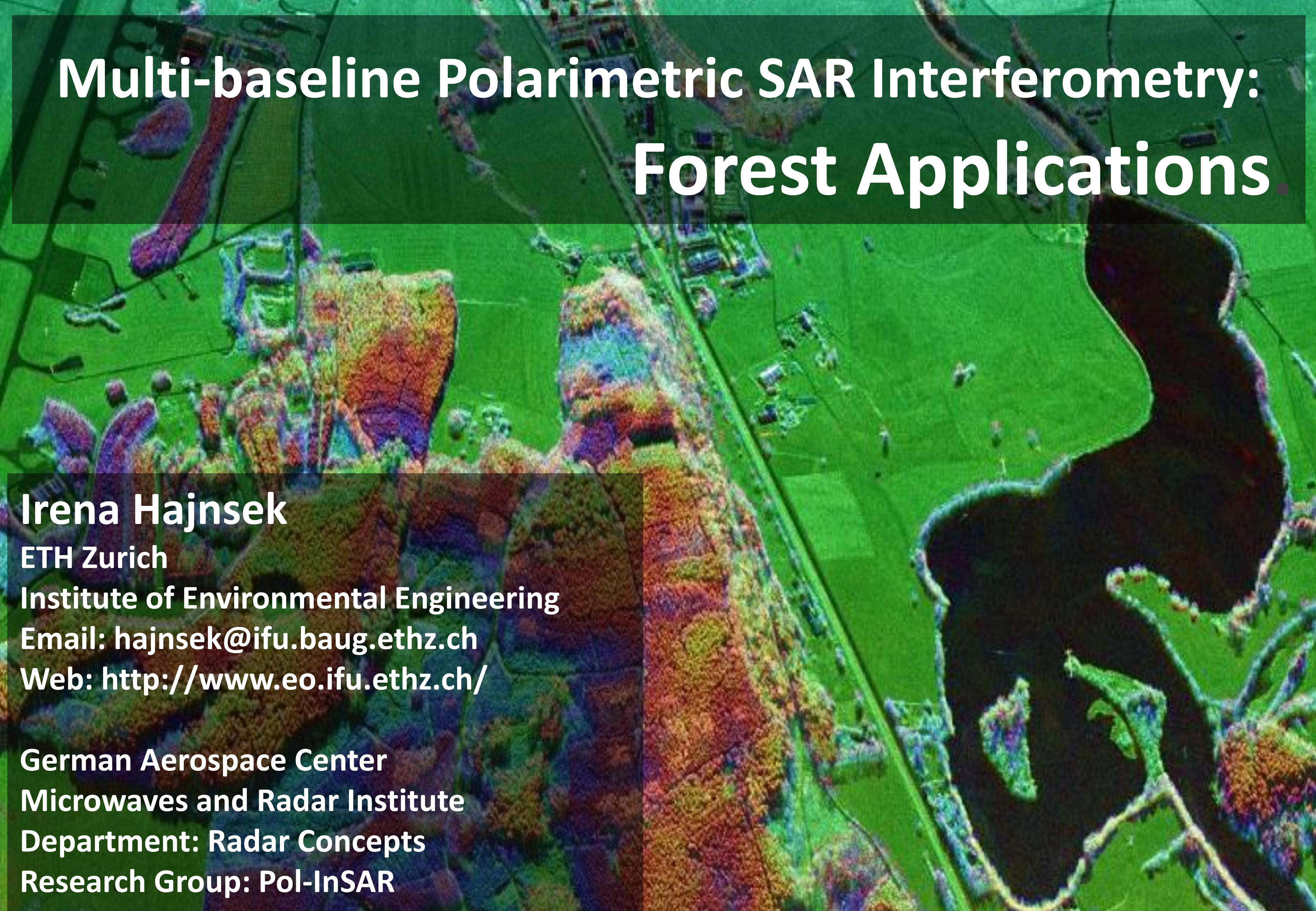

Multi-baseline Polarimetric SAR Interferometry: Forest Applications

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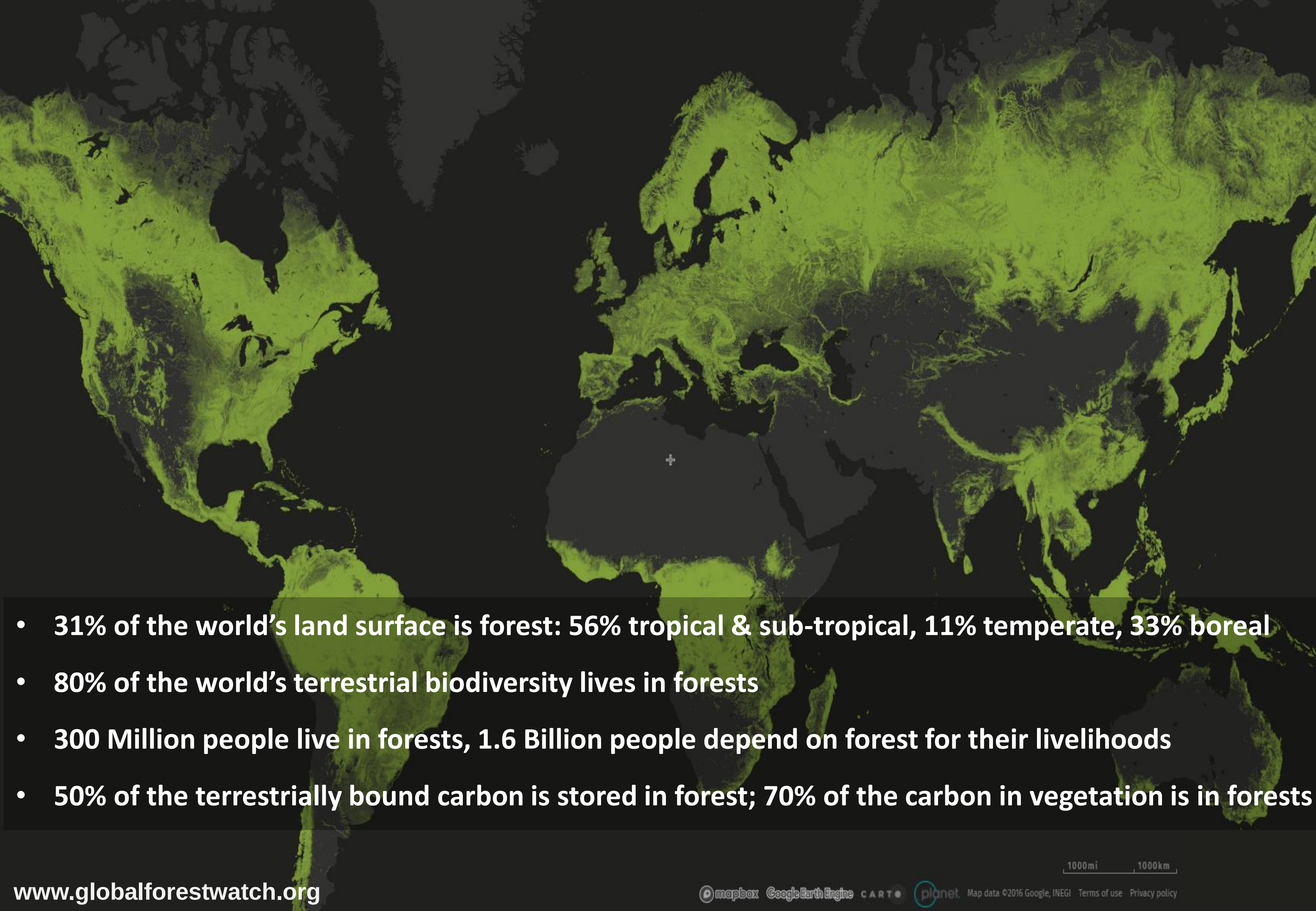
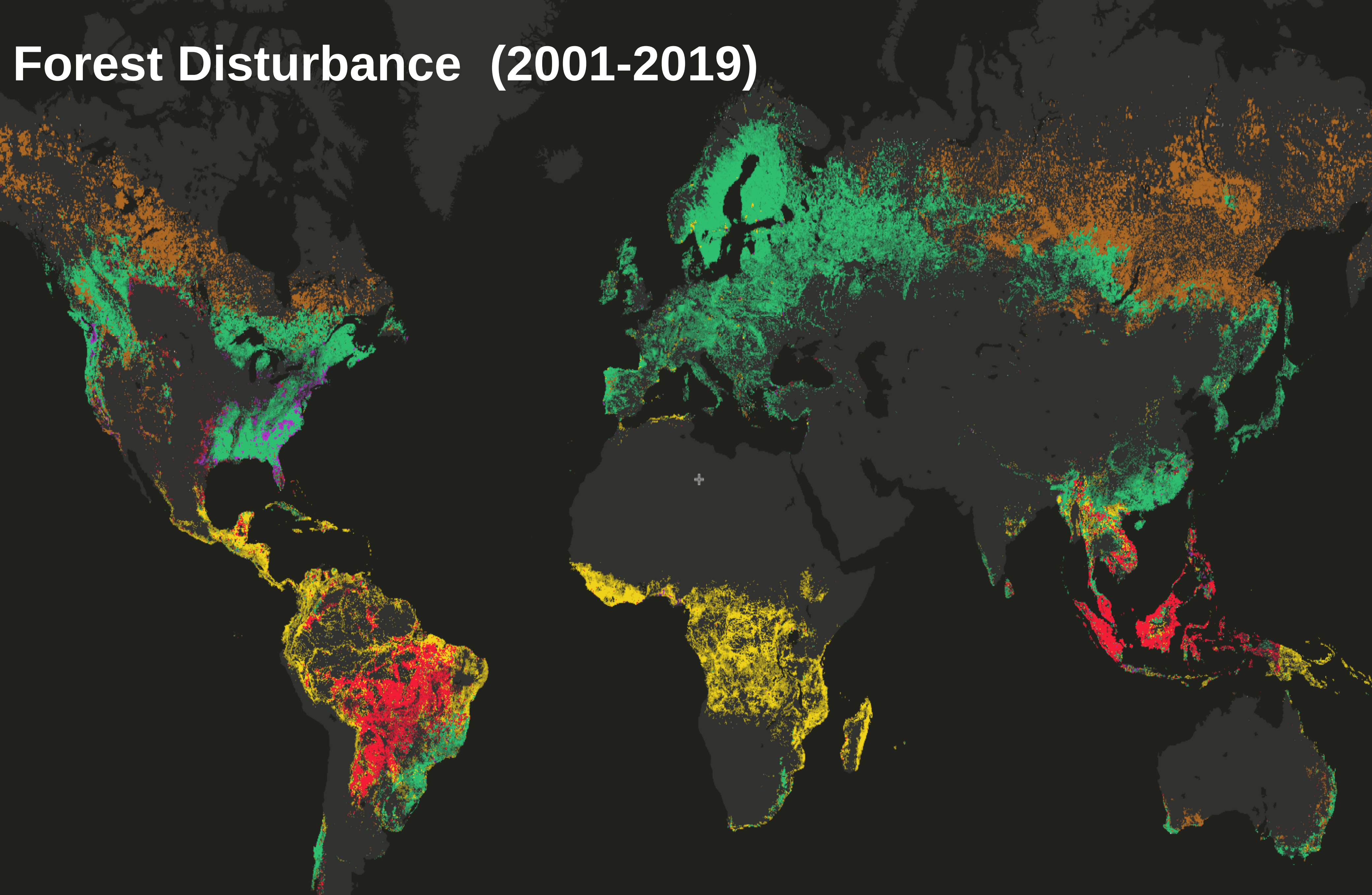
German Aerospace Center
Microwaves and Radar Institute
Department: Radar Concepts
Research Group: Pol-InSAR



- **31% of the world's land surface is forest: 56% tropical & sub-tropical, 11% temperate, 33% boreal**
- **80% of the world's terrestrial biodiversity lives in forests**
- **300 Million people live in forests, 1.6 Billion people depend on forest for their livelihoods**
- **50% of the terrestrially bound carbon is stored in forest; 70% of the carbon in vegetation is in forests**

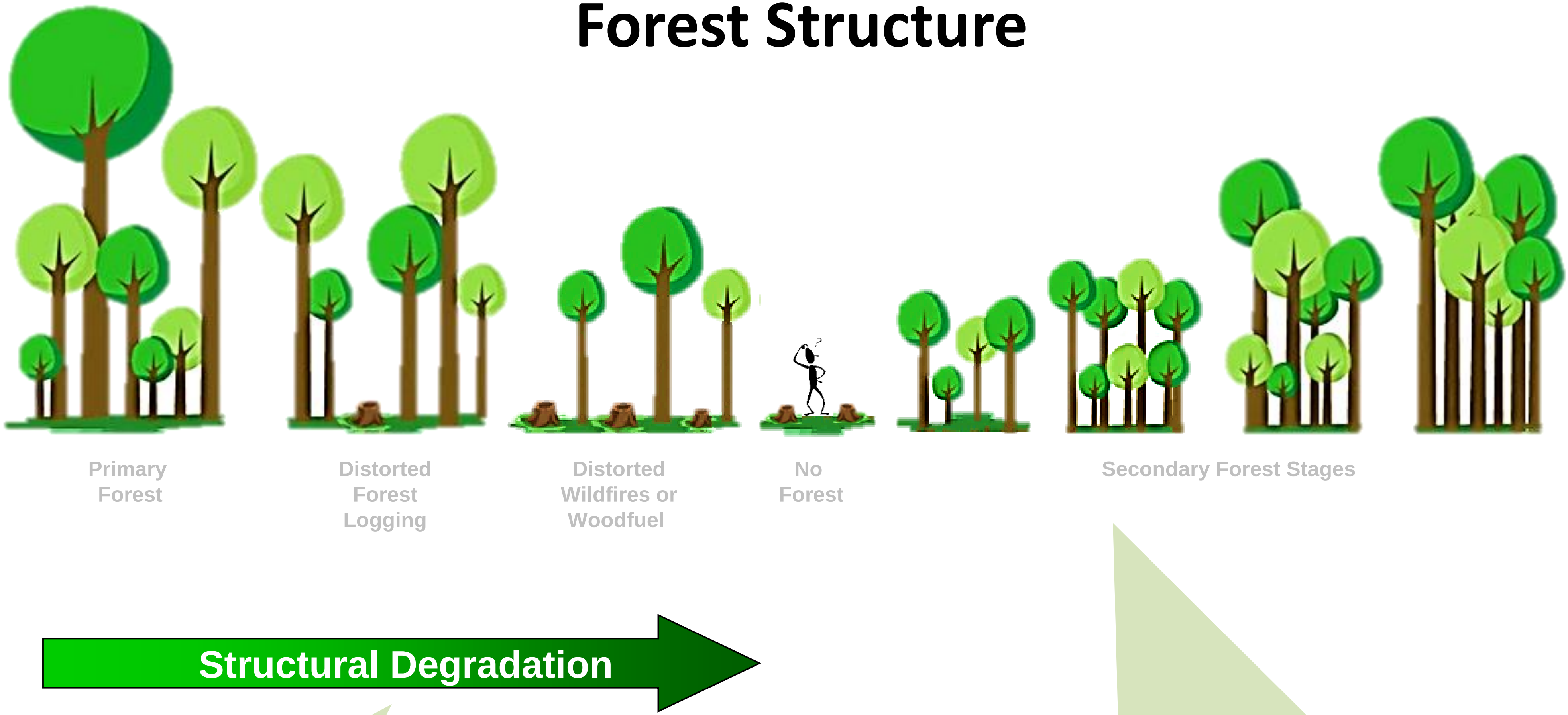
www.globalforestwatch.org

Forest Disturbance (2001-2019)



Commodity Driven Deforestration, Shifting Agriculture, Forestry, Wildfire, Urbanisation Curtis er al. 2018

Forest Structure



Degraded forests: forests which have been harvested beyond the natural growth capacity.

Secondary Forests: forests regenerating through a natural succession process after significant and/or total disturbance of the original forest. They show major difference in structure, species composition, and age profile compared to primary forests.

Climate change can modify role of vegetation

Europe 2003 drought:

30% decrease of productivity, forest transforms from C-sink 0.3 GtC to C-source: -0.5 GtC

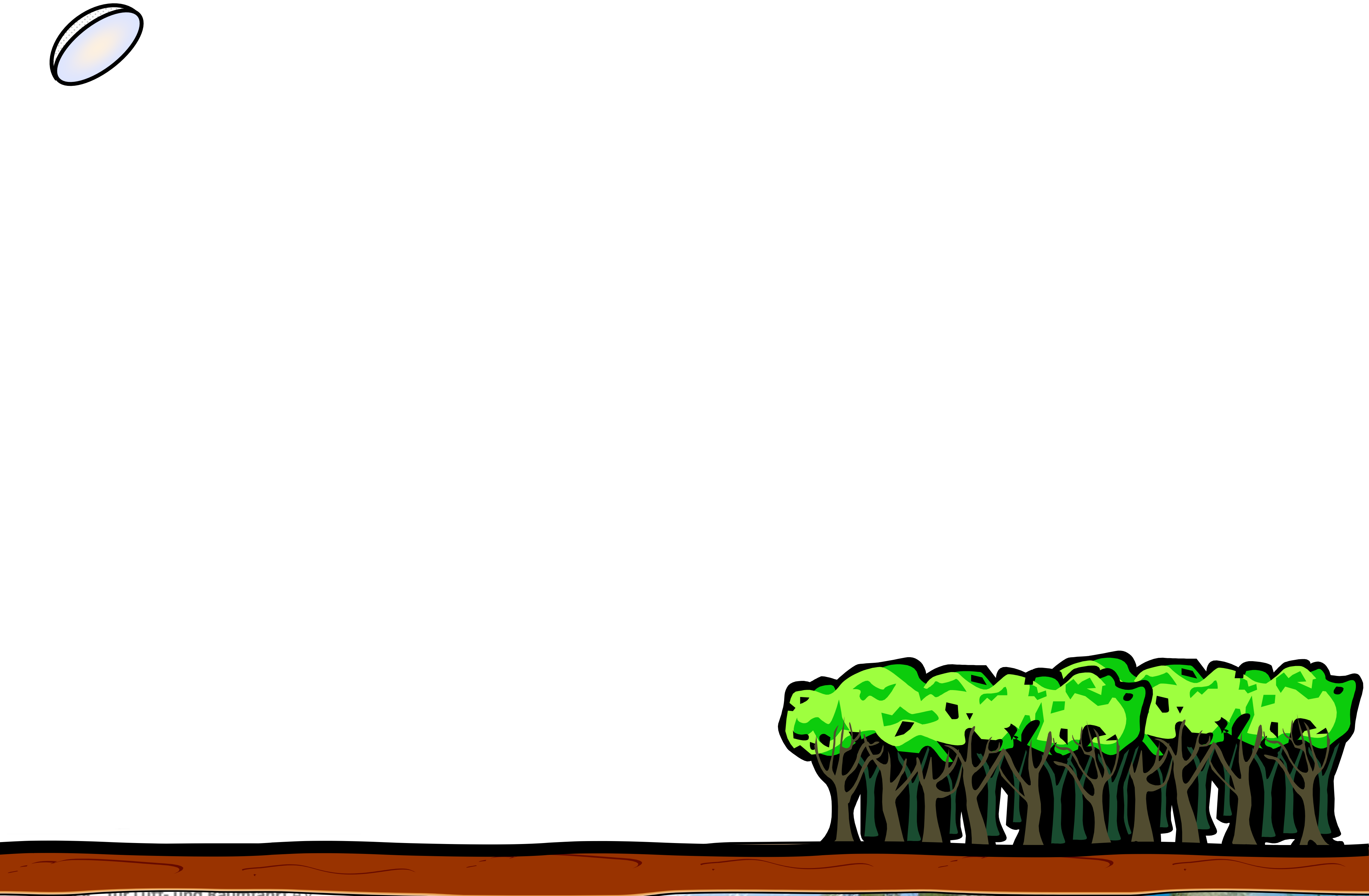
(Cias et al. 2005, Nature)

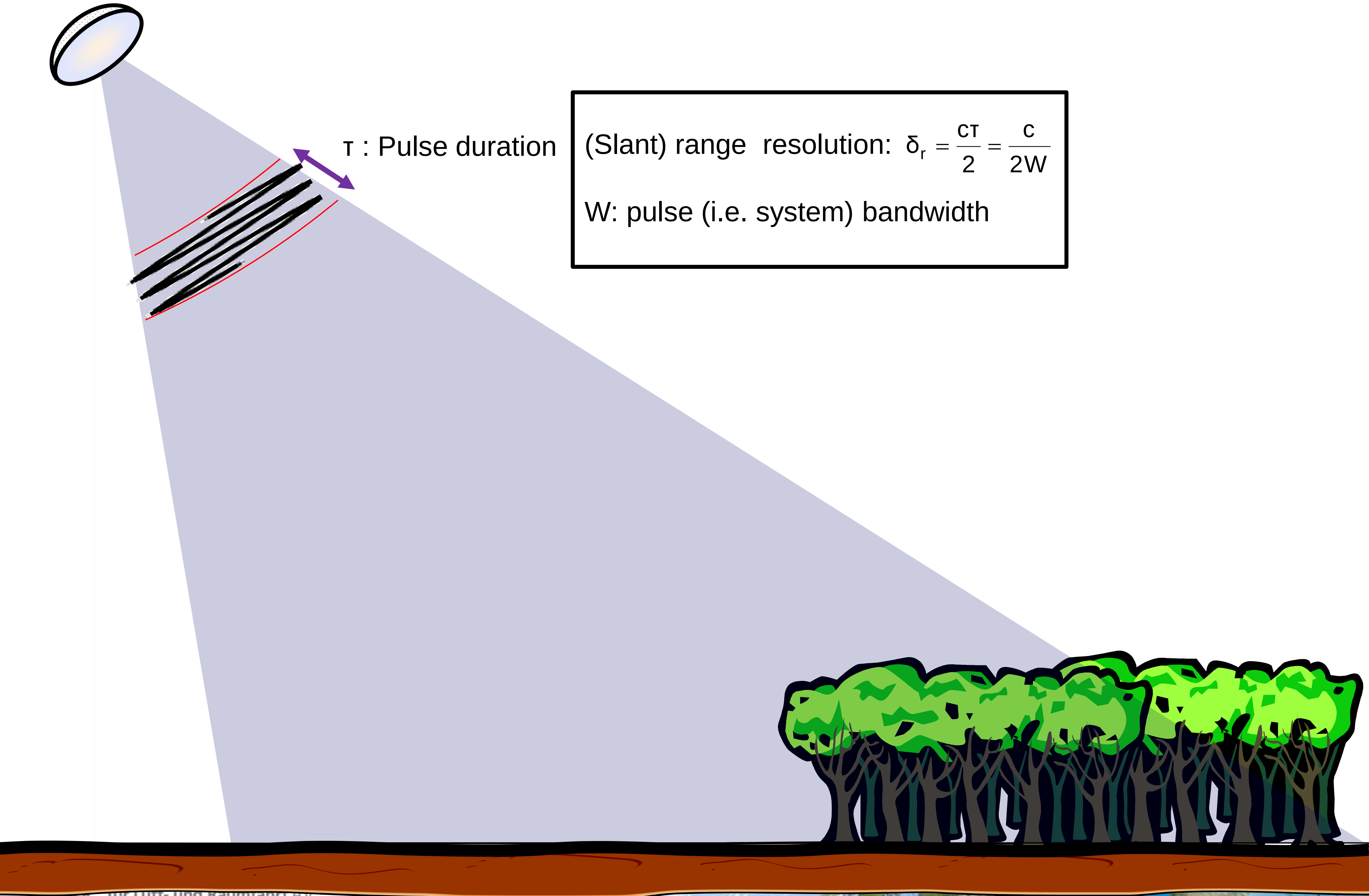
Amazon 2005 and 2010 droughts:

forests transforms from C-sink 0.5 GtC to C-source -1.2 GtC

(Phillips et al. 2009, Science, Lewis et al. 2011, Nature)

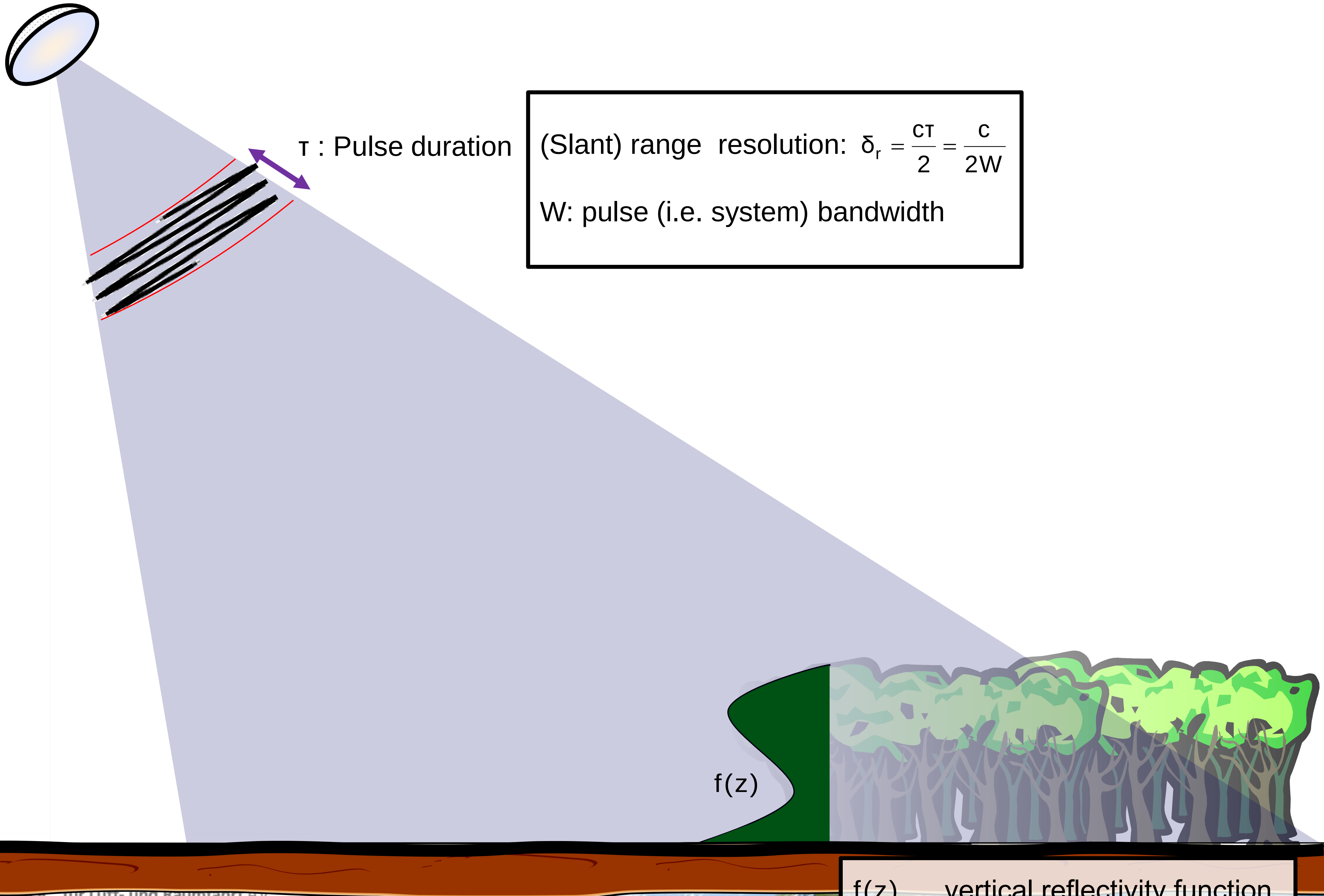
Does vegetation act as a carbon sink also in the future ?

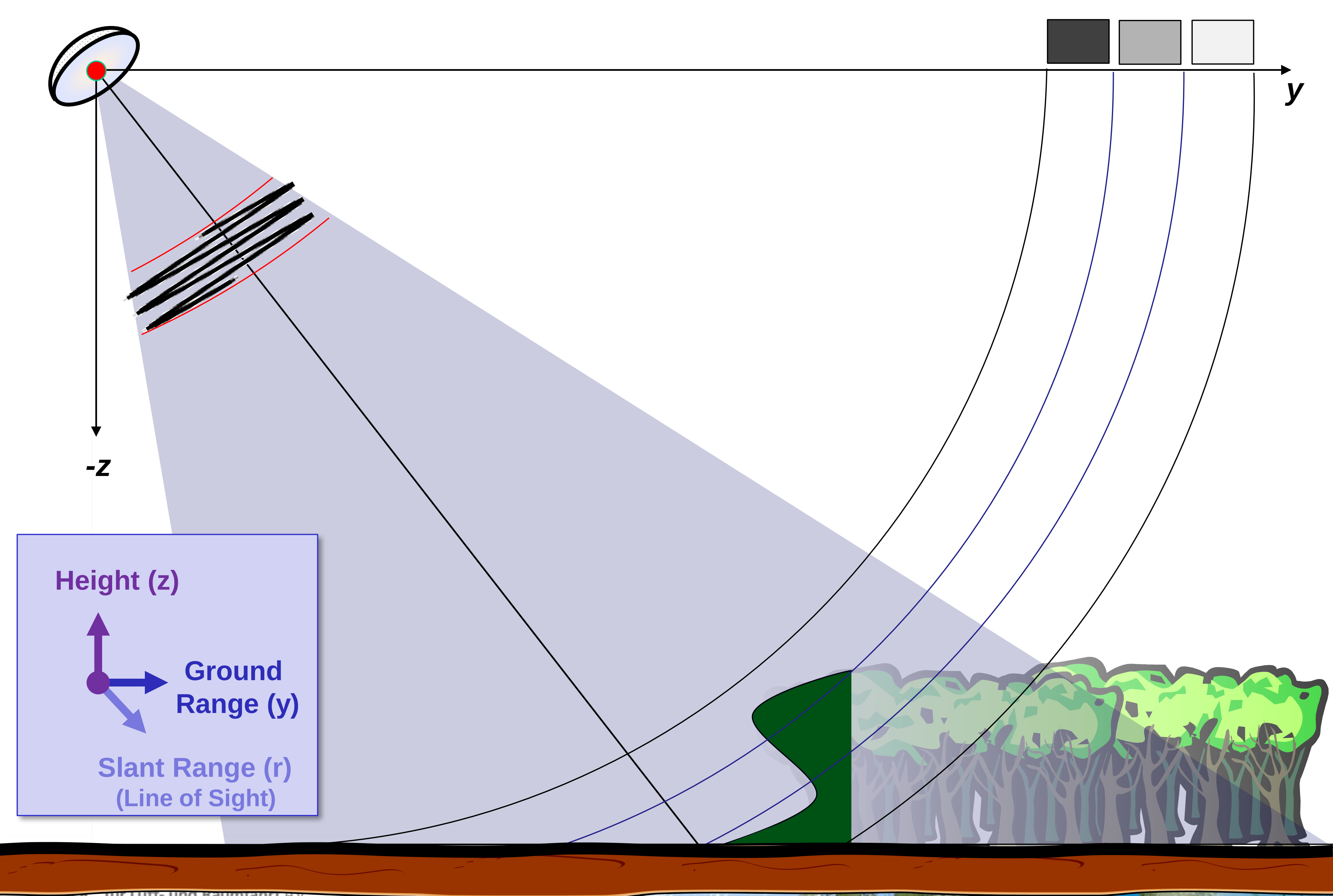


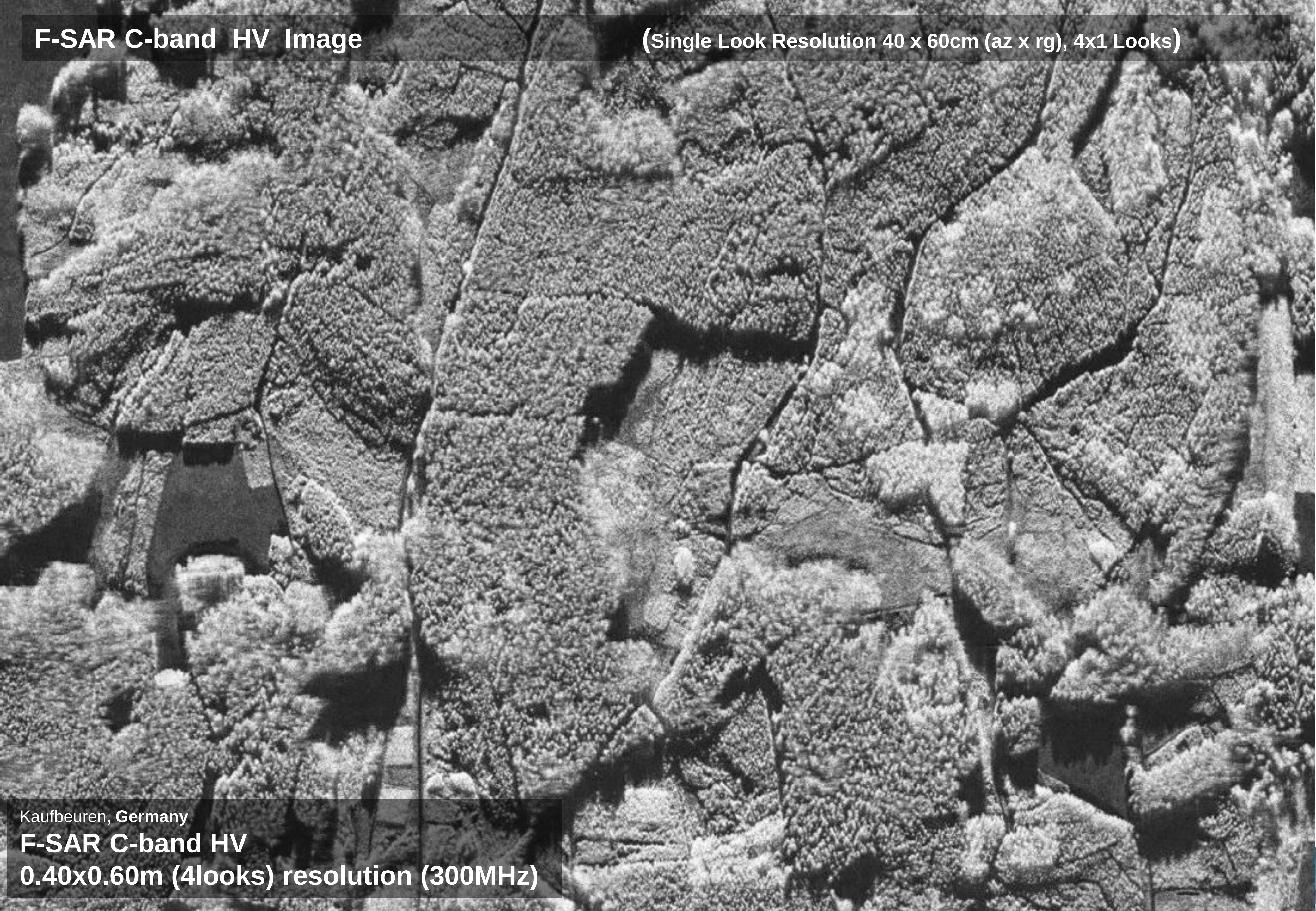


(Slant) range resolution: $\delta_r = \frac{c\tau}{2} = \frac{c}{2W}$

W: pulse (i.e. system) bandwidth

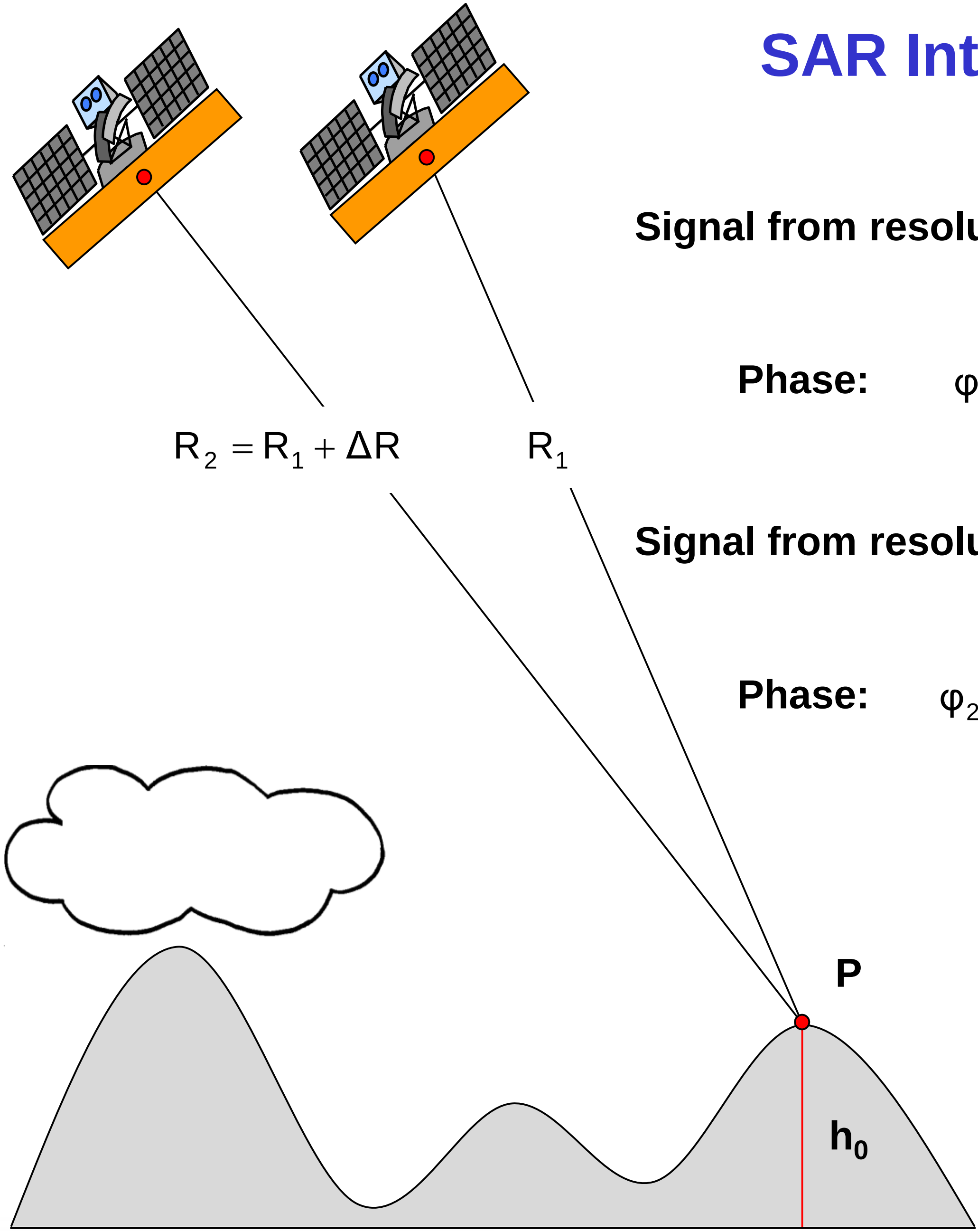

τ : Pulse duration
(Slant) range resolution: $\delta_r = \frac{c\tau}{2} = \frac{c}{2W}$
W: pulse (i.e. system) bandwidth
f(z)
f(z) … vertical reflectivity function


y
-z
Height (z)
Ground Range (y)
Slant Range (r)
(Line of Sight)


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)

Amazon Deforest Watch (Santarem) ALOS PalSAR

SAR Interferometry



Signal from resolution cell P in Image 1: $i_1 = |i_1| \exp[-i(2\frac{2\pi}{\lambda}R_1) + \varphi_{S1}]$

Phase: $\varphi_1 = \arg(i_1) = (2\frac{2\pi}{\lambda}R_1) + \varphi_{S1}$

Signal from resolution cell P in Image 2: $i_2 = |i_2| \exp[-i(2\frac{2\pi}{\lambda}R_2) + \varphi_{S2}]$

Phase: $\varphi_2 = \arg(i_2) = (2\frac{2\pi}{\lambda}R_2) + \varphi_{S2}$

Assuming $\varphi_{S1} = \varphi_{S2}$ **!!!**

Interferogram: $i_1 i_2^* = |i_1 i_2^*| \exp[-i(2\frac{2\pi}{\lambda}\Delta R)]$

Phase: $\varphi_{Int} = \frac{\mathrm{Re}\{i_1 i_2^*\}}{\mathrm{Im}\{i_1 i_2^*\}} = 2\frac{2\pi}{\lambda}\Delta R$

Deterministic !!!

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

Interferometric Coherence

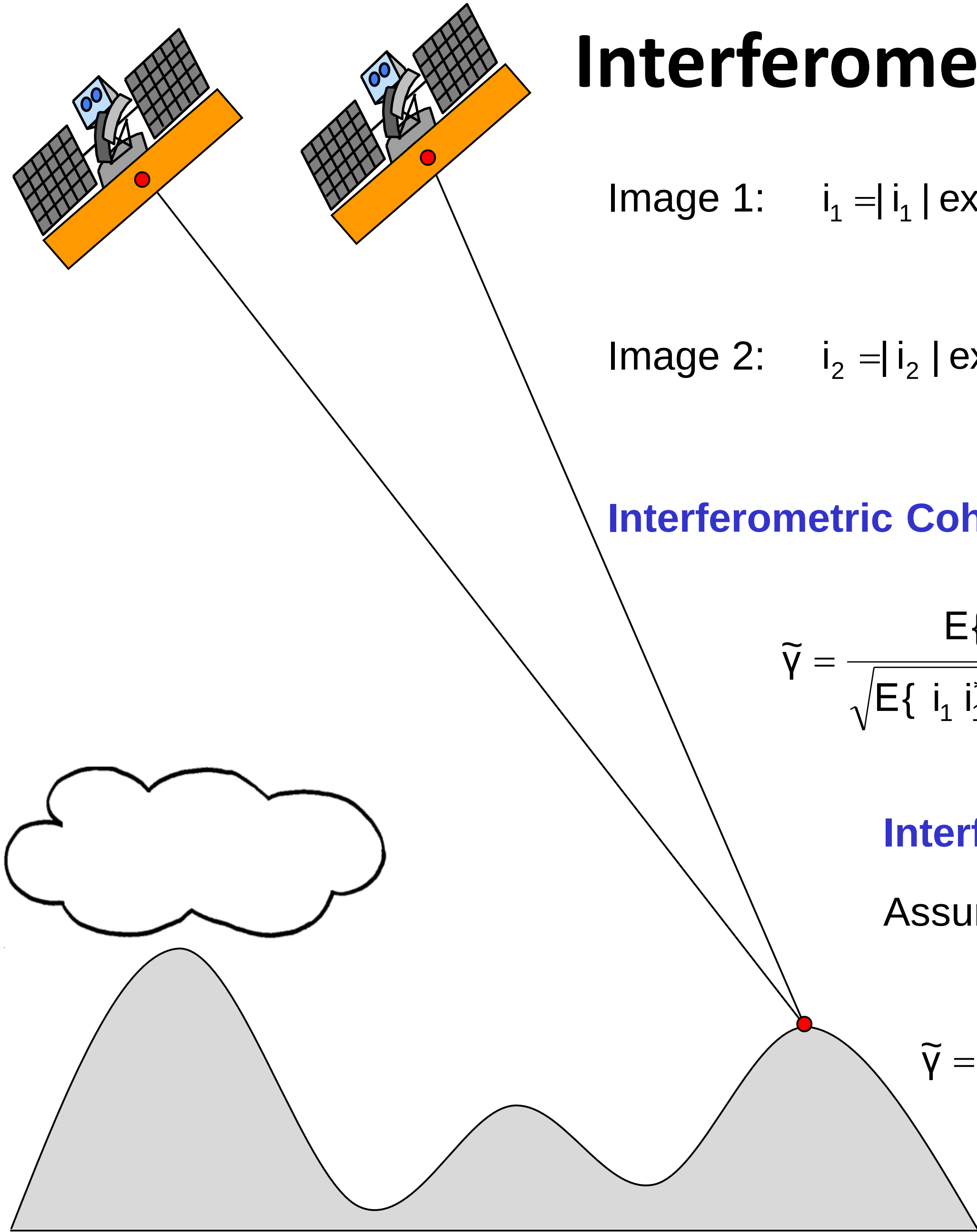


Image 1: $i_1 = |i_1| \exp[-i(2\frac{2\pi}{\lambda}R_1) + \varphi_{S1}]$

Image 2: $i_2 = |i_2| \exp[-i(2\frac{2\pi}{\lambda}R_2) + \varphi_{S2}]$

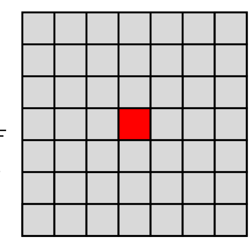
Interferometric Coherence: Normalised Complex Correlation Coefficient

$$\tilde{\gamma} = \frac{E\{\, i_1 i_2^* \,\}}{\sqrt{E\{\, i_1 i_1^* \,\}\; E\{\, i_2 i_2^* \,\}}} = \frac{|E\{\, i_1 i_2^* \,\}|\exp(i\varphi)}{\sqrt{E\{|i_1|^2\}\; E\{|i_2|^2\}}} \qquad 0 \leq |\tilde{\gamma}| \leq 1$$

Interferometric Coherence Estimation:

Assuming stationarity within the estimation window:

$$\tilde{\gamma} = \frac{\sum_{W} i_1[i,j]\; i_2^*[i,j]}{\sqrt{\sum_{W} |i_1[i,j]|^2 \sum_{W} |i_2[i,j]|^2}} = \frac{< i_1\, i_2^* >}{\sqrt{< i_1\, i_1^* >\; < i_2\, i_2^* >}}$$



Typical window size: 10 (3x3) – >100 pixels

InSAR Coherence

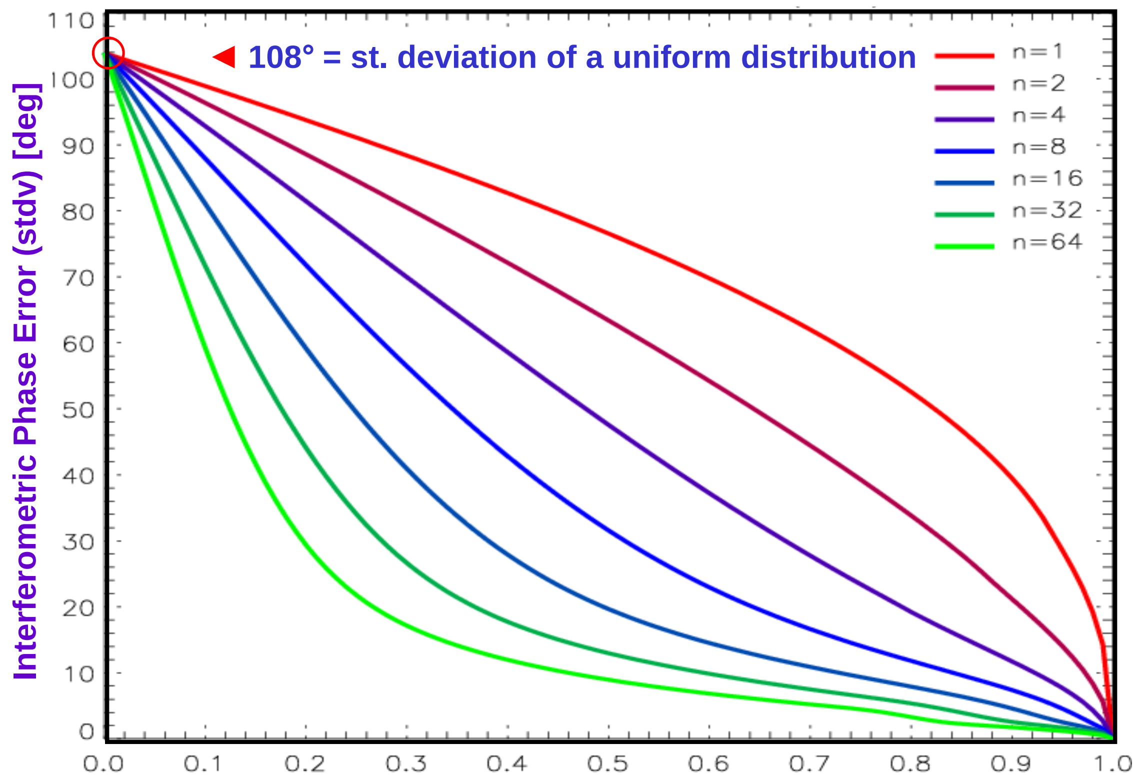
... is a measure of interferogram quality:

Standard Deviation of the InSAR Phase φ:

$$\sigma_\varphi = \sqrt{\int_{-\pi}^{\pi} \varphi^2 \mathrm{pdf}(\varphi) \cdot d\varphi}$$

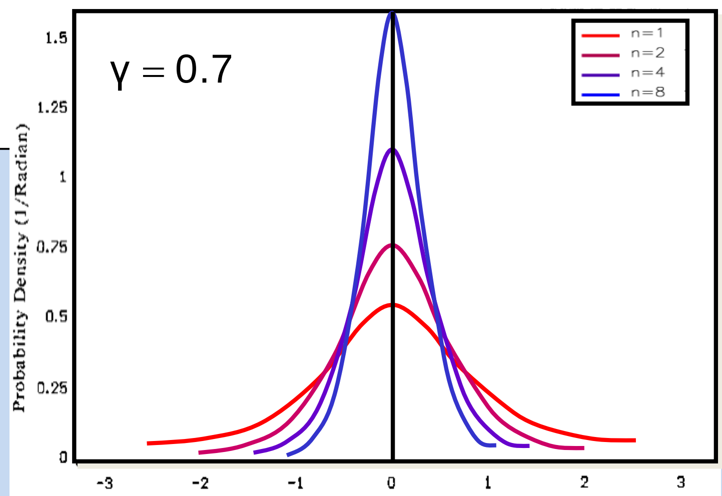
depends on ► the underlying coherence &

► the number of looks N.



An increase in decorrelation (= loss in coherence) is associated with an increase in the phase variance;

► Increased phase variance leads to increased height errors.



where: $\mathrm{pdf}(\varphi, N) = \frac{\Gamma(N+1/2)(1-|\gamma|^2)^2\beta}{2\sqrt{\pi}\Gamma(N)(1-\beta^2)^{N+1/2}} + \frac{(1-|\gamma|^2)^N}{2\pi} F(N,1;1/2;\beta^2)$

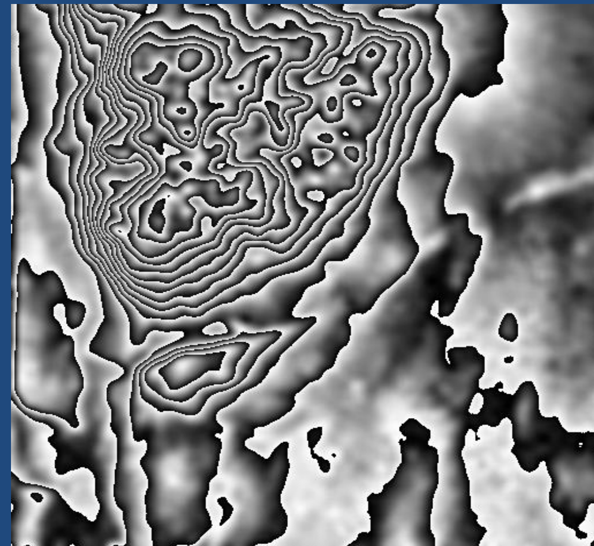
► F is a Gauss hypergeometric function and $\beta = |\gamma| \cos(\varphi - \bar{\varphi})$

► **N is the number of Looks**

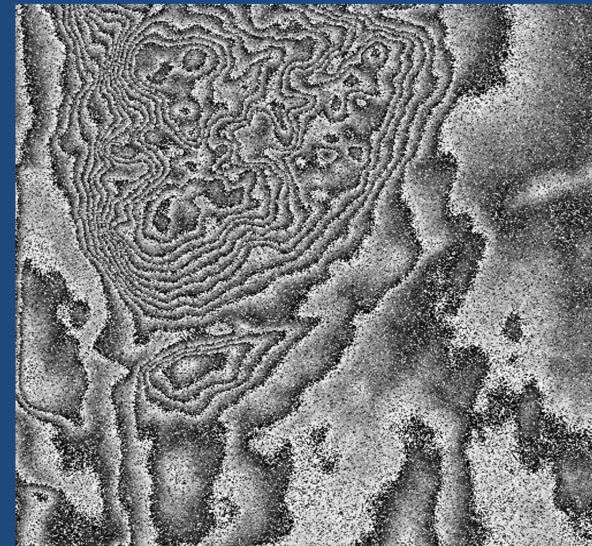
Interferometric Phase Images

Simulation

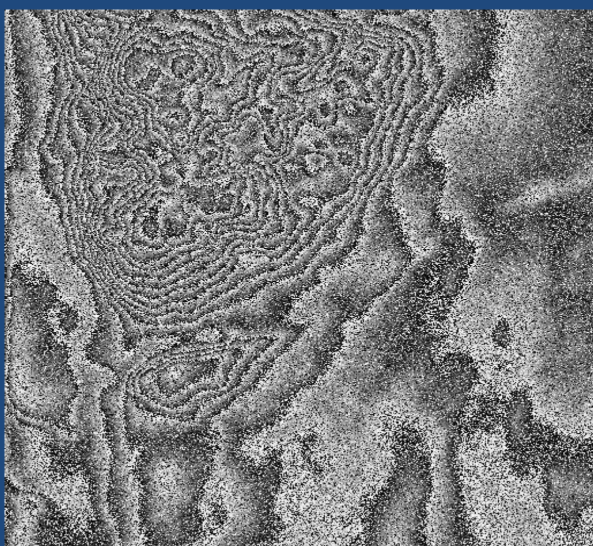
Absolute Phase



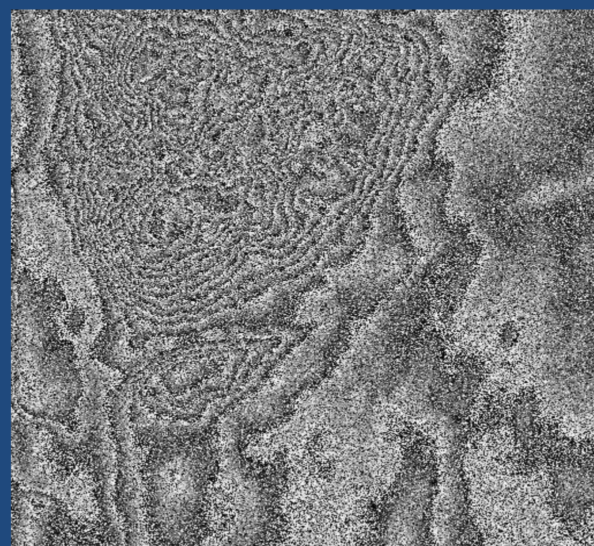
Coherence=1.0 Looks=1



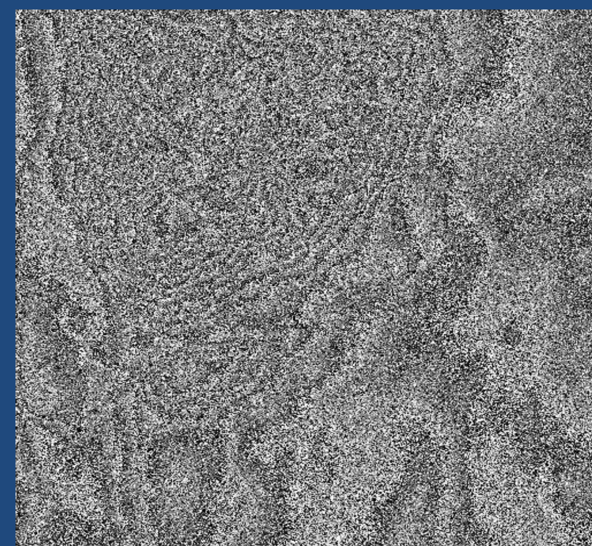
Coherence=0.8 Looks=1



Coherence=0.6 Looks=1

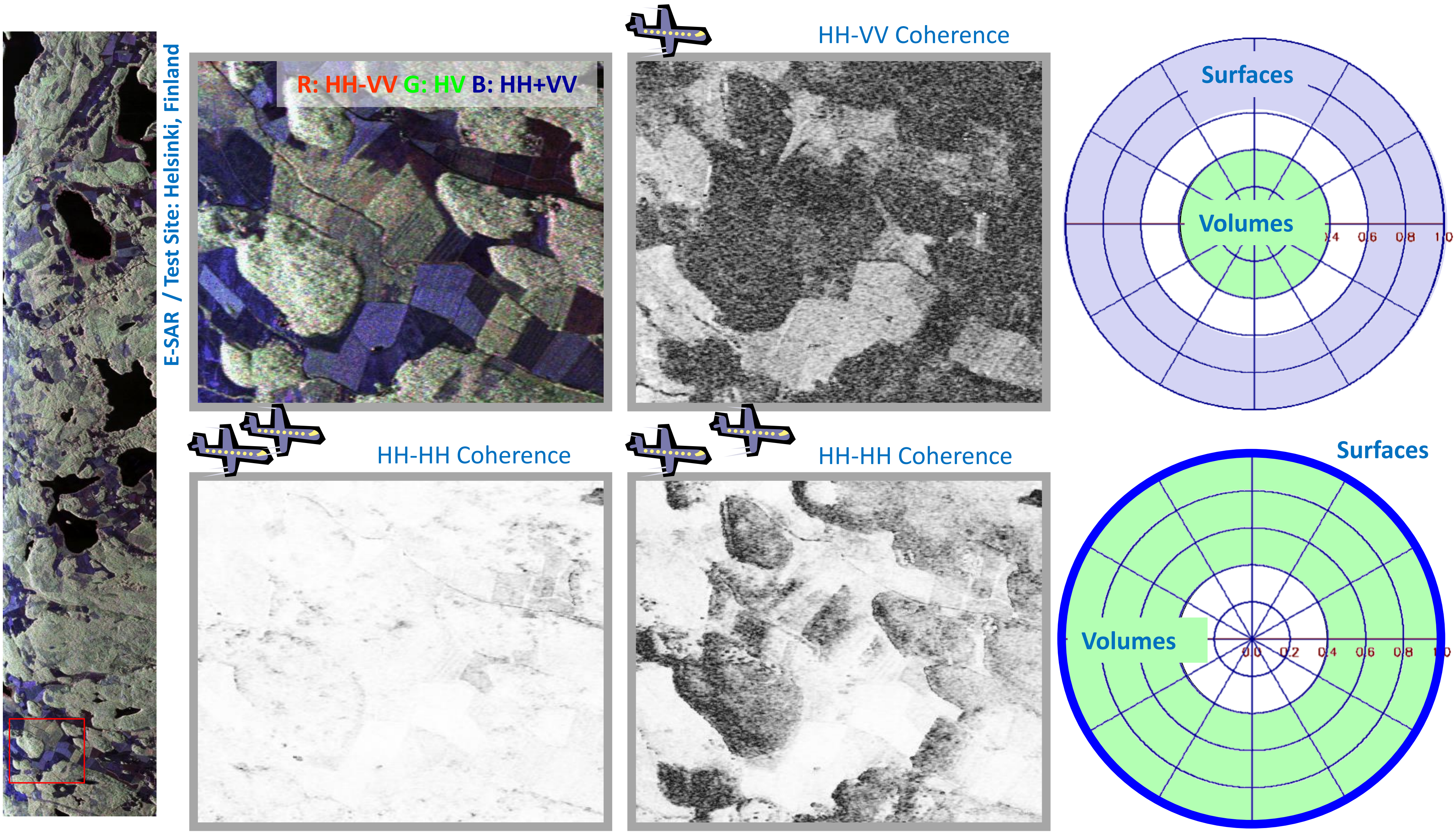


Coherence=0.4 Looks=1



Coherence=0.2 Looks=1

Why is Interferometry important for Volume Scatterers?



SAR Interferometry for Volume Structure

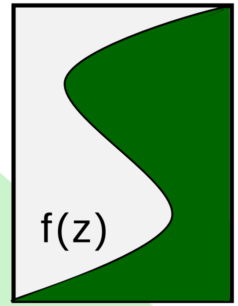
S_1 S_2

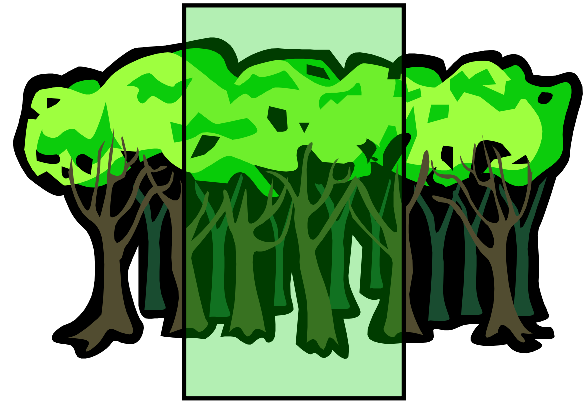
Interferometric Coherence

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

Volume Coherence

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



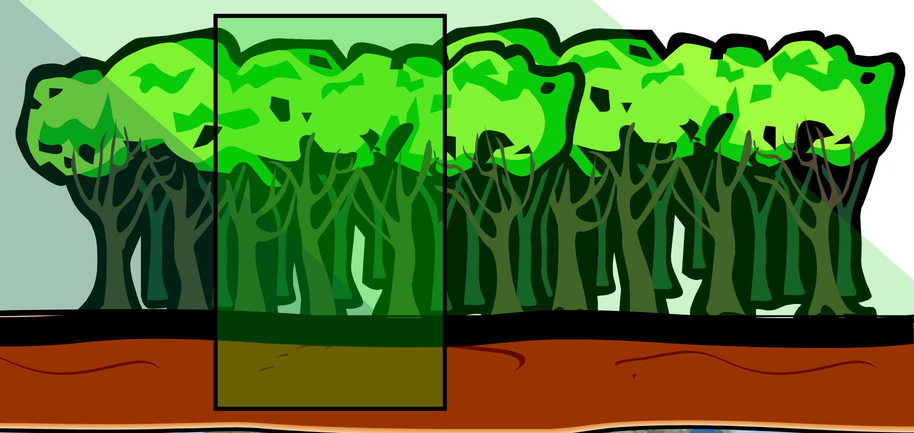


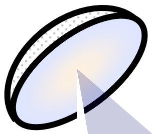
$f(z)$ … vertical reflectivity function

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

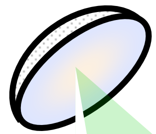
$$\tilde{\gamma} = \tilde{\gamma}_{Temporal} \; \gamma_{SNR} \; \tilde{\gamma}_{Vol}$$

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





S_1 S_2



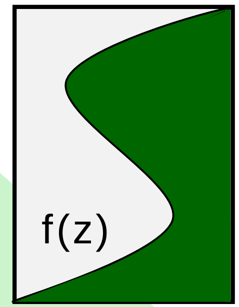
Interferometric Coherence

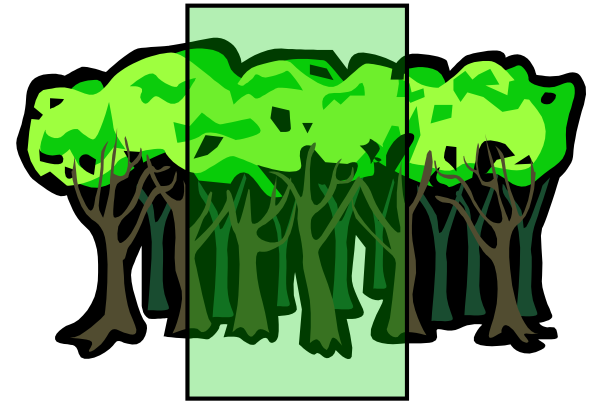
$$\tilde{\gamma}(S_1\,S_2) = \frac{<S_1\,S_2^*>}{\sqrt{<S_1\,S_1^*>\,<S_2\,S_2^*>}}$$

SAR Interferometry for Volume Structure

Volume Coherence

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





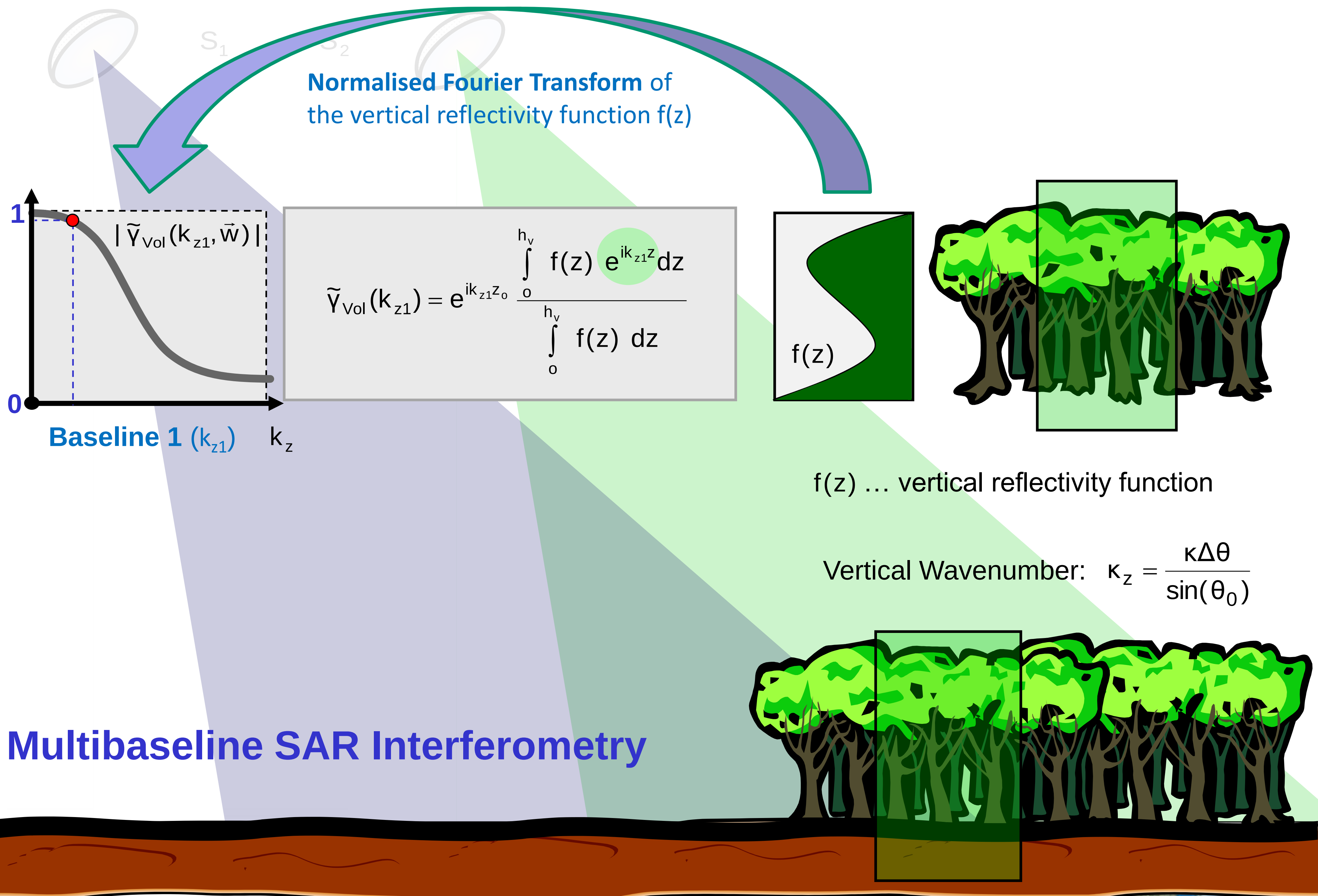
$f(z)$ … vertical reflectivity function

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

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

- $\tilde{\gamma}_{Temporal}$ … 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.



Multibaseline SAR Interferometry

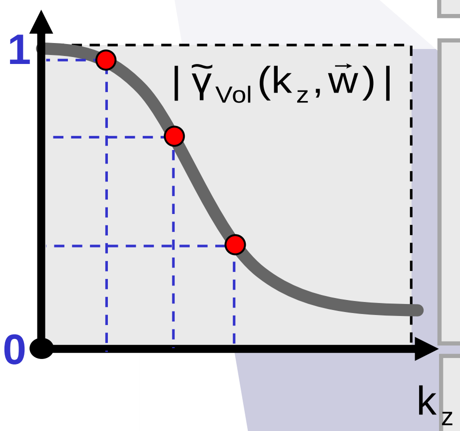
Multibaseline SAR Interferometry

Baseline 3 (k_{z3})

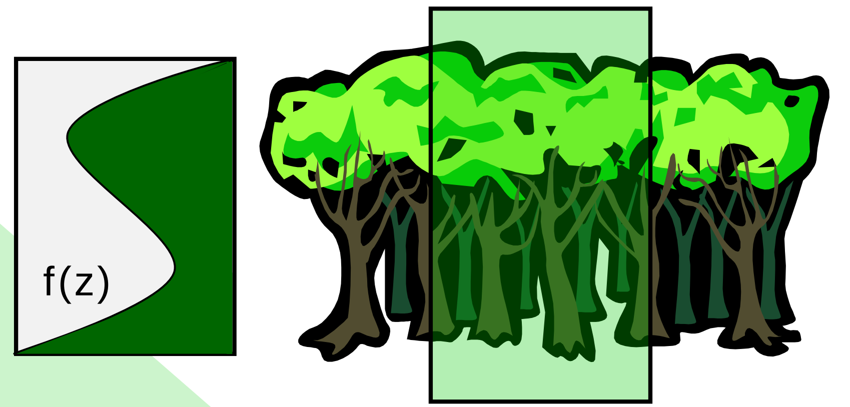
$$\tilde{\gamma}_{Vol}(k_{z3}) = e^{ik_z z_o}\,\frac{\int_o^{h_v} f(z)\, e^{ik_{z3}z}\,dz}{\int_o^{h_v} f(z)\,dz}$$

$$\tilde{\gamma}_{Vol}(k_{z1}) = e^{ik_{z1} z_o}\,\frac{\int_o^{h_v} f(z)\, e^{ik_{z1}z}\,dz}{\int_o^{h_v} f(z)\,dz}$$

$$\tilde{\gamma}_{Vol}(k_{z2}) = e^{ik_z z_o}\,\frac{\int_o^{h_v} f(z)\, e^{ik_{z2}z}\,dz}{\int_o^{h_v} f(z)\,dz}$$



Baseline 2 (k_{z2})



f(z) … vertical reflectivity function

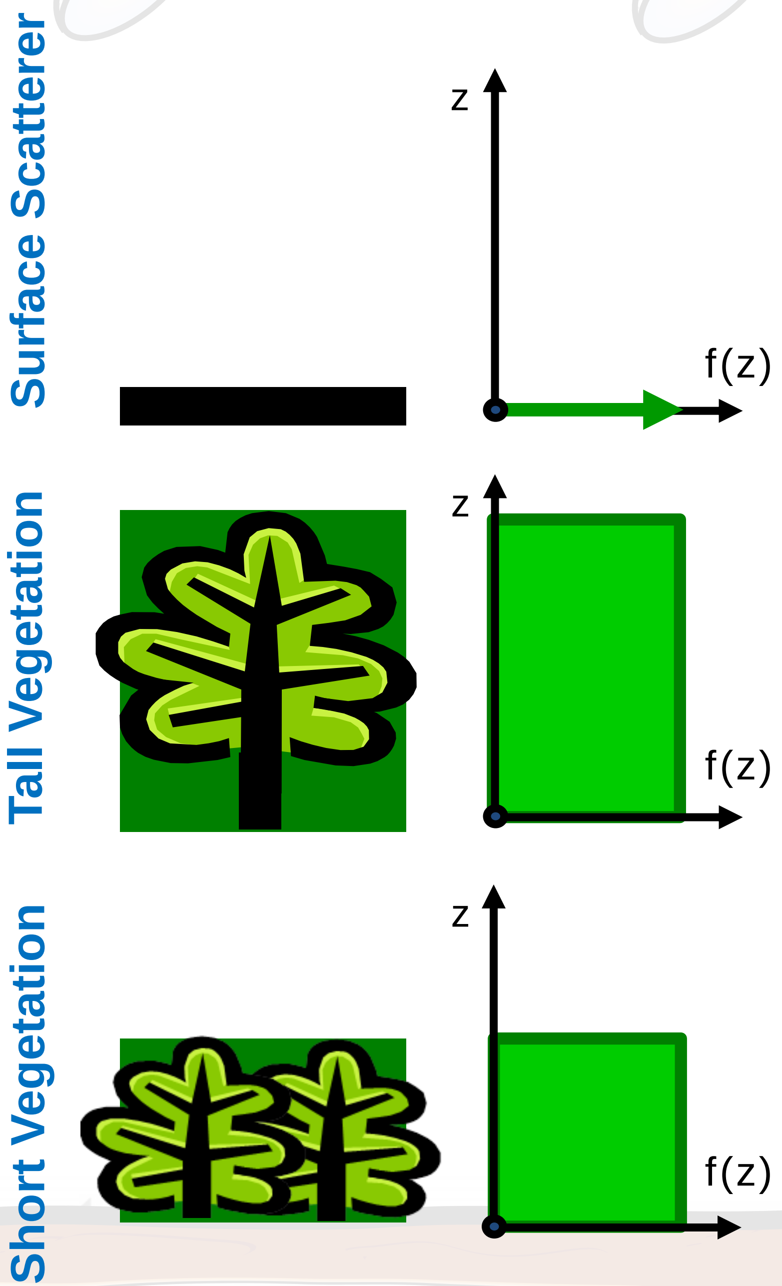
Vertical Wavenumber: $\kappa_z = \dfrac{\kappa\Delta\theta}{\sin(\theta_0)}$

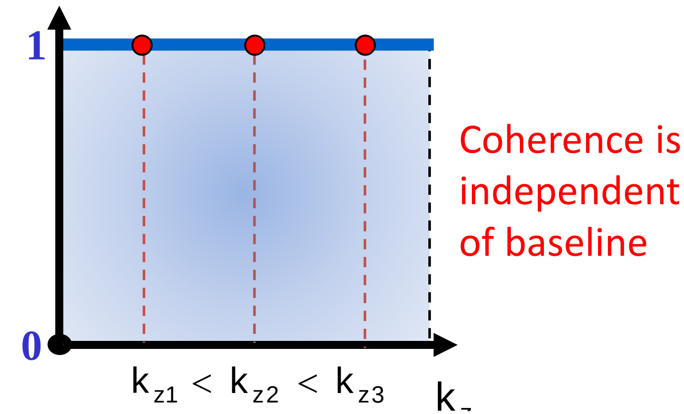
Multi-baseline measurements allow to sample **the spectrum of the vertical reflectivity** FT{f(z)} **@ different (spatial) frequencies** (k_z).

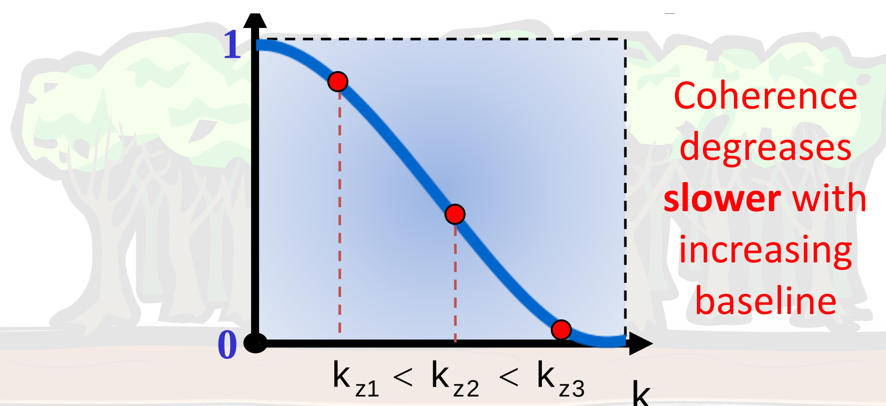
Vertical Reflectivity Function f(z)

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

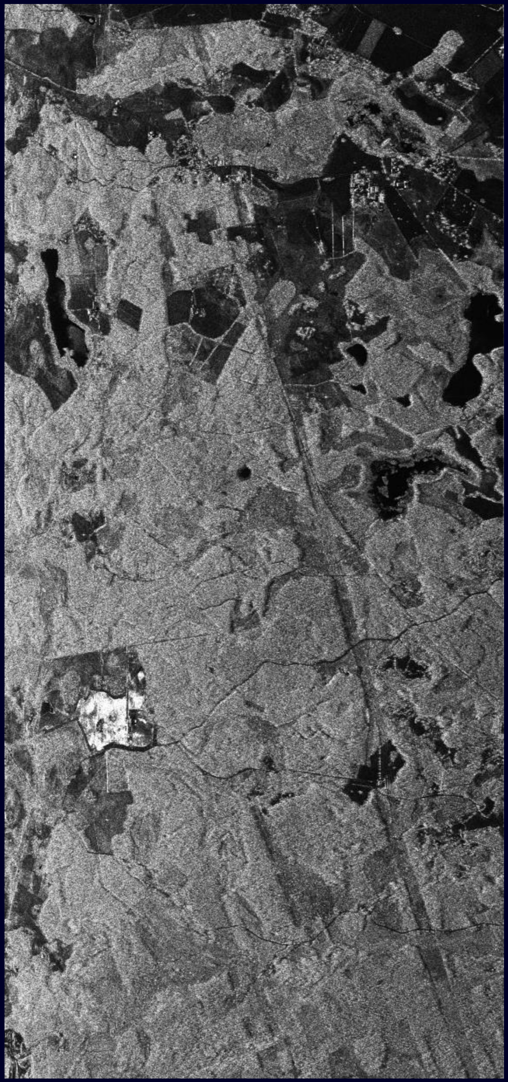
$$|\tilde{\gamma}_{Vol}(k_z)| = \frac{\left|\int_0^{h_v} f(z)\, e^{ik_z z} dz\right|}{\int_0^{h_v} f(z)\, dz}$$





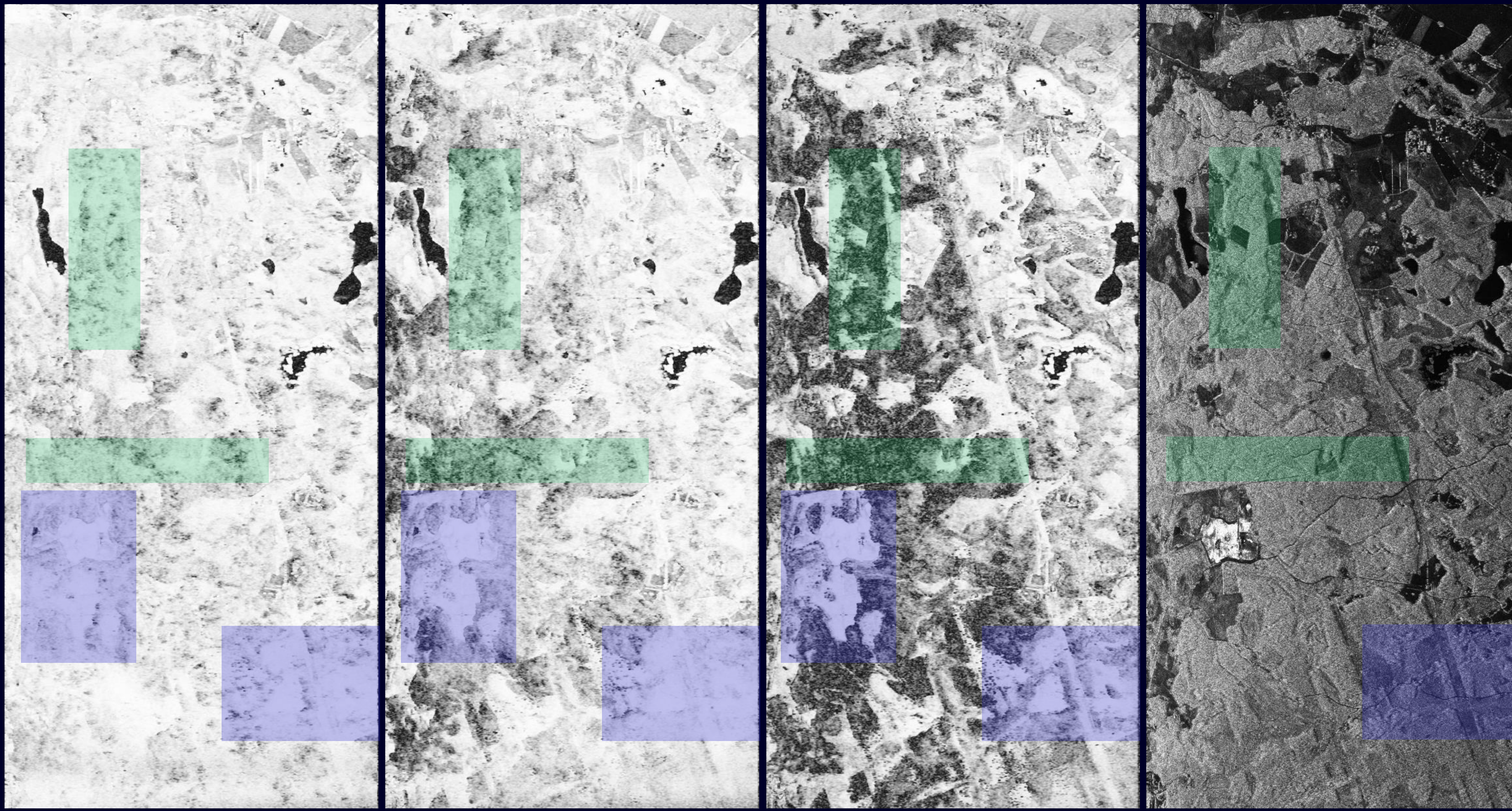


Amplitude Image



Amplitude Image HH

Interferometric Coherence: Volume Decorrelation

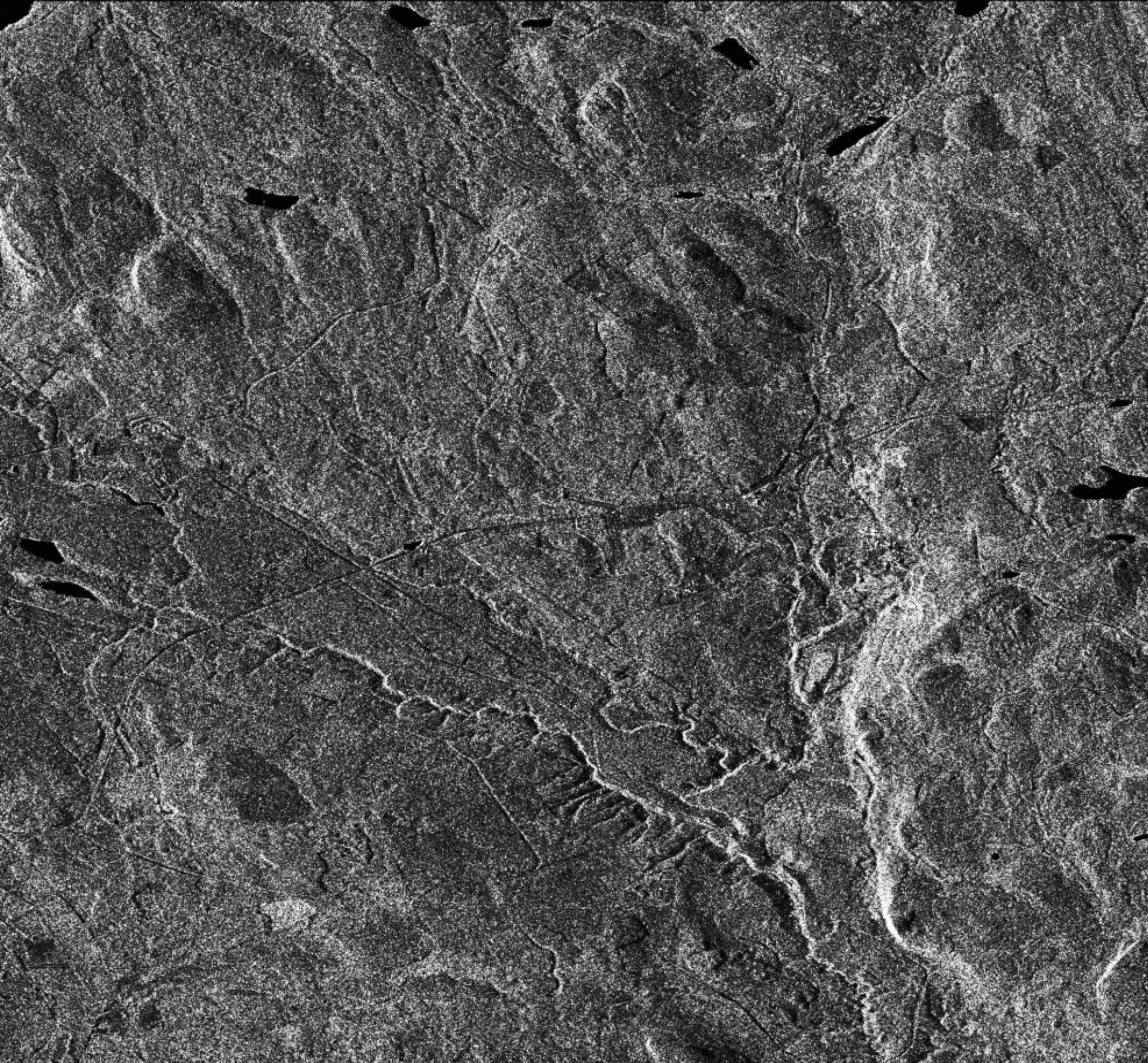


Spatial Baseline 3m

8m

16m

24m

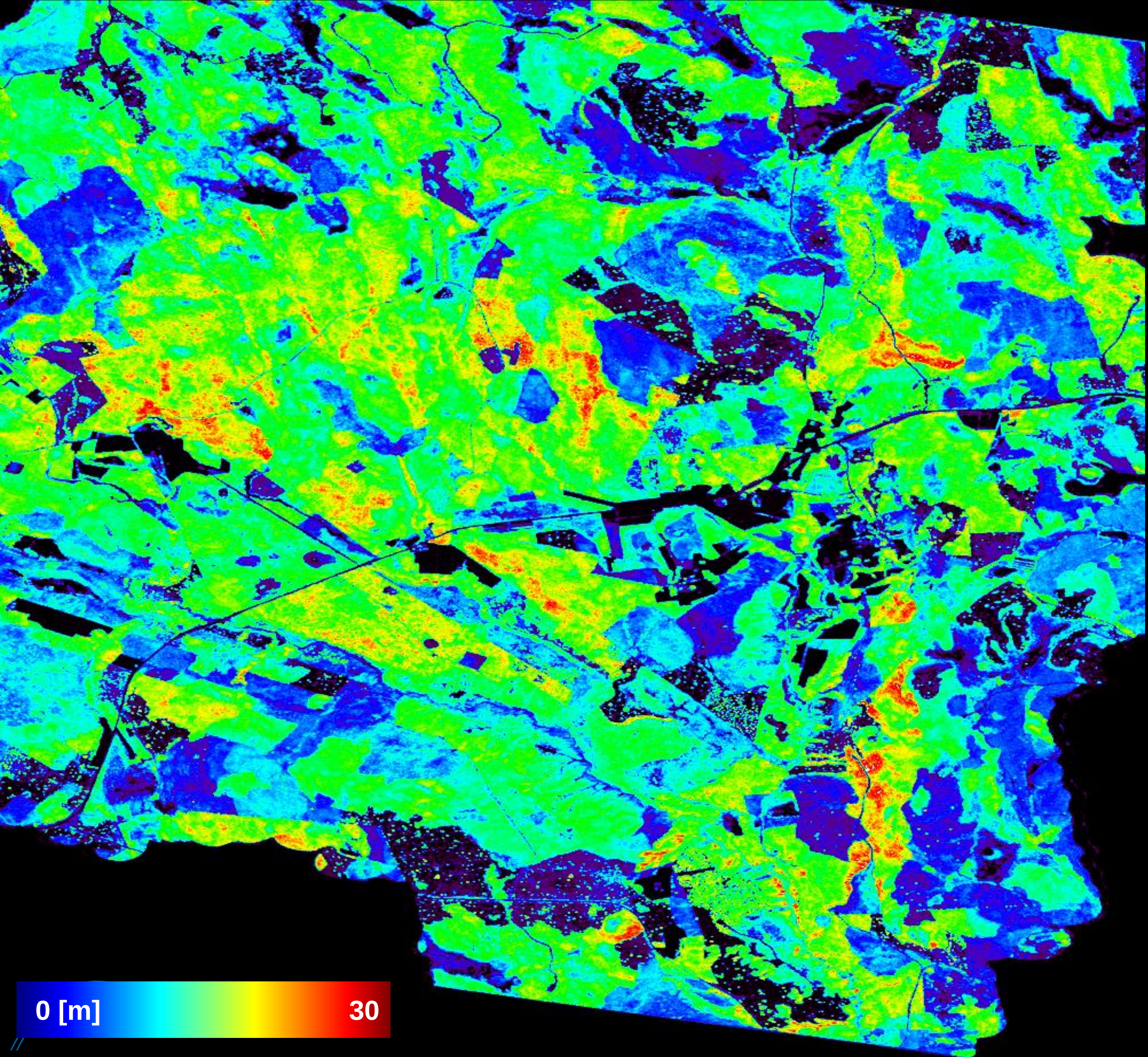


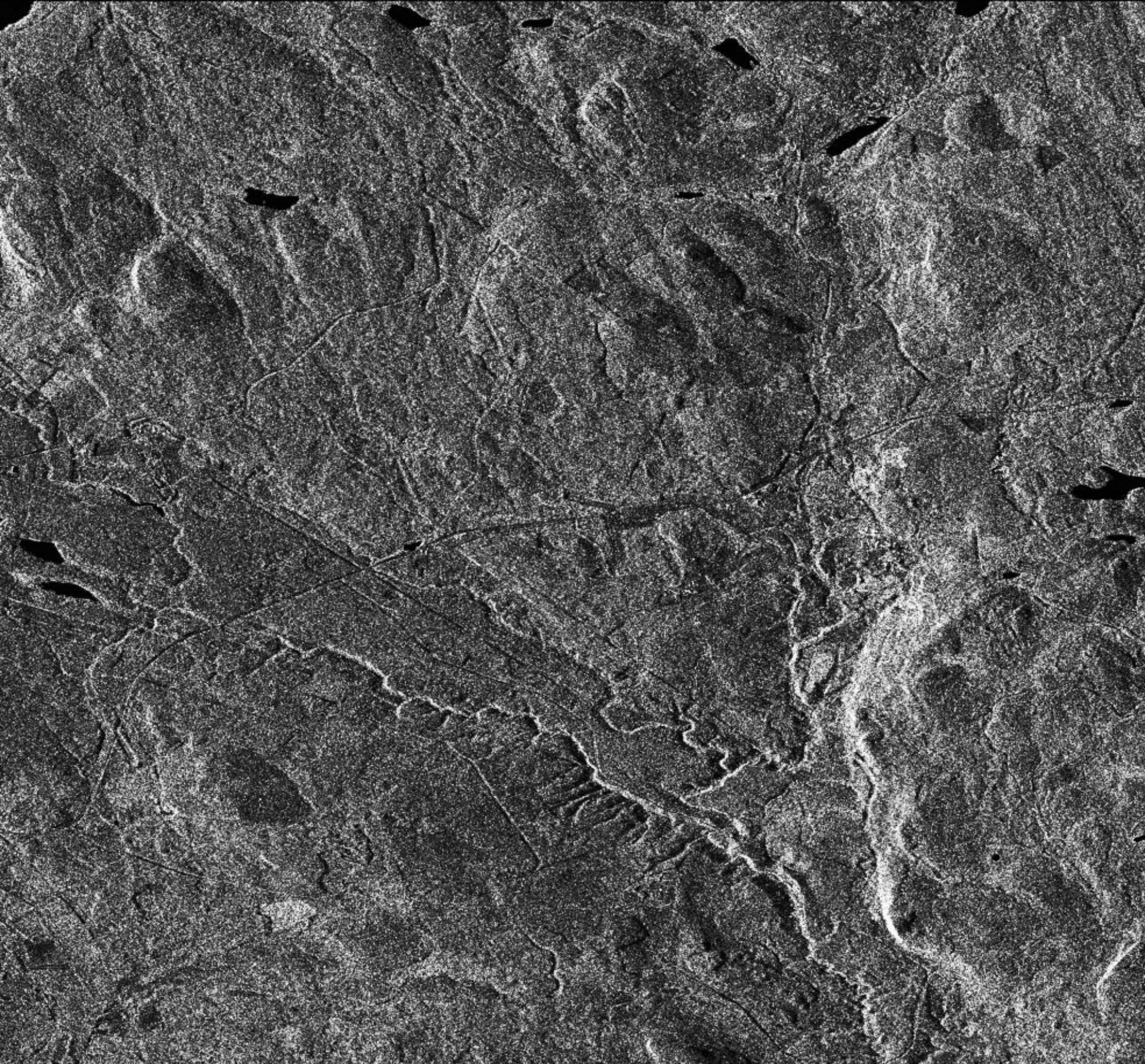
Test Site: Krycklan, Sweden

Radar Backscatter

Test Site: Krycklan, Sweden

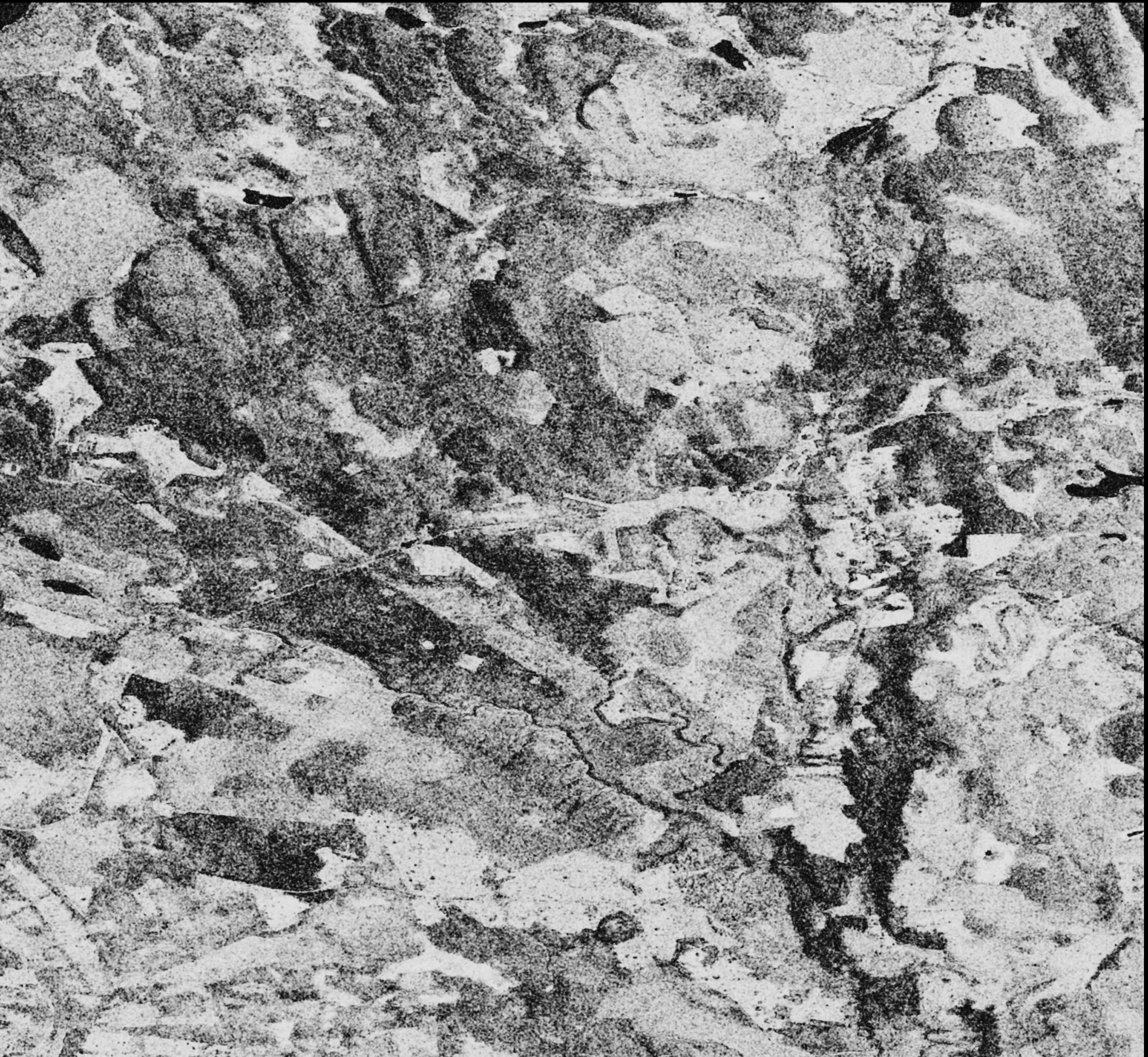
Forest Height





Test Site: Krycklan, Sweden

Radar Backscatter

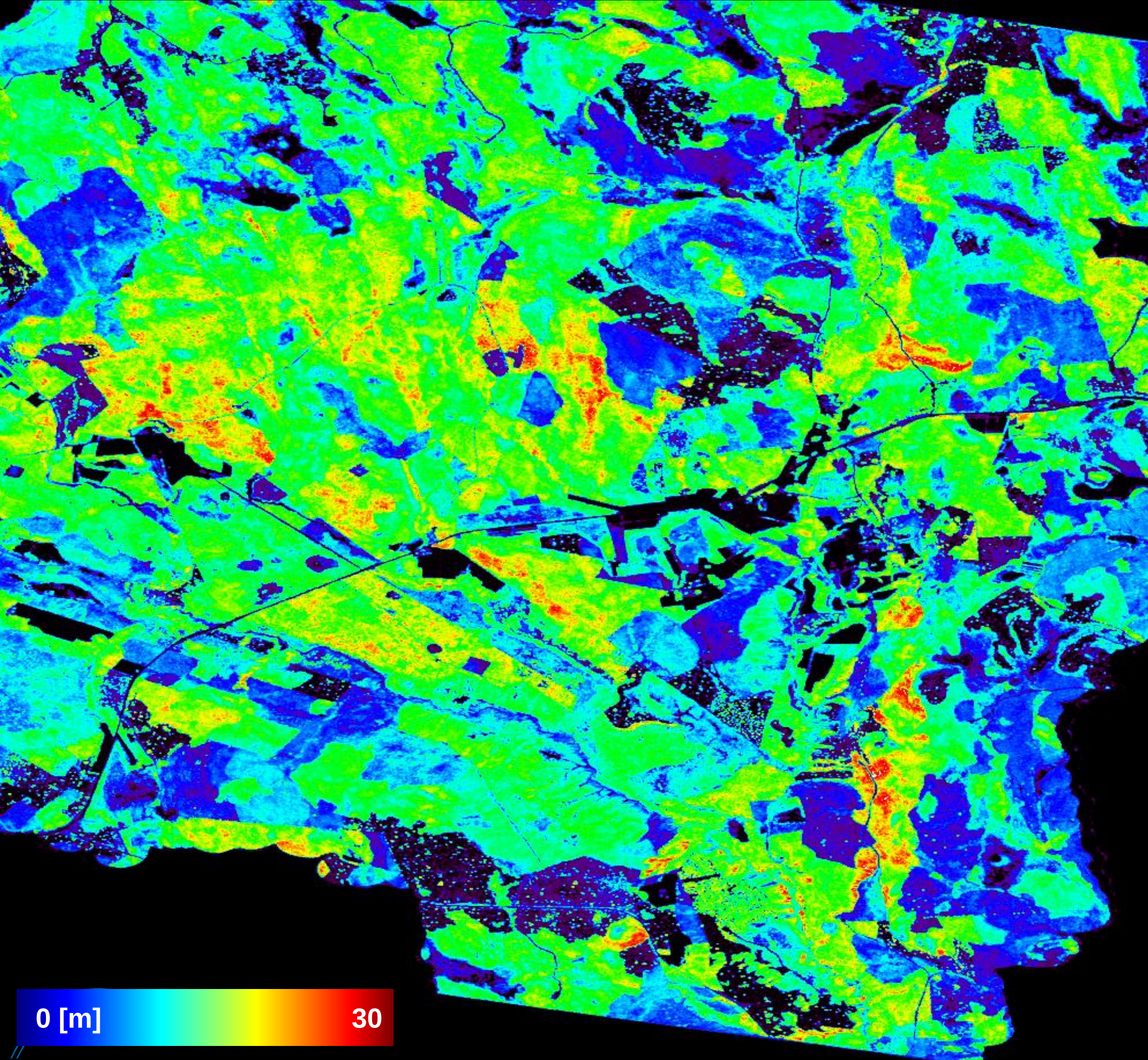


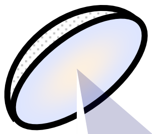
Test Site: Krycklan, Sweden

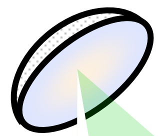
InSAR Coherence

Test Site: Krycklan, Sweden

Forest Height





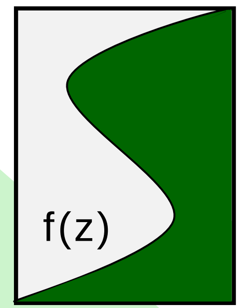


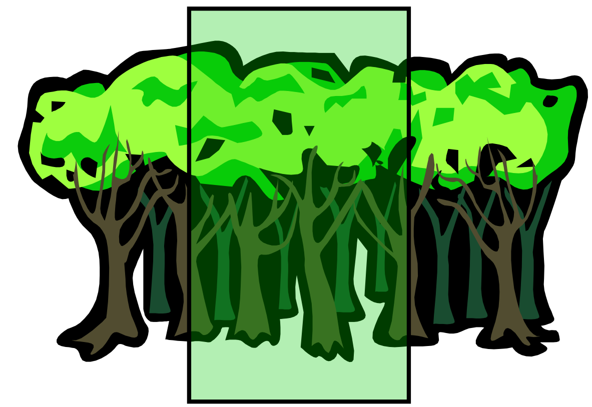
Interferometric Coherence

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

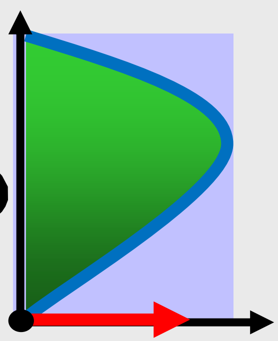
Volume Coherence

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





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

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

$$I = \int_0^{h_V} \exp(i\kappa_z z') f_V(z') dz'$$

$$I_0 = \int_0^{h_V} f_V(z') dz'$$

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

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

$f_V(z)$ has to be parameterised (N param)

Volume Height h_V

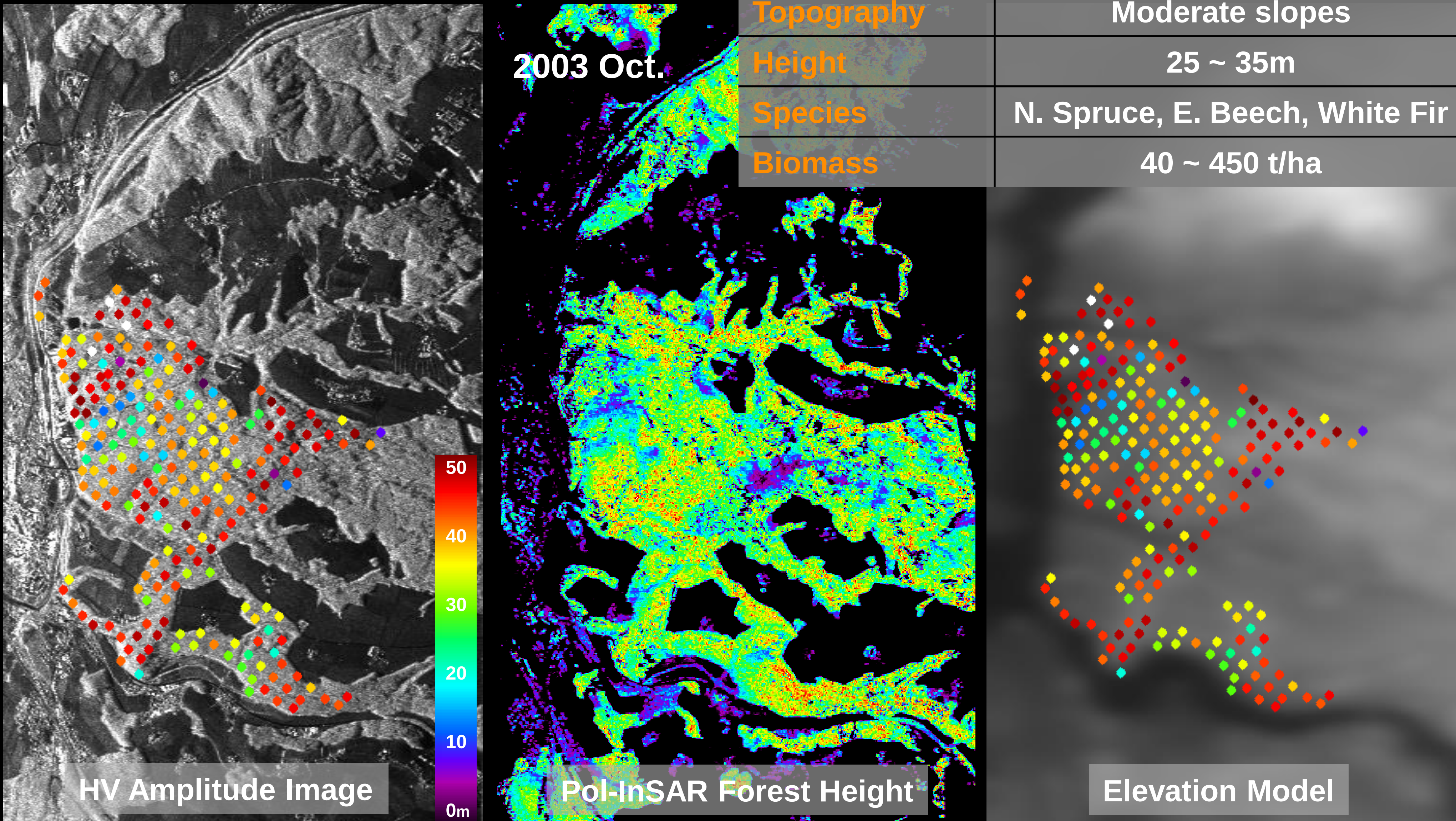
Topography φ_0

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

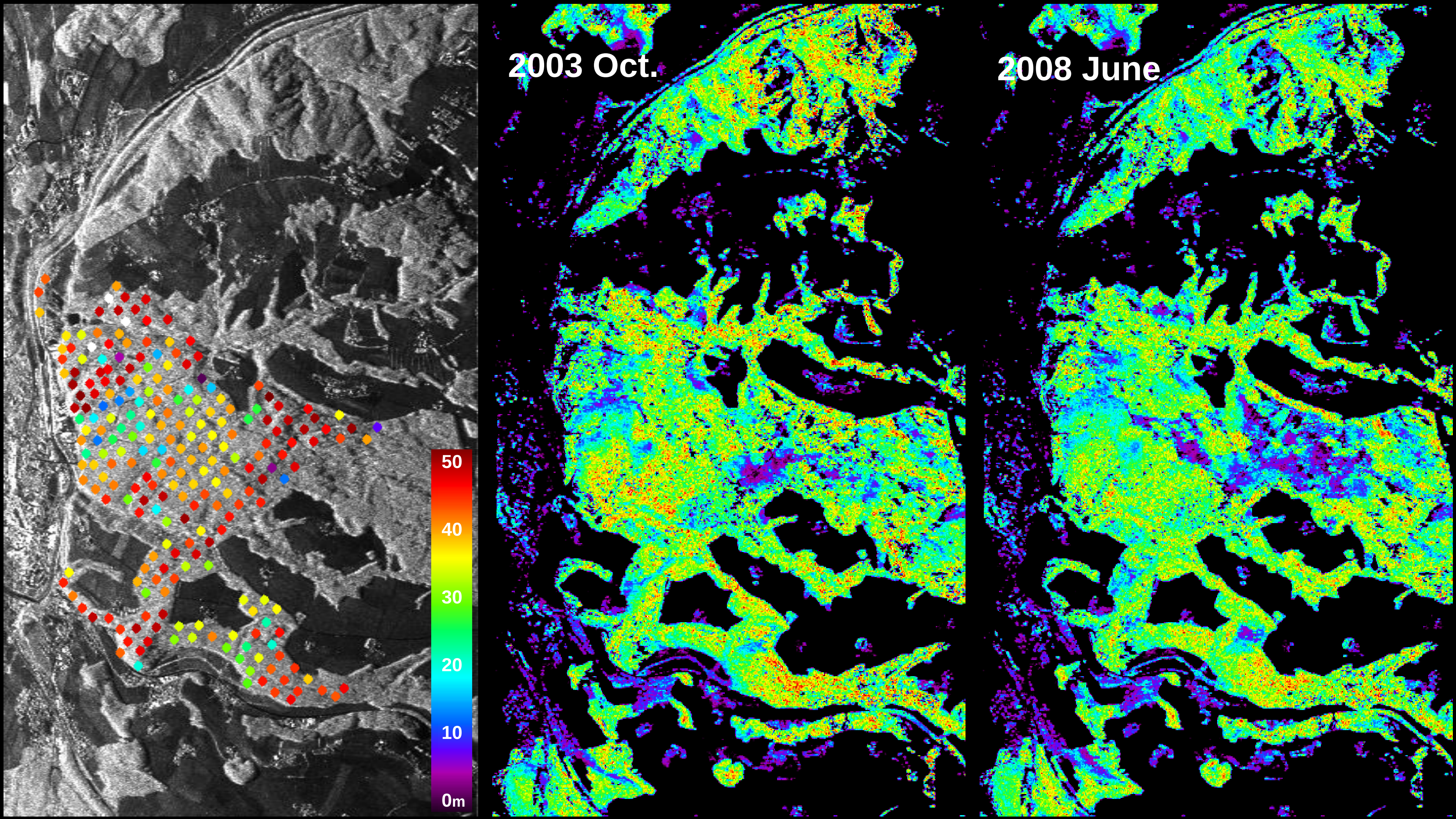
3+N Unknowns

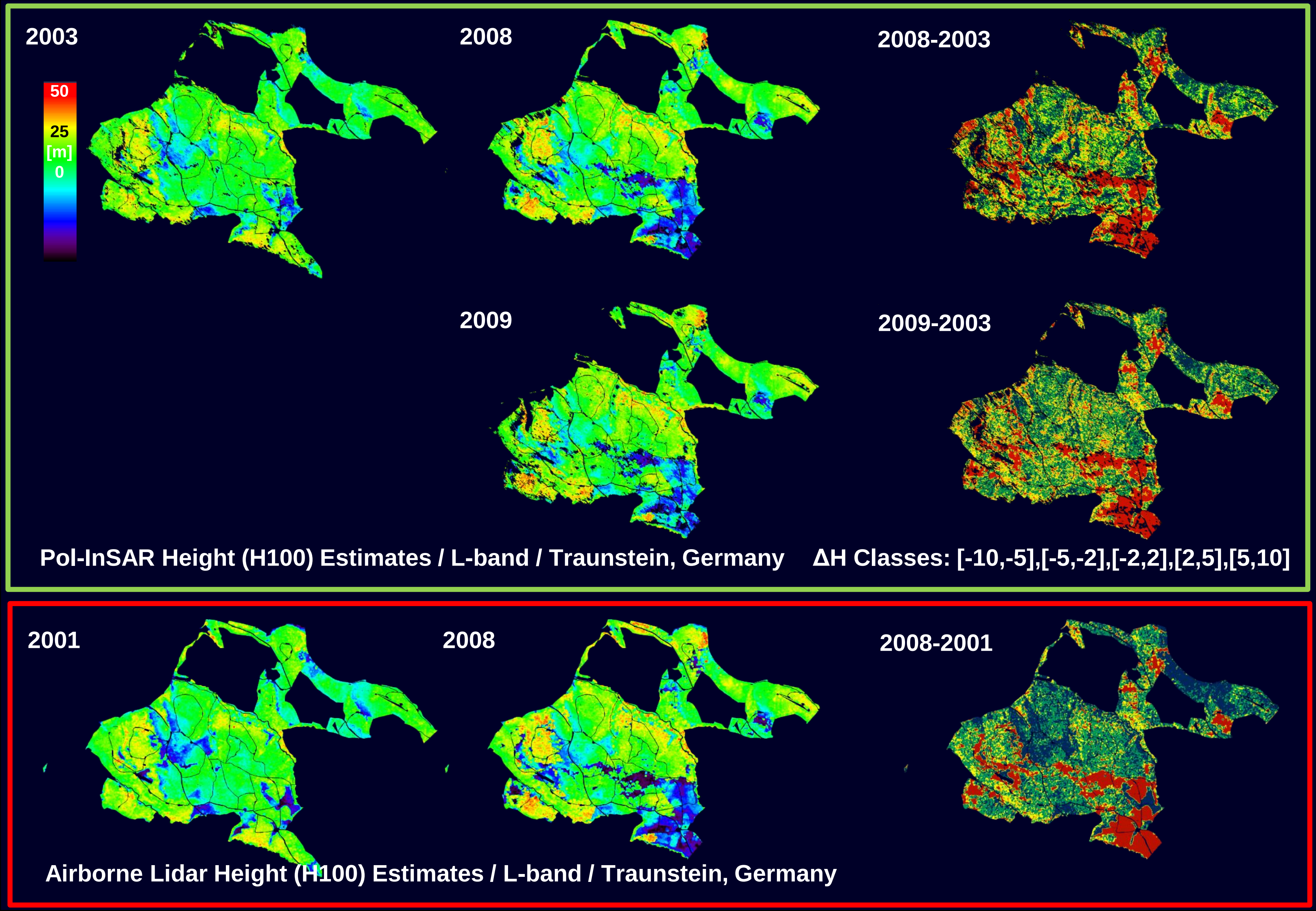
Traunstein Test Site

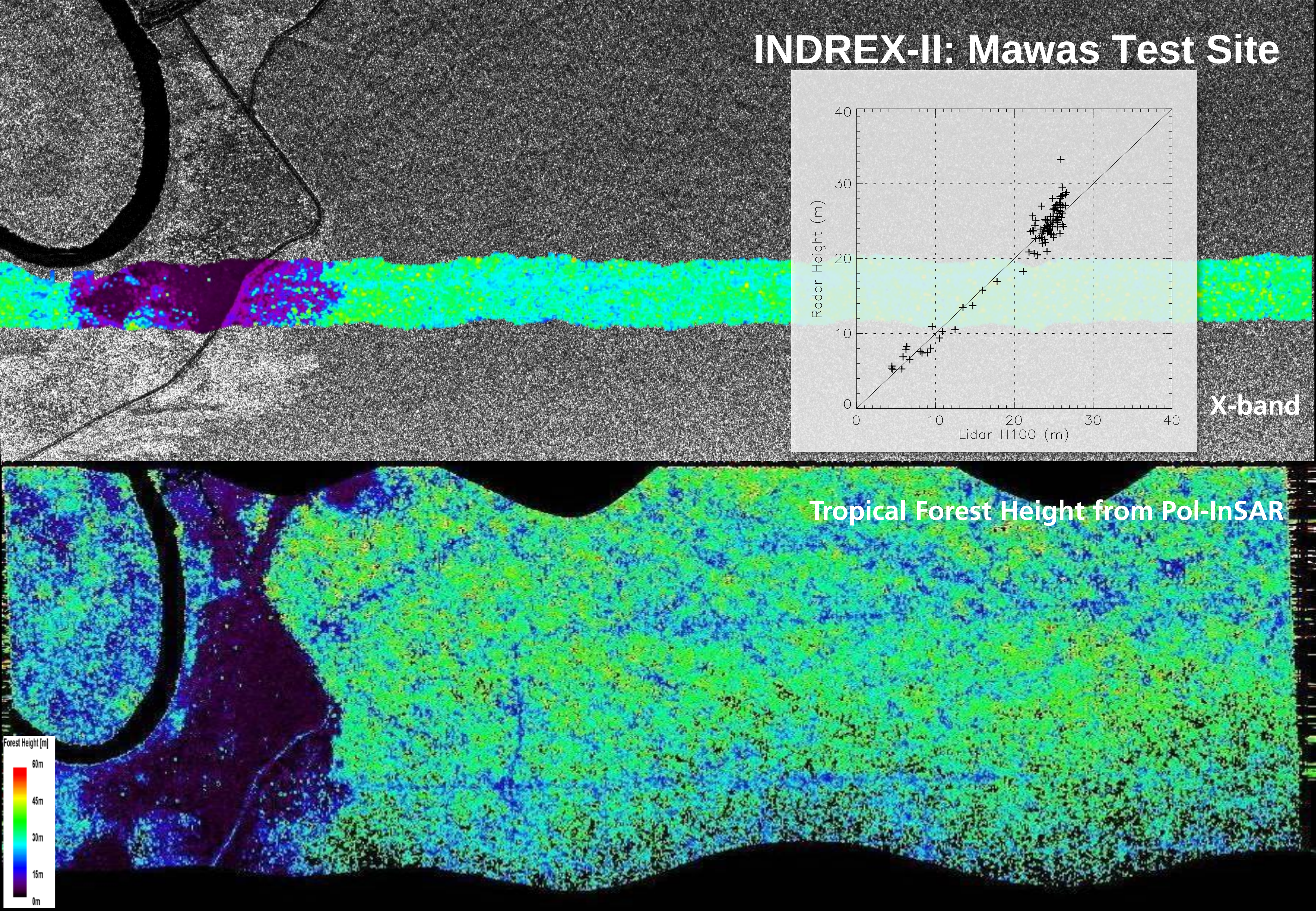
Forest type	Temperate
Topography	Moderate slopes
Height	25 ~ 35m
Species	N. Spruce, E. Beech, White Fir
Biomass	40 ~ 450 t/ha

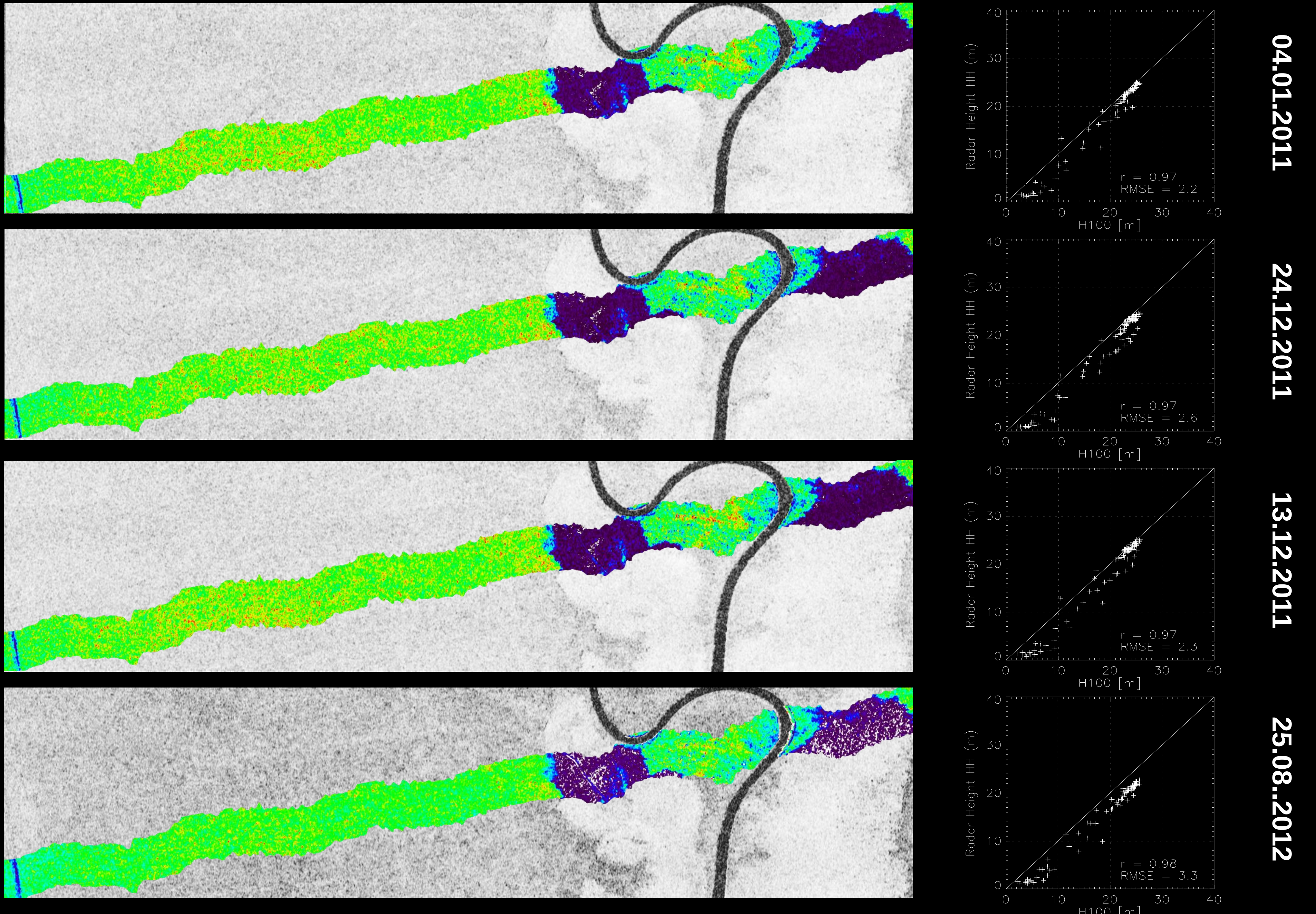


Traunstein Test Site

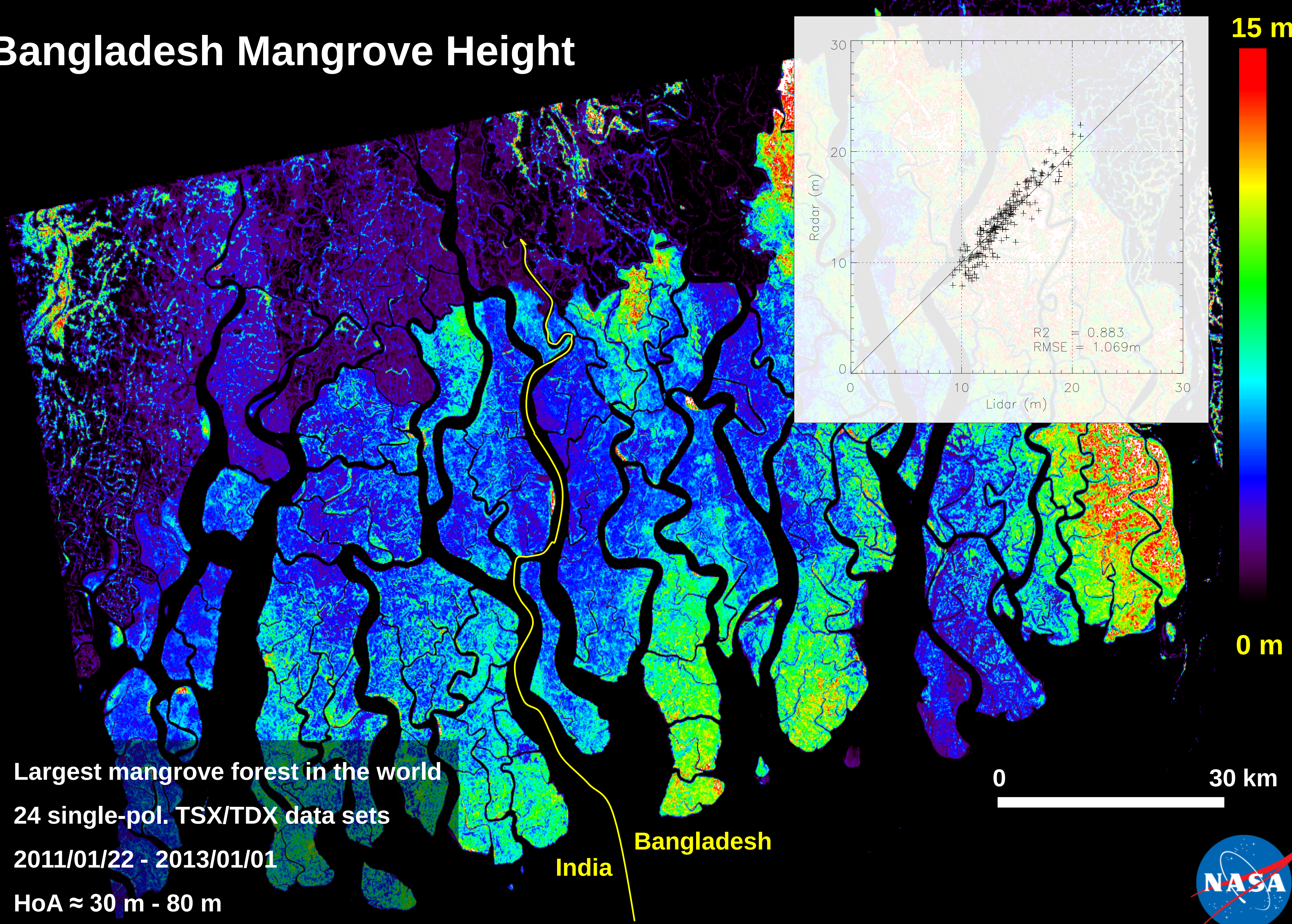



2003
50
25
[m]
0
2008
2008-2003
2009
2009-2003
Pol-InSAR Height (H100) Estimates / L-band / Traunstein, Germany
ΔH Classes: [-10,-5],[-5,-2],[-2,2],[2,5],[5,10]
2001
2008
2008-2001
Airborne Lidar Height (H100) Estimates / L-band / Traunstein, Germany


INDREX-II: Mawas Test Site
Radar Height (m)
Lidar H100 (m)
X-band
Tropical Forest Height from Pol-InSAR
Forest Height [m]
60m
45m
30m
15m
0m


04.01.2011
Radar Height HH (m)
H100 [m]
r = 0.97
RMSE = 2.2
24.12.2011
Radar Height HH (m)
H100 [m]
r = 0.97
RMSE = 2.6
13.12.2011
Radar Height HH (m)
H100 [m]
r = 0.97
RMSE = 2.3
25.08.2012
Radar Height HH (m)
H100 [m]
r = 0.98
RMSE = 3.3

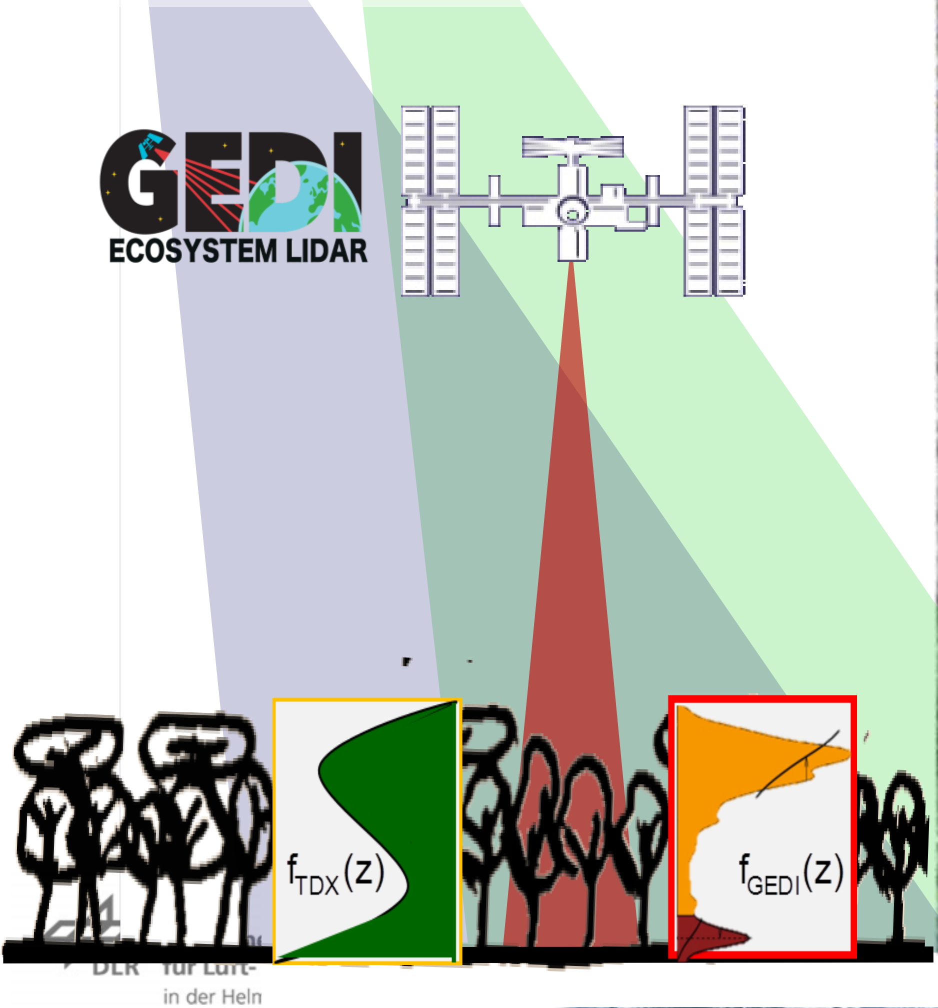
Bangladesh Mangrove Height



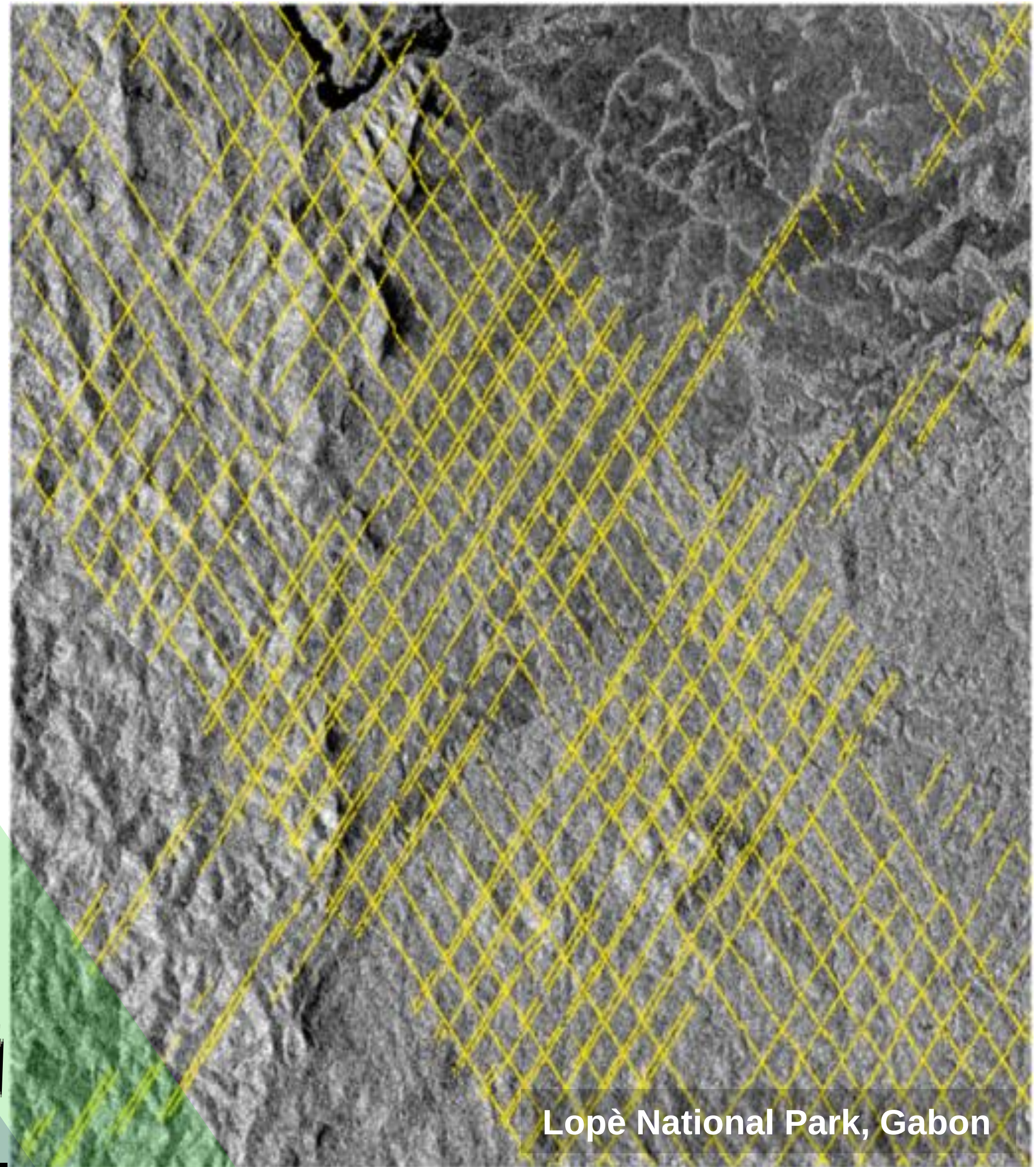
- Largest mangrove forest in the world
- 24 single-pol. TSX/TDX data sets
- 2011/01/22 - 2013/01/01
- HoA ≈ 30 m - 80 m

Forest Height from TD-X / GEDI Data Fusion

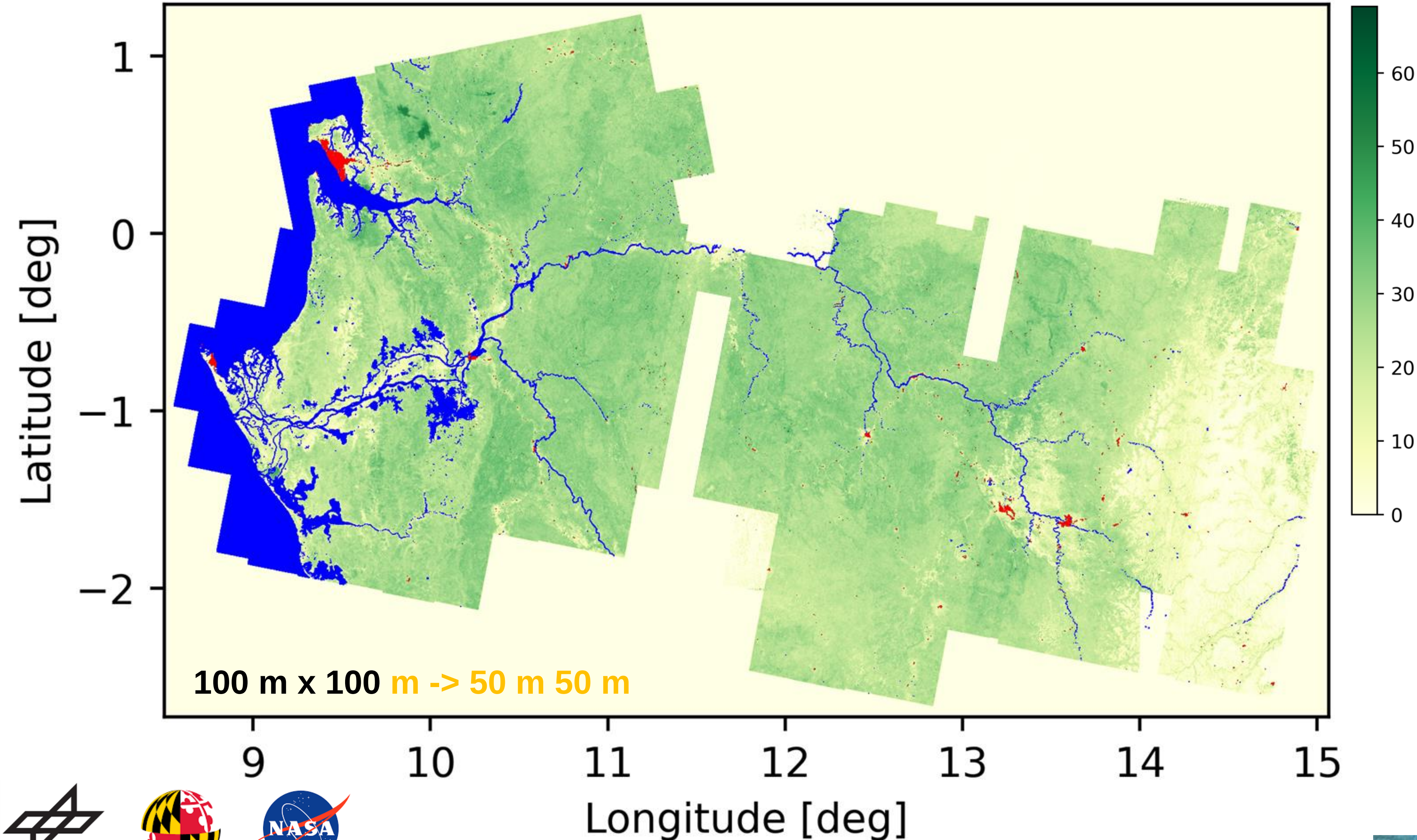
Forest Height estimation from the fusion of continous TDX InSAR data and discrete GEDI meassurements



TD-X Backscatter & GEDI Tracks

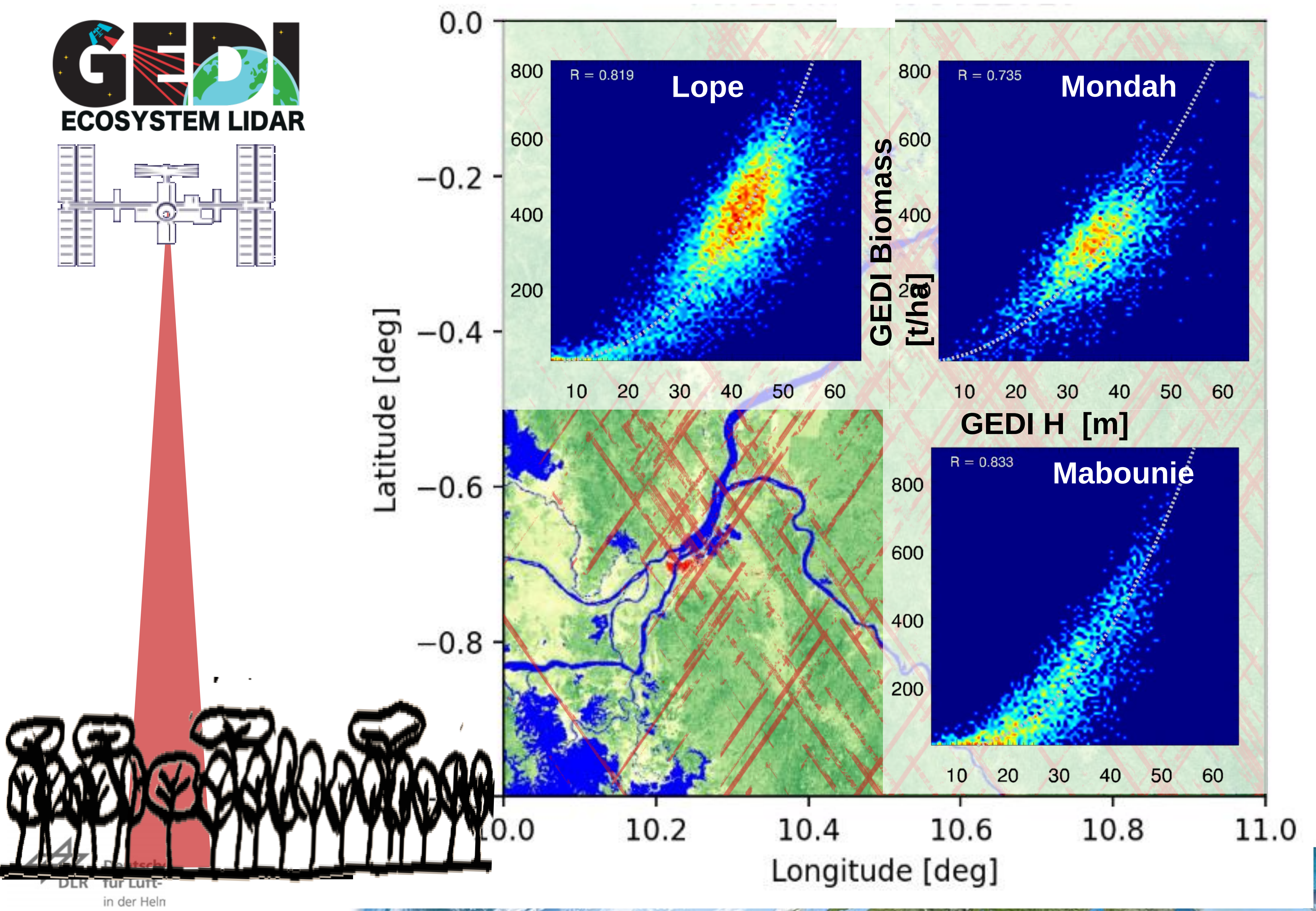


Forest Height Map Gabon: 200 TanDEM-X Scenes + 35K GEDI Footprints

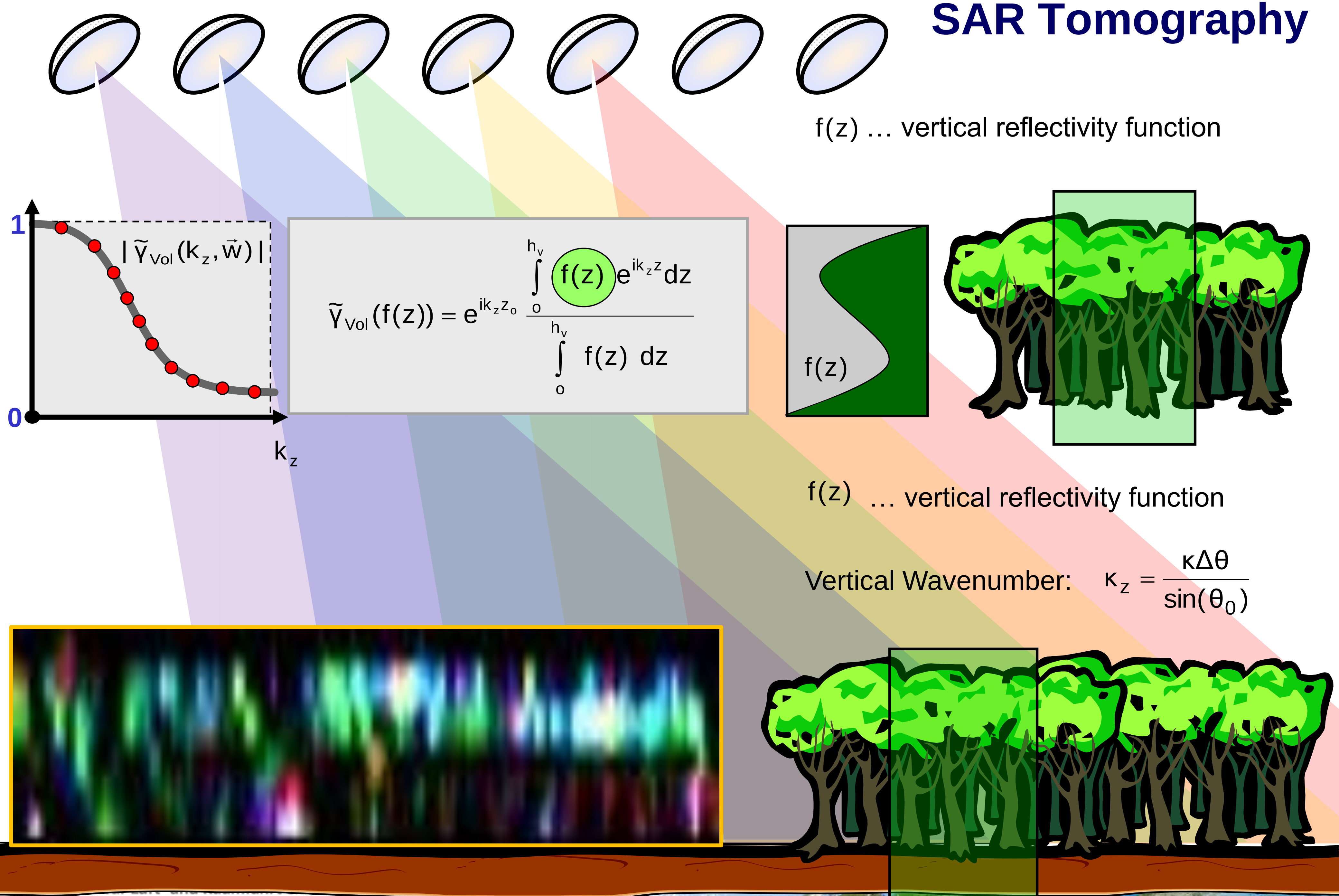


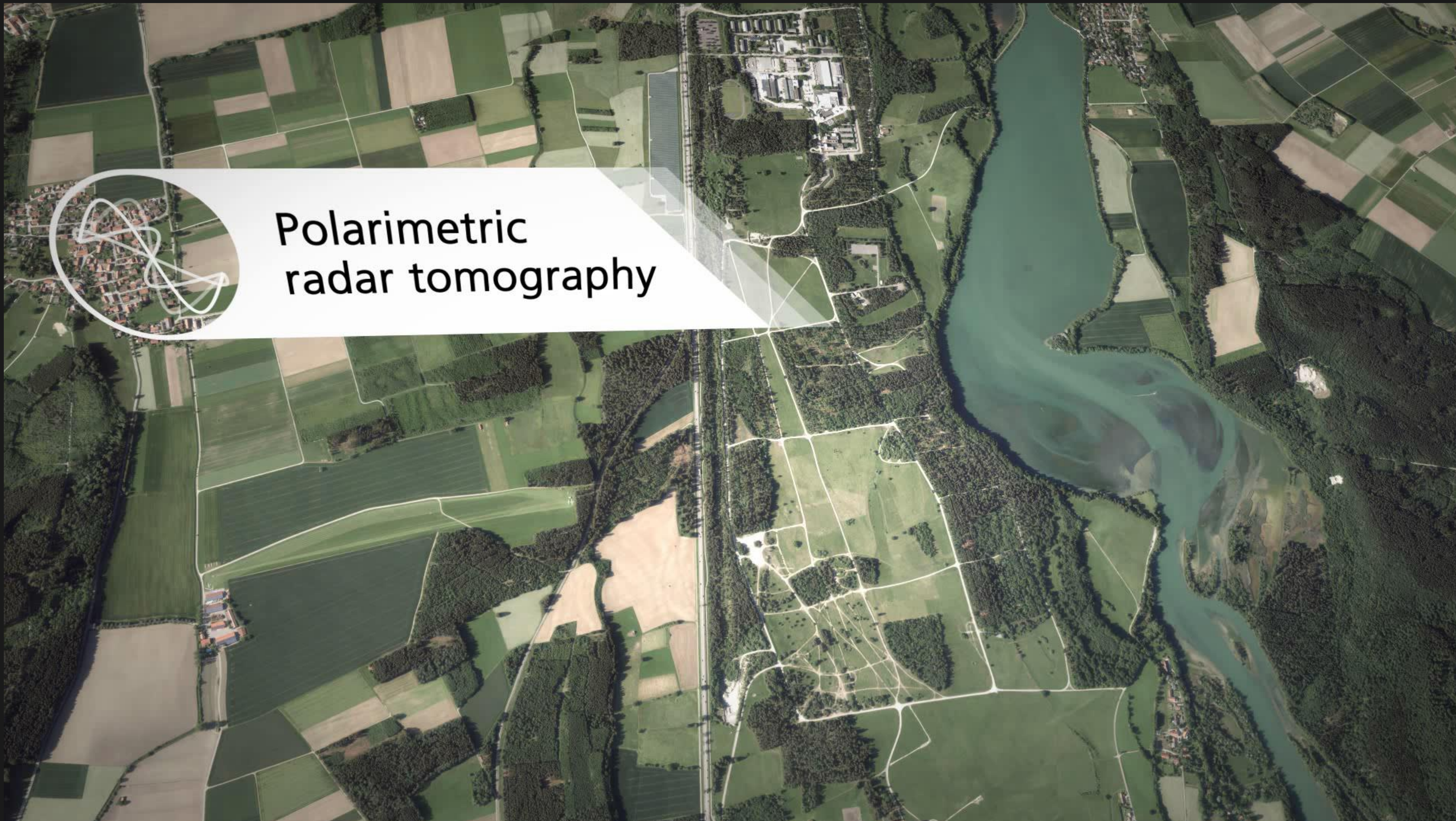
DLR

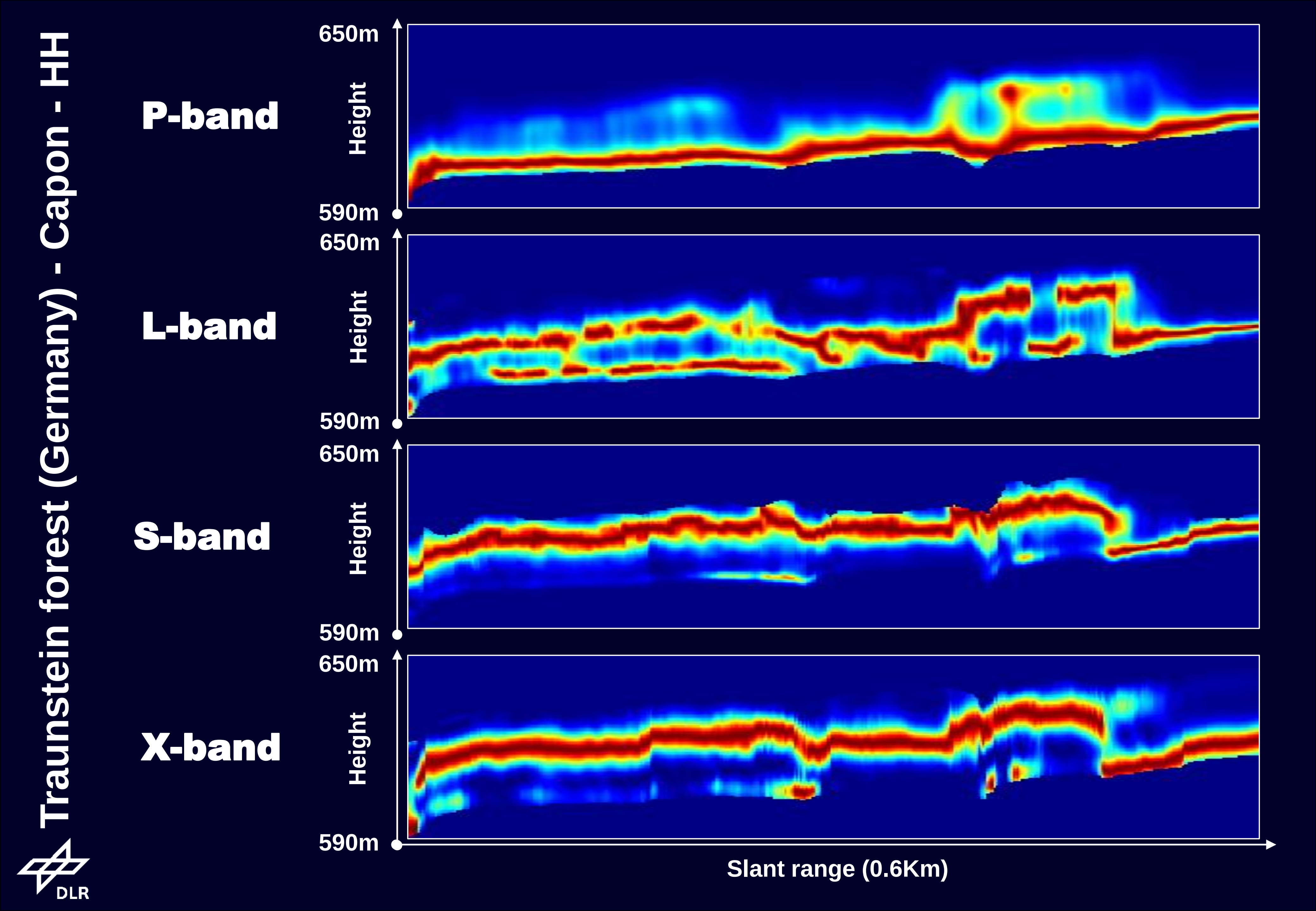
in der Helmholtz-Gemeinschaft


GEDI
ECOSYSTEM LIDAR
Lope
R = 0.819
Mondah
R = 0.735
Mabounie
R = 0.833
GEDI Biomass [t/ha]
GEDI H [m]
800
600
400
200
10
20
30
40
50
60
Latitude [deg]
0.0
−0.2
−0.4
−0.6
−0.8
Longitude [deg]
10.0
10.2
10.4
10.6
10.8
11.0
DLR

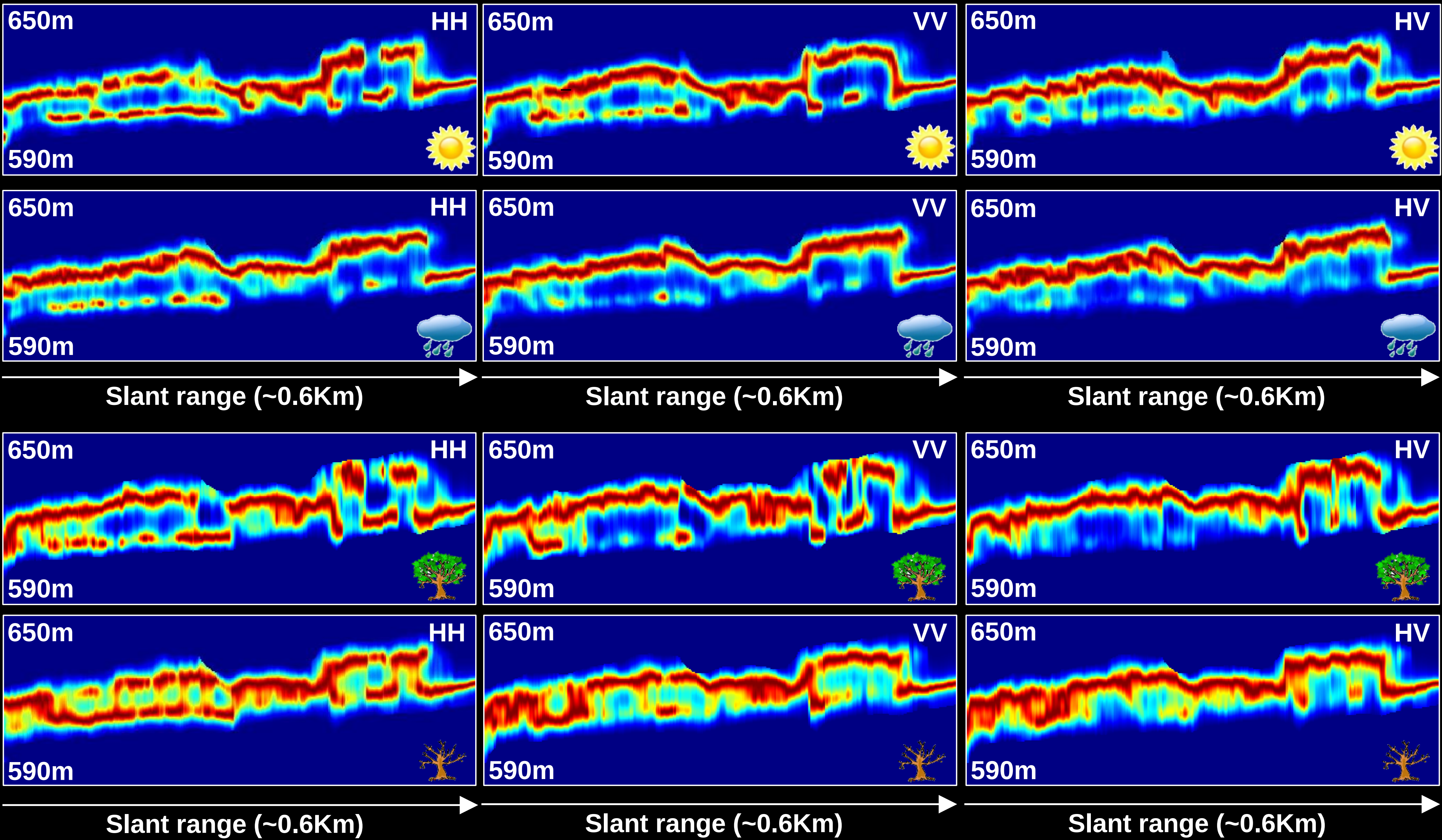
SAR Tomography




Polarimetric
radar tomography


Traunstein forest (Germany) - Capon - HH
P-band
L-band
S-band
X-band
650m
590m
Height
Slant range (0.6Km)
DLR

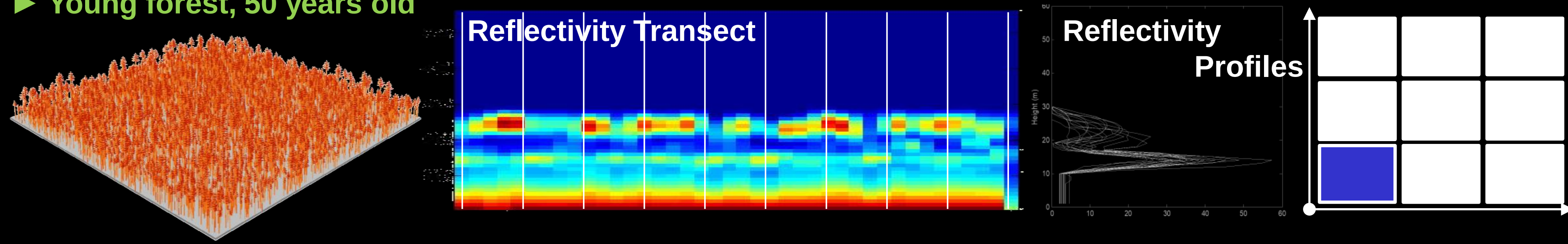
Temporal variations at L-band (Capon)



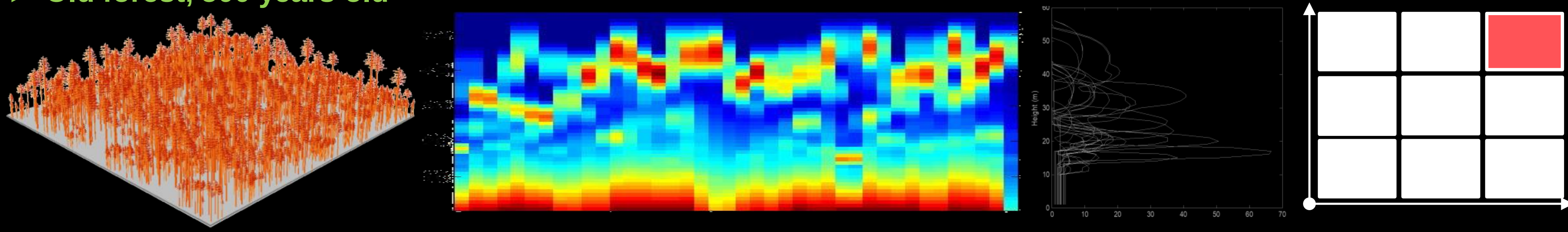
Forest Structure Characterisation

Helmholtz Alliance:
Remote Sensing and Earth System Dynamics

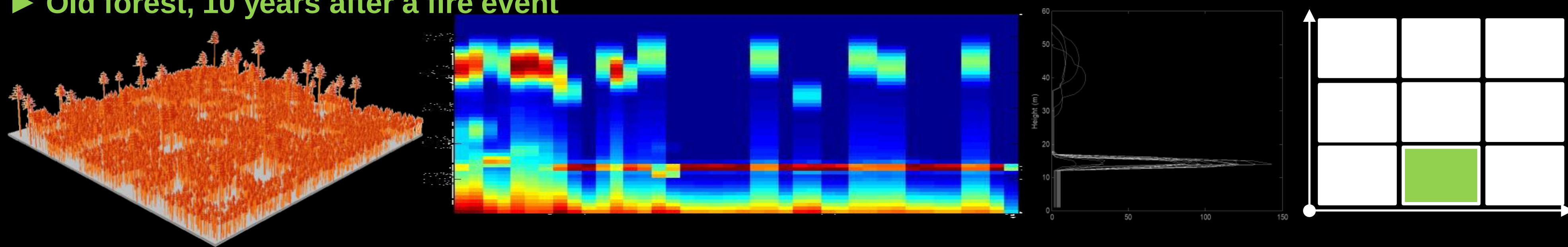
- Young forest, 50 years old



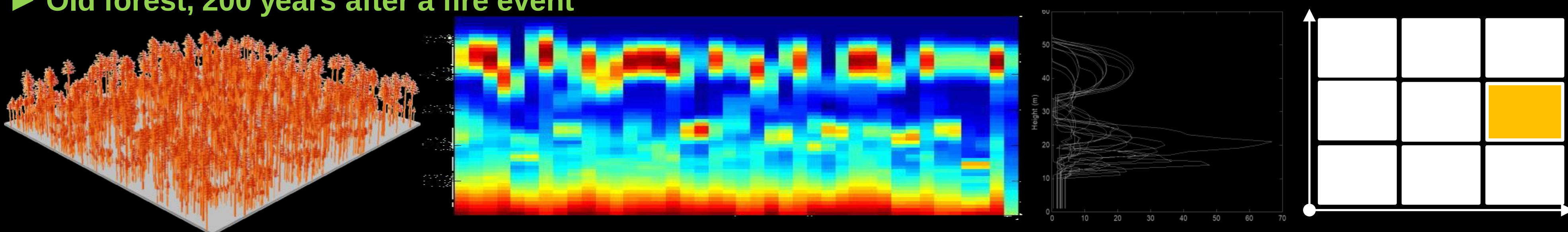
- Old forest, 500 years old

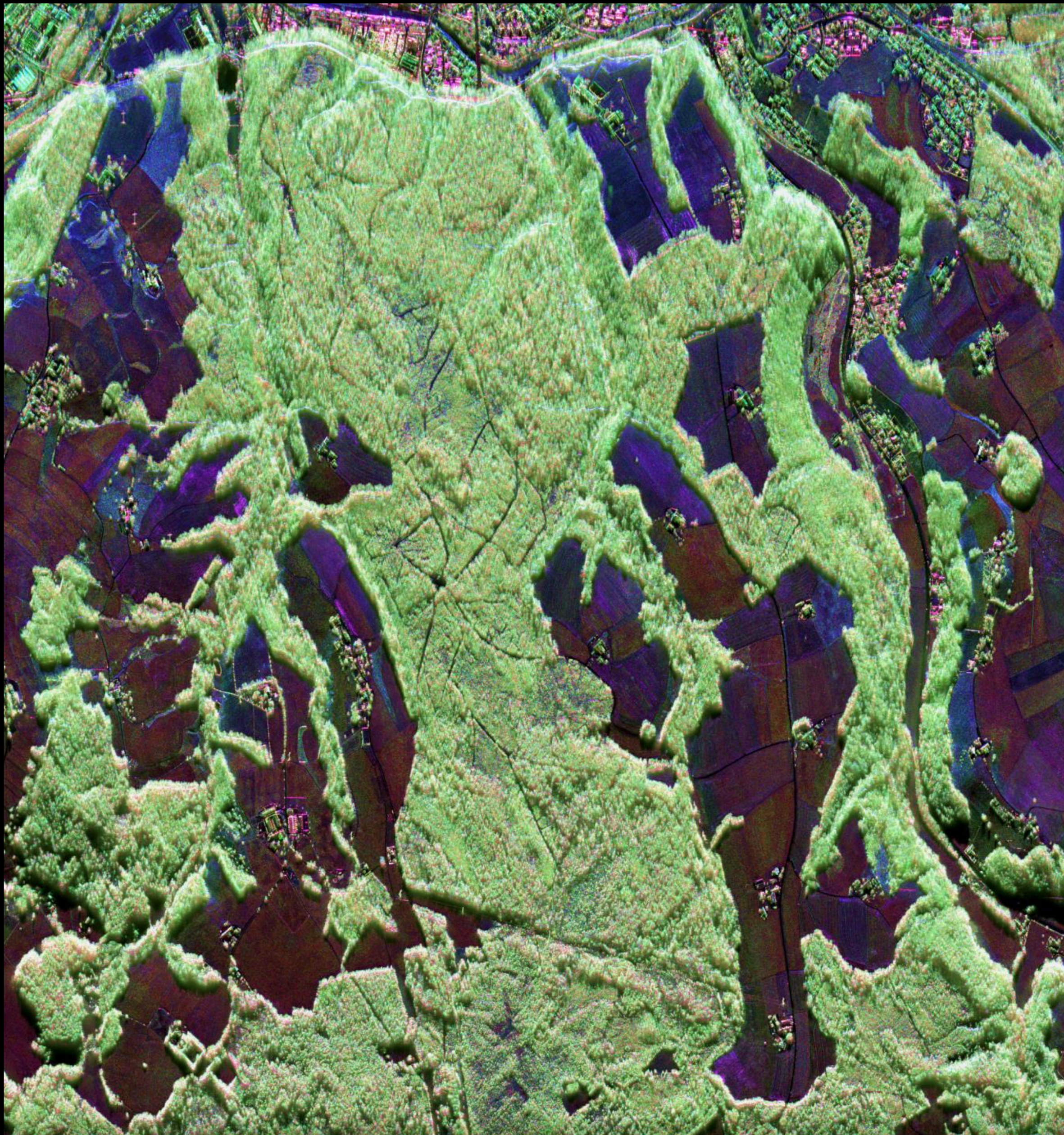


- Old forest, 10 years after a fire event

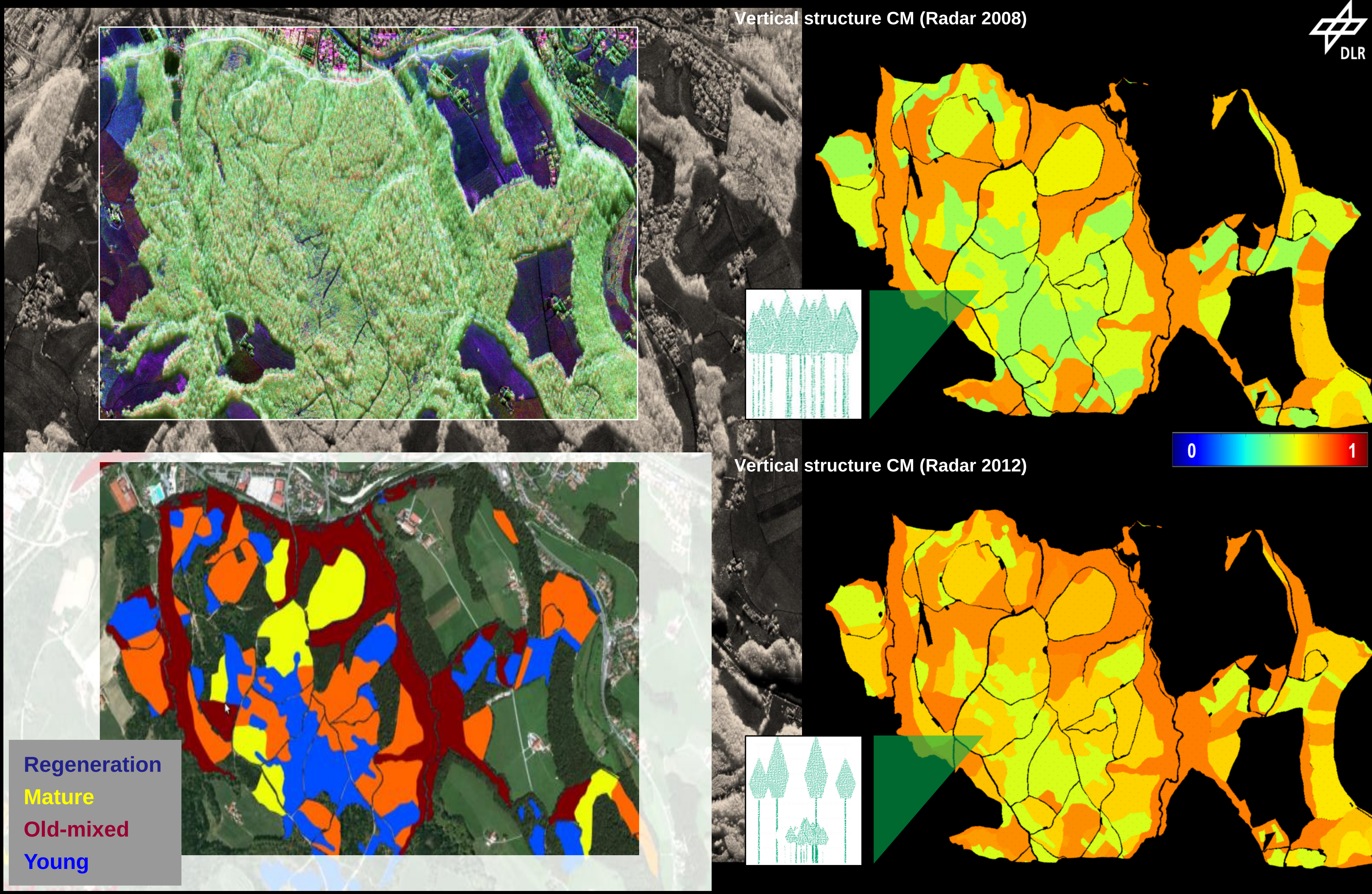


- Old forest, 200 years after a fire event



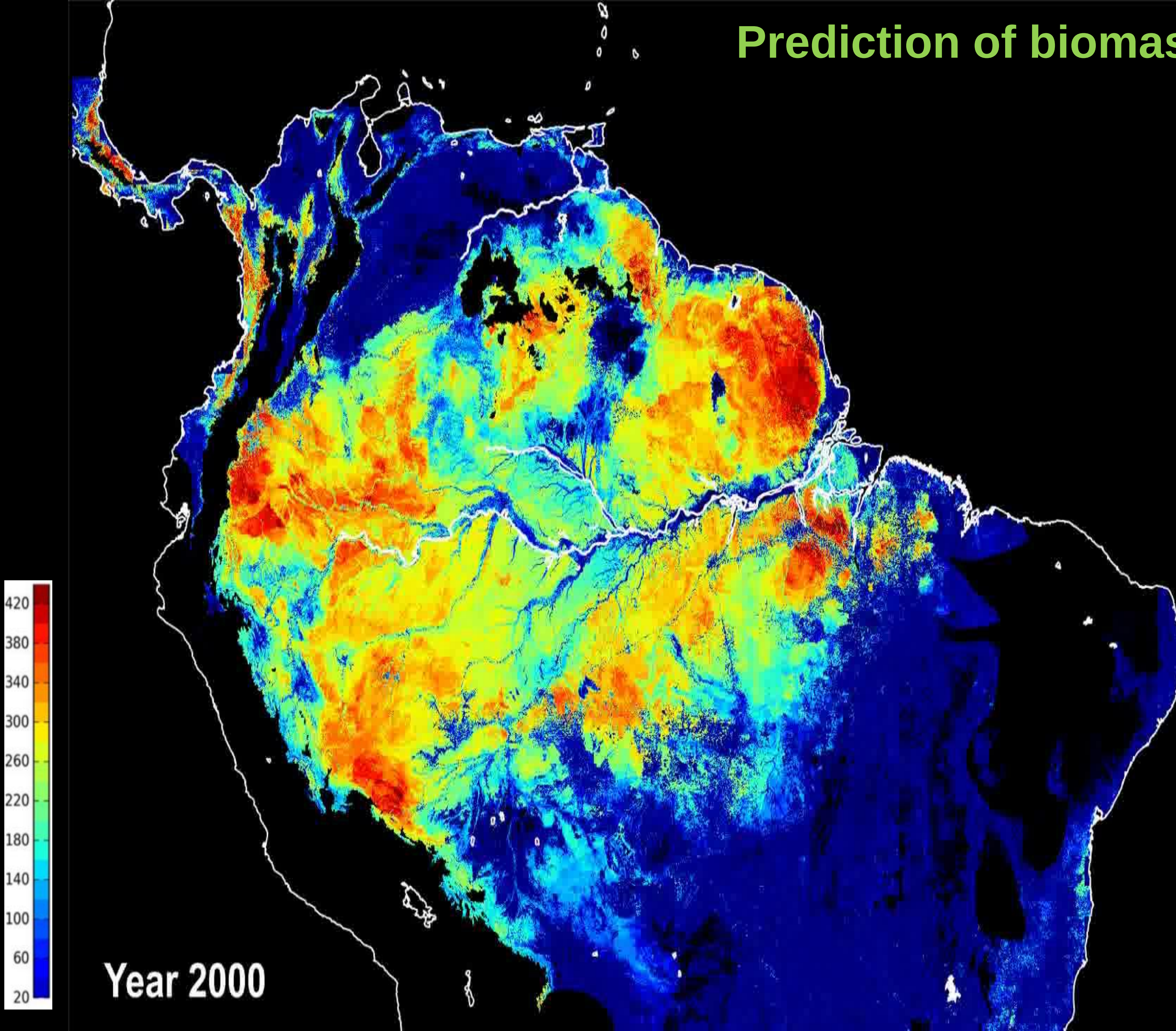


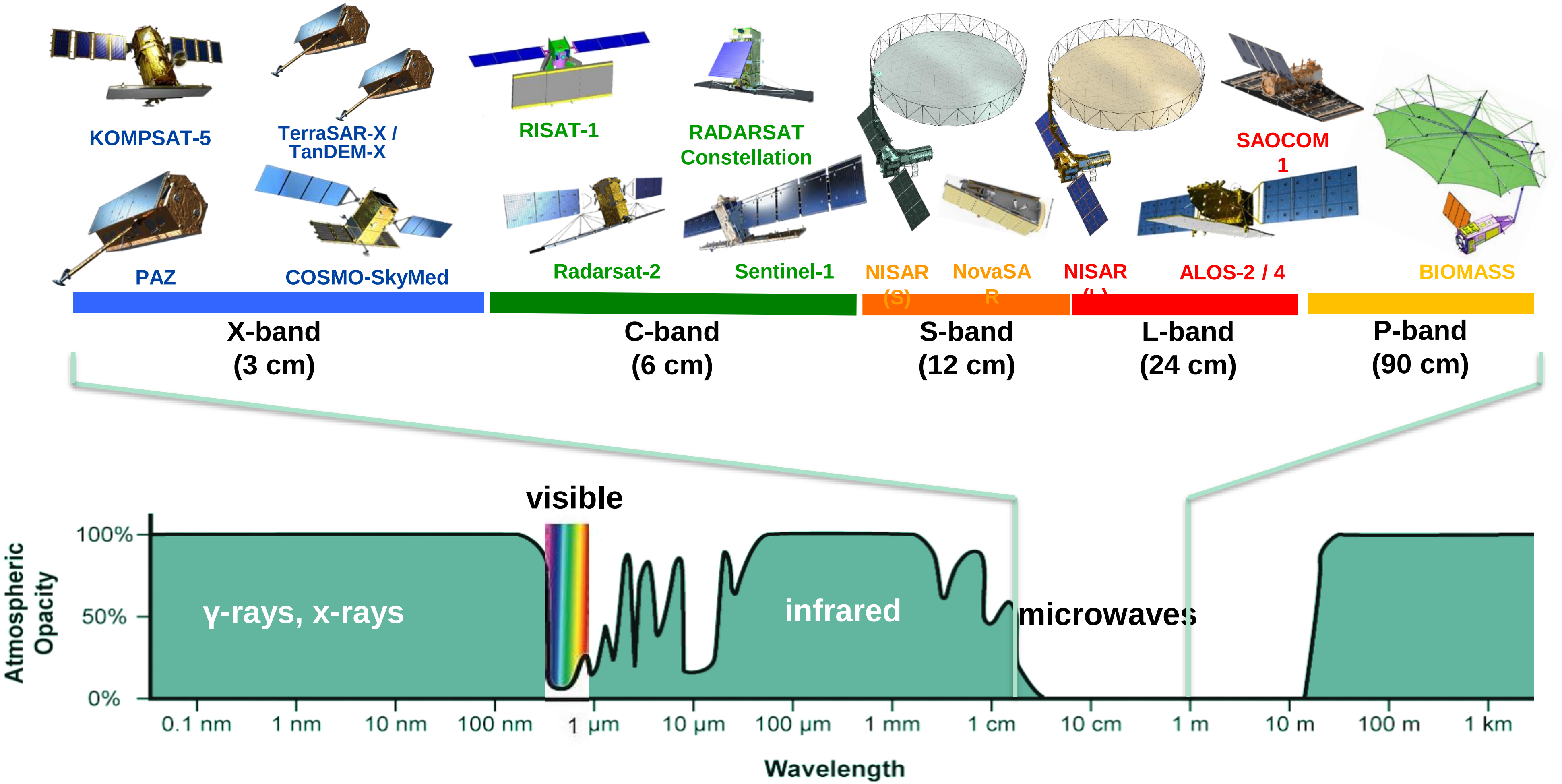
Forest Structure Classification (25x25 m): Traunstein, Germany, 2008 / 2012



Forest Structure Classification (25x25 m): Traunstein, Germany, 2008 / 2012

Prediction of biomass dynamics

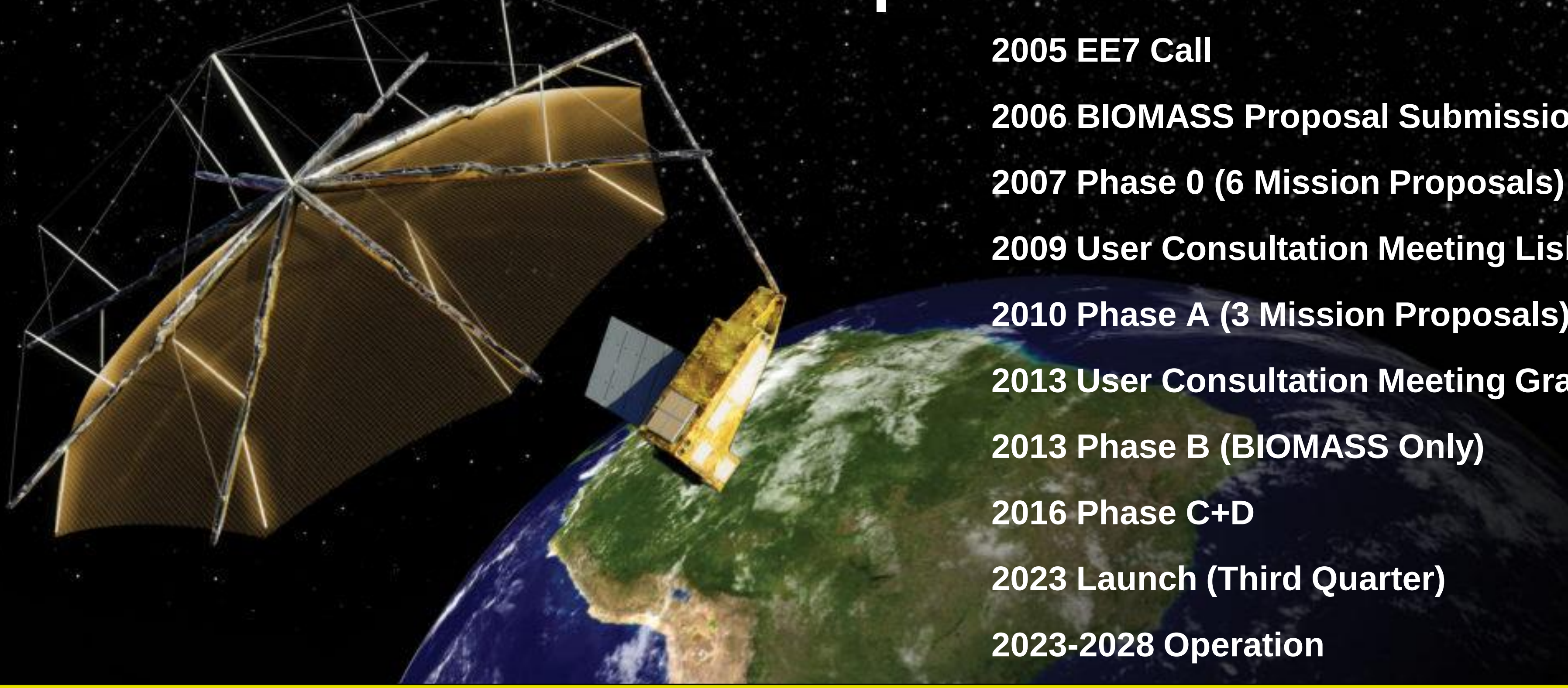




We do not know how to combine multifrequency measurements in a model framework !

We do not know how to combine measurements at different spatial (temporal) scales !

biomass - ESA's 7th Earth Explorer Mission



2005 EE7 Call

2006 BIOMASS Proposal Submission

2007 Phase 0 (6 Mission Proposals)

2009 User Consultation Meeting Lisbon

2010 Phase A (3 Mission Proposals)

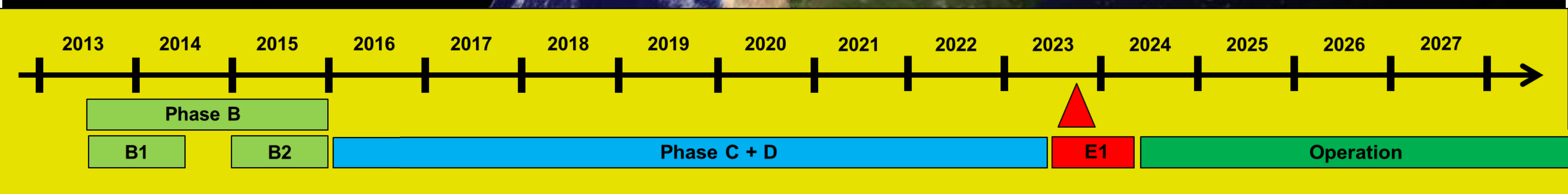
2013 User Consultation Meeting Graz

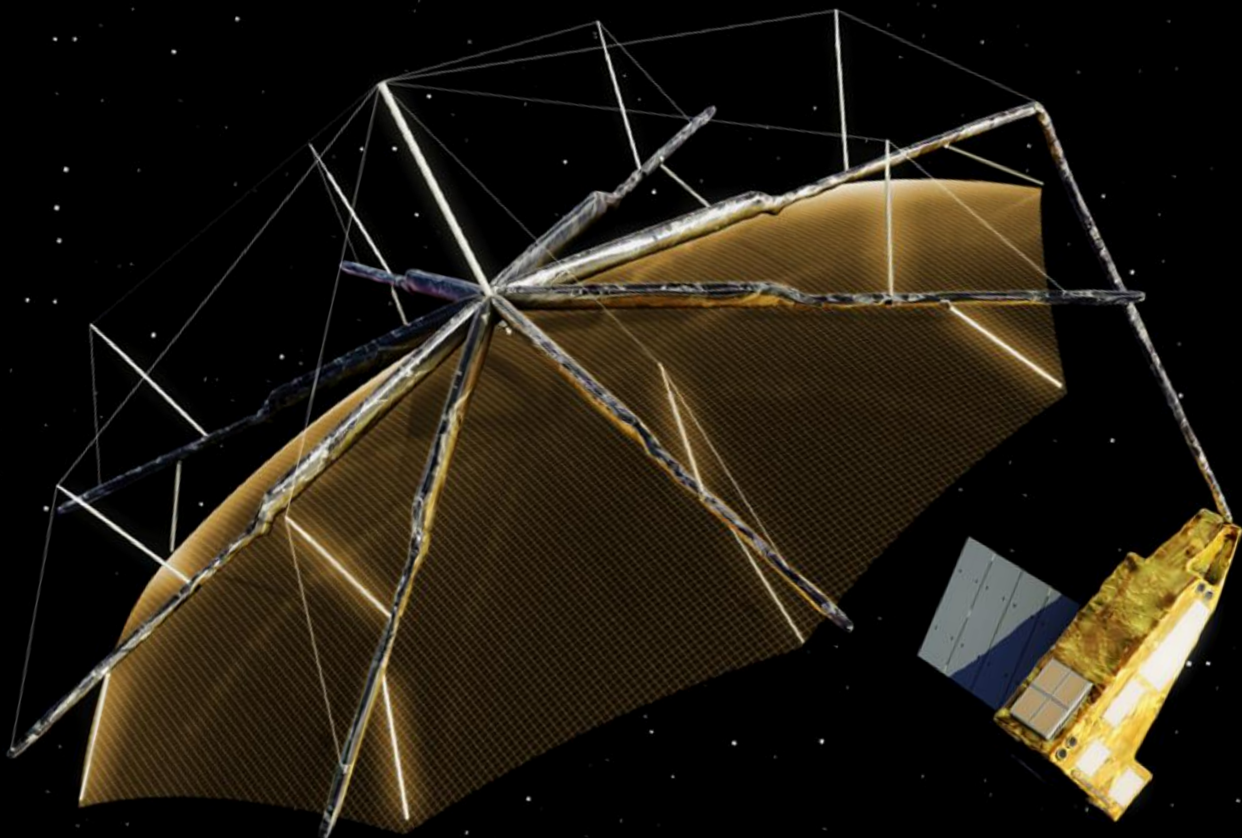
2013 Phase B (BIOMASS Only)

2016 Phase C+D

2023 Launch (Third Quarter)

2023-2028 Operation





- ✓ Single satellite, operated in a polar sun-synchronous orbit
- ✓ Full polarimetric P-band (435 MHz, λ=69cm) SAR (Synthetic Aperture Radar) with 6 MHz bandwidth
- ✓ Two mission phases: Tomography (year 1), Interferometry (year 2-5)
- ✓ Multi-repeat pass interferometry (3 passes in nominal operations) with a 3 days repeat cycle
- ✓ Global coverage in 7.5 months (228 days) on both asc. and des. passes
- ✓ 5 years lifetime

BIOMASS Mission Products

Level 2 Product	Definition	Information Requirements
Forest biomass	Above-ground biomass expressed in $t\ ha^{-1}$.	• 200 m resolution • RMSE of 20% or 10 $t\ ha^{-1}$ for biomass < 50 $t\ ha^{-1}$
Forest height	Upper canopy height defined according to the H100 standard	• 200 m resolution • RMSE better than 30% for trees higher than 10 m
Severe disturbance	Map product showing areas of forest clearance	• 50 m resolution • detection at a specified level of significance

- **1 near-global map of biomass and height from tomography in the first 14 mission months;**
- **updated biomass and height maps from polarimetry and interferometry every 7.5 months for the rest of the 5-year mission;**
- **annual maps of deforestation.**

BIOMASS Mission Algorithm & Analysis Platform (MAAP)

Virtual research environment:

- ✓ Ease of data access and sharing
  - Remote sensing data from ESA science missions (and complementary/similar missions)
  - Ground data from ESA campaigns (field data and Cal/Val)
- ✓ Allow data processing (product generation)
- ✓ Allow joint code / algorithm development (Product Algorithm Laboratory), addressing intellectual property rights issues
- ✓ Enable interoperability of data/code/algorithms
- ✓ Support transparency in research, development and validation
- ✓ Ease information sharing and networking

Multi-baseline Polarimetric SAR Interferometry: Forest Applications.