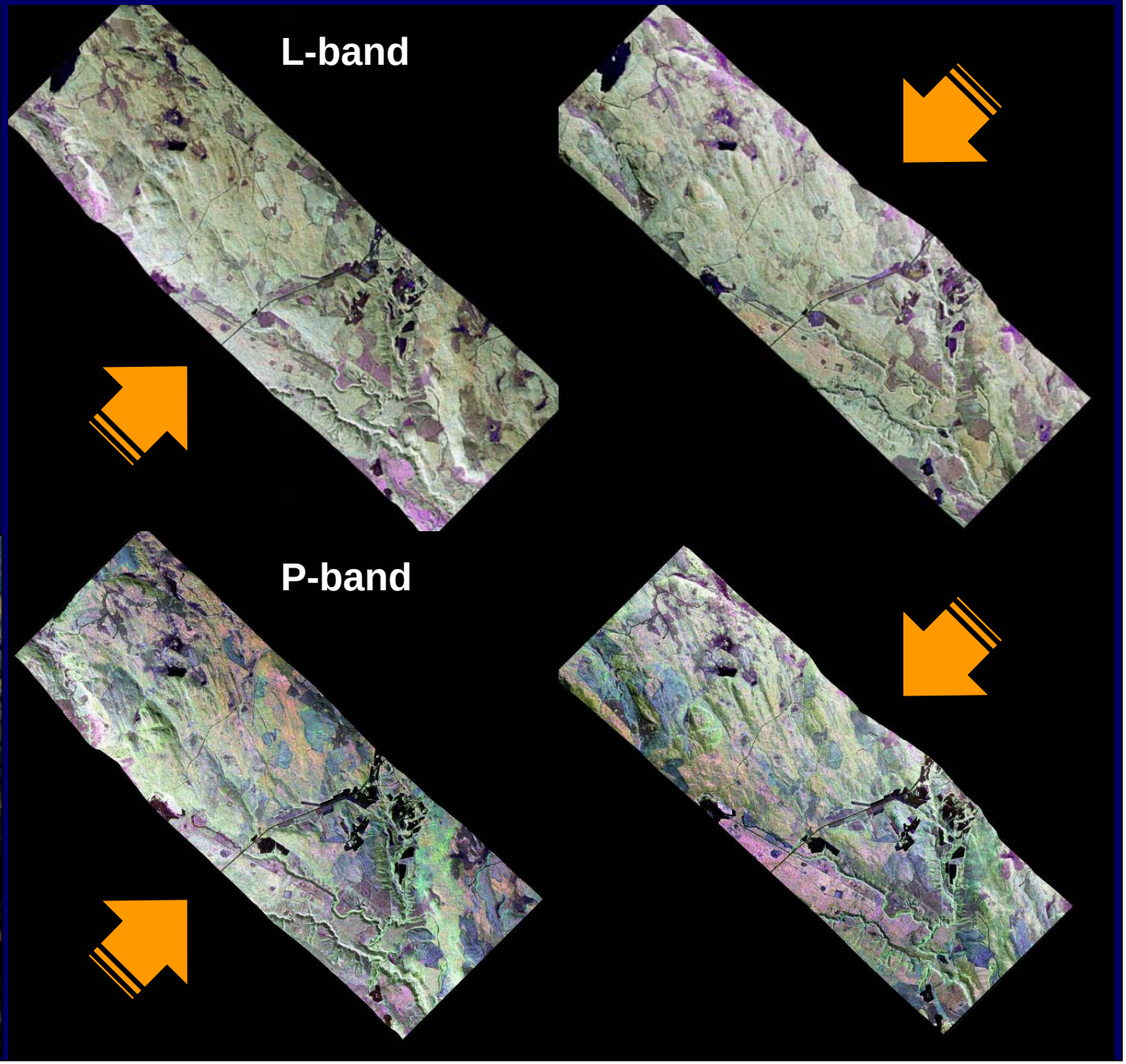


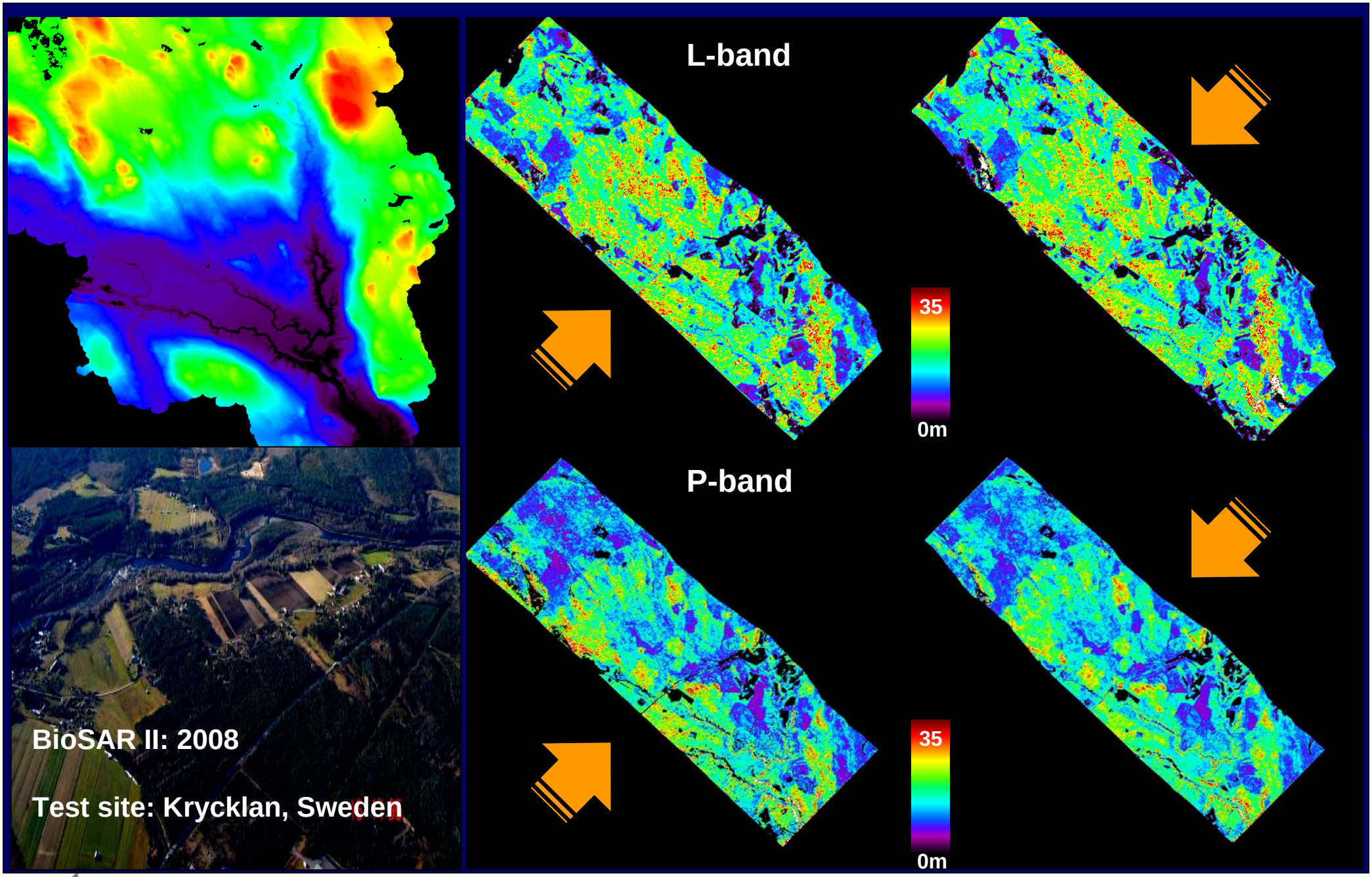
Injune, QL, Australia

Prifysgol Cymru Aberystwyth 1872 The University of Wales

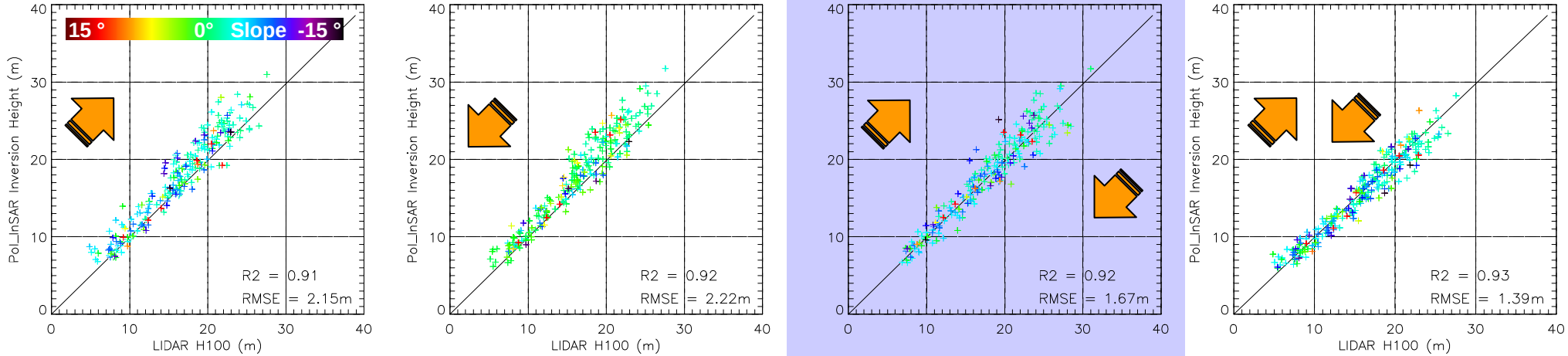



BioSAR II: 2008
Test site: Krycklan, Sweden
Forest heights: < 30m (M ~ 17)
Biomass range: < 220t/ha (M ~ 90)
Pine, Spruce, Birch & Mixed stands
Hilly Terrain / Steep local slopes

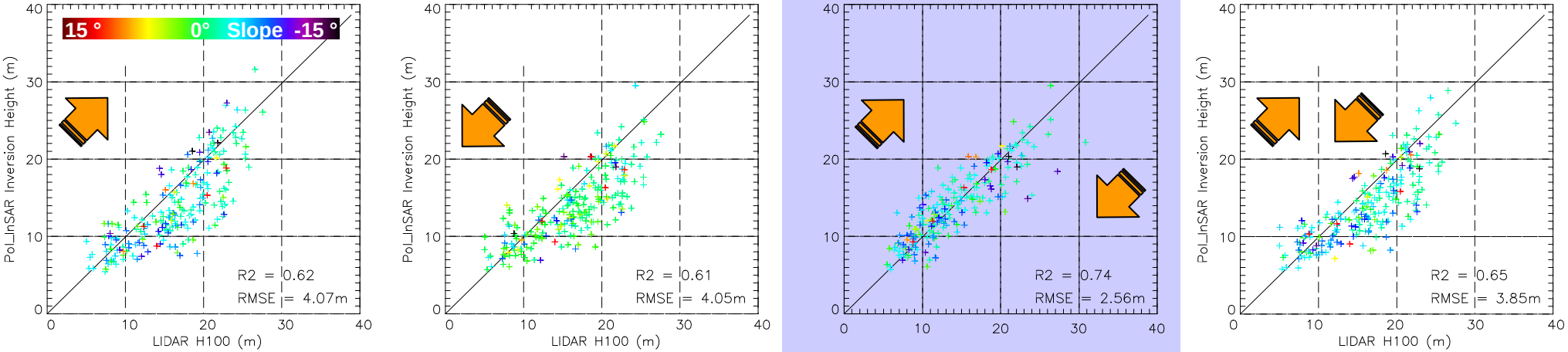

L-band
P-band

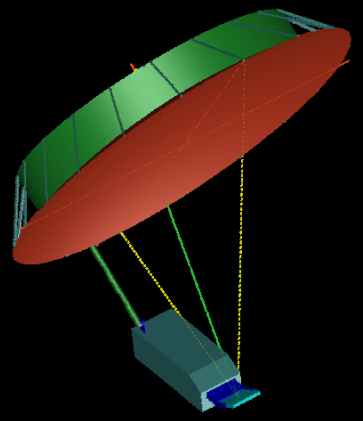
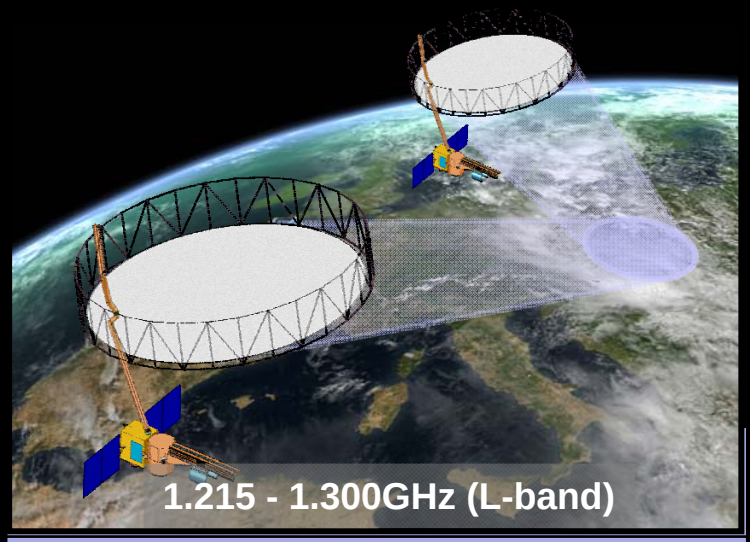

L-band
35
0m
P-band
35
0m
BioSAR II: 2008
Test site: Krycklan, Sweden

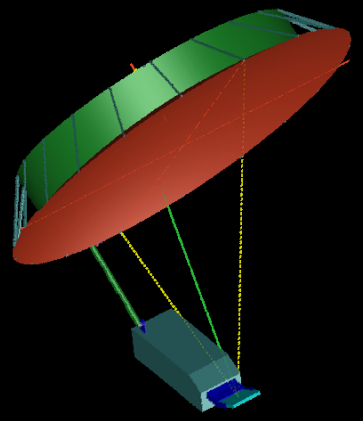
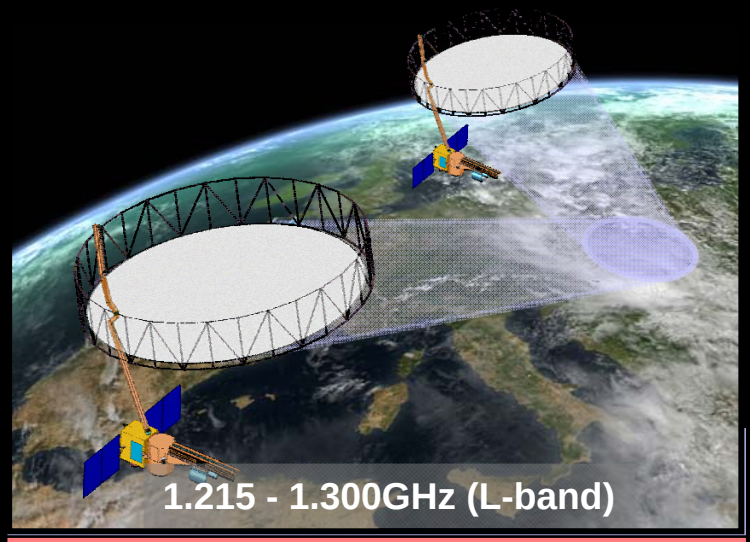
L-band


15 °
0°
Slope
-15 °
Pol_InSAR Inversion Height (m)
LIDAR H100 (m)
R2 = 0.91
RMSE = 2.15m
R2 = 0.92
RMSE = 2.22m
R2 = 0.92
RMSE = 1.67m
R2 = 0.93
RMSE = 1.39m

P-band


15 °
0°
Slope
-15 °
Pol_InSAR Inversion Height (m)
LIDAR H100 (m)
R2 = 0.62
RMSE = 4.07m
R2 = 0.61
RMSE = 4.05m
R2 = 0.74
RMSE = 2.56m
R2 = 0.65
RMSE = 3.85m

biomass		Tandem-L
		
435MHz (P-band)	Central Frequency	**1.215 - 1.300GHz (L-band)**
6	Bandwidth [MHz]	**85**
12.5 m (Az) x 25m (Rg)	Geometric Resolution SLC [m]	**7m (Az) x 1.75m (Rg)**
580	Orbit [km]	**650**
-28 / -30	NESZ [dB]	**-28 / -30**
1	Absolute Radiometry [dB]	**.5**
.5	Relative Radiometry [dB]	**.5**
5-10	Phase Accuracy [deg]	**5**
>-20	Rg / Az Ambiguity Ratio [dB]	**> -20**
Quad	Polarimetry	**Quad**
Repeat-Pass (Tmp Baseline ≥ 25D)	Interferometry	**Single-Pass**

biomass		Tandem-L
		
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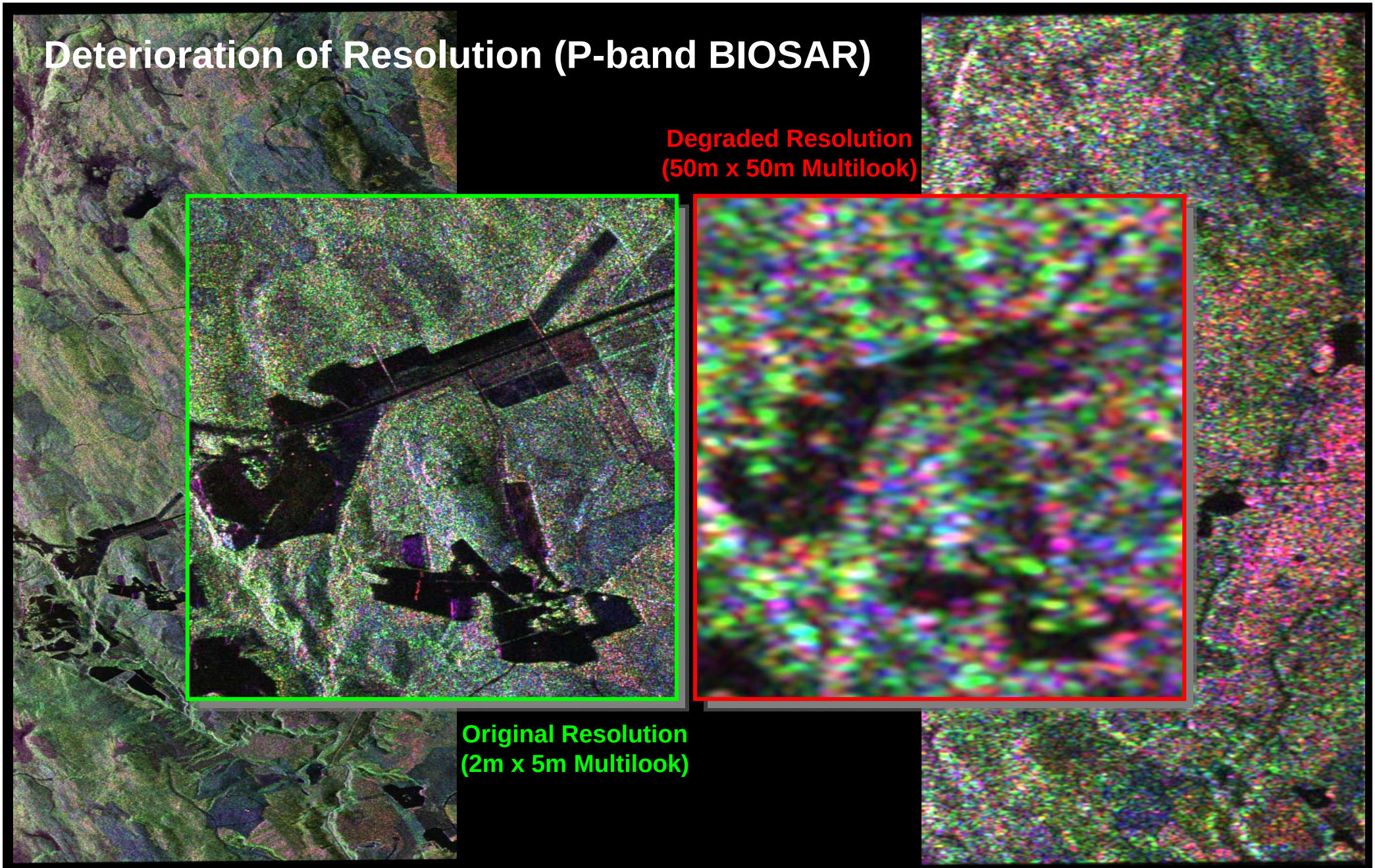
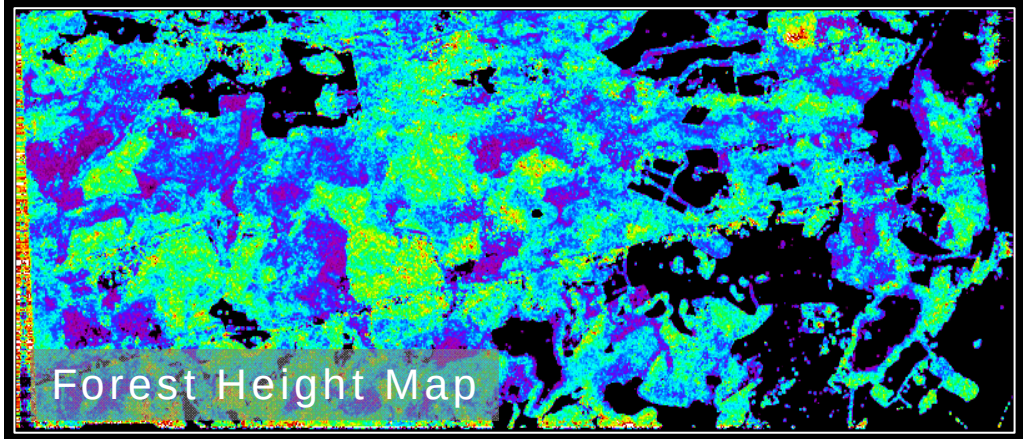
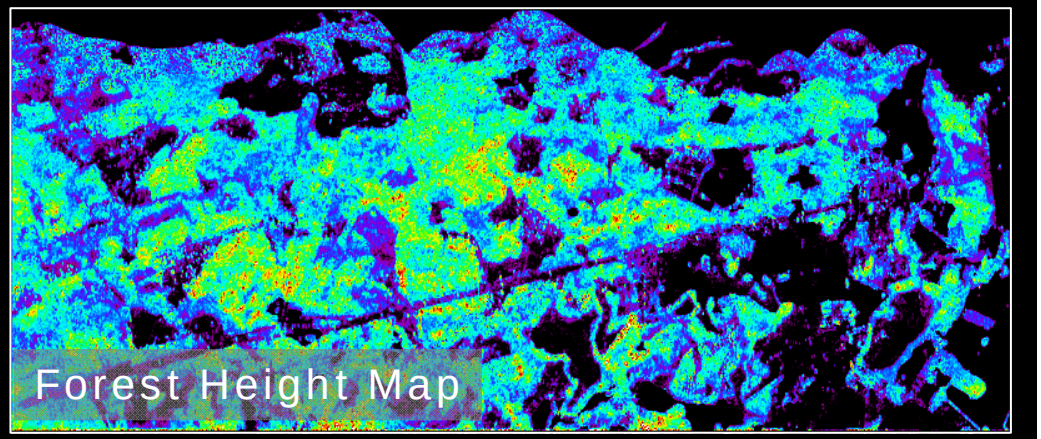
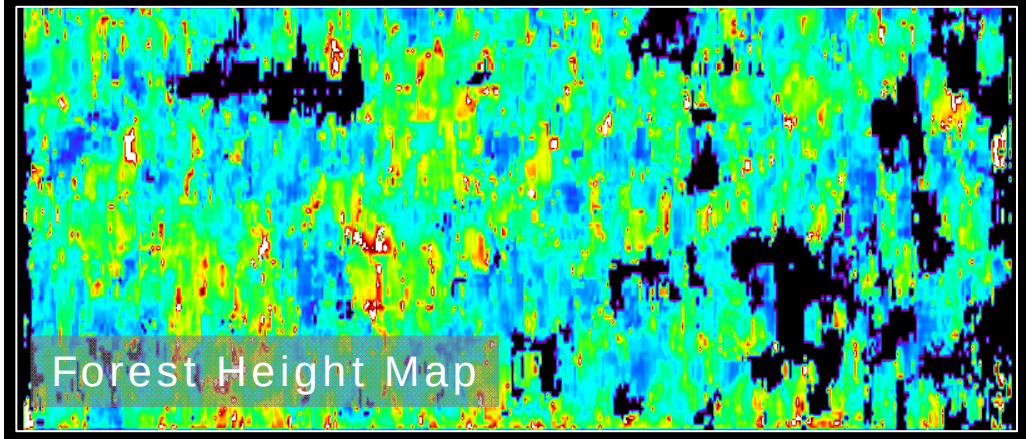
5-10	Phase Accuracy [deg]	**5**
>-20	Rg / Az Ambiguity Ratio [dB]	**> -20**
Quad	Polarimetry	**Quad**
Repeat-Pass (Tmp Baseline ≥ 25D)	Interferometry	**Single-Pass**

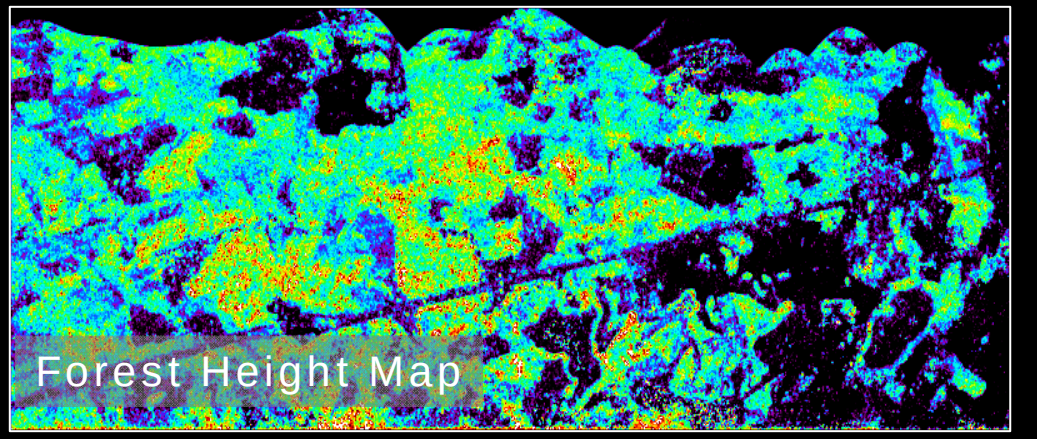
Deterioration of Resolution (P-band BIOSAR)











Bio & Geo-Physical Parameter Retrieval Algorithm Definition for Active Remote Sensing at P- & L-band Study

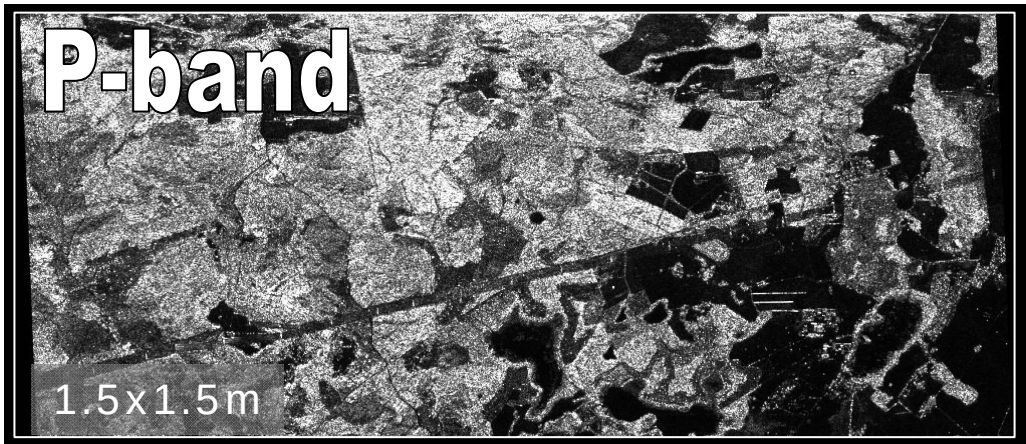
AFL

Prifysgol Cymru Aberystwyth 1872 The University of Wales

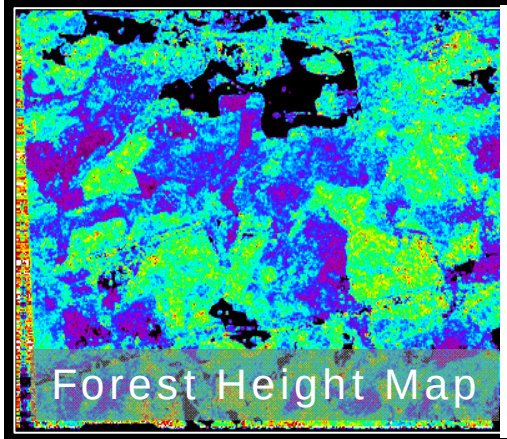
SarVision

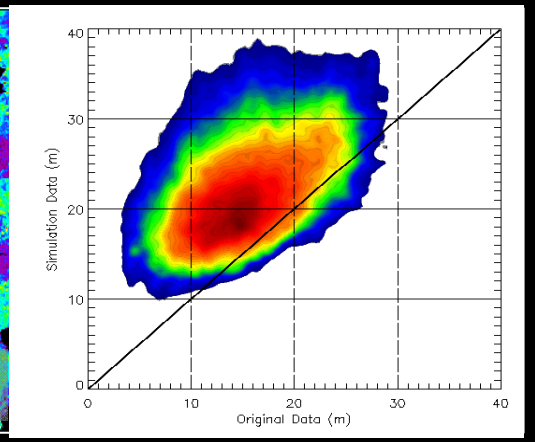
ONERA

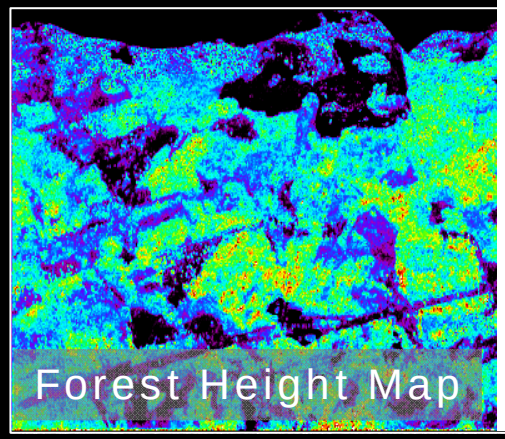
esa

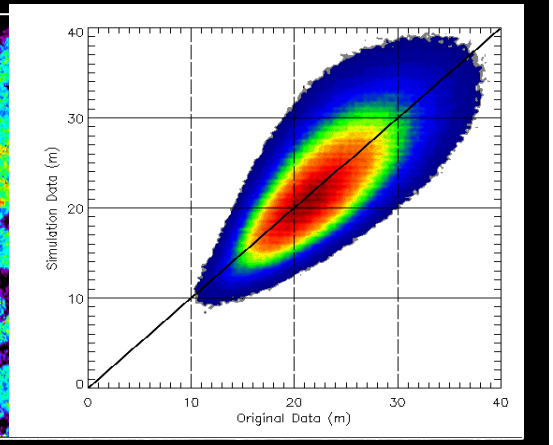

P-band
1.5x1.5m

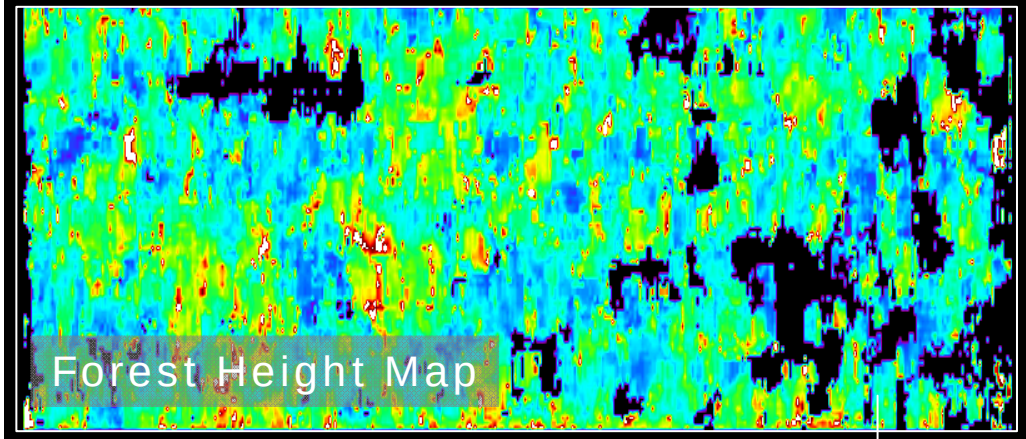
L-band
1.5x1.5m

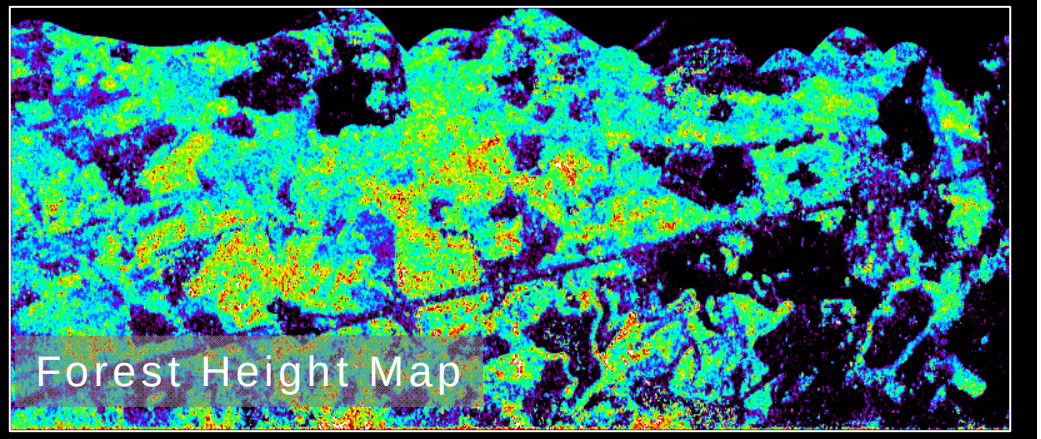

Forest Height Map


Simulation Data (m)
Original Data (m)
0
10
20
30
40


Forest Height Map


Simulation Data (m)
Original Data (m)
0
10
20
30
40

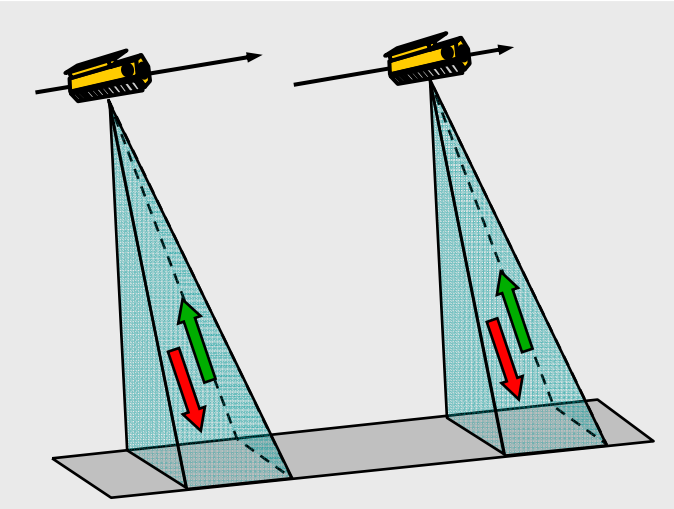

Forest Height Map


Forest Height Map

TANDEM
DLR
EADS
ASTRIUM
infoterra

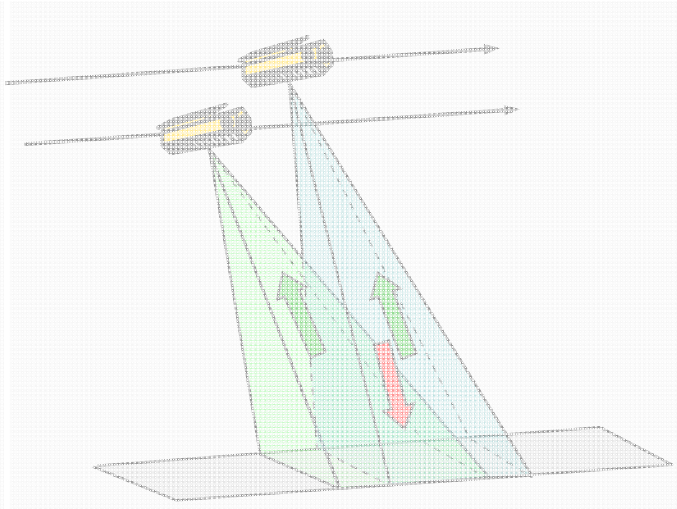
TanDEM-X Data Acquisition Modes

Pursuit Monostatic



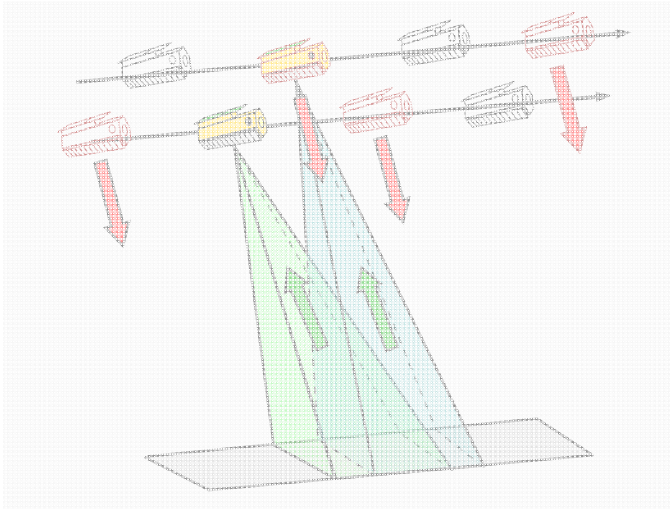
- **both satellites transmit and receive independently**
- susceptible to temporal decorrelation & atmospheric disturbances
- no PRF and phase synchronisation required (backup solution)

Bistatic



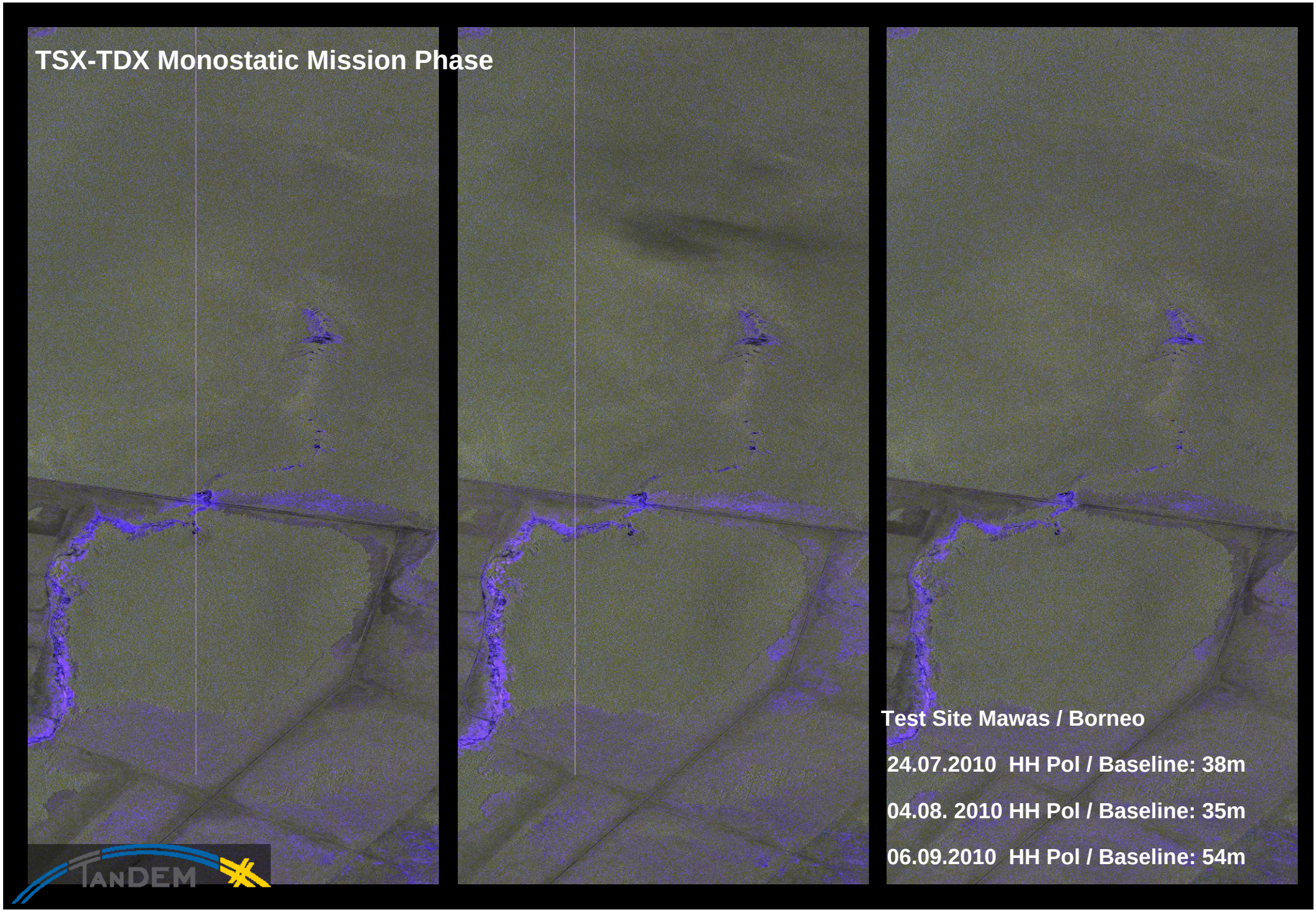
- one satellite transmits and both satellites receive simultaneously
- small along-track displacement required for Doppler spectra overlap
- requires PRF and phase synchronisation

Alternating Bistatic



- transmitter alternates between PRF pulses
- provides three interferograms with two baselines in a single pass
- enables precise phase synchronisation, calibration & verification

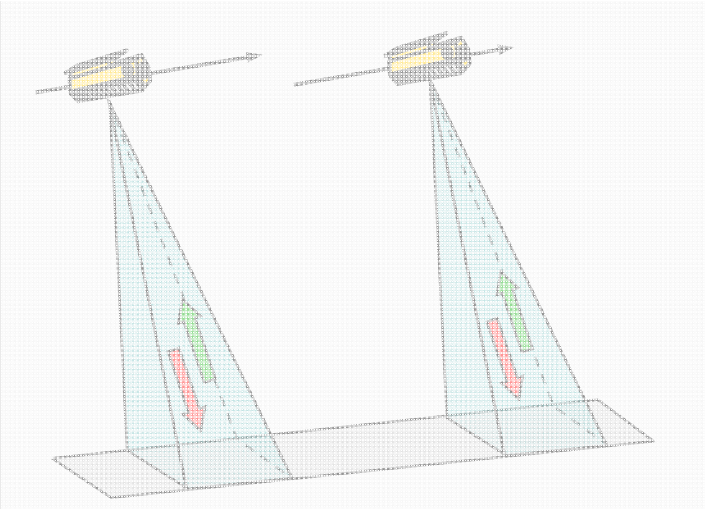
Standard DEM Mode


TSX-TDX Monostatic Mission Phase
Test Site Mawas / Borneo
24.07.2010 HH Pol / Baseline: 38m
04.08. 2010 HH Pol / Baseline: 35m
06.09.2010 HH Pol / Baseline: 54m
TANDEM

TSX-TDX Monostatic Mission Phase

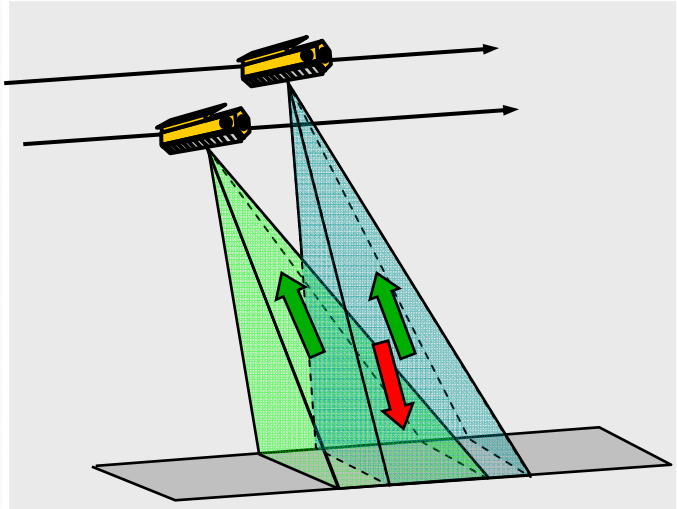
TanDEM-X Data Acquisition Modes

Pursuit Monostatic



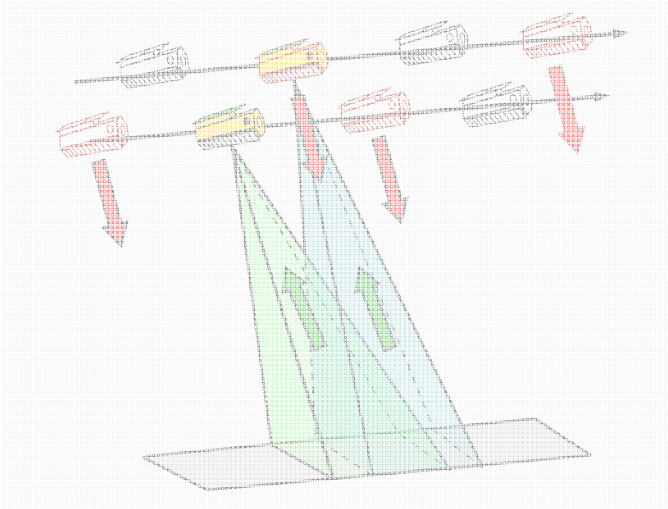
- both satellites transmit and receive independently
- susceptible to temporal decorrelation & atmospheric disturbances
- no PRF and phase synchronisation required (backup solution)

Bistatic



- **one satellite transmits and both satellites receive simultaneously**
- small along-track displacement required for Doppler spectra overlap
- requires PRF and phase synchronisation

Alternating Bistatic

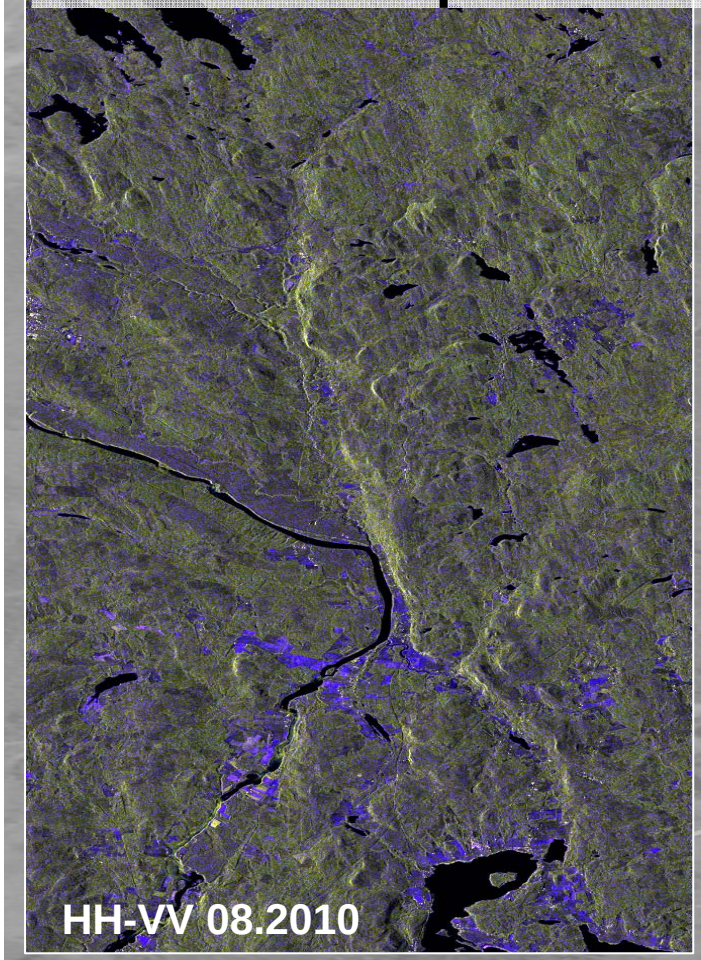


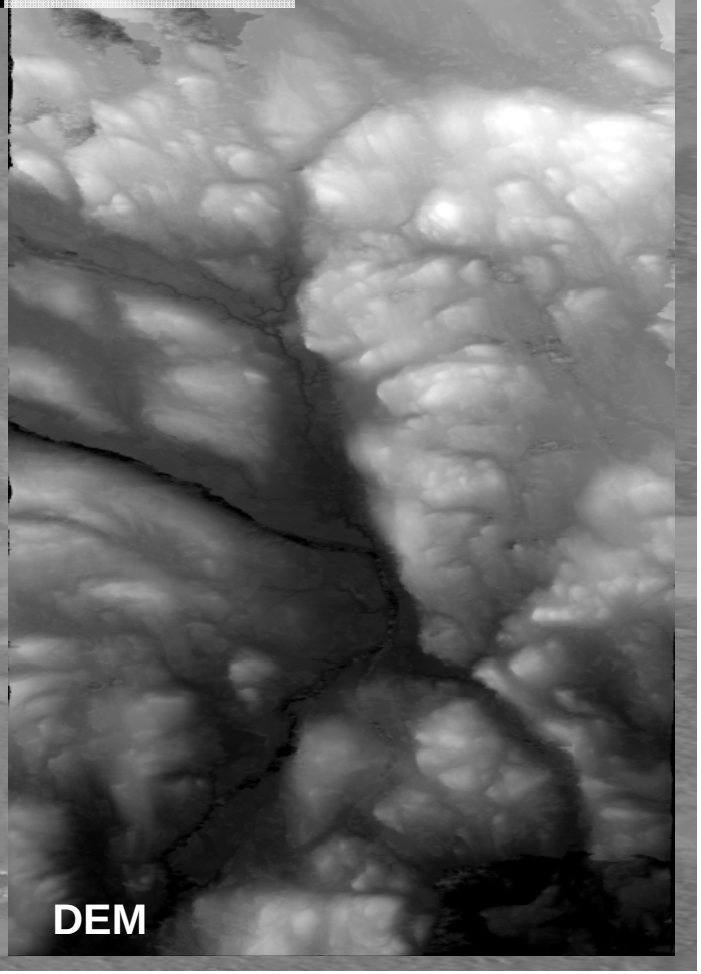
- transmitter alternates between PRF pulses
- provides three interferograms with two baselines in a single pass
- enables precise phase synchronisation, calibration & verification

Standard DEM Mode

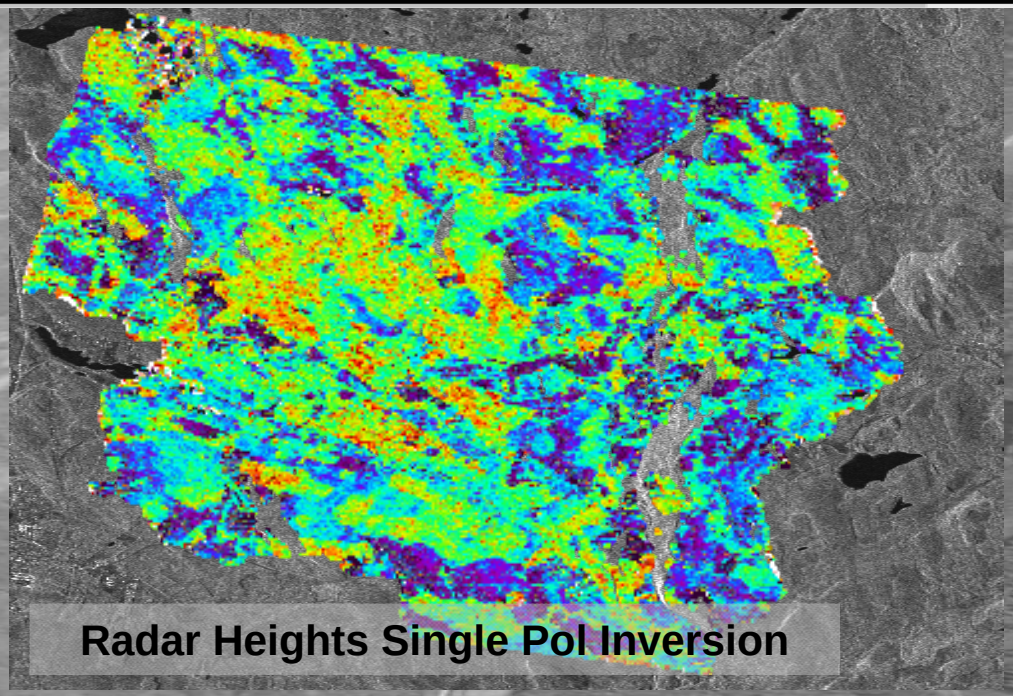
Test Site: Krycklan, Sweden

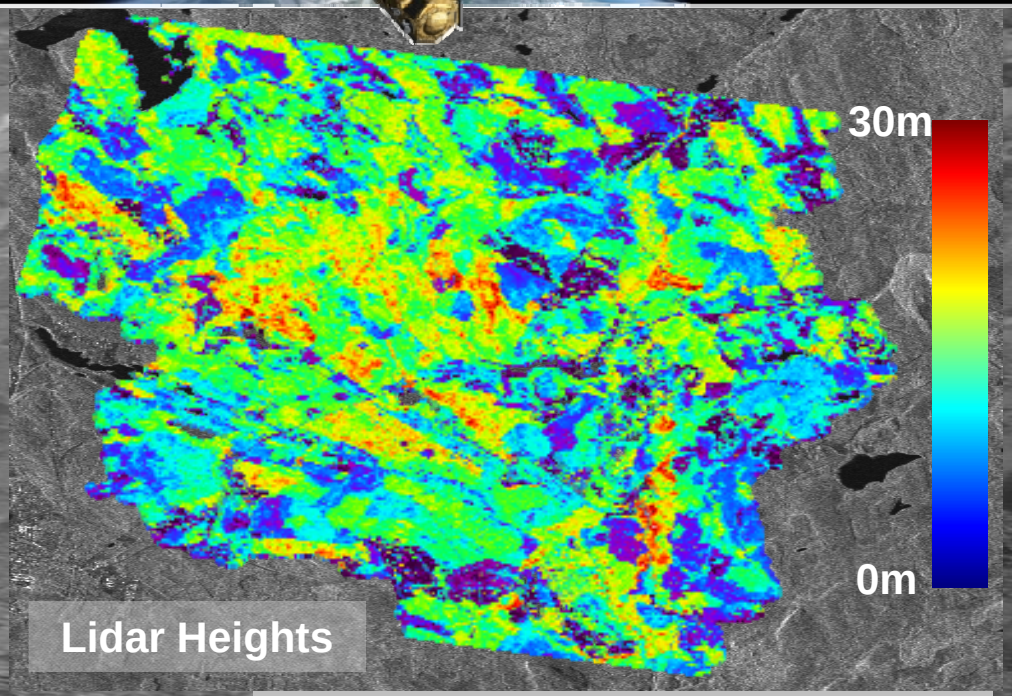
Date	Baseline [m]	Incidence angle	K_z	Height of ambiguity	Polarisation
19. August 2010	137	32°	0.17	38m	HH / VV

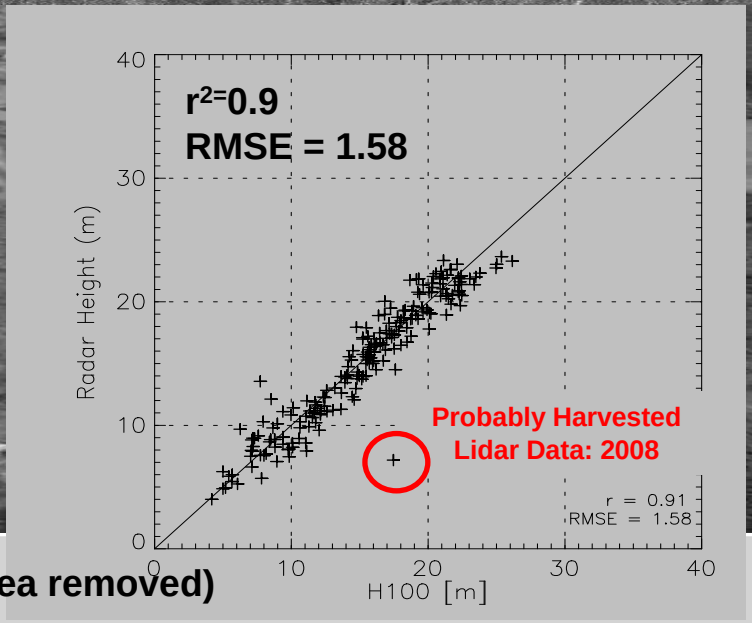




Forest Height Estimation: 1 Pol + DEM

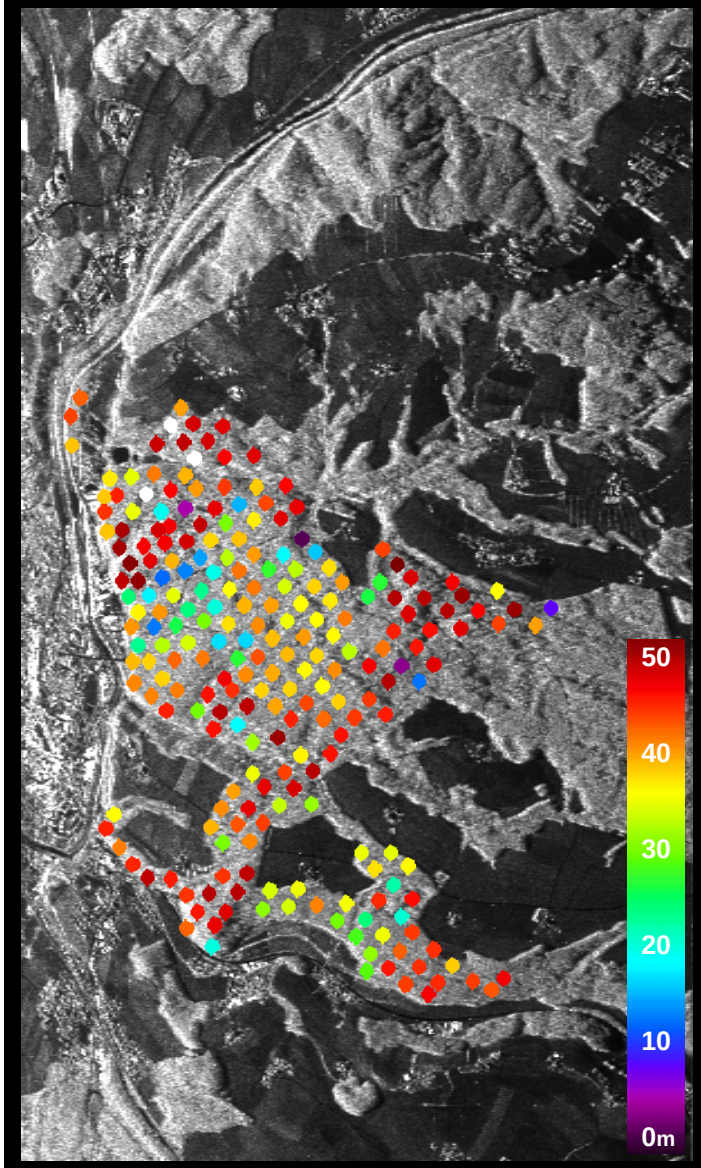


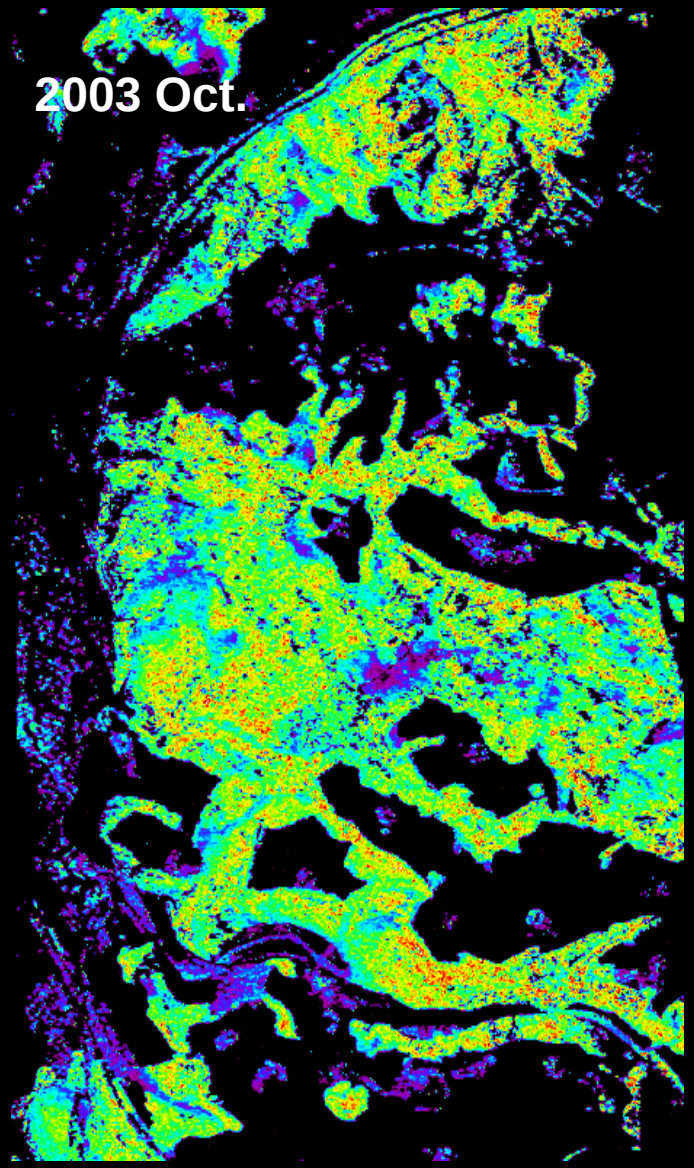


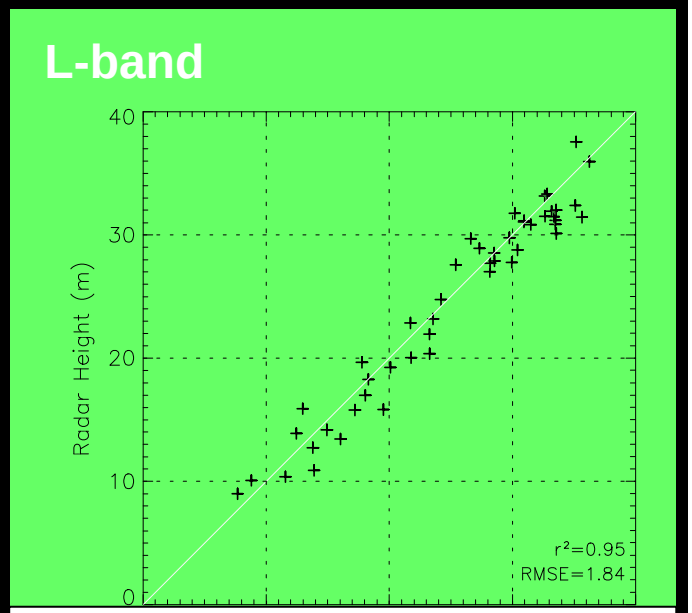


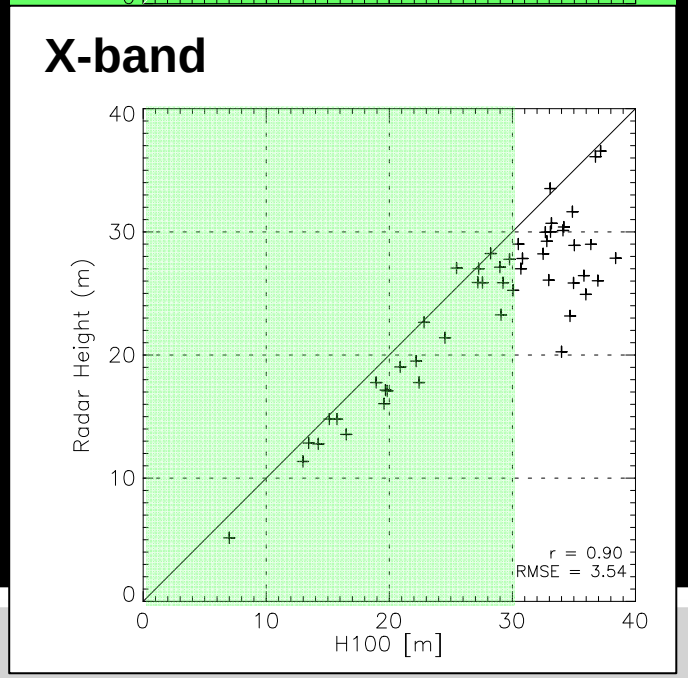
$r^2 = 0.91$ - $r^2 = 0.93$ (harvested area removed)

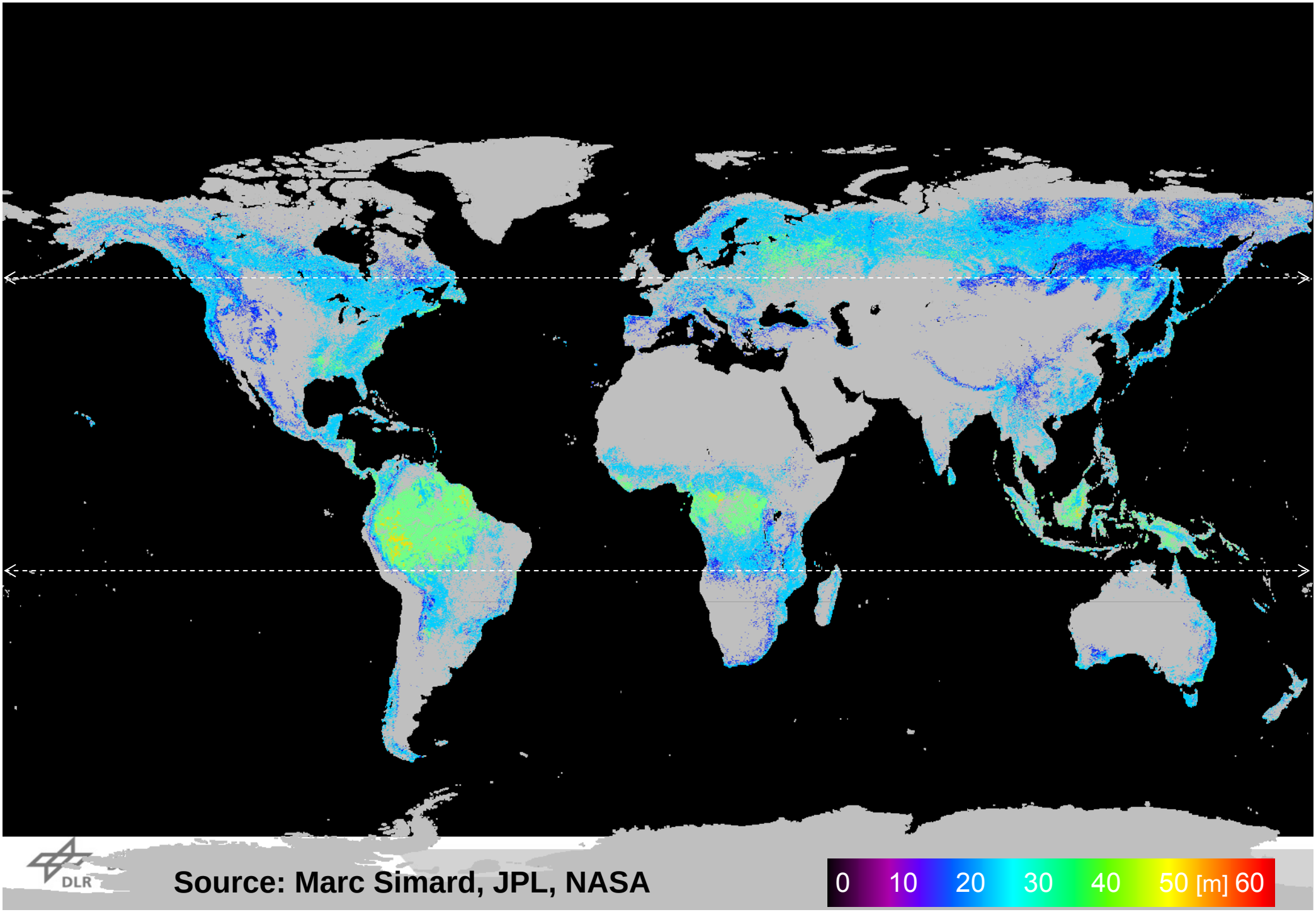
Traunstein Test Site











Source: Marc Simard, JPL, NASA

Here we are …

Multi-Baseline Polarimetric SAR Interferometry:

- Accurate (<10%) estimation of forest top height at high spatial resolutions (20-50m Grid);
- Low frequency vertical forest structure can be resolved by a “realistic” number of acquisitions (20-50m Grid).

Above ground forest Biomass:

- Structure based (AG) Biomass estimators promise accuracy and stability across very different forest conditions;
- Mapping of “radar” structure to biomass structure has to be resolved.

Implementation:

- Choice of Frequency is associated with certain physical limitations as well as implementation constrains:

  L-band is - for most forest conditions - the “optimum” frequency for vegetation structure parameter estimation.

- Temporal decorrelation is the most critical parameter with respect to Pol-InSAR performance

Uniqueness of Pol-InSAR: Global Mapping @ High Spatial Resolution

State of the art implementation is able to provide at a spatial resolution on the order of 7x2m

global (**single/dual-pol**) coverage every week

- ► forest / non-forest mapping at 10x10m

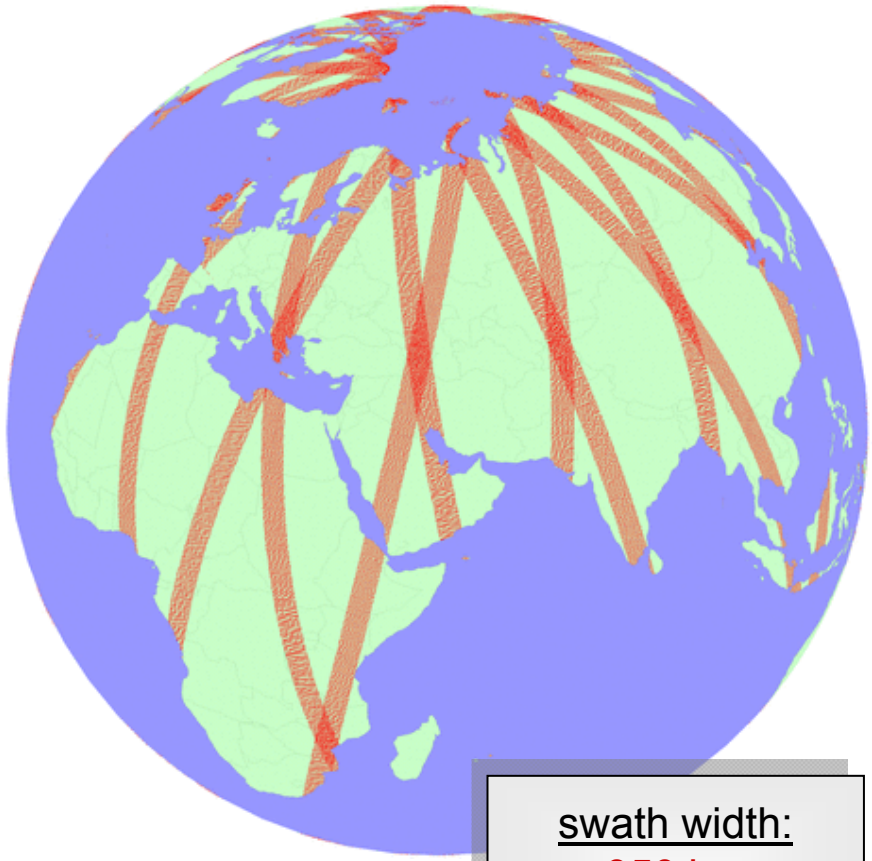
global (**quad-pol**) coverage every 2 weeks

- ► forest height change detection at 30x30m

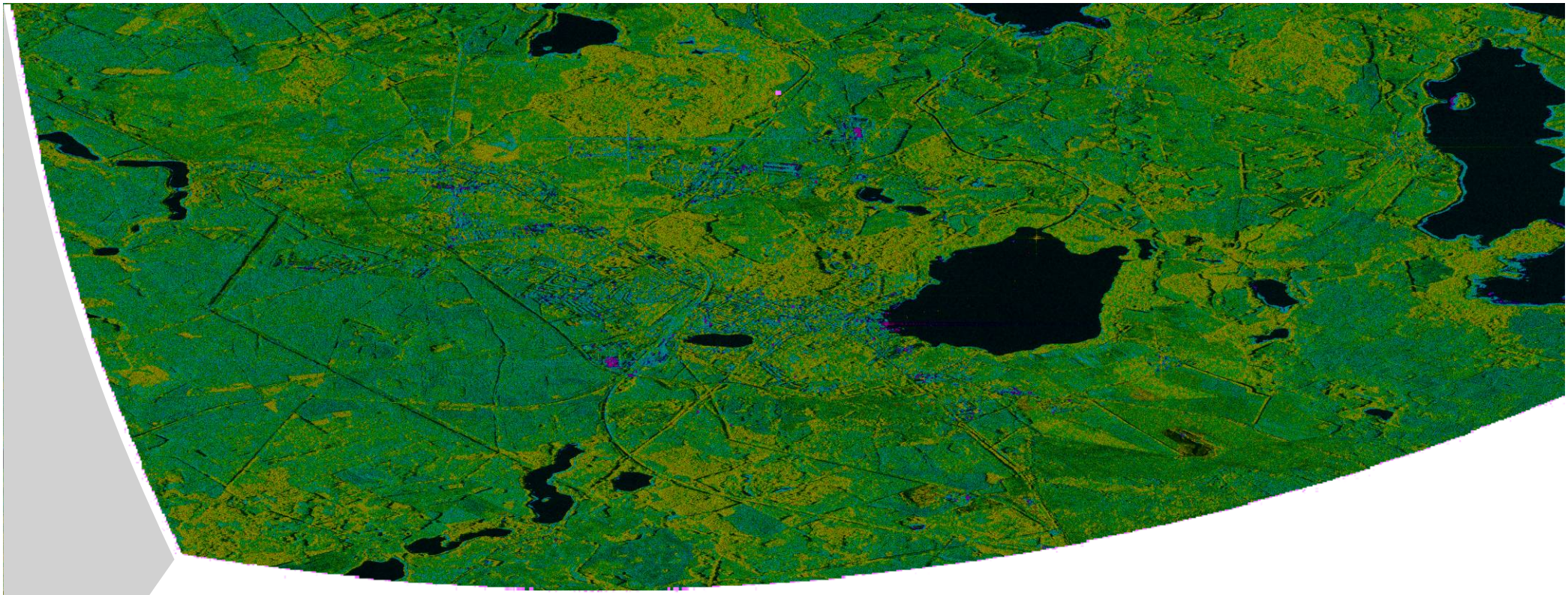
global structure map (6 baselines) every 2 months

- ► forest height map at 30x30m
- ► forest structure map 50x50m

Day 1



swath width:
350 km
duty cycle:
30 min / Orbit



Polarimetric SAR Interferometry (Pol-InSAR)

for Structural Forest Parameter Estimation

K. Papathanassiou, F. Kugler, A. Torano Caioya, M. Padrini, I. Hajnsek

German Aerospace Center (DLR)

Microwaves and Radar Institute (DLR-HR)