SAR Techniques & Applications for Forestry

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Outline

I. Introduction

forest cover mapping, forest cover change mapping (deforestation, forest fires, wind damage...

II. Important forest parameters

biomass, forest height, forest structures…

III. SAR for forest applications - some basics

scattering in forests, penetration depths of signal in forests, linking SAR measures with forest parameters

IV. SAR techniques for forest applications

- Backscatter analysis
- Interferometry: Phase analysis & Coherence analysis
- Polarimetry
- Polarimetric Interferometry
- SAR (Polarimetric) Tomography

Why Forest Observation?

- ***Forests*** cover approximately ***33% of the Earth's land surface*** (Jensen, 2000)

- Forests play an important role in the global carbon cycle, since ***each year forests absorb approximately 1/12 of the Earth's atmospheric CO_2 stock*** (Malhi et al., 2002)

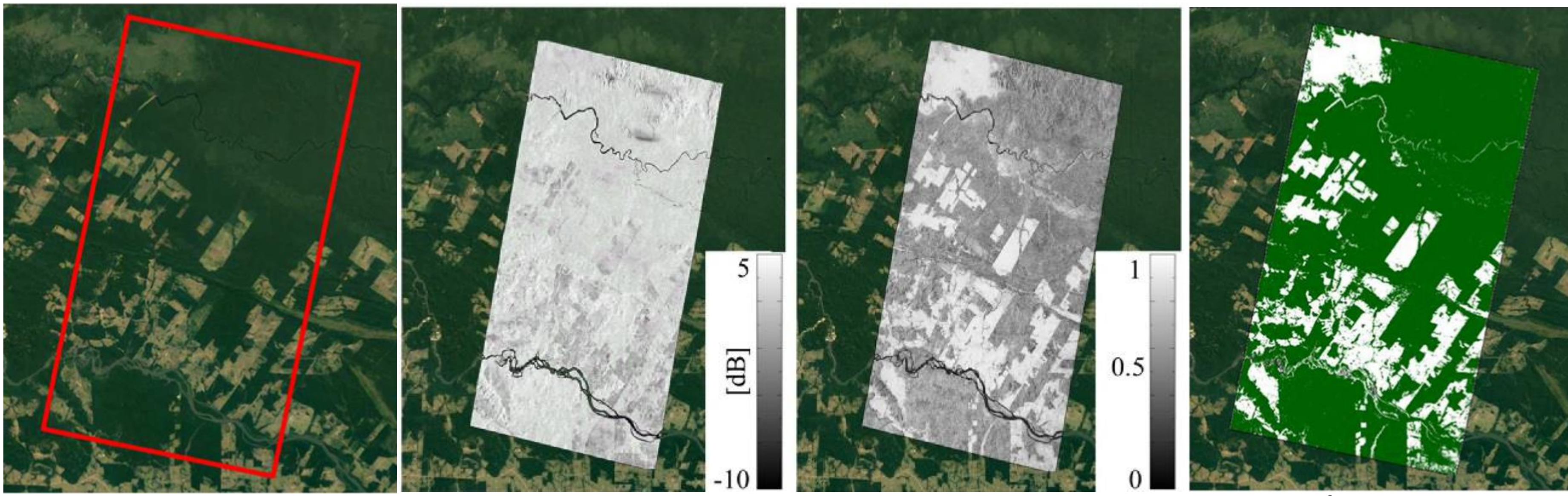
- ***Forested*** ecosystems account for app. ***72% of the Earth's terrestrial carbon storage*** (Malhi et al., 2002)

- Therefore, Vegetation biomass is a ***larger global store of carbon than the atmosphere*** (FAO, 2009)

- Between 1850 and 2011, humans have released app. ***480 Gt (480 BILLION TONS!!!) of CO_2 into the atmosphere*** through fossil fuel burning and land use changes (e.g. deforestation and fires) (Ghasemi et al., 2011)

What can we observe?

- Forest Cover Mapping -



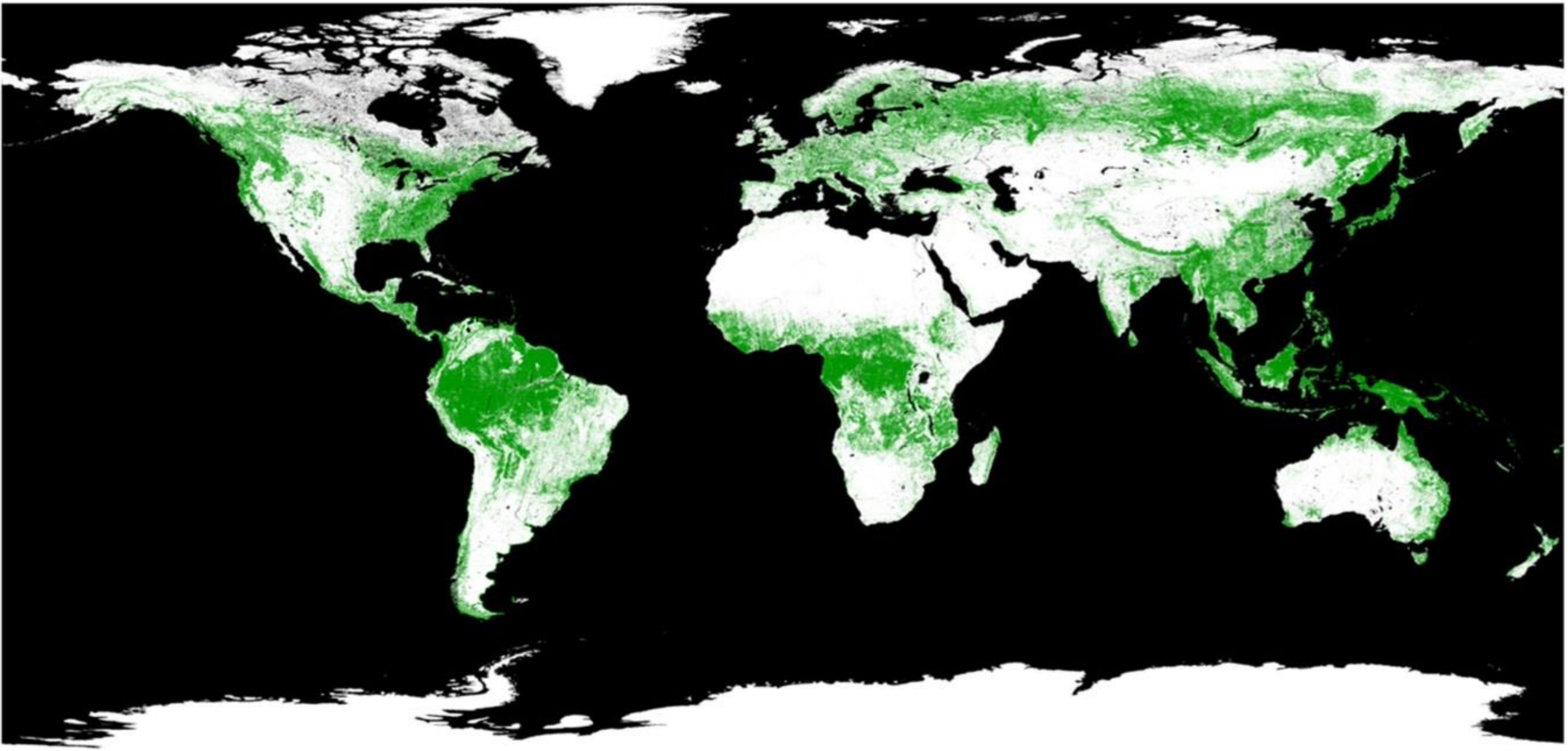
GoogleEarth Image | **Normalized backscatter** | **Interferometric coherence** | **Forest/non-forest map**

TanDEM-X forest/non-forest map over Amazon forest

Martone et al. (2018).

What can we observe?

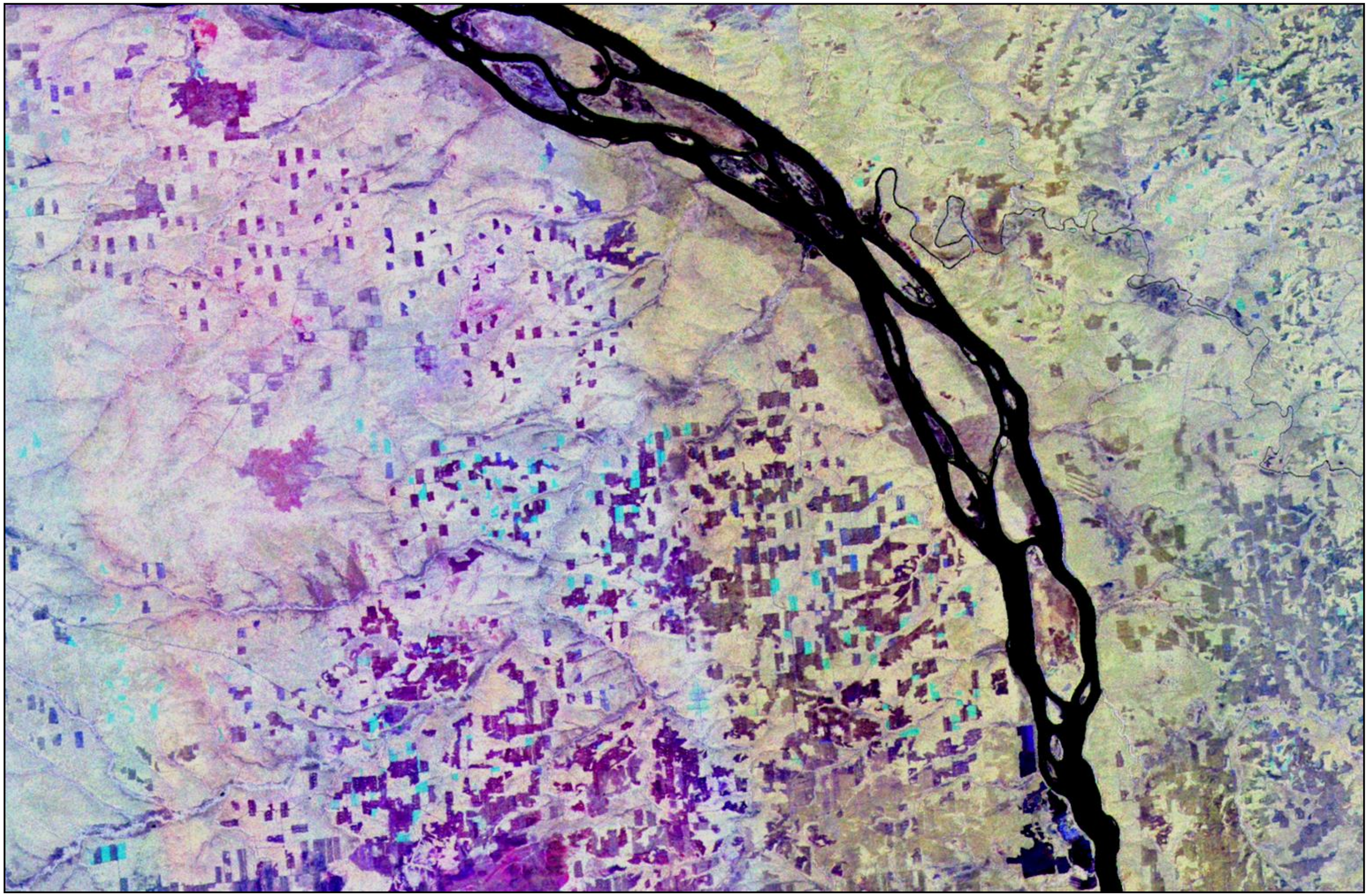
- Forest Cover Mapping -



Global TanDEM-X forest/non-forest map at 50 m × 50 m sampling

Martone et al. (2018).

Forest Cover Change Mapping - Deforestation -



Observe clear-felling (ALOS PALSAR, Multitemporal Composite, Siberia)

What can we observe?

Forest Cover Change Mapping - Forest Fires -

Observe damage by forest fires (mid-August 2010, fires close to Moscow)

Wind damage area

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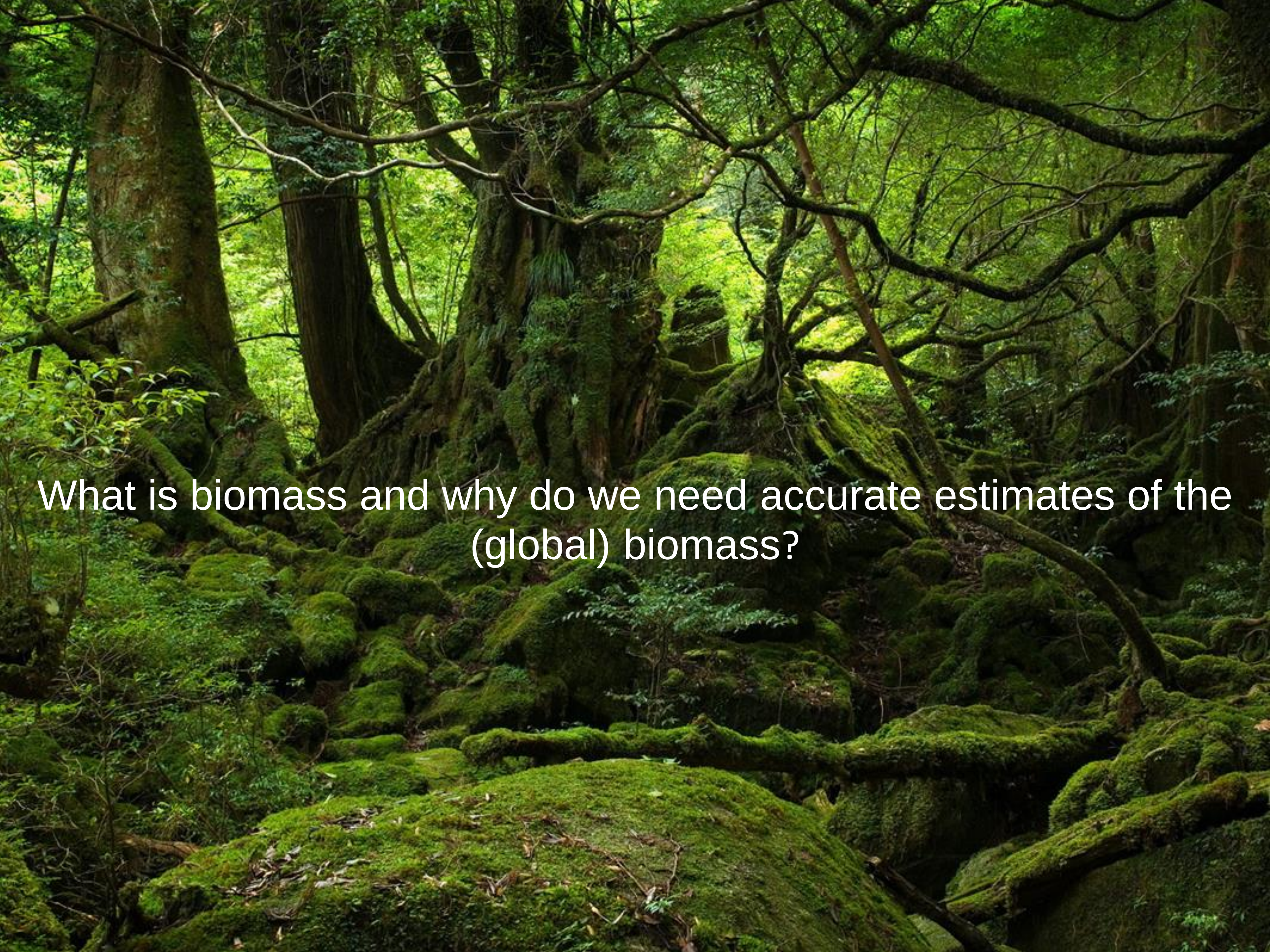


What is biomass and why do we need accurate estimates of the (global) biomass?

Why do we need to estimate forest biomass?

- Forest biomass can be defined as the amount (mass) of dry organic matter of plant origin

- It is the basic parameter for characterizing the distribution of carbon in the biosphere

- For a better understanding and quantification of:

    - the ***global carbon cycle***
    - ***global warming***
    - terrestrial ***carbon stocks and fluxes*** in forests
    - terrestrial ***carbon sources and sinks***

- Information of forest biomass is needed to ***support sustainable forest resource management***

Main components of biomass distribution

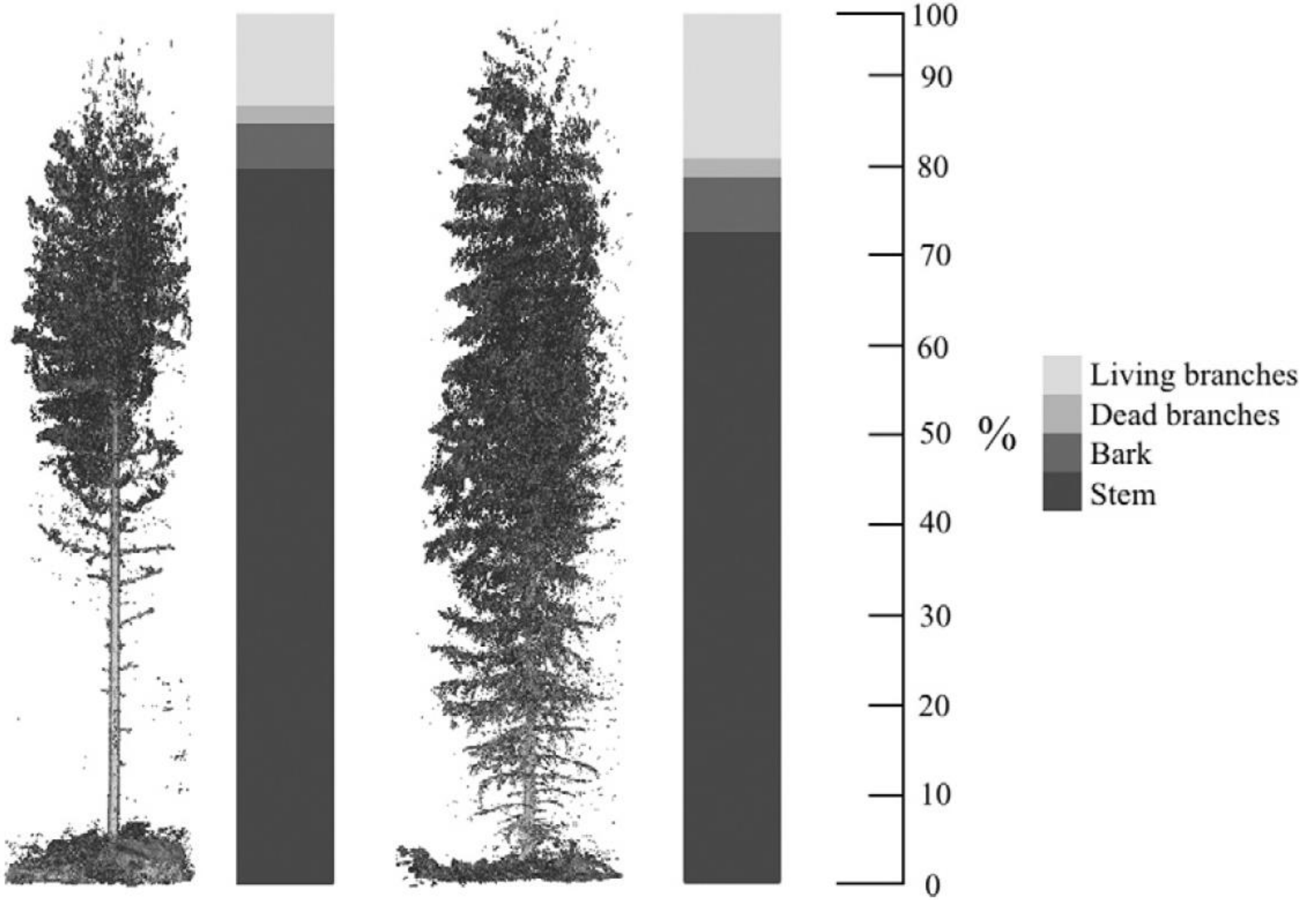
Phytomass (>90%)
- Above-ground (approx. 80%)
  - Stem (> 90%)
  - Branches (< 10 %)
  - Leaves (2-4 %)
  - Undergrowth (?)
- Below-ground i.e. roots (ca. 20 %)

Zoomass (<10 %)

[After Mette et al., 2002]

- Stem Biomass is strongly related to the commercially interesting biomass.
- The major part of forest biomass is concentrated in the major trees. The contribution of minor trees (and hidden biomass) to total biomass is rather low
- Characterizing biomass using tree height will cover 75-95% of the vegetated earth and could directly characterize 80-90% of the aboveground biomass stock

Main components of biomass distribution



Field-measured biomass distributions for different sections (stem, bark, living and dead branches) of the tree for Scots pine and Norway spruce

Kankare et al. (2013).

Forest biomass

In Forestry, the biomass calculation is based on measurements of trunk diameter and height of sample populations of trees:

$$Biomass_{forest} = N \times \pi \times \left(\frac{1}{2}\,\mathrm{dbhmid}\right)^2 \times hmid \times \rho \times fz$$

$Biomass_{forest}$ [t/ha]	is defined as aboveground woody of trunk and branches exceeding 7 cm diameter
$\mathbf{dbh}_{\mathrm{mid}}$ [cm]	is the mean diameter at breast height 1.3 m
h_{mid} [m]	is the height of the tree
ρ [g/cm³]	is the species-specific wood density
f_z []	is a form factor (= 0.4-0.5, constant in a first order approximation)
N	is the tree density (tree number per area unit)

The product of $N \times \pi \times \left(\frac{1}{2}\,\mathbf{dbh}_{mid}\right)^2$ is also called **basal area**

Forest biomass

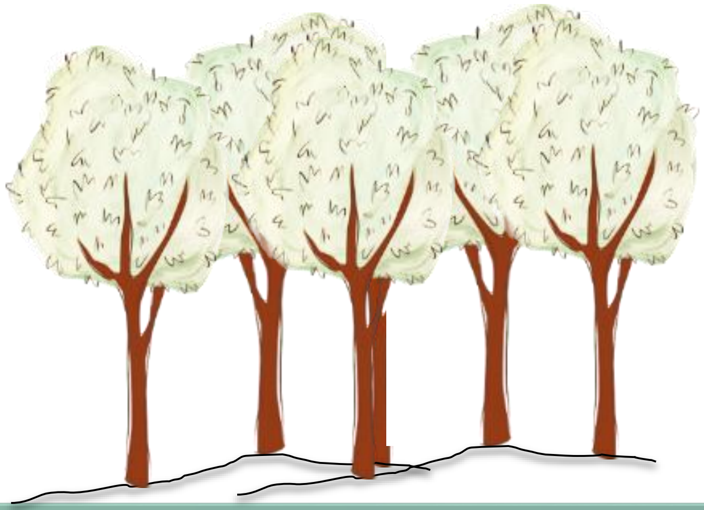
Although no remote sensing technique allows a direct measurement of biomass, we can still derive estimations of biomass :

- the **sensitivity of the backscatter** to the biomass
- the **sensitivity of interferometric coherence** to the forest volume, hence biomass
- estimation of **forest height** with SAR data

forest height plays an important role for

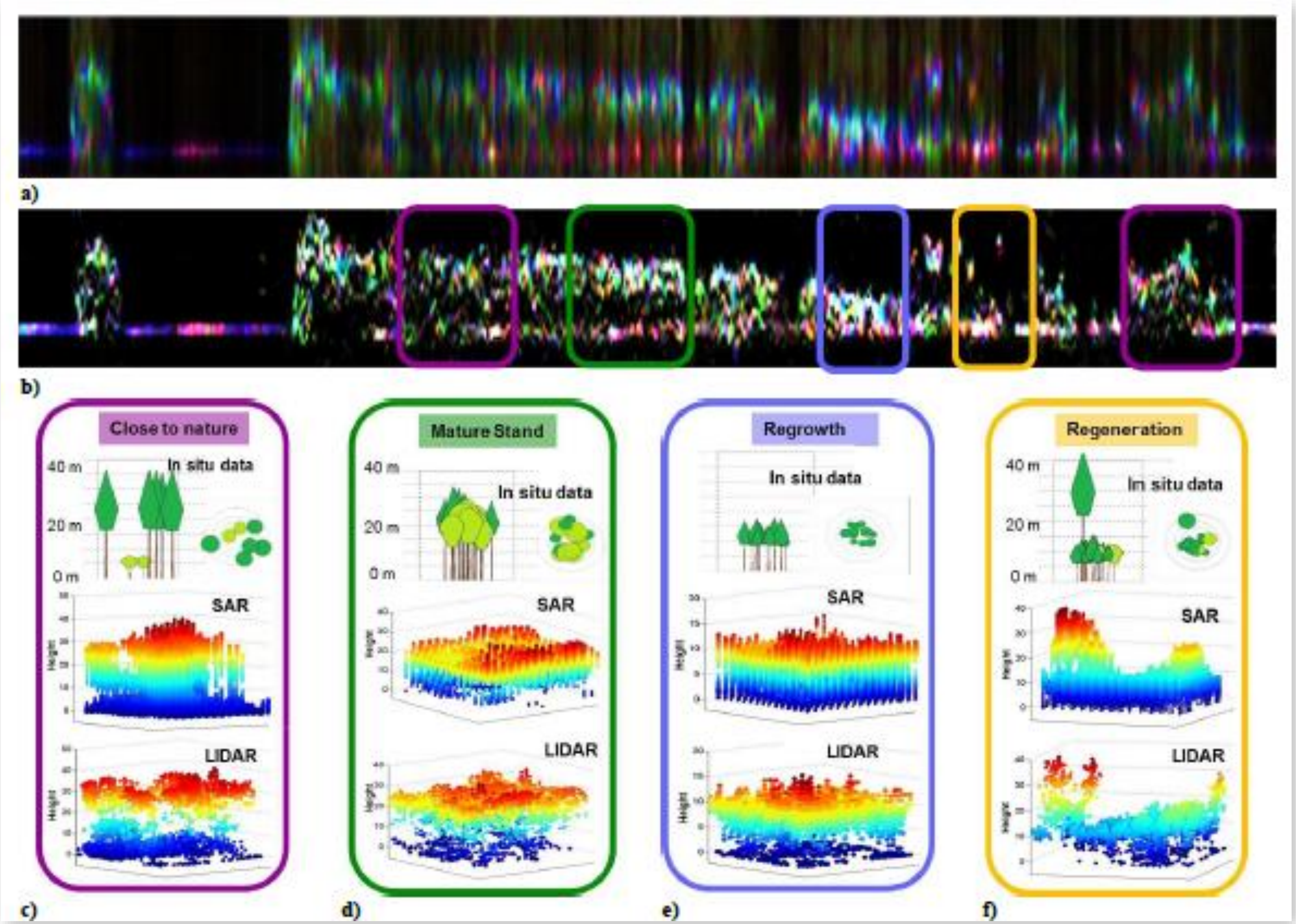
estimation of forest volume & aboveground biomass!

-Allometric relations between biomass & forest height-



Forest structure

Forest structure implies the horizontal and vertical variability of the tree distribution



(a)-(b) Pauli representation of the tomogram with Capon and with the Compressive Sensing.
(c)-(f) Examples of inventory plots (50x50 m) with different structures, as represented with field, LIDAR and TomoSAR data.

[Tello et al., 2015]

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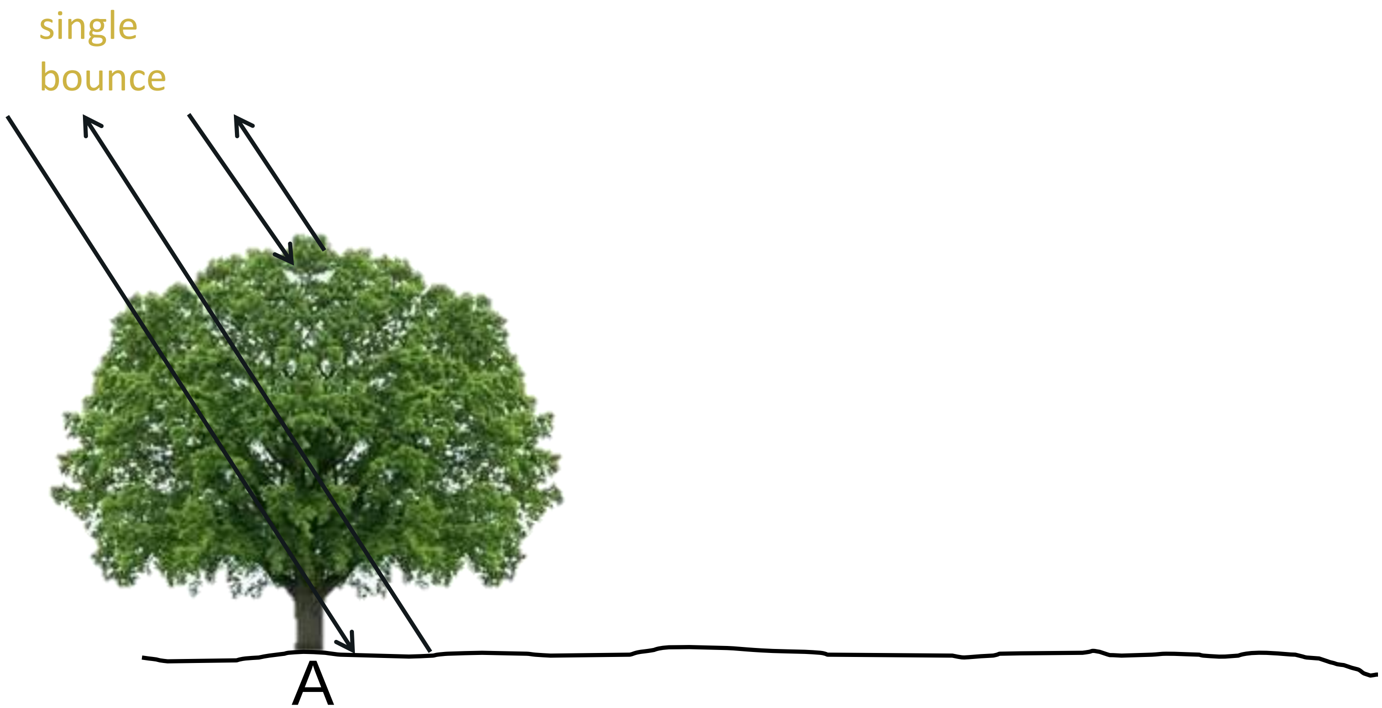
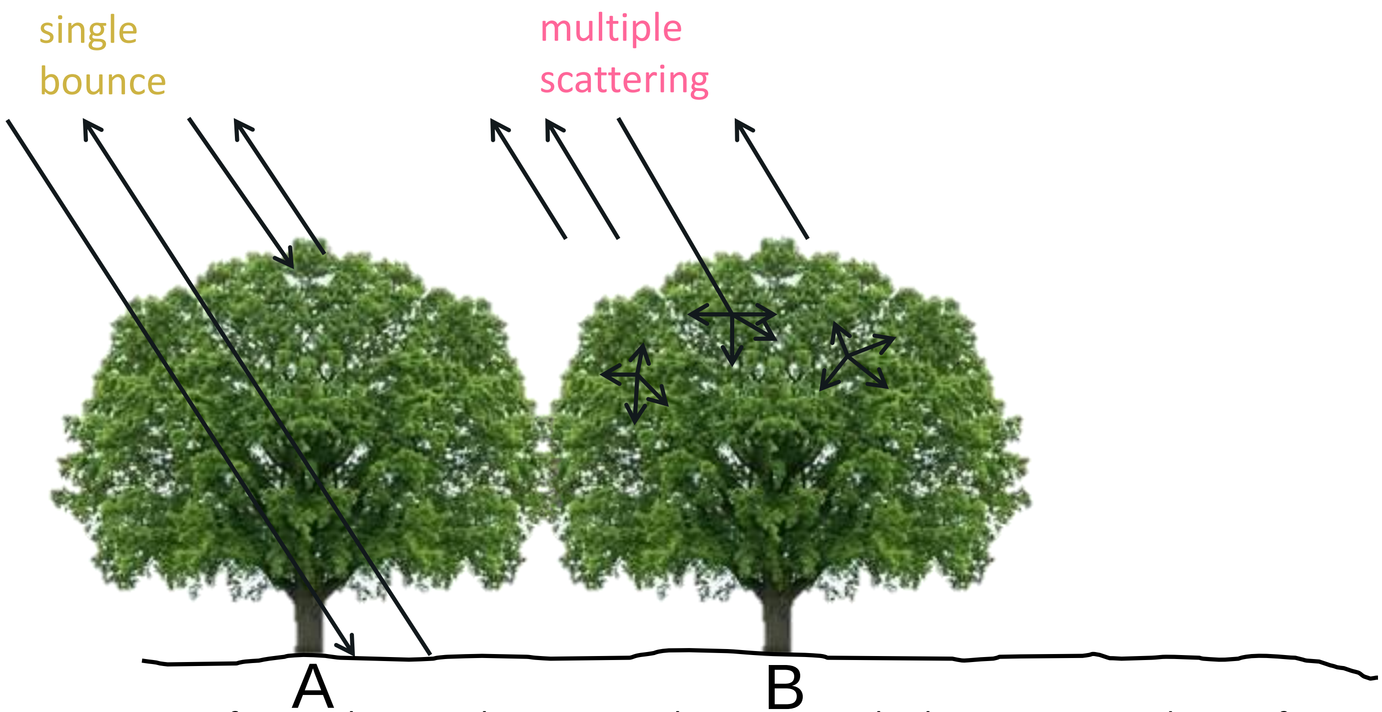
Scattering mechanisms in forest



A - When a wave reflects off only one target and returns to the instrument this is known as direct scattering (or “single bounce”). This occurs when the wave hits a target that is at an orientation such that the wave is returned directly to the radar.

Fig.: Global Biomass (after METTE et al., 2002).

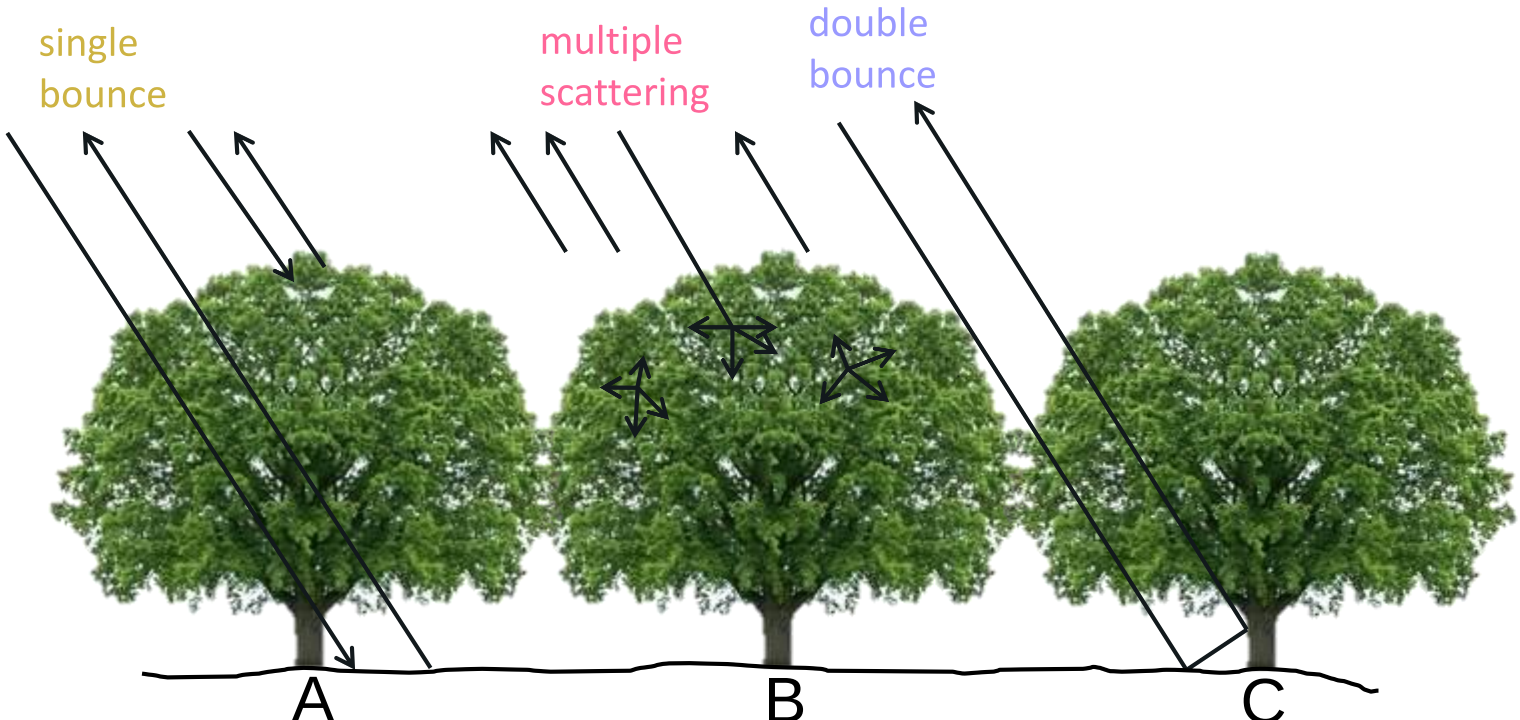
Scattering mechanisms in forest



B - Cases of more than two bounces are known as multiple scattering and occur frequently in environments such as dense forest canopies between trunks, branches, and twigs.

Fig.: Global Biomass (after METTE et al., 2002).

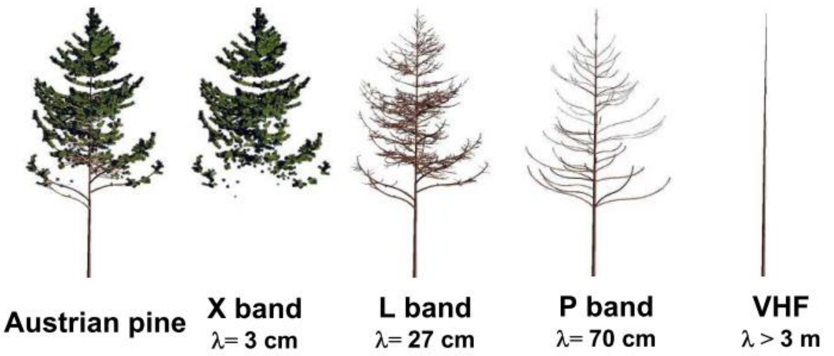
Scattering mechanisms in forest



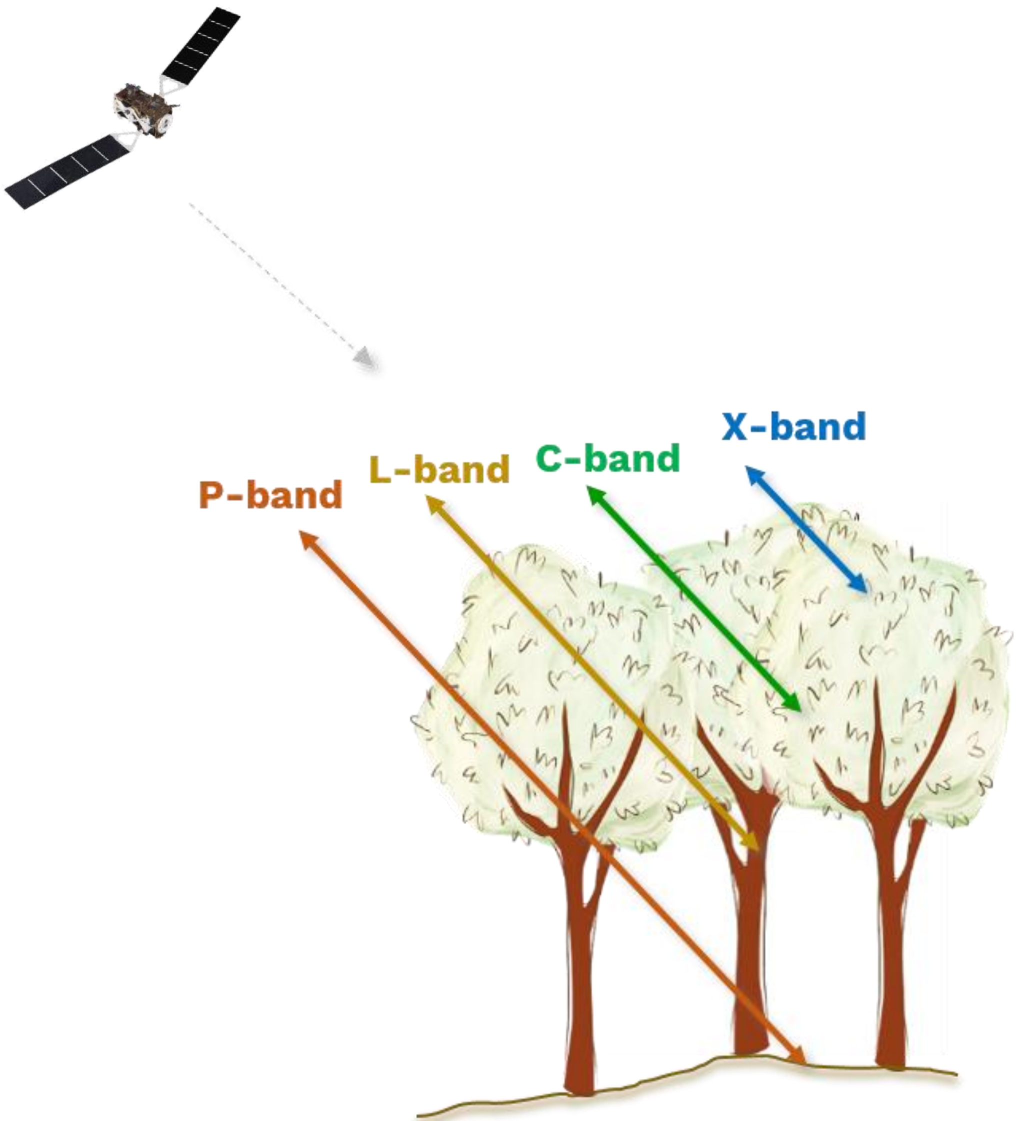
C - If the wave reflects off two surfaces before returning to the instrument, such as often arises in urban areas between ground and wall, or in forests between ground and tree trunks or between trunks and twigs, this is termed “double bounce”.

Fig.: Global Biomass (after METTE et al., 2002).

Penetration of SAR signal into forests



(Le Toan, 2001)



Penetration of SAR signal into forests

C- band L- band

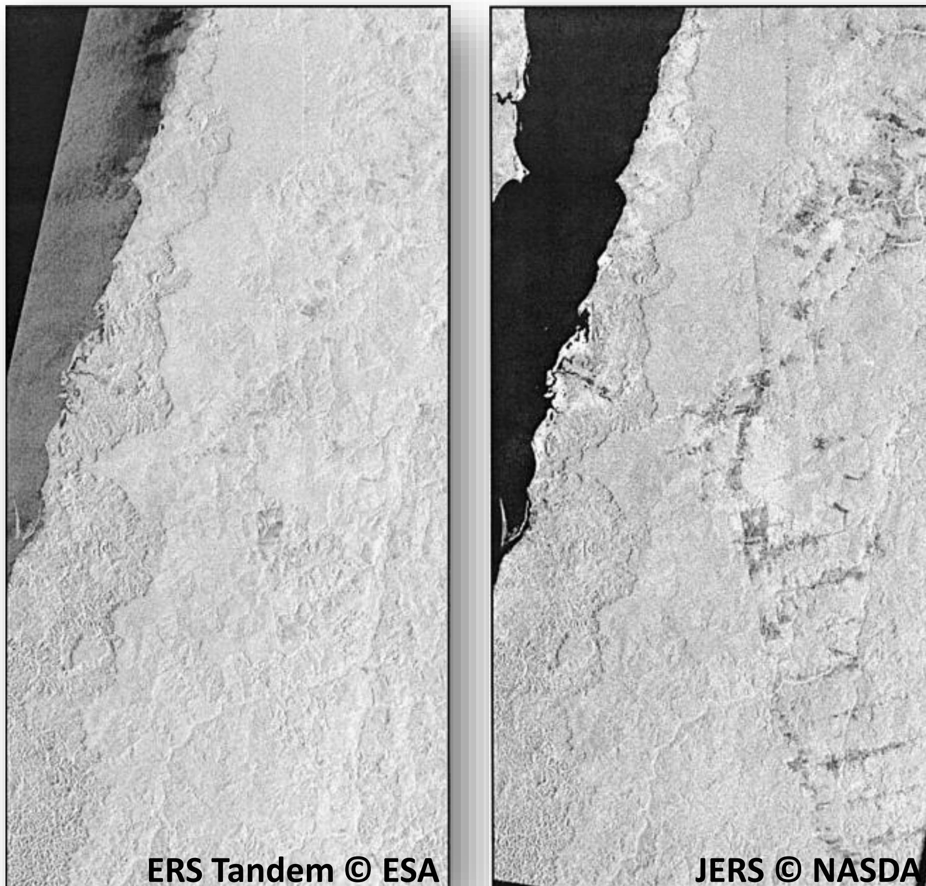
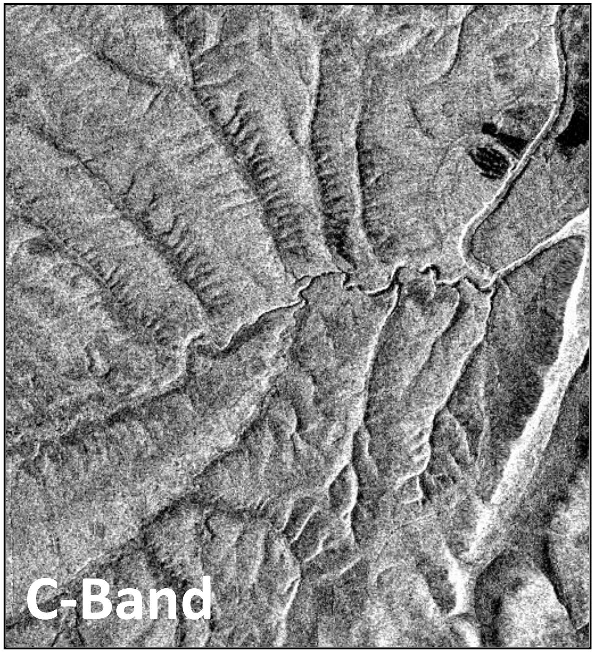
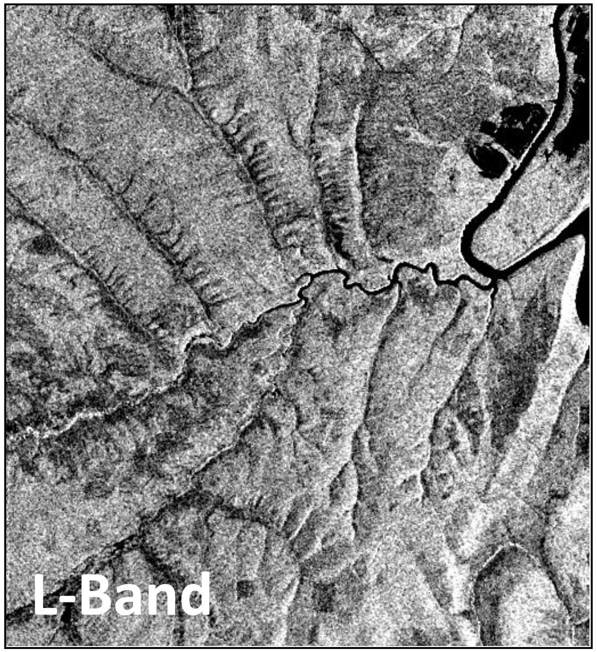


Fig.: ERS Tandem (C-band) JERS (L-band) intensity image (size 50 km by 100 km) (LUCKMAN et al., 2000).

Different wavelengths in forest observation



- *Small dynamic range*
- *Variable response to water*
- *Variable response to open areas*



- *Medium dynamic range*
- *Stable response to water*
- *Possible to identify agricultural fields*

Fig.: Different wavelengths in biomass estimation and coherence (Le Toan et al., 2001).

Why forest observation with SAR?

compared to optical remote sensing data or in-situ measurements

- Higher spatial coverage
- Higher temporal resolution (repeat cycle e.g. 11 days)
  - ⇒ Remotely sensed data therefore can be used to fill spatial, attributional, and temporal gaps in forest inventory data
- Contactless
  - ⇒ Detection of unknown regions
- Retrospective analysis
  (archived SAR data since 1991 (but not globally))
- Microwaves enable a weather- and illumination-independent imaging process

Challenges of SAR data in forest observation

(compared to optical remote sensing data or in-situ measurements)

- Limitations in applicability of RS data for AGB estimation are related to
  - Backscatter saturation, especially in mature forests with complex stand structure
  - In rugged or mountainous regions, topography can affect vegetation reflectance and influence relationships between backscattering values and AGB → topographic correction is necessary
  - Complex interactions of SAR signal
- Satellite approaches to estimate biomass are still in pre-operational state

[FAO, 2009; GHASEMI et al., 2011]

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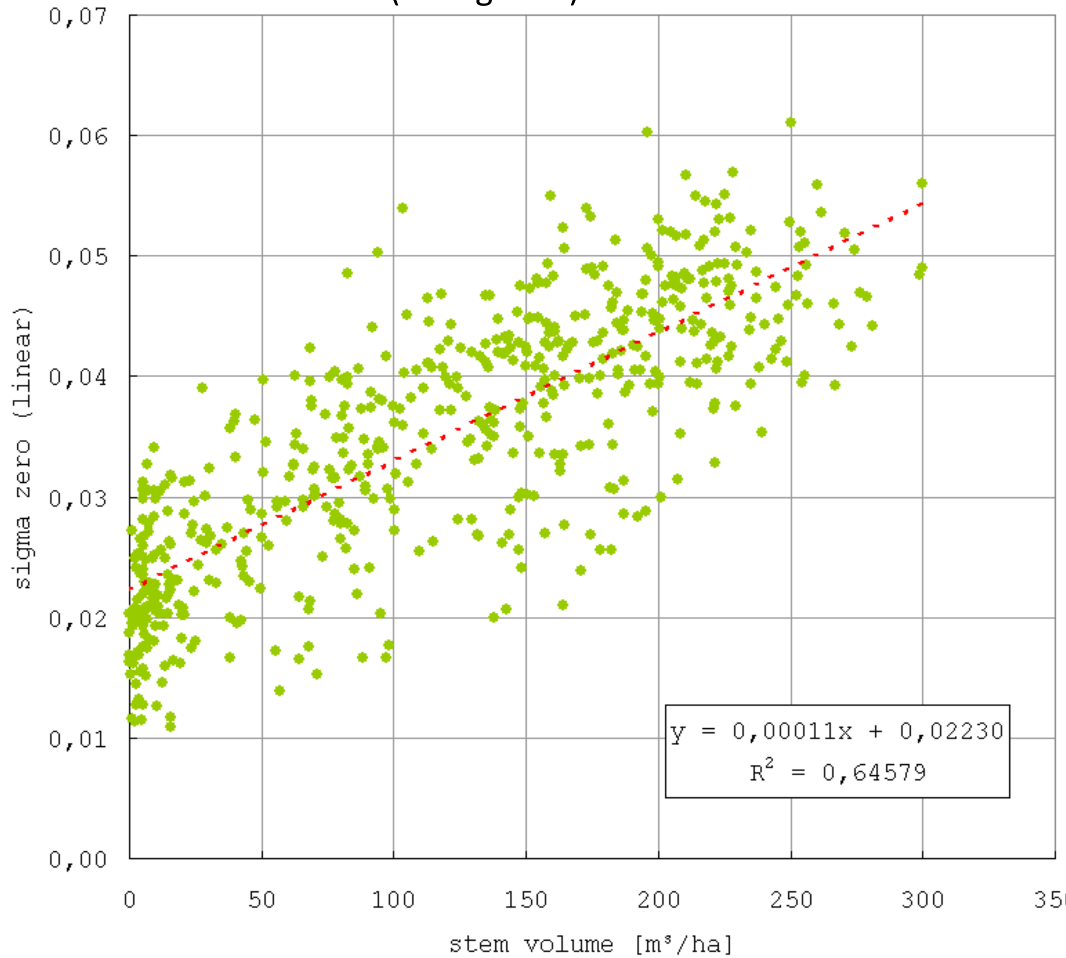
Backscatter analysis: correlation with stem volume

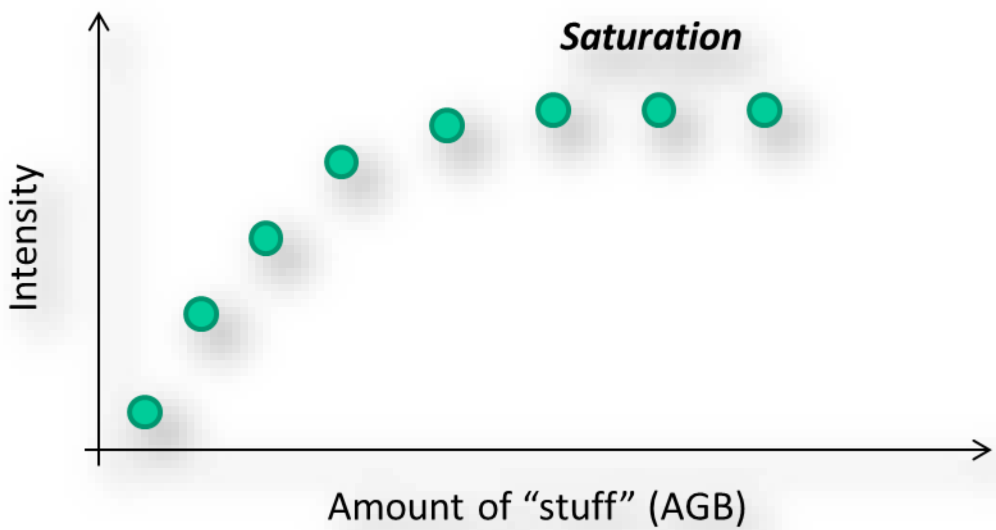
- Correlation between SAR data and stem volume -

Stem volume vs. backscatter (HV)
(05aug2007) – 12.5 m data



Saturation problem in Backscatter analysis

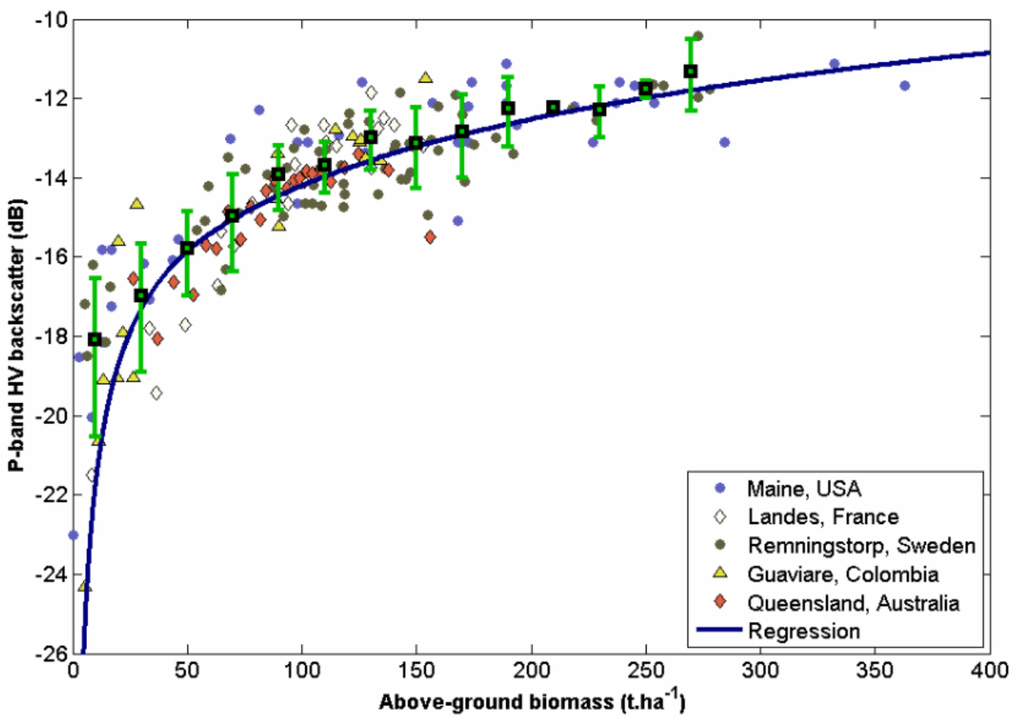
- Saturation means the ***SAR response levels offs***, i.e. the slope of the regression line approach zero.
- ***Biomass is not longer predictable from the signal***.



[after WOODHOUSE]

Saturation problem in Backscatter analysis

Regression analysis of radar backscatter with forest AGB.



SATURATION PROBLEM

Fig.: Regression analysis of radar backscatter with forest AGB. **P-band HV** backscattering coefficient plotted against AGB from experiments conducted at five different forests. The green points with error bars represent the mean value and standard deviation of all points falling within a biomass bin of +/- 10 tons/ha. The line is a regression curve applied to the full dataset. The corresponding RMSE in biomass is 51.6 tons/ha and the coefficient of determination $r^2 = 0.67$ (Credis: LE TOAN, in ESA, 2008).

Saturation problem in Backscatter analysis

<u>The saturation level depends on:</u>

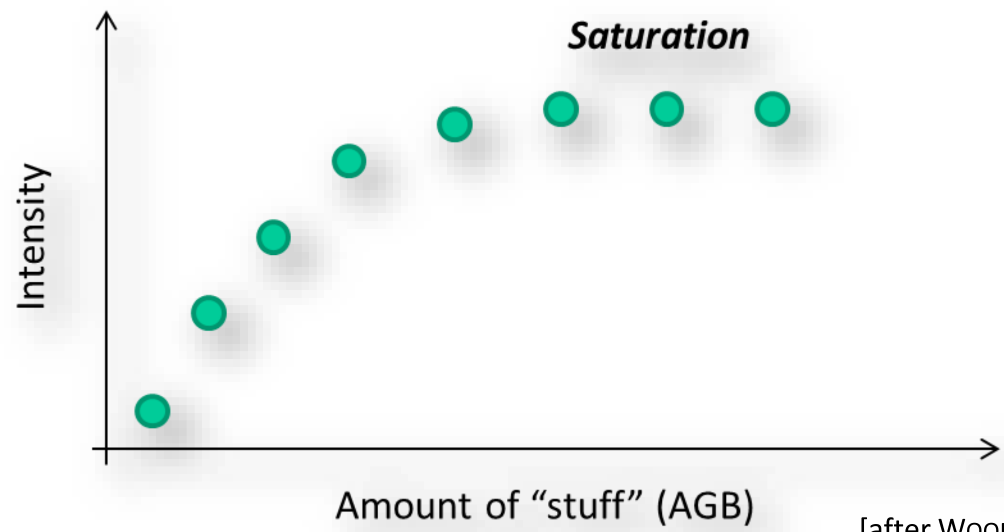
Wavelength (i.e. different bands, such as C, L, P)

Polarization (HV, HH and VV)

Object characteristics (vegetation stand structure and ground conditions)

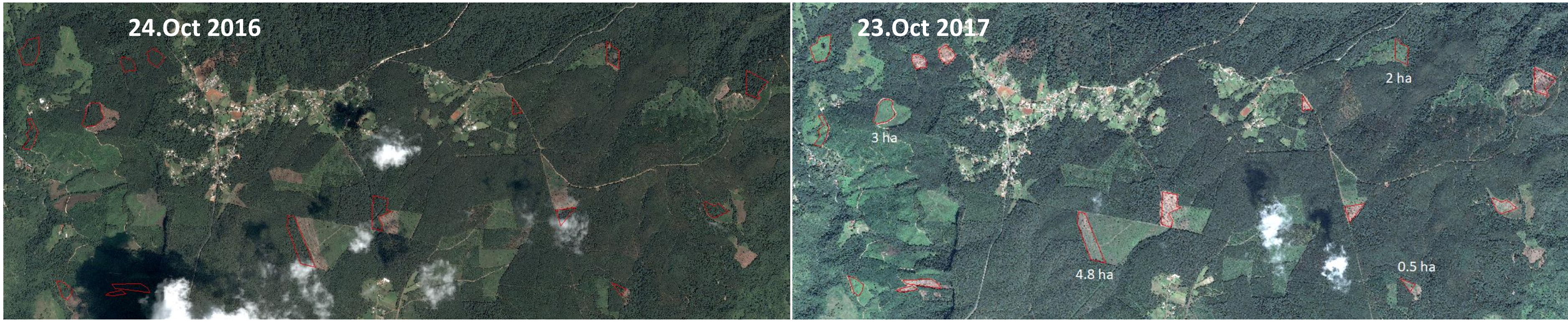
Incidence angle

Available time series (number of images)



[after WOODHOUSE]

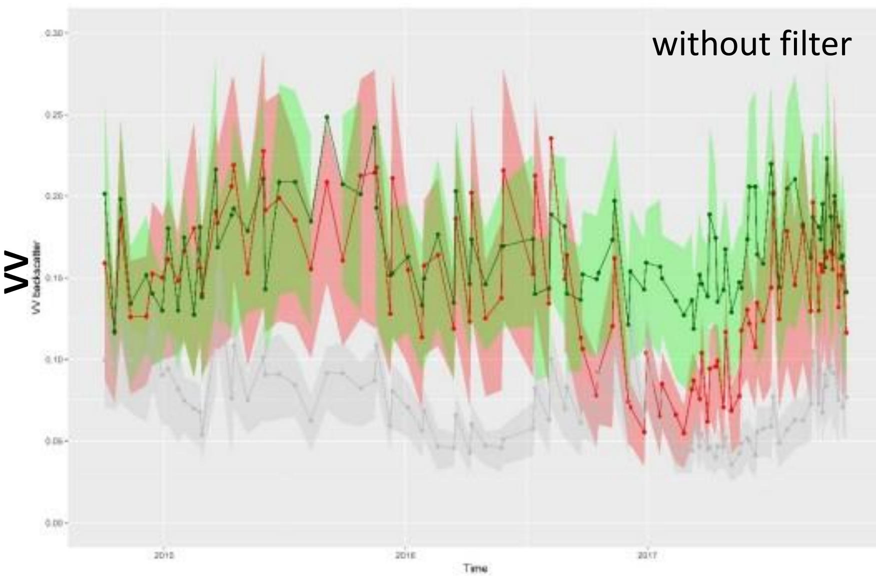
Backscatter – time series analysis

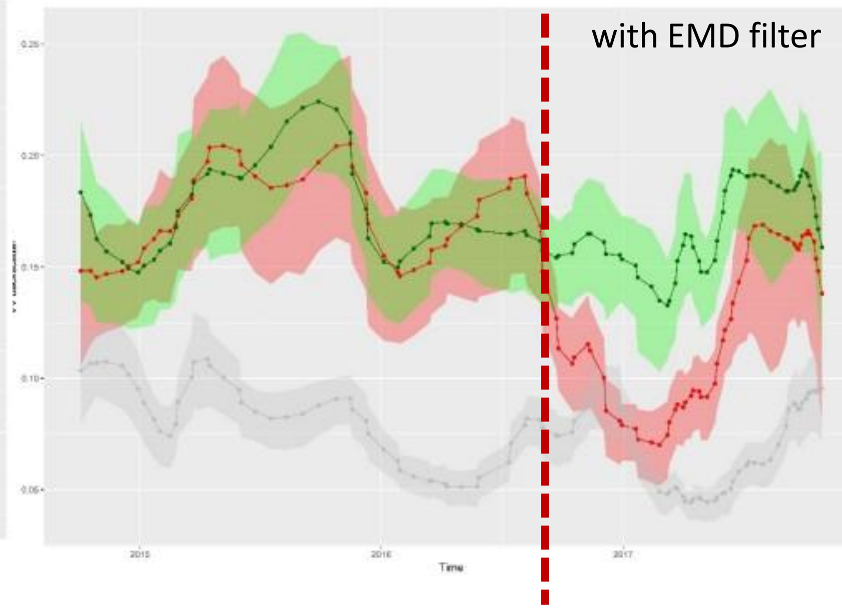


SEN4REDD

Sensor: Pleíades

Location: Central Mexico -Temperate forests





Deforestation

- Deforestation
- Forest
- Agriculture

EMD filter: Filter in time domain & preserve spatial resolution [Cremer, 2018]

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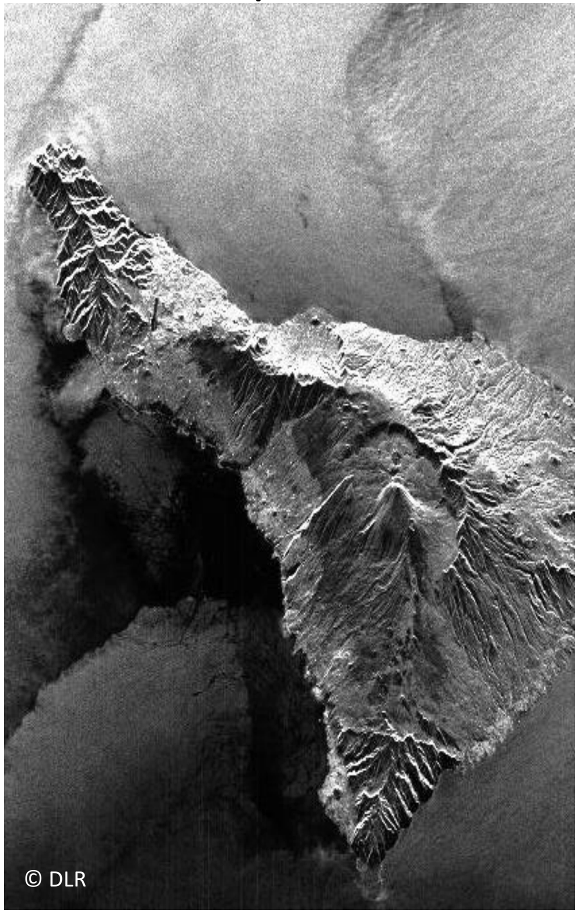
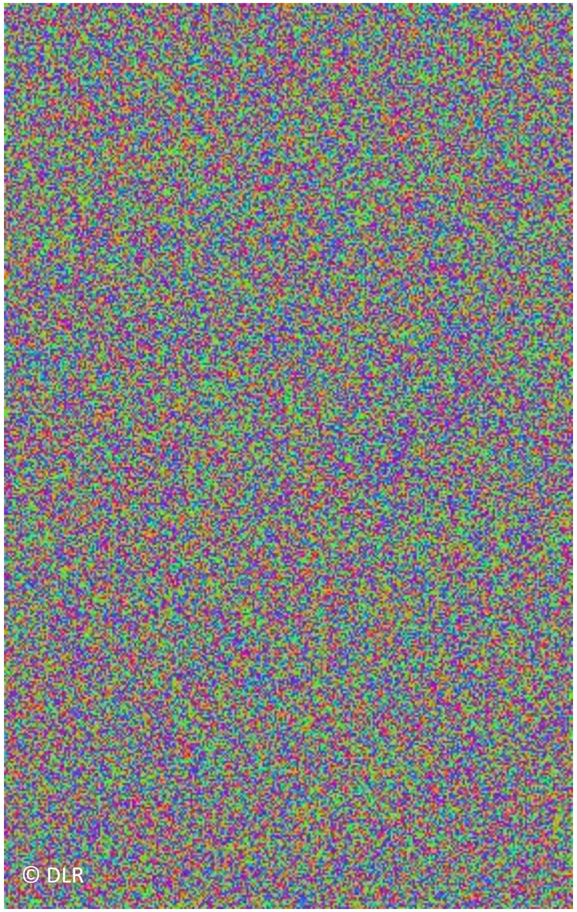
A complex SAR image

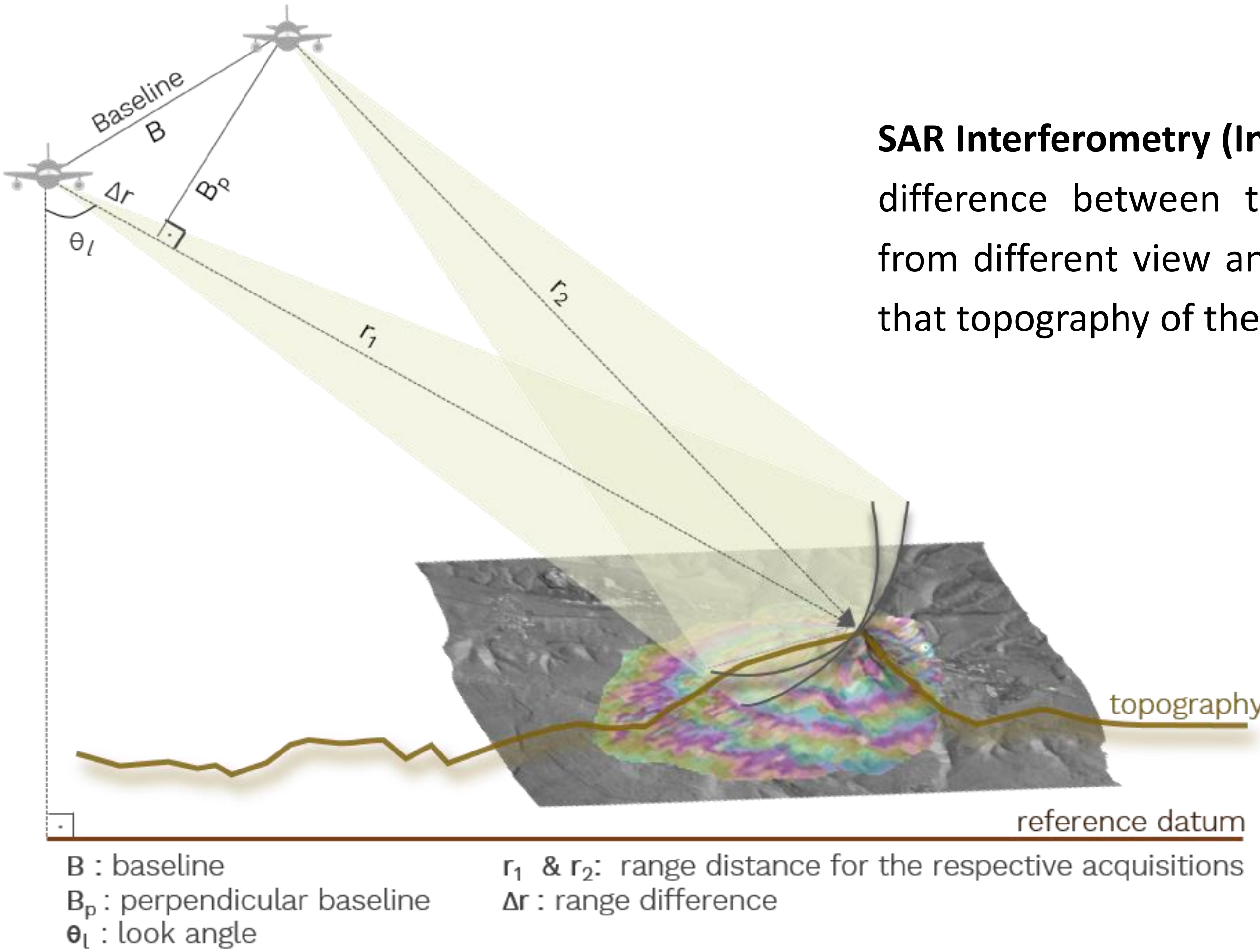
A complex SAR image can be decomposed into …

Amplitude & Phase





SAR Interferometry

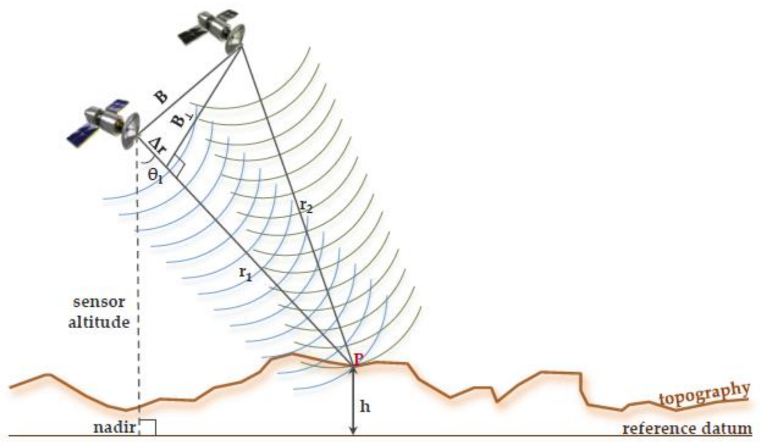


SAR interferometry imaging geometry

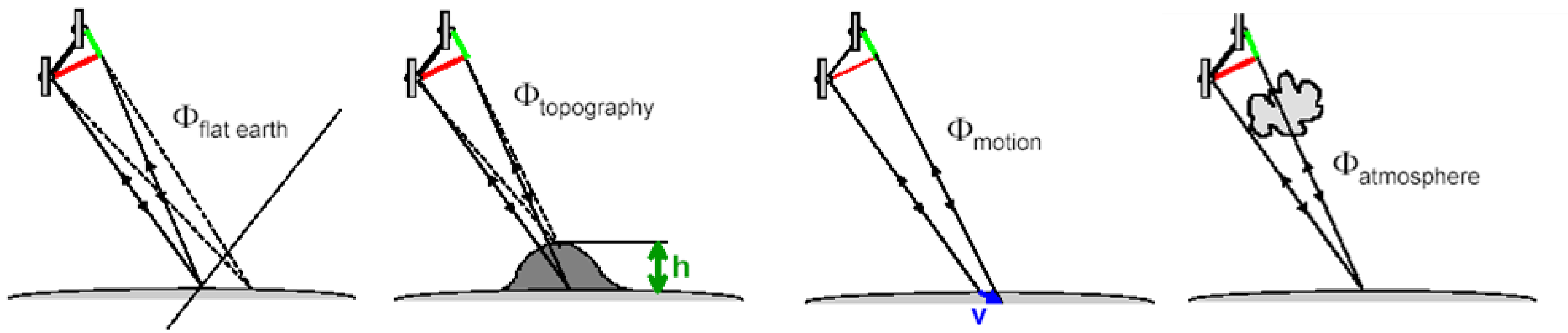
SAR Interferometry (InSAR) makes use of the phase difference between two complex valued images from different view angle, i.e. forming baseline, so that topography of the area can be imaged.

Interferometric phase

Interferometric Phase is composed of many different phase terms



In the absence of deformation, or removal of phase due to deformation & flat-earth and compensation of phase due to atmospherical artefacts digital surface models can be estimated.



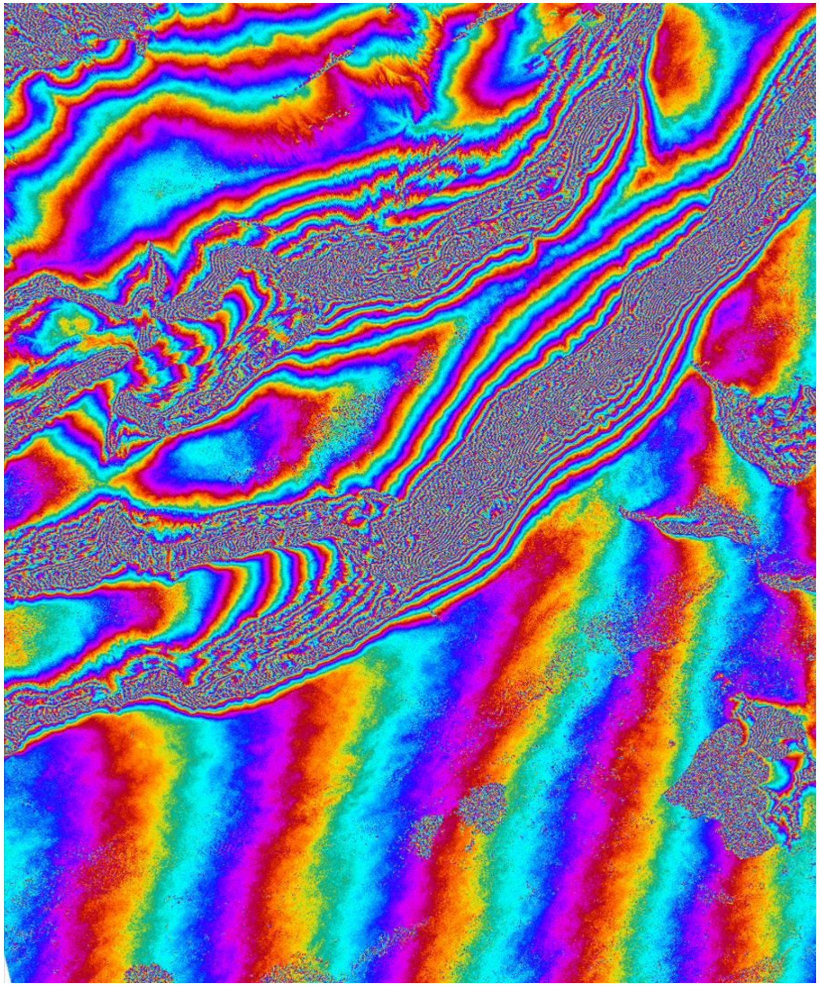
$$\Phi = \Phi_{flatearth} + \Phi_{topography} + \Phi_{motion} + \Phi_{atmosphere} + \Phi_{noise}$$

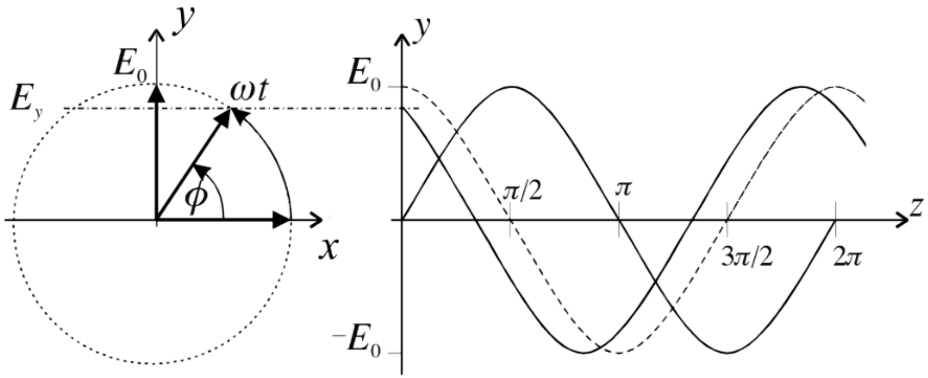
Interferometric phase

ERS SAR image
Bachu, China
approx. 100 km × 80 km

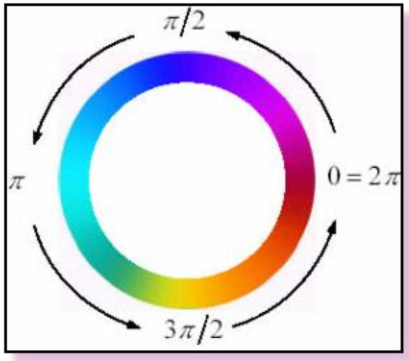
Interferometric phase

Interferometric phase
Bachu, China
approx. 100 km × 80 km



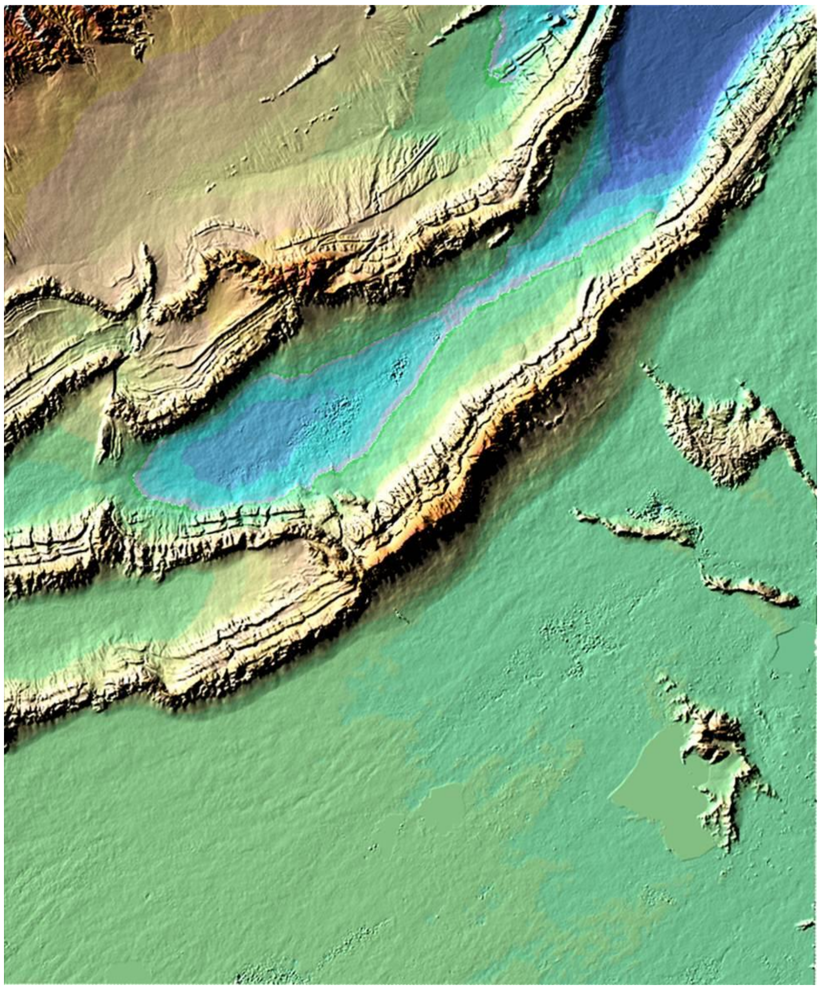


color wheel



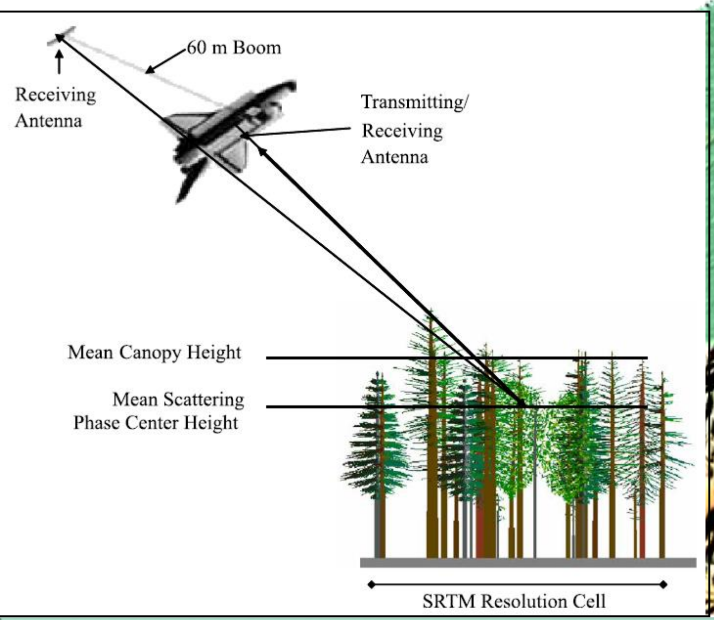
Phase is always ambiguous w.r.t. integer multiples of 2π
→ phase unwrapping required!

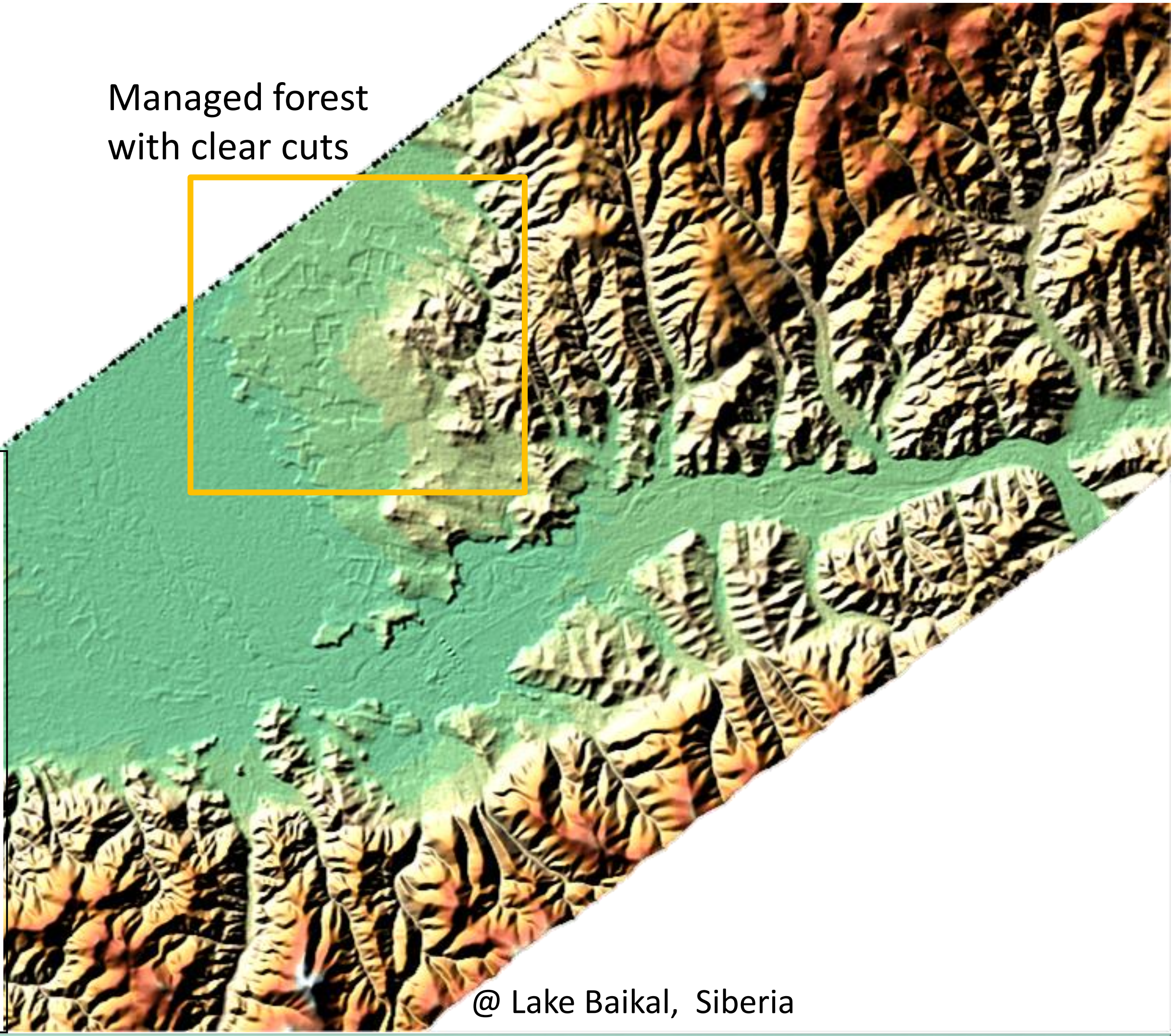
Interferometric phase



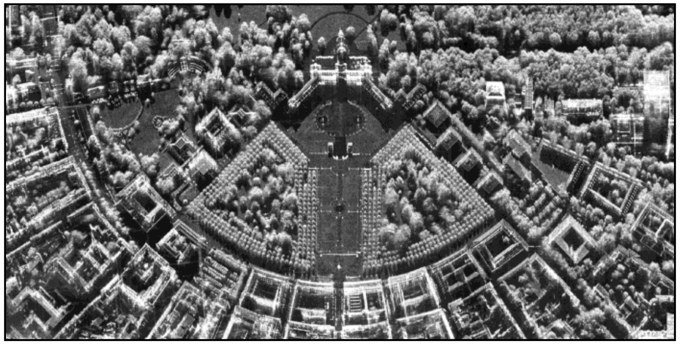
InSAR DEM
Bachu, China
approx. 100 km × 80 km

Interferometric phase analysis for forests

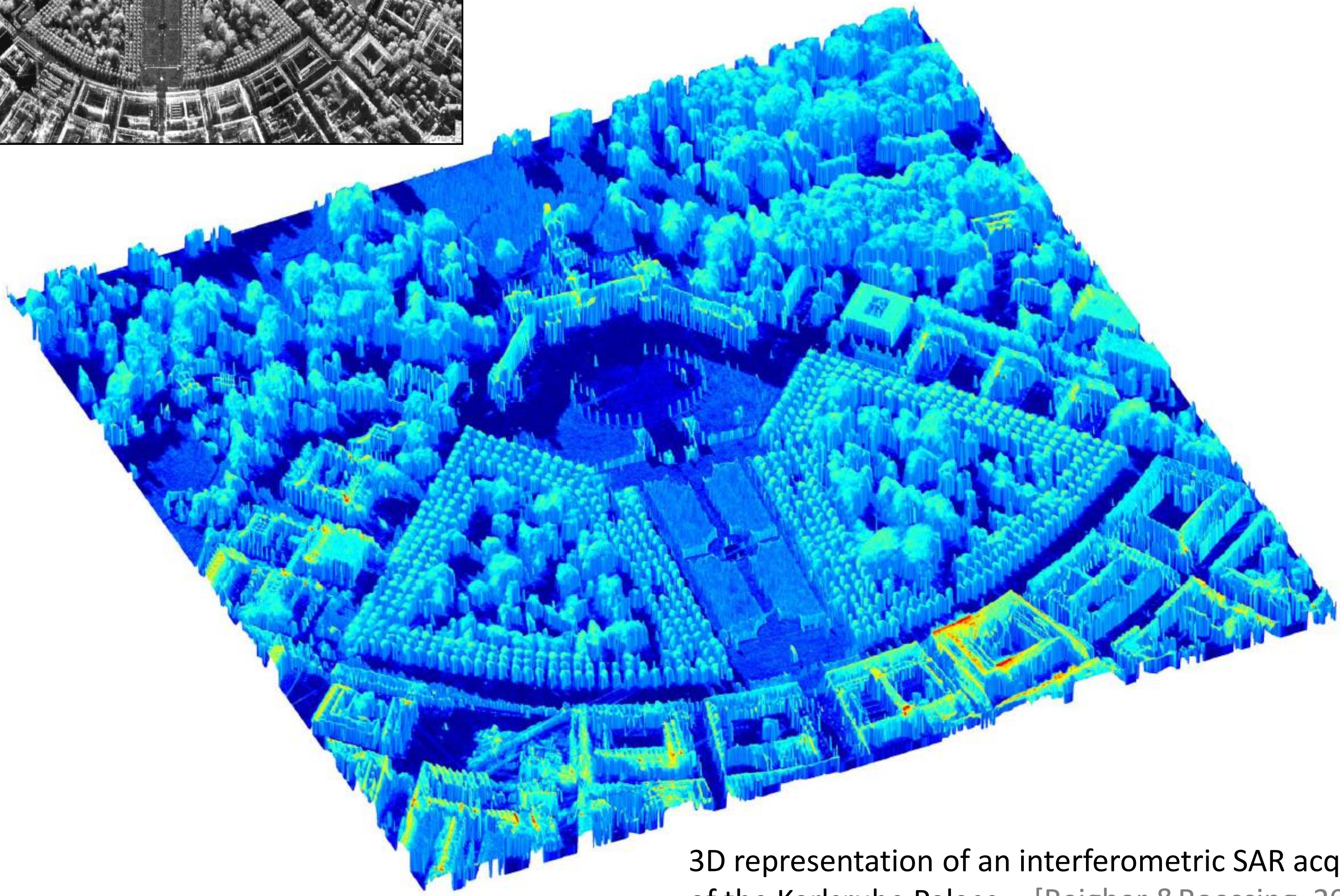




Interferometric phase analysis for forests



Trees acquired at superhigh resolution (X-band)



3D representation of an interferometric SAR acquisition of the Karlsruhe Palace [Reigber &Roessing, 2008]

SAR Interferometry: InSAR phase & Coherence

Interferometric phase is the phase difference of two SAR images

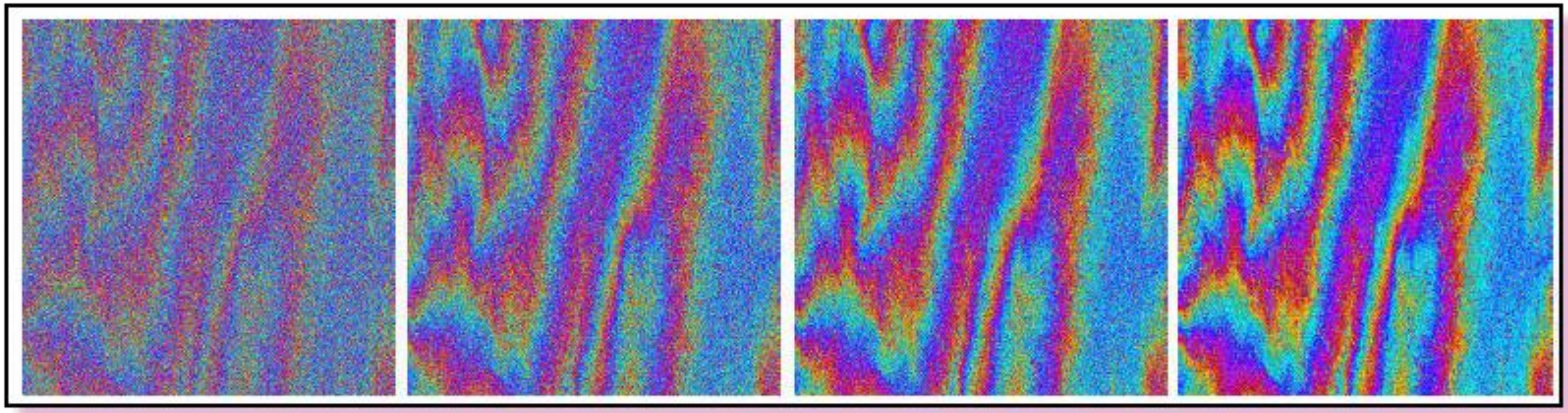
Interferometric coherence is the cross-correlation coefficient of the SAR image pair estimated over a small window.

Coherence between both SAR images gives information about

- SAR image similarity
- the interferometric phase noise content

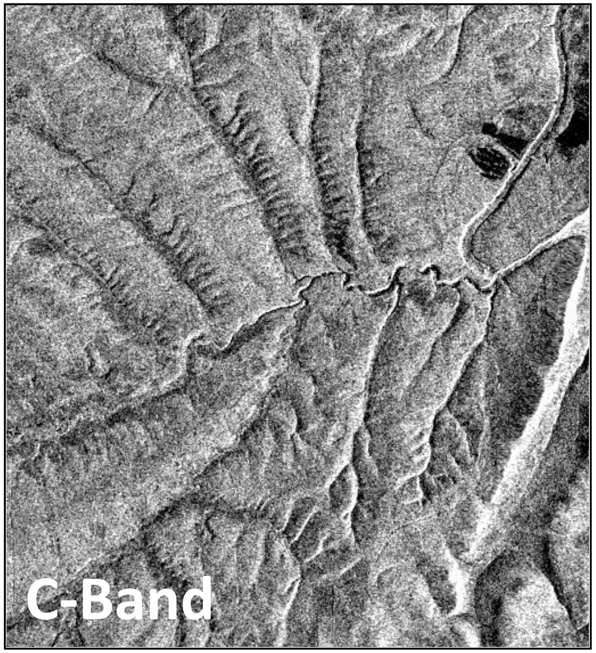
$$\gamma = \frac{\langle s_2 s_1{}^* \rangle}{\sqrt{\langle s_1 s_1{}^* \rangle \langle s_2 s_2{}^* \rangle}}$$

S1: Image 1, S2: Image 2
The coherence value ranges from 0 (the interferometric phase is just noise) to 1 (complete absence of phase noise)



$|\gamma| = 0{,}28$ $|\gamma| = 0{,}5$ $|\gamma| = 0{,}65$ $|\gamma| = 0{,}82$

Different wavelengths in forest observation



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- *Variable response to water*
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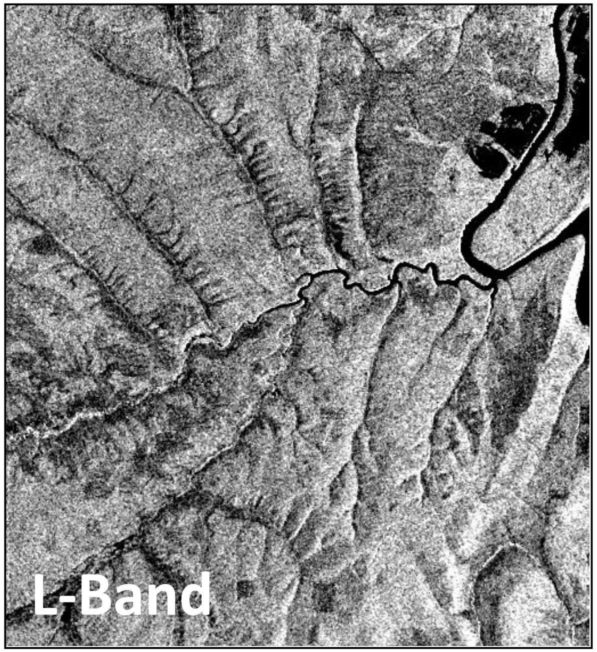

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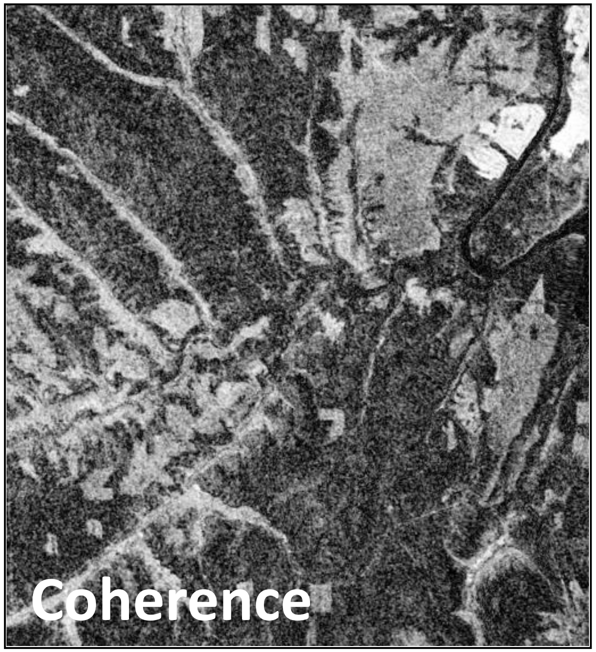


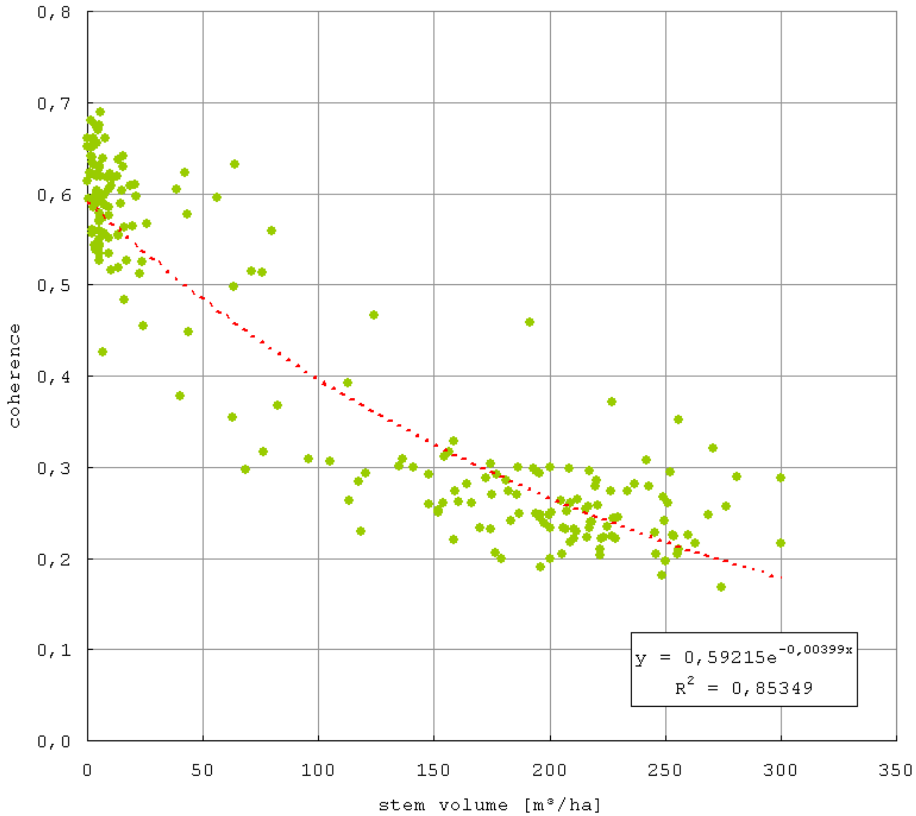
- *Higher contrast between forest/non forest*
- *Confusion between water and dense forest*

Fig.: Different wavelengths in biomass estimation and coherence (LE TOAN et al., 2001).

Interferometric coherence

- Interferometric Coherence – correlation of two complex SAR images

Stem volume vs. Coherence (05feb2008-22mar2008) – 12.5 m data



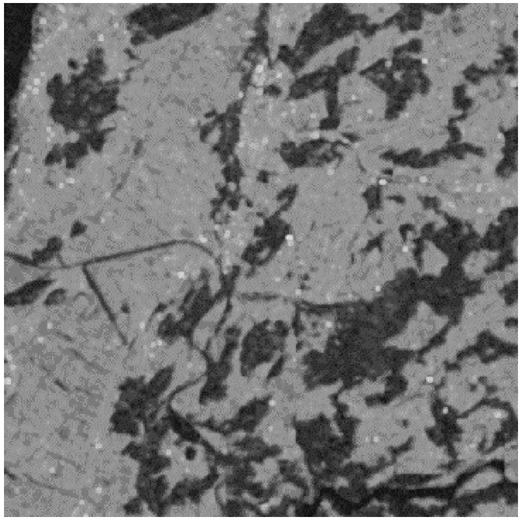
Coherence is reduced by:

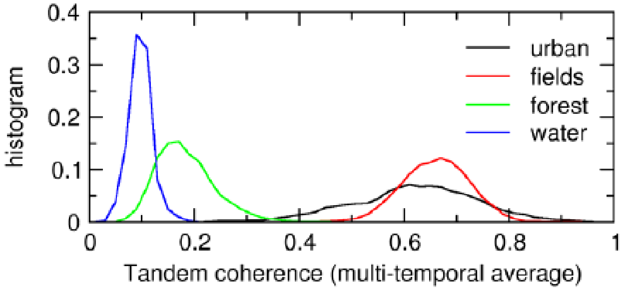
- Temporal decorrelation
- Geometric decorrelation
- Atmosphere
- Noise

Interferometric coherence : temporal decorrelation

Fig. 33: Temporal Change of the surface (PALLAN o. J.:o. S.).

Interferometric coherence : temporal decorrelation

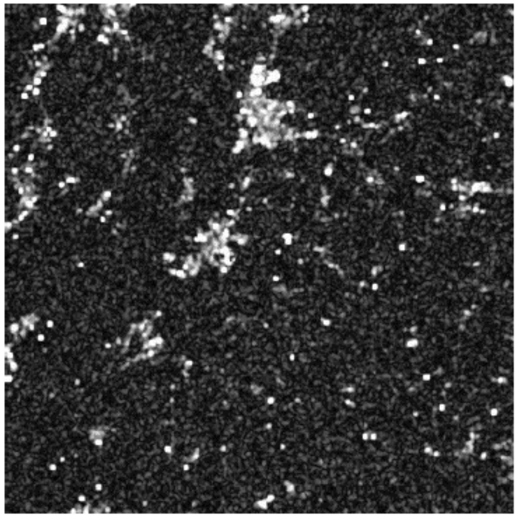


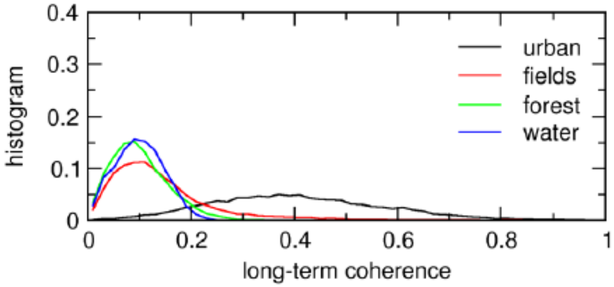


Histogram of averaged coherence of main classes

ERS tandem

(**1 day**)





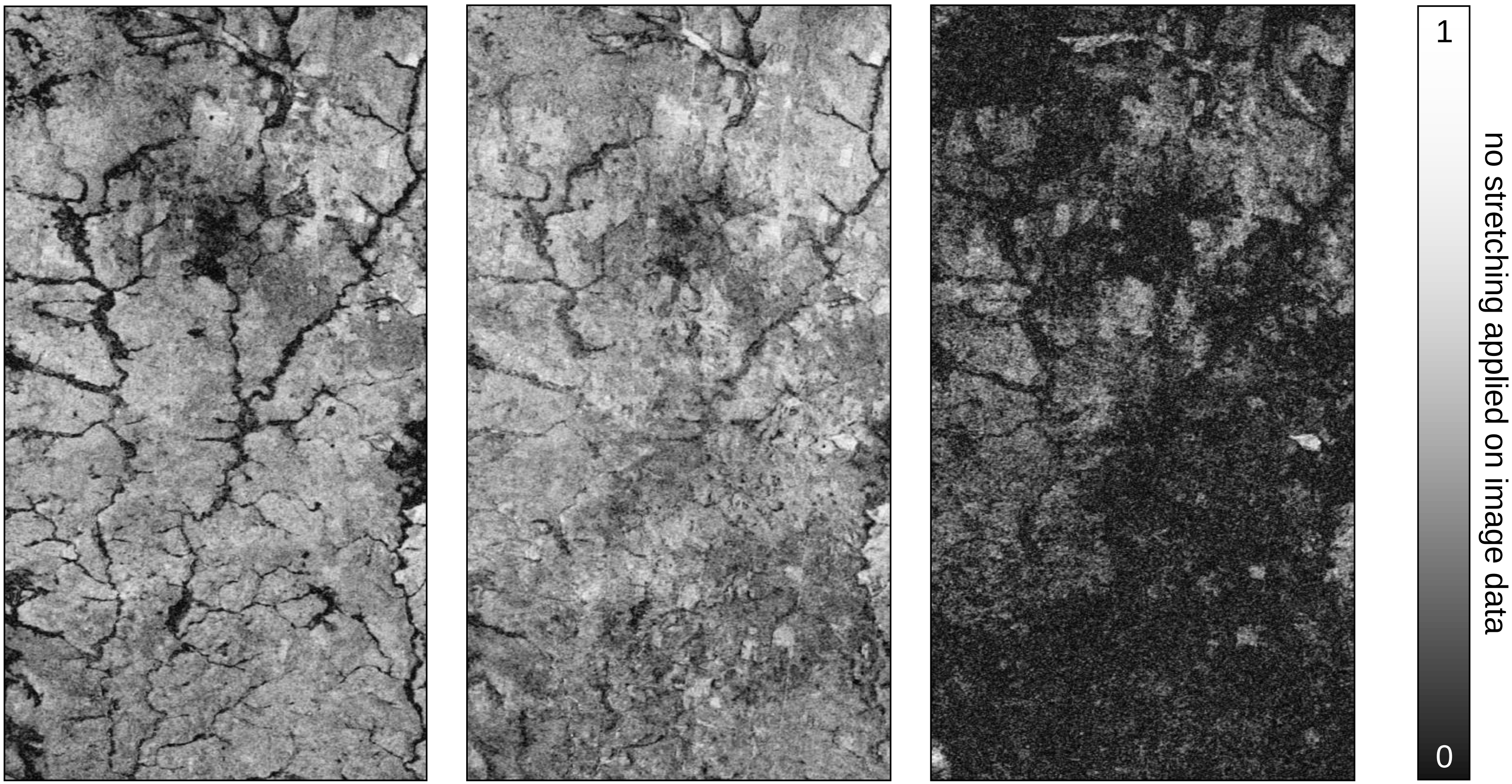
Histogram of long-time coherence of main classes

ERS long-term

(**35 days**)

[Strozzi, T., Sommerschule 2002]

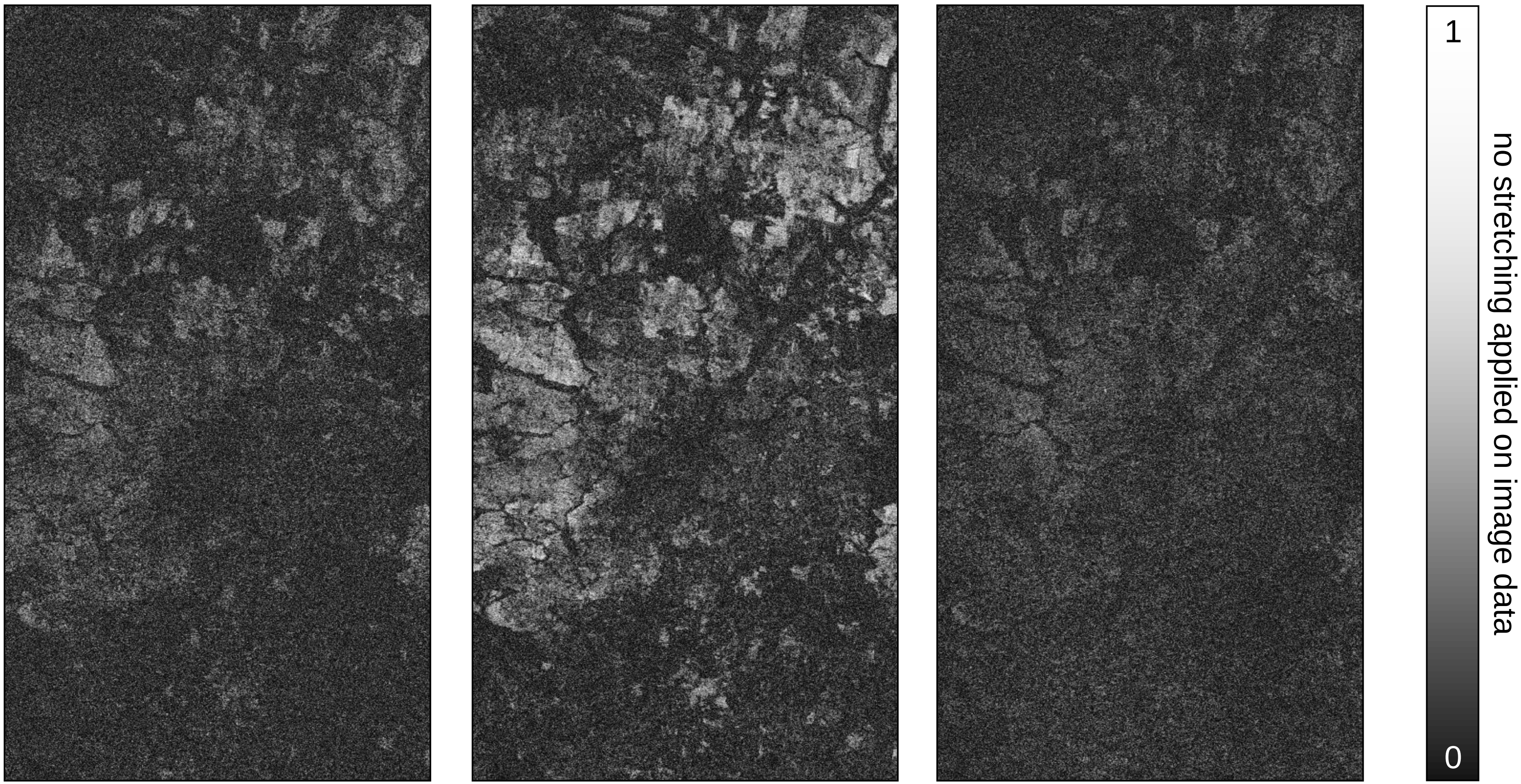
Coherence Images – Examples Chunsky N – **Summer-Summer** (Temp. Baseline 46 days)



20jun07_05aug07 05aug07_20sep07 22jun08_07aug08

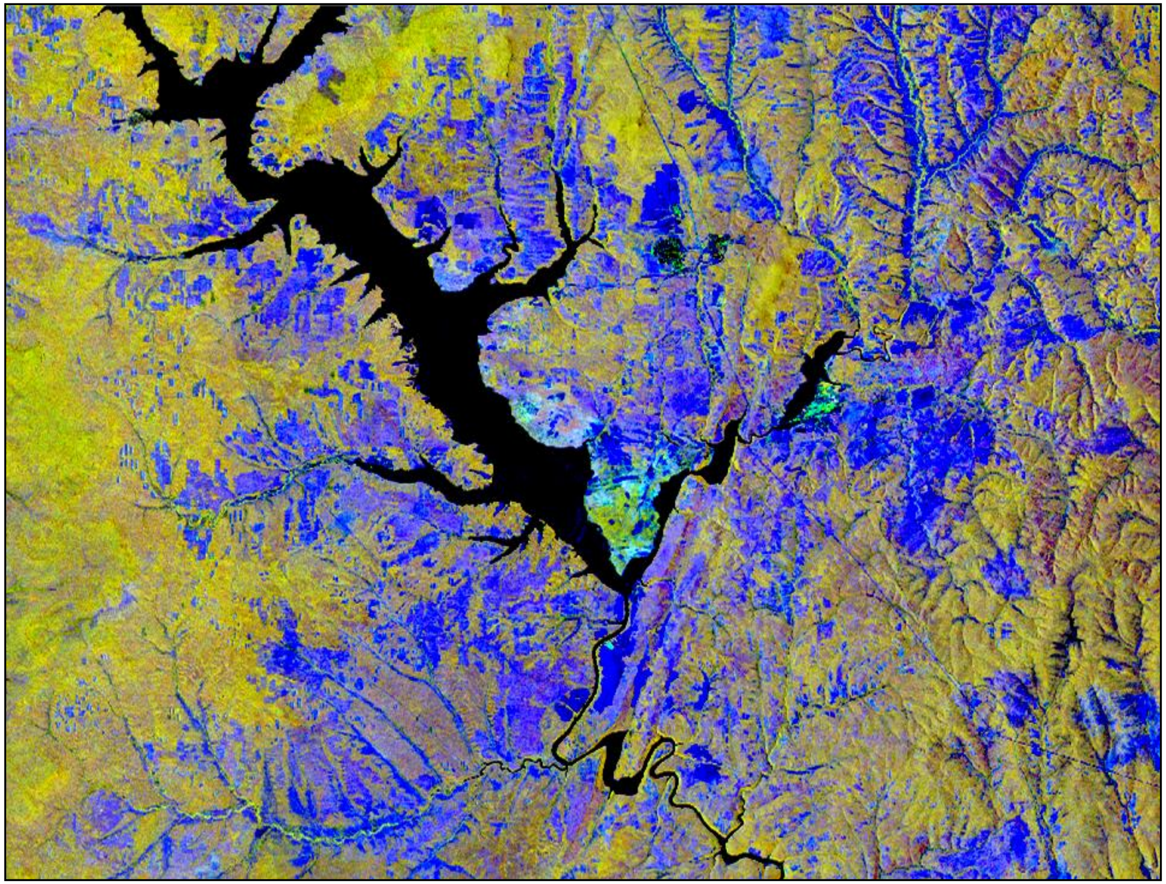
Interferometric coherence : temporal decorrelation due to different seasons

Coherence Images – Examples Chunsky N – **Winter-Summer**

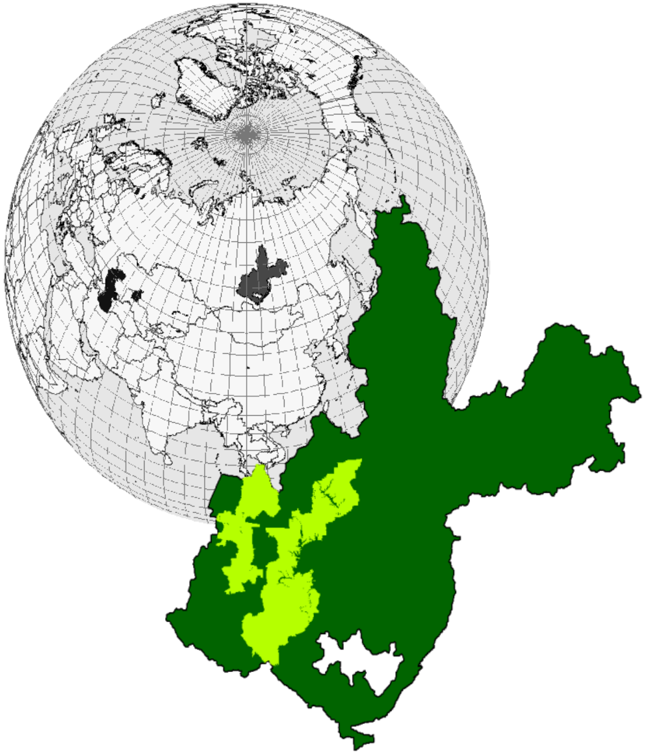


05feb08_20jun07   05nov07_20jun07   22mar08_20sep07

Forest cover mapping using Intensity and Coherence

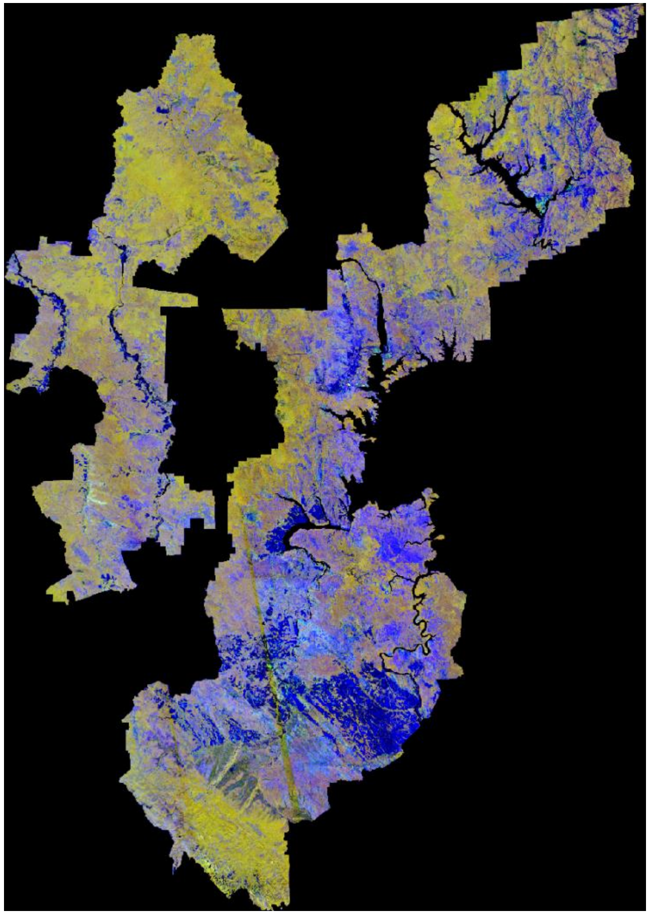


Composite of **HV** & **HH** backscatter and winter **coherence**

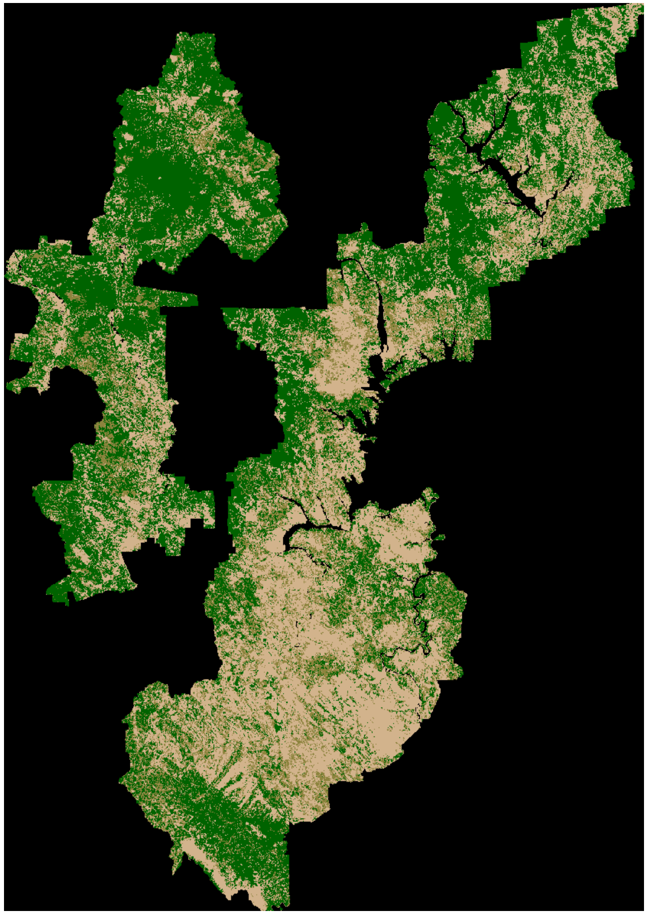


Test area (light green patch, right image) in the centre of the prototype area

Forest cover mapping using Intensity and Coherence



SAR data (HV/HH/Coherence)



Map (forest: green, very low biomass forest: brownish green, non-forest: light brown)

Outline

I. Introduction

forest cover mapping, forest cover change mapping (deforestation, forest fires, wind damage...

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biomass, forest height, forest structures…

III. SAR for forest applications - some basics

scattering in forests, penetration depths of signal in forests, linking SAR measures with forest parameters

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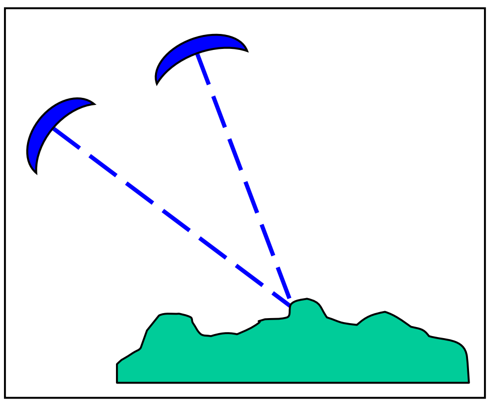
- **Polarimetry**
- Polarimetric Interferometry
- SAR (Polarimetric) Tomography

Interferometry vs Polarimetry

- The Phase is essential for **Interferometry** and **Polarimetry**
- Both techniques require at least two complex SAR images

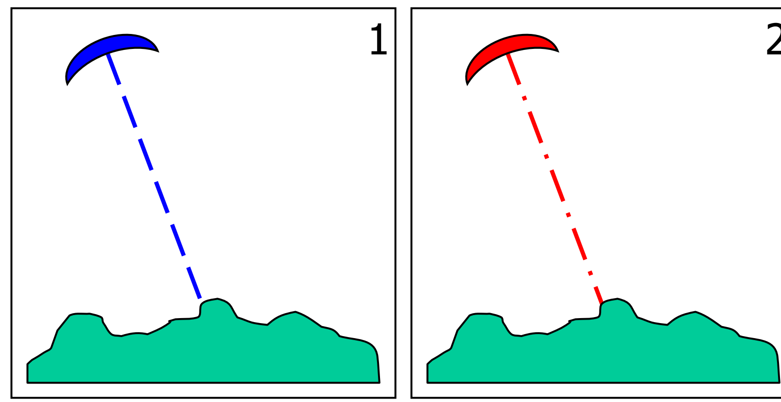
Interferometry

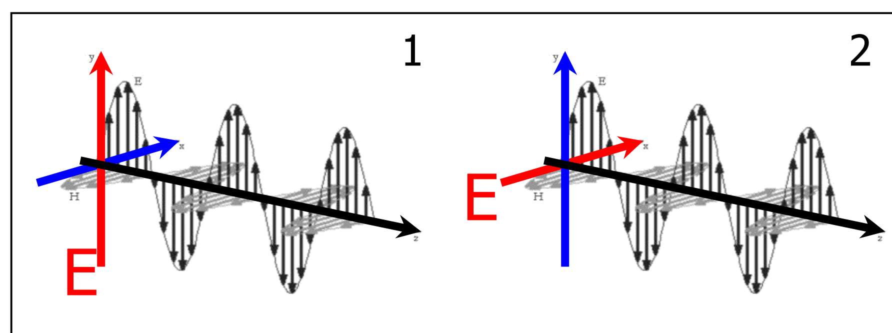
A) Same polarisation – different position



Polarimetry

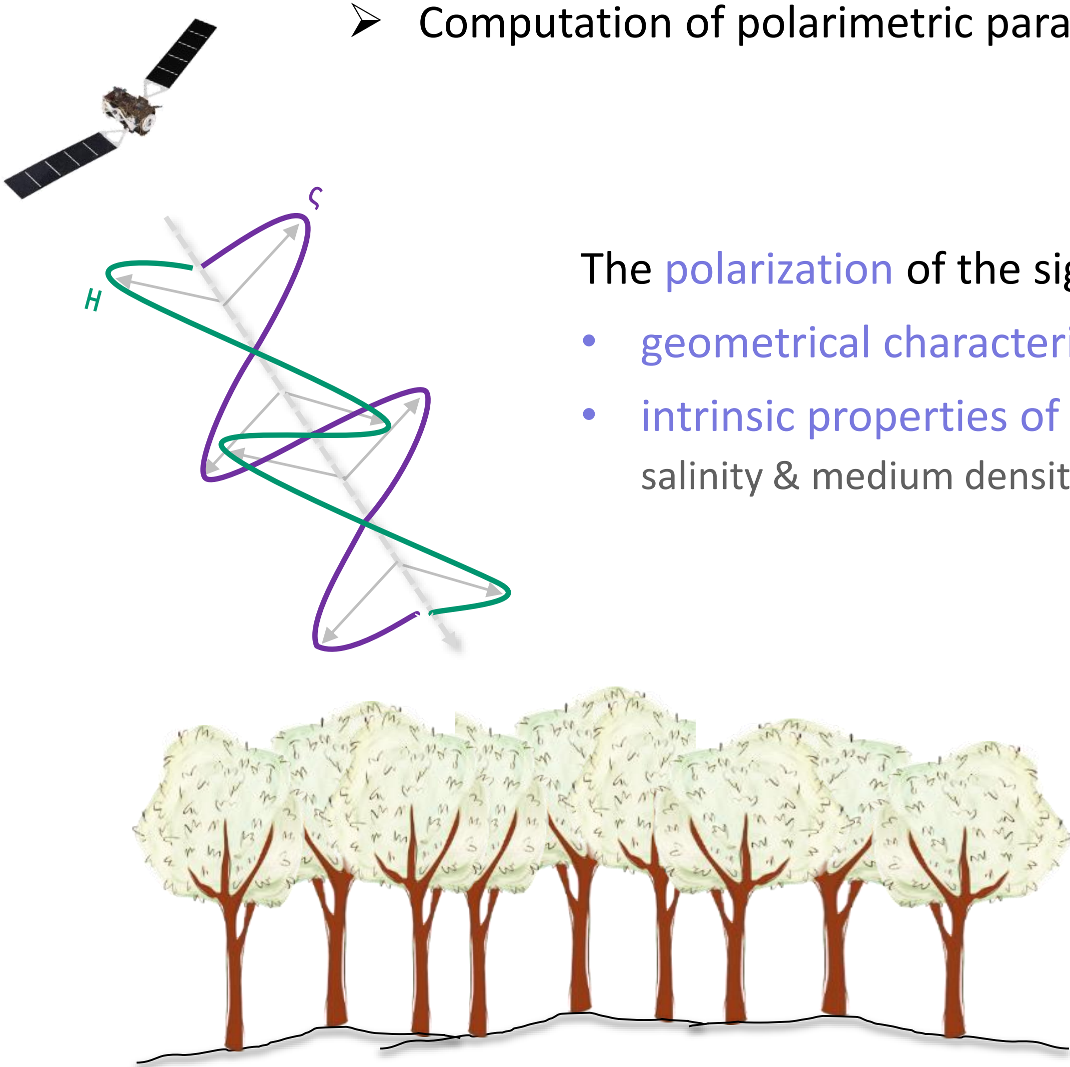
B) Same position – different polarisation





Polarimetry

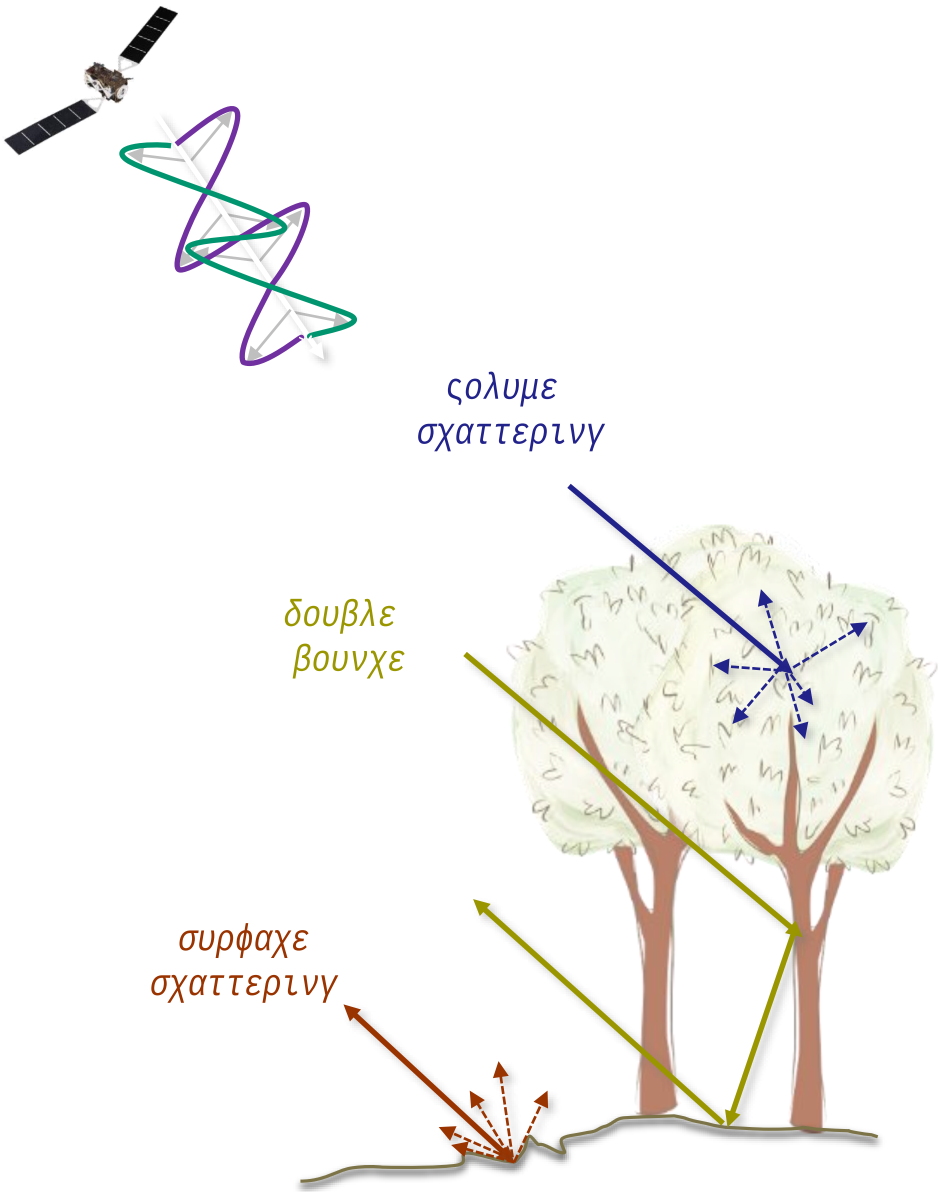
- Investigation backscatter at different polarisations
- Computation of polarimetric parameters



The polarization of the signal can be linked to:

- geometrical characteristics like shape, roughness & orientation
- intrinsic properties of the scatterer like humidity /moisture, salinity & medium density

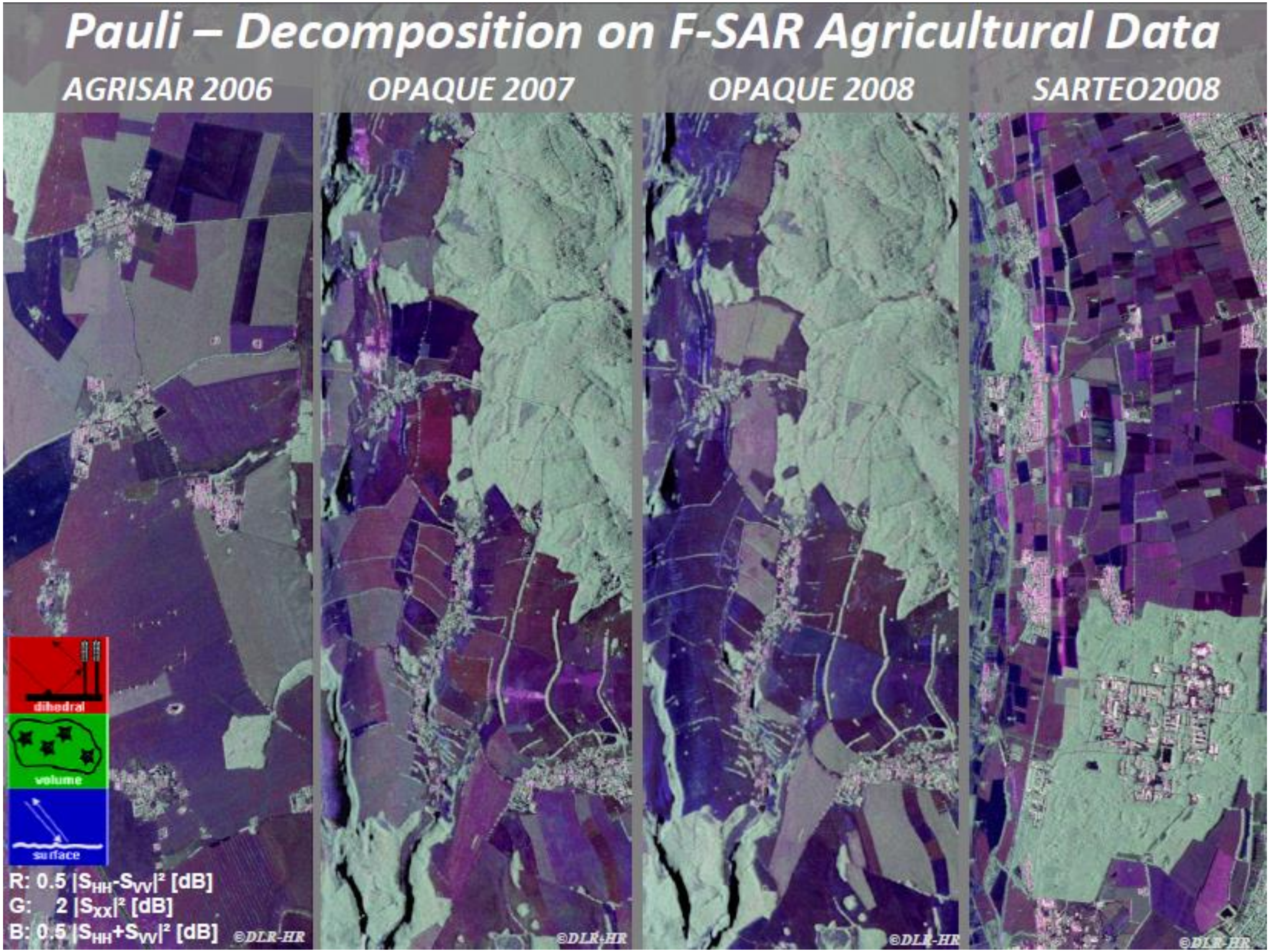
Different polarizations



type of polarization affects the sensitivity to different scattering mechanisms.

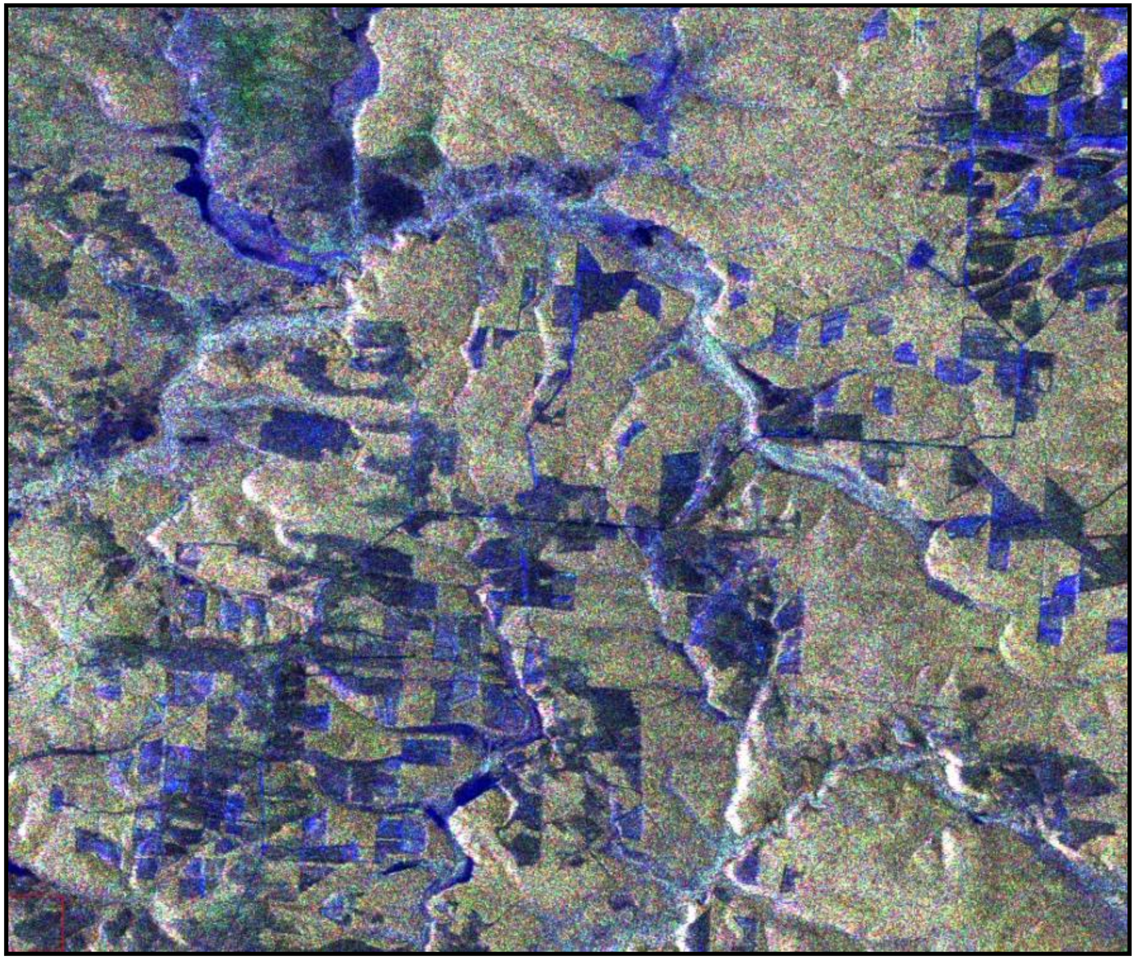
- co-polarization (**HH, VV**) is more sensitive to the surface scattering and double-bounce,
- cross-polarization (**HV, VH**) is more to the volume

Polarimetric decomposition example



Polarimetry - example

- Investigation of clear cuts based on polarimetric parameters



Pauli Decomposition

$S_{HH} + S_{VV}$	Surface Scattering
$S_{HH} - S_{VV}$	Double Bounce
$2S_{HV}$	Volume Scattering

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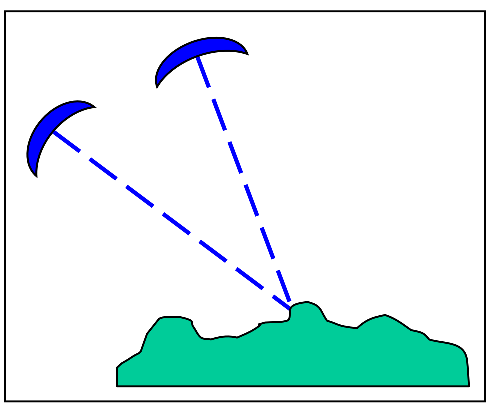
Polarimetric Interferometry (PolInSAR)

- Height localisation of different scattering mechanism
- Requires coherent interferometric pair of polarimetric data

A) Same polarisation – different position

B) Same position – different polarisation



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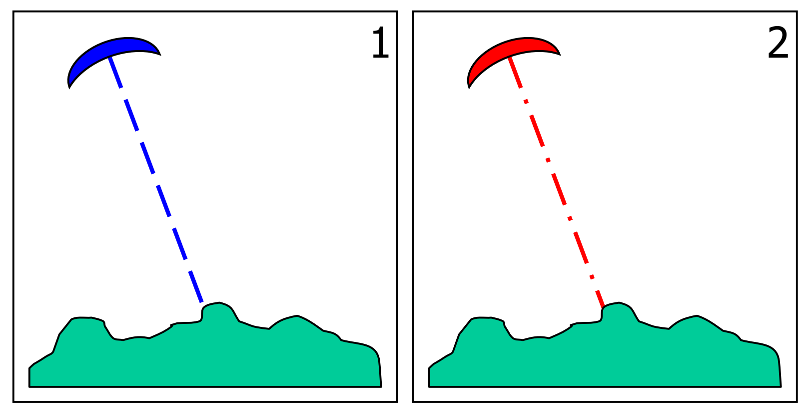
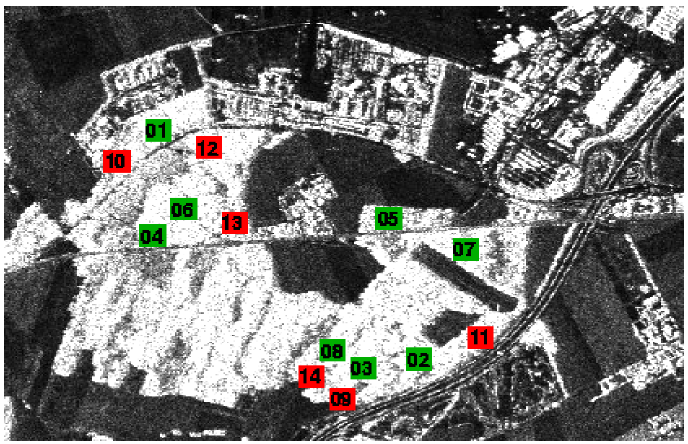


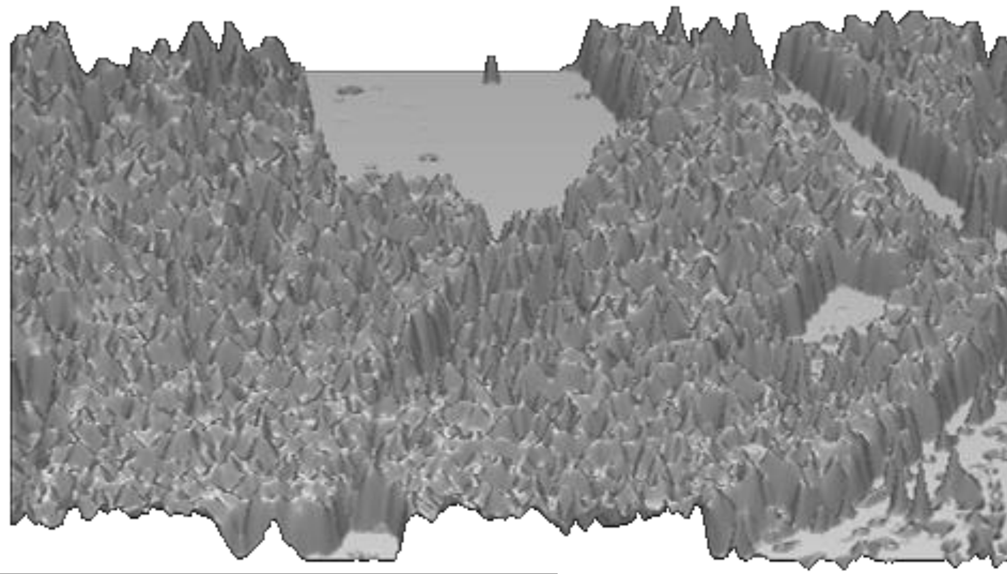
Interferometry

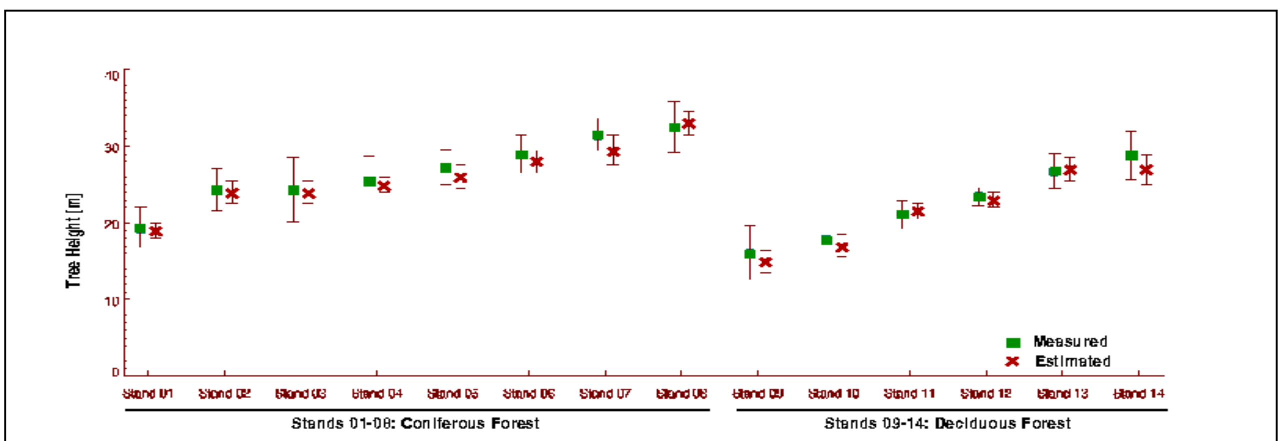
Polarimetry

Tree height from PolInSAR

Combination of polarimetry and interferometry leads to separation of scattering mechanisms within a resolution cell.







Airfield Oberpfaffenhofen
L-Band pol. InSAR result

Tree height

(Papathanassiou & Cloude, 2001)

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- Polarimetric Interferometry
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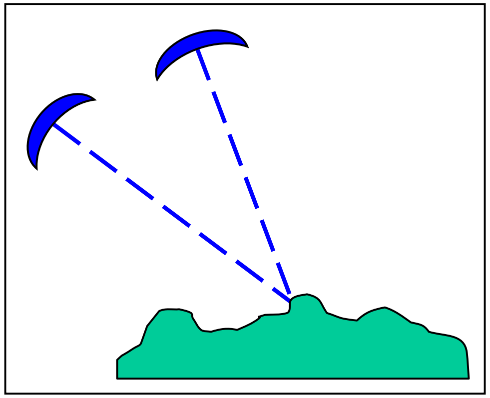
SAR Tomography (TomoSAR)

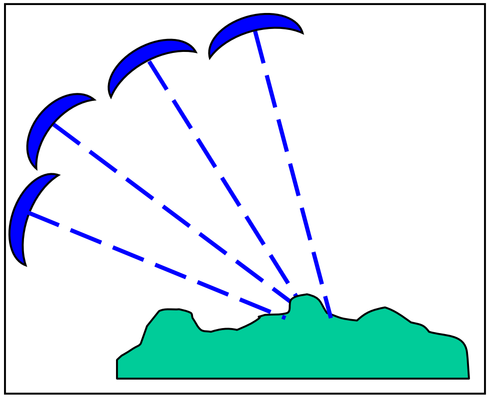
- Height localisation of different scattering mechanism
- Requires multiple coherent interferometric pairs

Same polarisation – different position



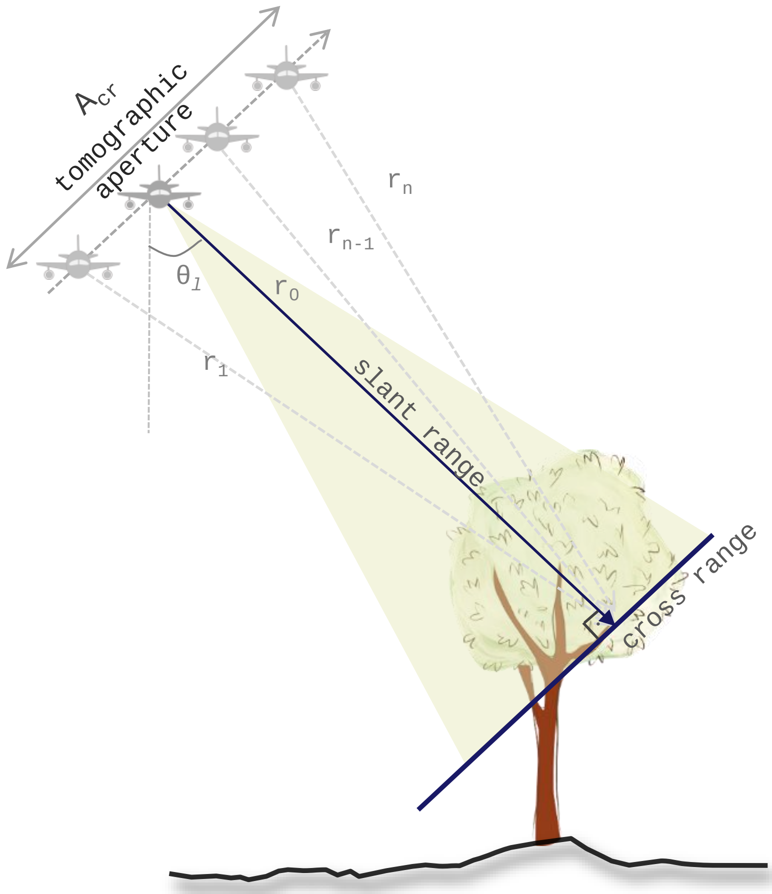
Interferometry

Same polarisation – many different positions



Tomography

SAR Tomography imaging geometry



A_{cr} : cross range (tomographic) aperture
r_0 : slant range of the master track
$r_1 \ldots r_n$: slant range of the slave tracks
θ_1 : look angle

SAR Tomography uses multiple acquisitions from slightly different viewing angles forming an aperture in elevation and locates the scatterers along the elevation which is perpendicular to the radars line of sight.

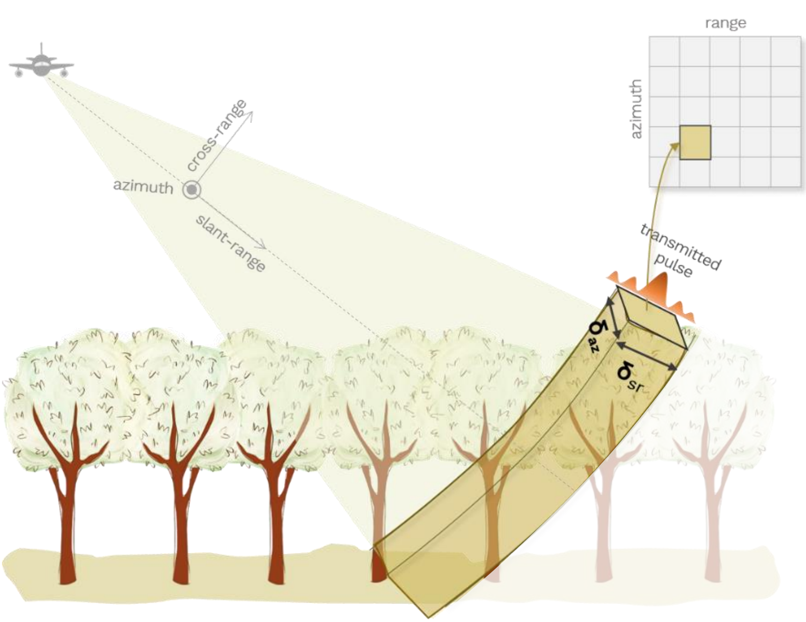
SAR Tomography resolution cell

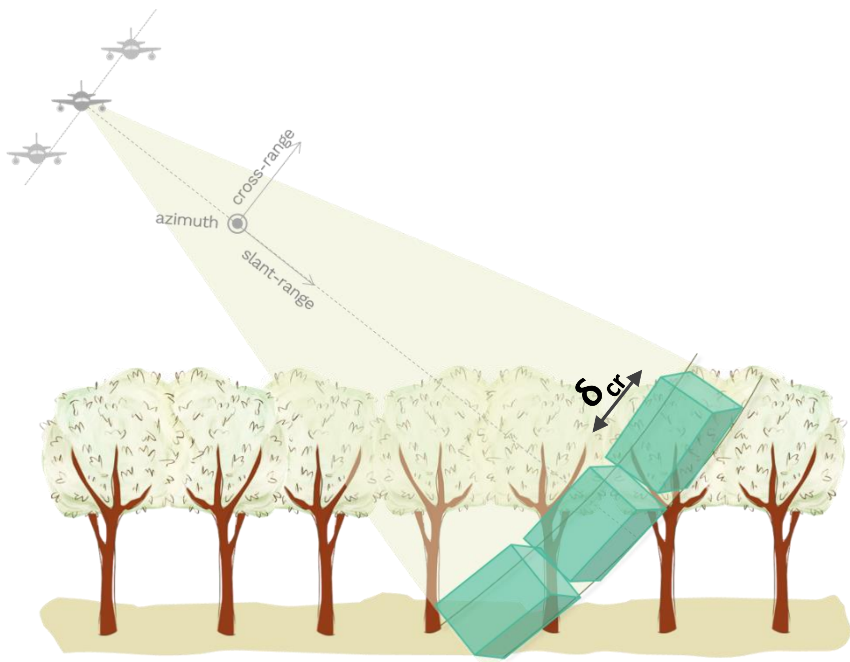
The 2D resolution cell depends on :

- Pulse bandwidth along slant range (W)
- Synthetic aperture in azimuth (A_{az})

The 3D resolution cell depends on :

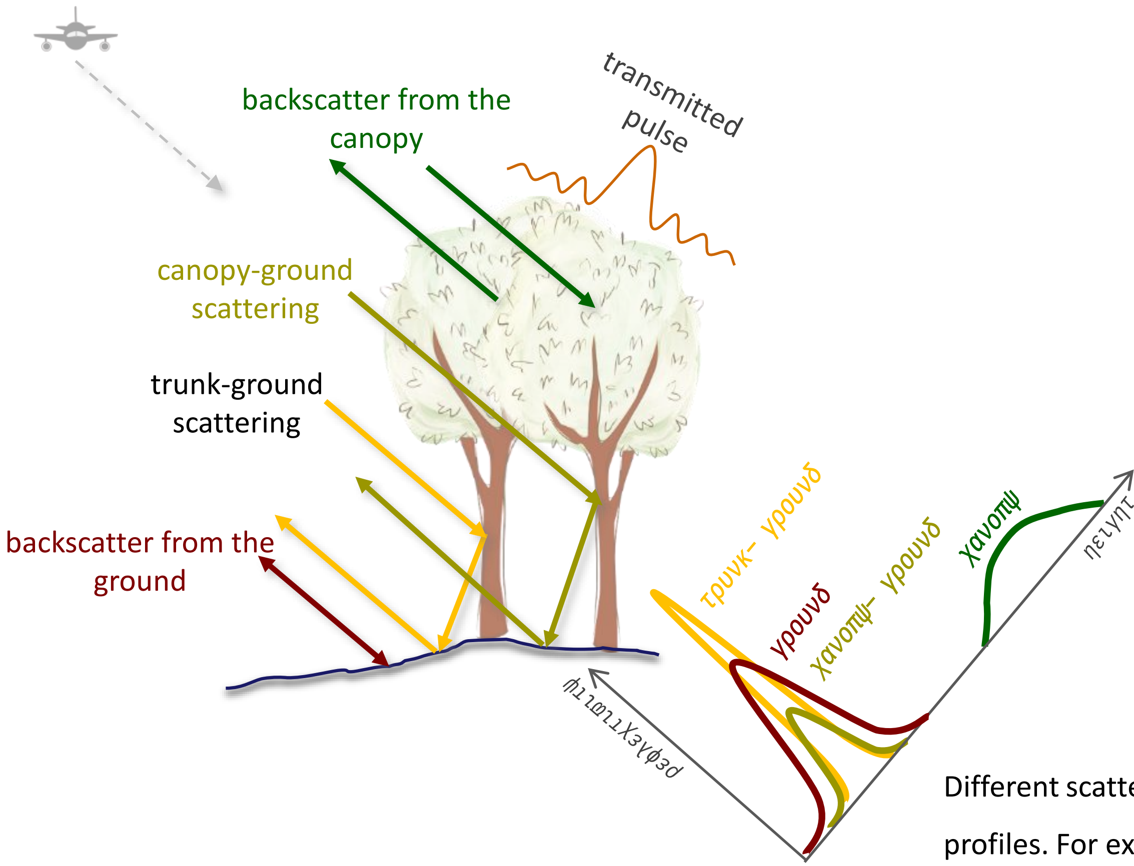
- Pulse bandwidth along slant range (W)
- Synthetic aperture in azimuth (A_{az})
- Synthetic aperture in cross range (A_{cr})



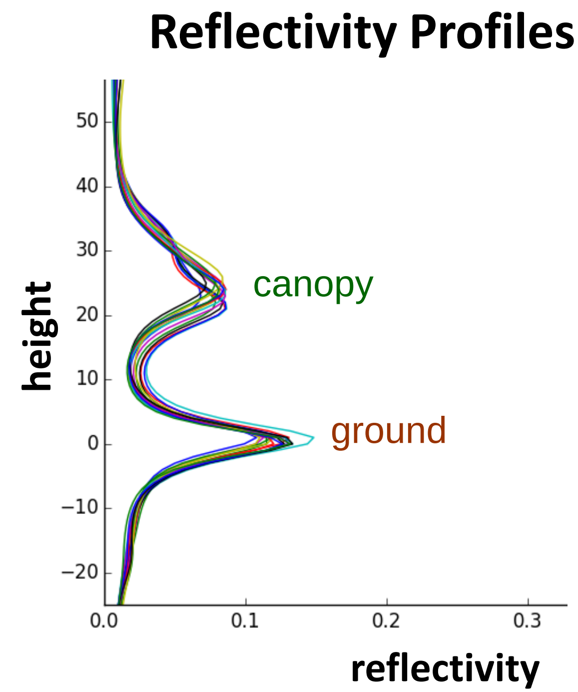


SAR resolution cell Tomographic SAR resolution cell

SAR Tomography reflectivity profiles

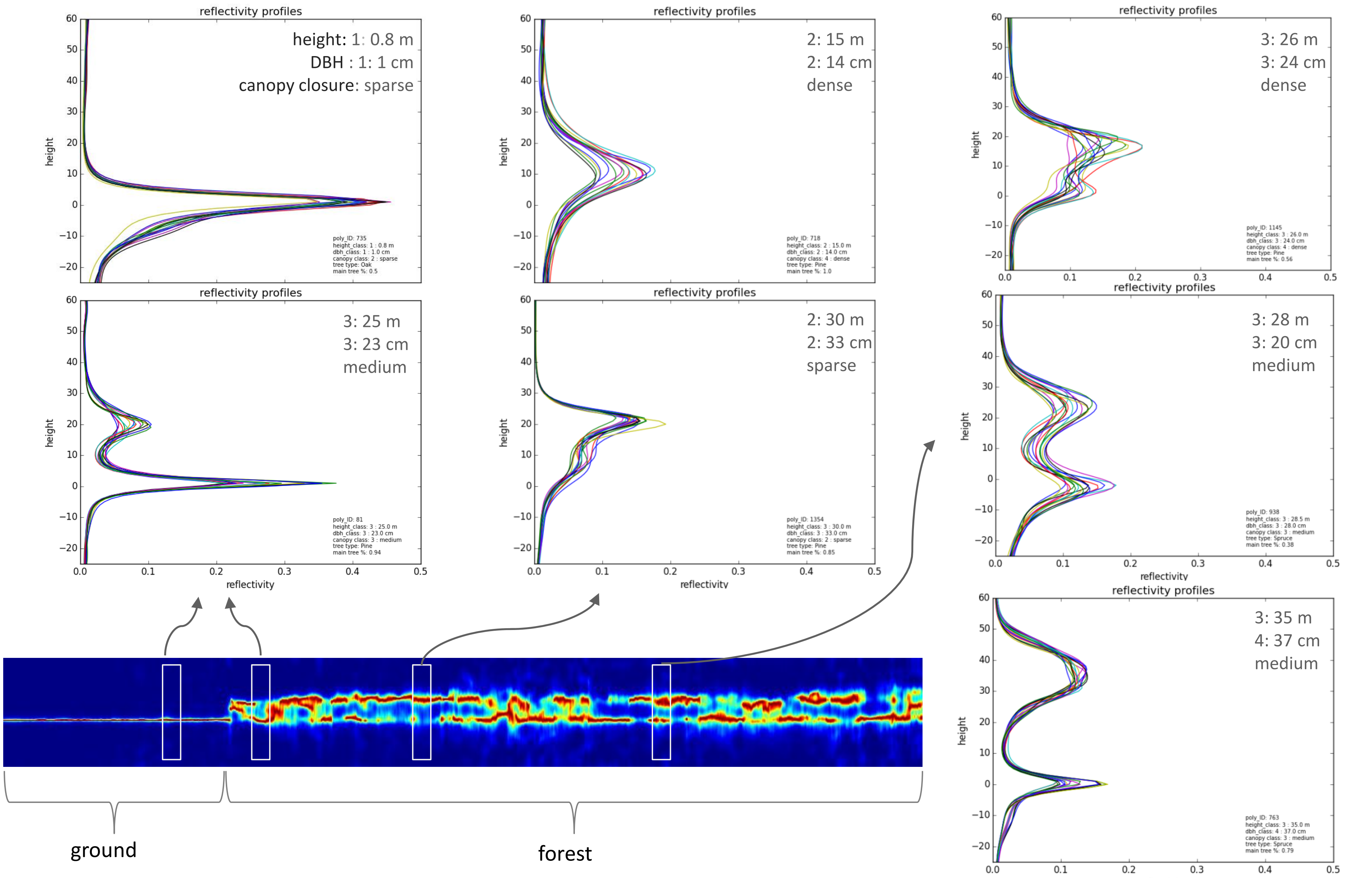


[Tebaldini, 2012]

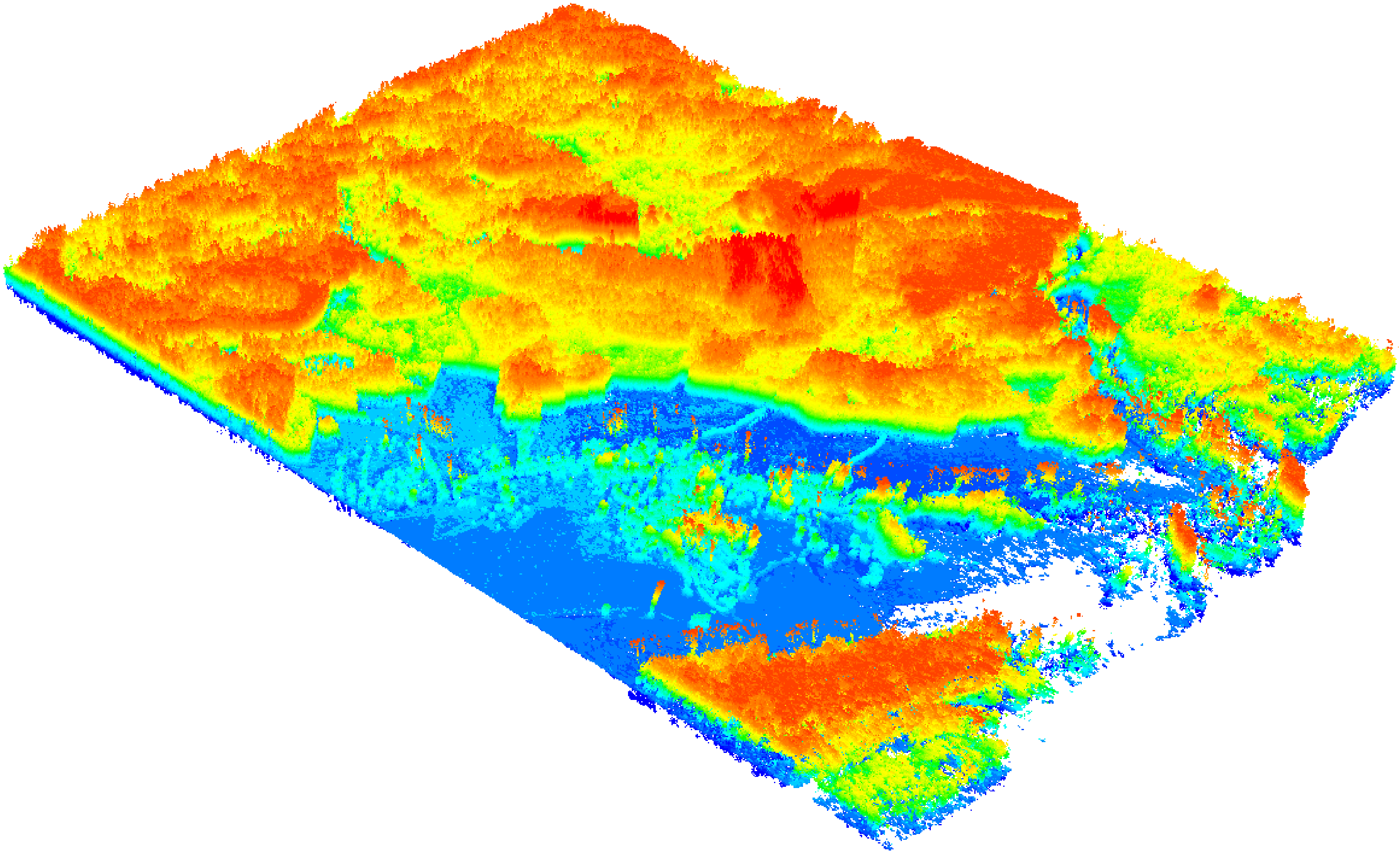


Different scattering mechanisms (SM) result in different reflectivity profiles. For example, forest scenarios can be characterized by : double-bounce, surface and volume scattering mechanisms.

SAR Tomography reflectivity profiles



3D model of the Forest

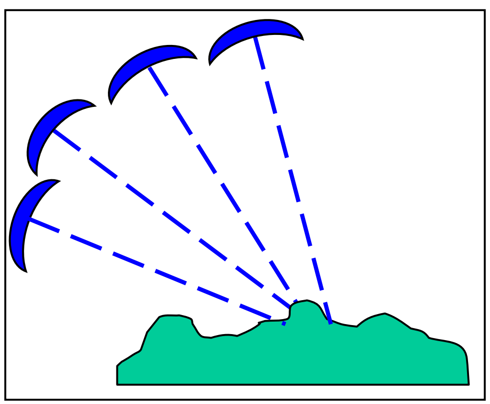


Point cloud derived from TomoSAR reflectivity profiles over Trockenborn, Germany

Polarimetric SAR Tomography (PolTomoSAR)

- Horizontal information on backscatter intensity (and backscattering mechanism)
- Requires many coherent interferometric SAR images

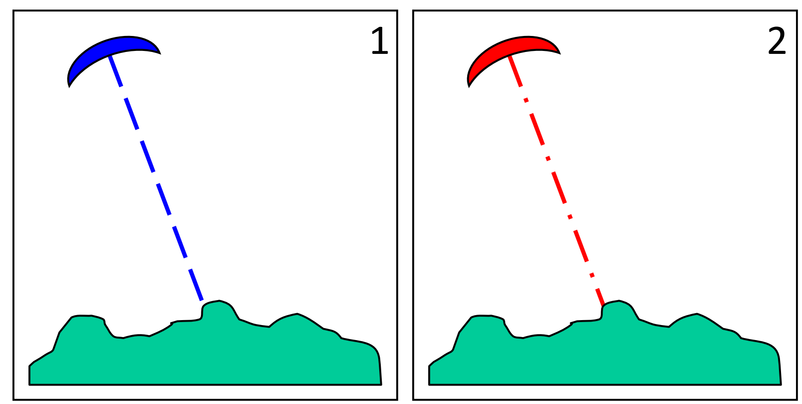
Same polarisation – many different positions



Tomography

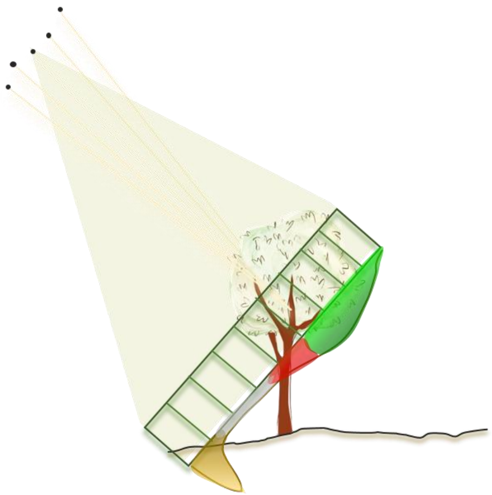
+

Same position – different polarisation



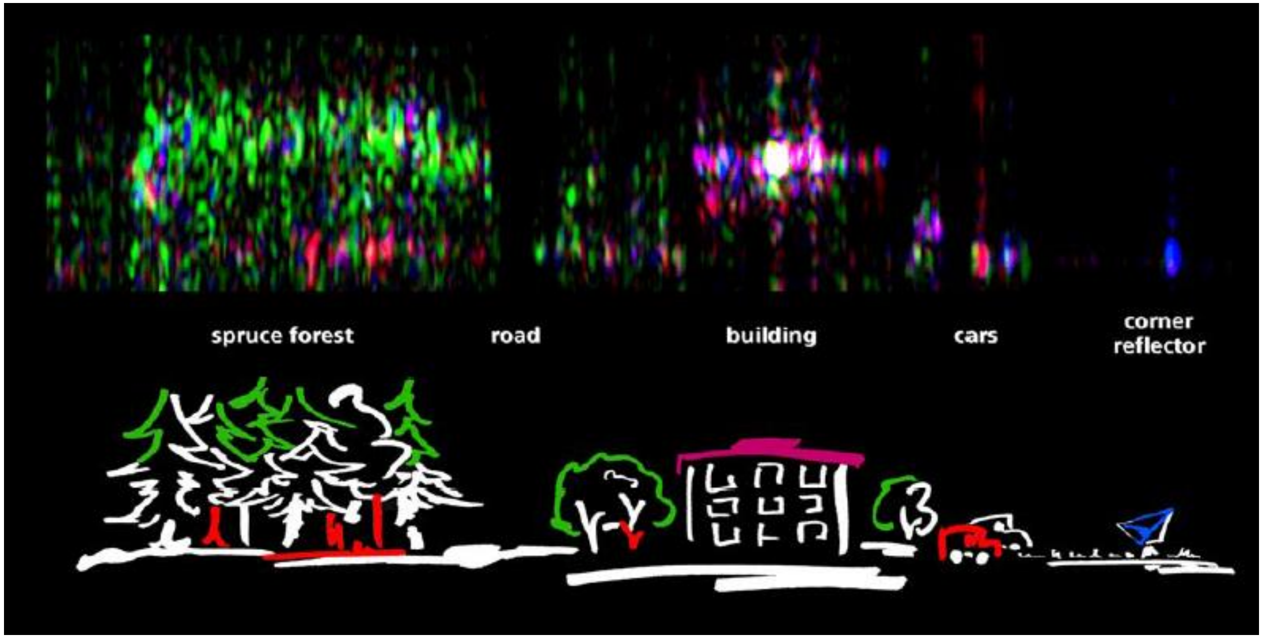
Polarimetry

Polarimetric SAR Tomography (PolTomoSAR)



It is also possible to combine polarization and tomography so that different scattering contributions can be separated depending on the elevation.

L-band E-SAR data with 13 tracks, Oberpfaffanhofen, Germany



Upper image: tomographic azimuth slice with Polarimetric color composite using Pauli basis

Odd bounce = HH + VV

Even bounce = HH – VV

Volume scattering = 2*HV

Lower image: Schematic representation of the imaged area

[Reigber & Moreira 2000]

SAR Techniques: Review

1. **Backscatter analysis** (wavelength, polarisation, incidence angle, number of images)
2. **Interferometry: Phase analysis** (wavelength, incidence angle, high coherence required, temporal and spatial baselines)
3. **Interferometry: Coherence analysis** (wavelength, polarisation, incidence angle, temporal and spatial baseline, number of images, acquisition conditions)
4. **Polarimetry** (wavelength, incidence angle, number of images)
5. **Polarimetric Interferometry** (wavelength, polarisation, incidence angle, temporal and spatial baseline)
6. **SAR (Polarimetric) Tomography** (wavelength, polarisation, incidence angle, spatial baseline, high coherence required, number of images)

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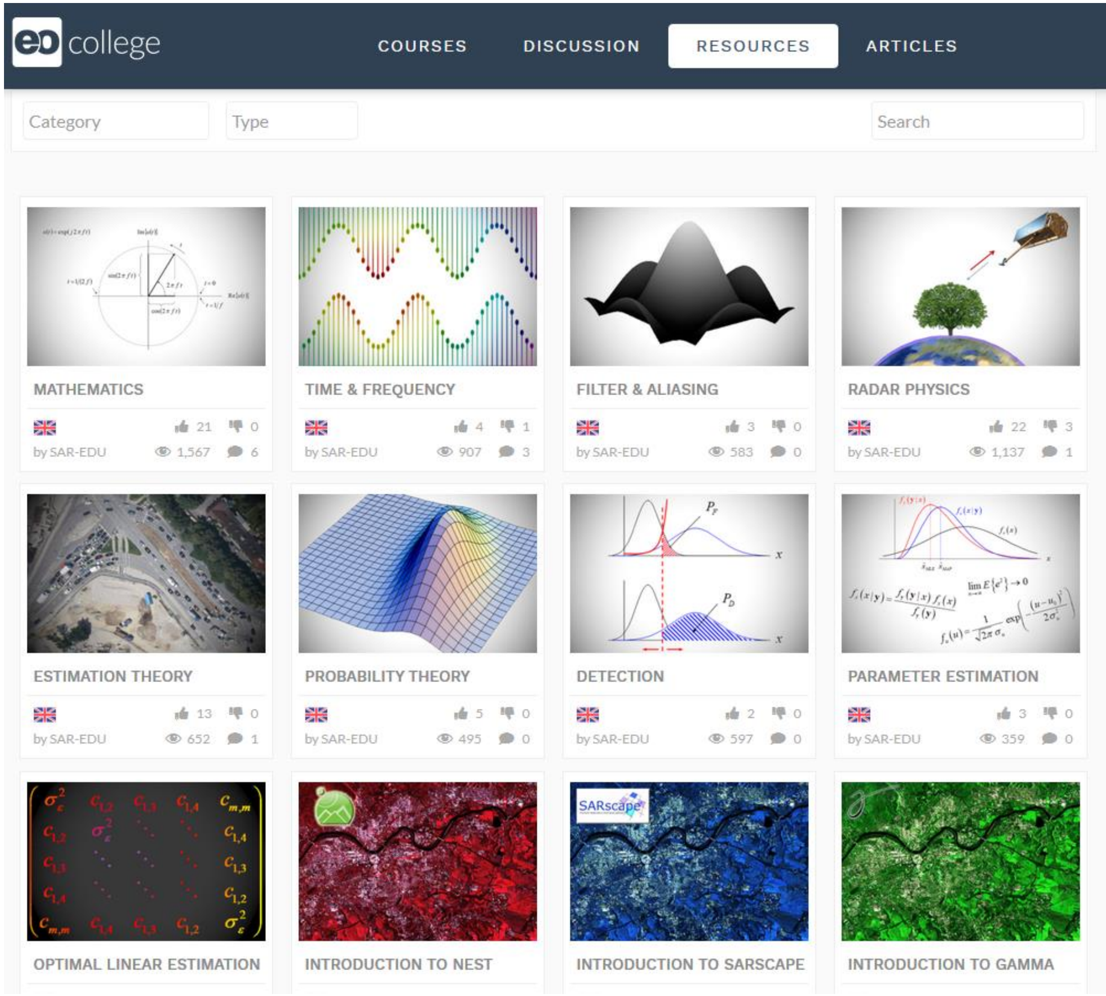
Your hub to learn Earth observation.
Here you can discuss with the EO



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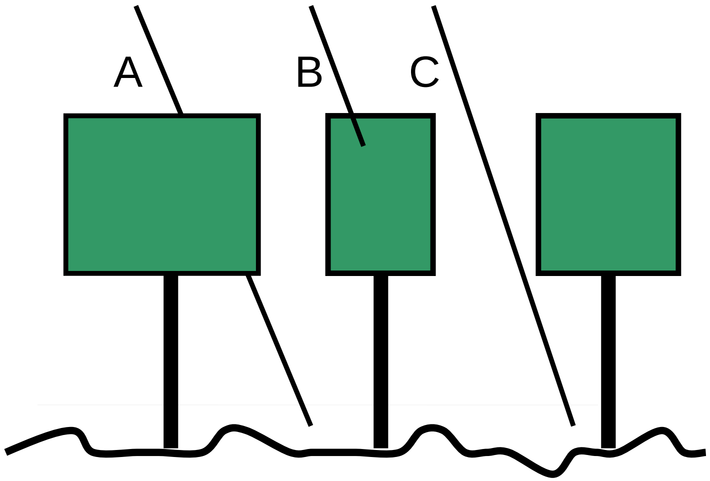
Modeling Example: A Water Cloud-like model

A water cloud with gaps is close to reality and easy to handle

$$\sigma^o_{for} = (1-\eta)\sigma^o_{gr} + \eta\sigma^o_{gr} T_{tree} + \eta\sigma^o_{veg}(1-T_{tree})$$

Canopy cover (η)

tree transmissivity (T_{tree})
(depends on tree height
and signal attenuation)



Water cloud with gaps

The model expresses the forest backscatter as function of the area-fill factor η, i.e. the forest canopy cover

For applications it can be written in terms of growing stock volume

$$\sigma^o_{for} = \sigma^o_{veg}\left(1 - e^{-\beta V}\right) + \sigma^o_{gr} e^{-\beta V}$$

Unknown (σ^o_{veg}, V, σ^o_{gr})

σ_{gr}	ground backscatter
σ_{veg}	canopy backscatter
β	forest transmissivity coefficient

Linking SAR measures & forest parameters - Example

BIOMASAR GSV map of Central Siberia

- 1 km resolution
- 2,400,000 km^2
- ENVISAT ASAR – Global Monitoring mode (Jan. 2005 – Feb. 2006)
- GLC 2000 land cover used as background