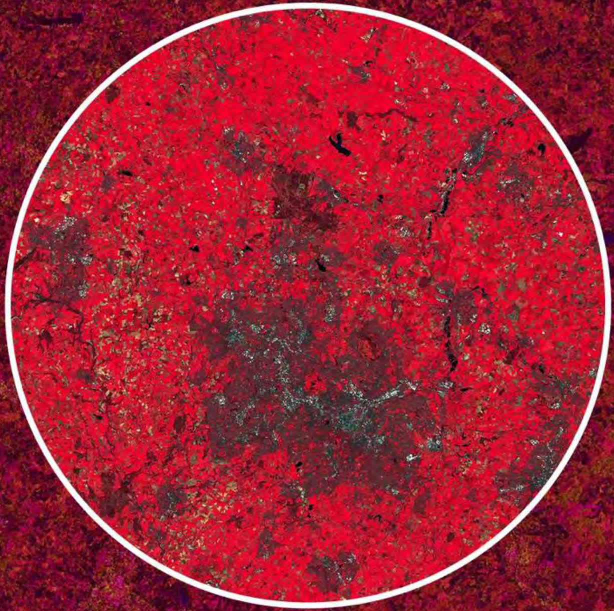
National Centre for Earth Observation
NATURAL ENVIRONMENT RESEARCH COUNCIL

UNIVERSITY OF LEICESTER

esa

→ 8th ADVANCED TRAINING COURSE ON LAND REMOTE SENSING

10–14 September 2018
University of Leicester | United Kingdom



Forestry applications with Polarimetry and Interferometry (Lecture)

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UNIVERSITÉ DE RENNES 1

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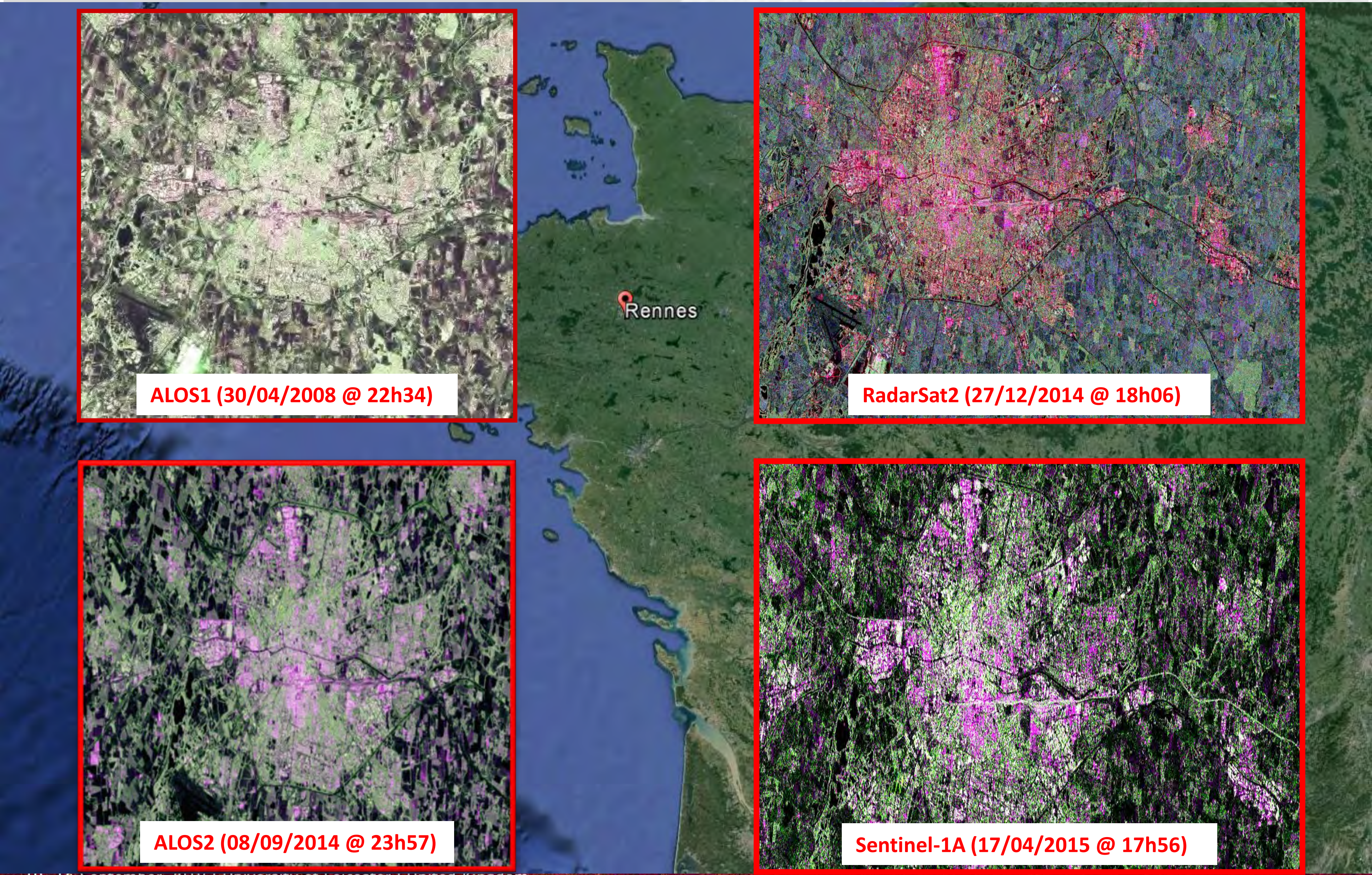
SHINE

SAR & **H**yperspectral multi-modal **I**maging and sig**N**al processing, **E**lectromagnetic modeling

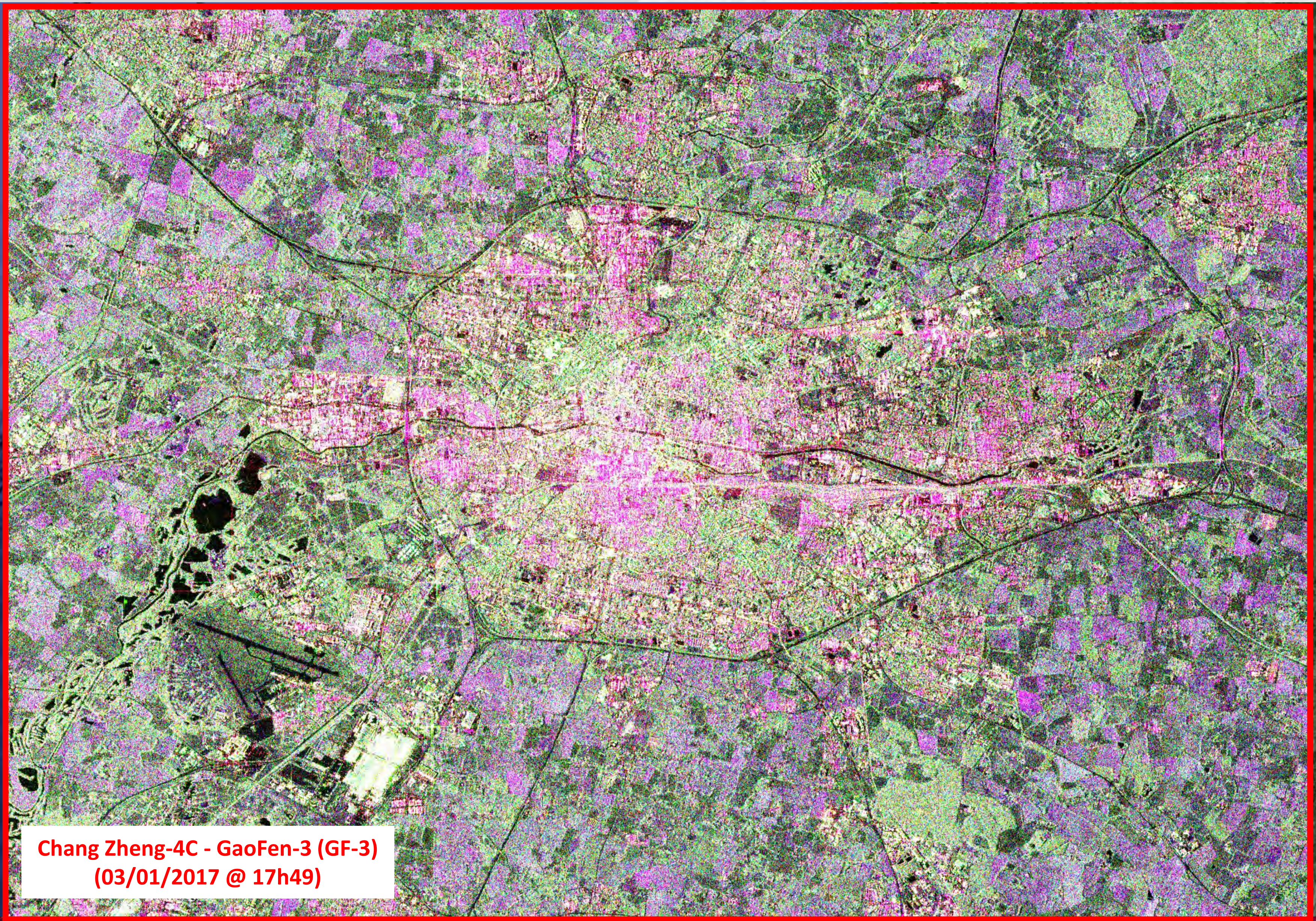
UNIVERSITÉ DE RENNES 1

Rennes - Britanny

Rennes - Britanny



Rennes - Britanny



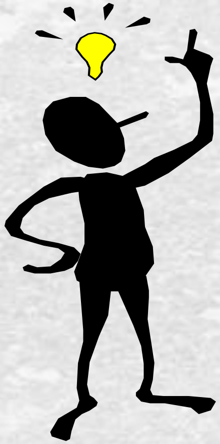
Objectives

To provide the minimum, but necessary, amount of knowledge required

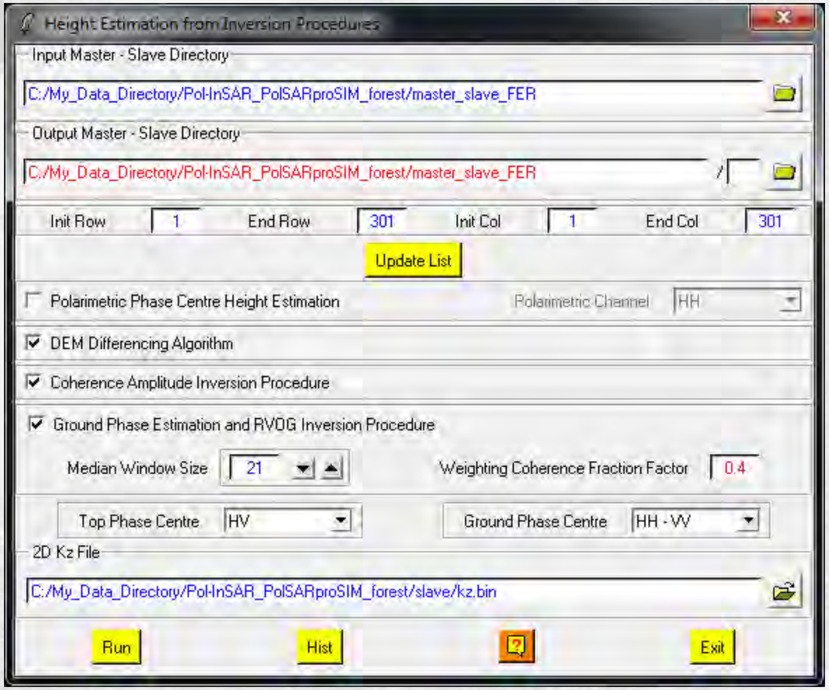
to understand and to practice :

SAR Polarimetry + Interferometry (Pol-InSAR)

for forestry applications



Objectives

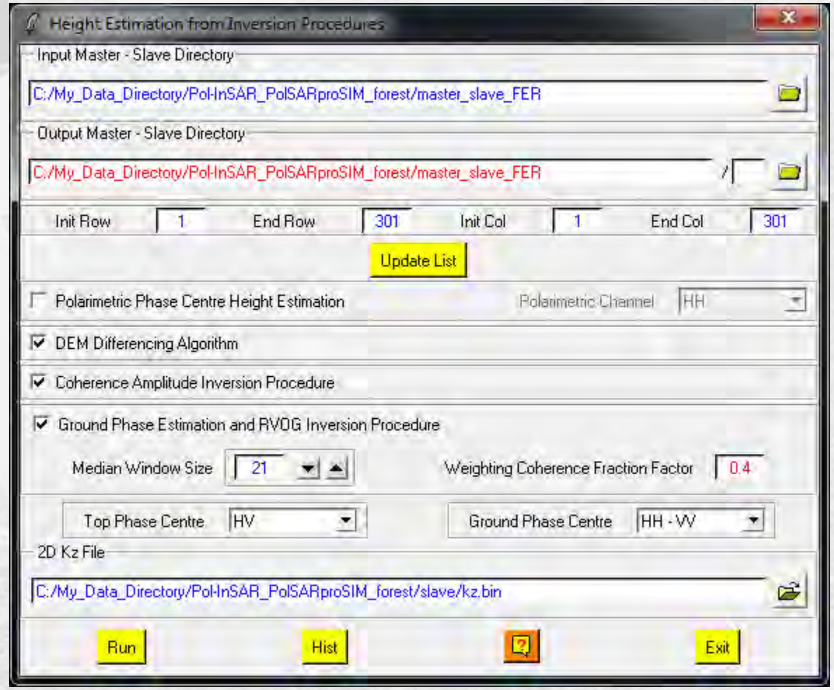


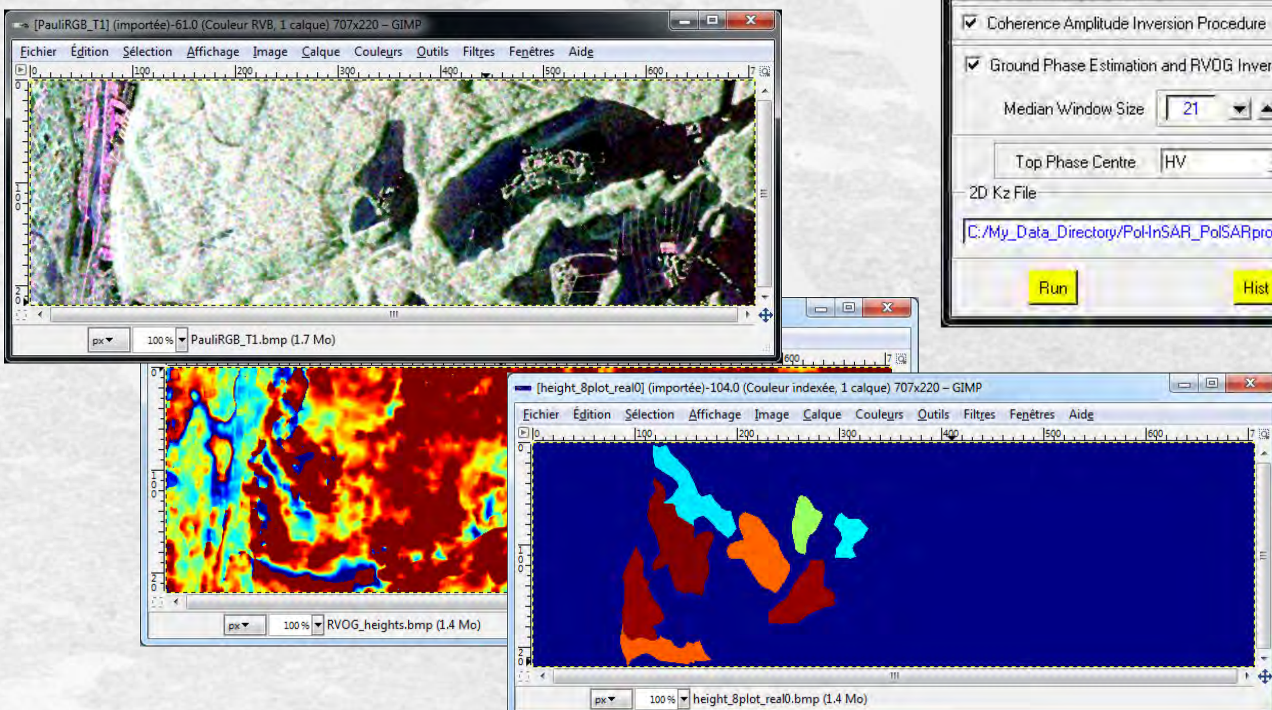
PolSARpro - practicals

Objectives

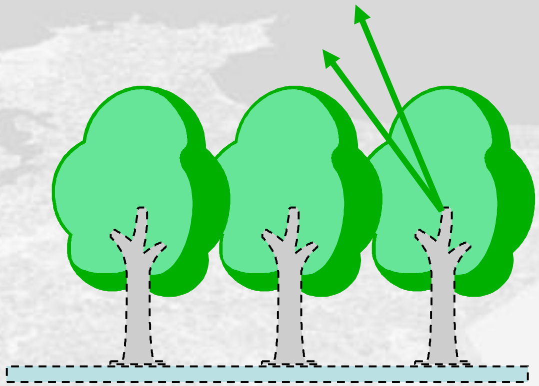
INVERSION PROCEDURES

- DEM Differencing Algorithm
- Coherence Amplitude Inversion Procedure
- Ground Phase Estimation &
- RVOG Inversion Procedure





Objectives



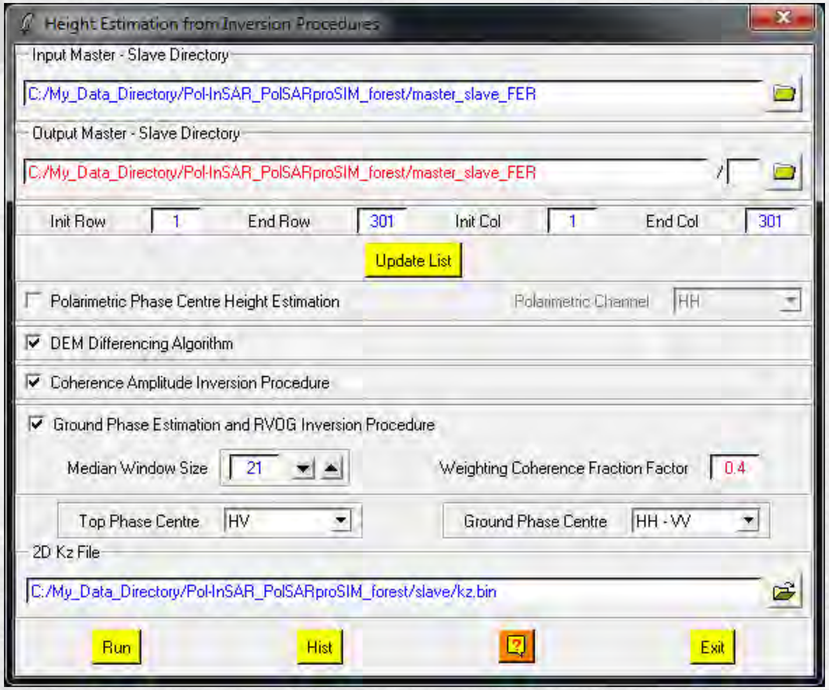
SAR

+

Interferometry

+

Polarimetry



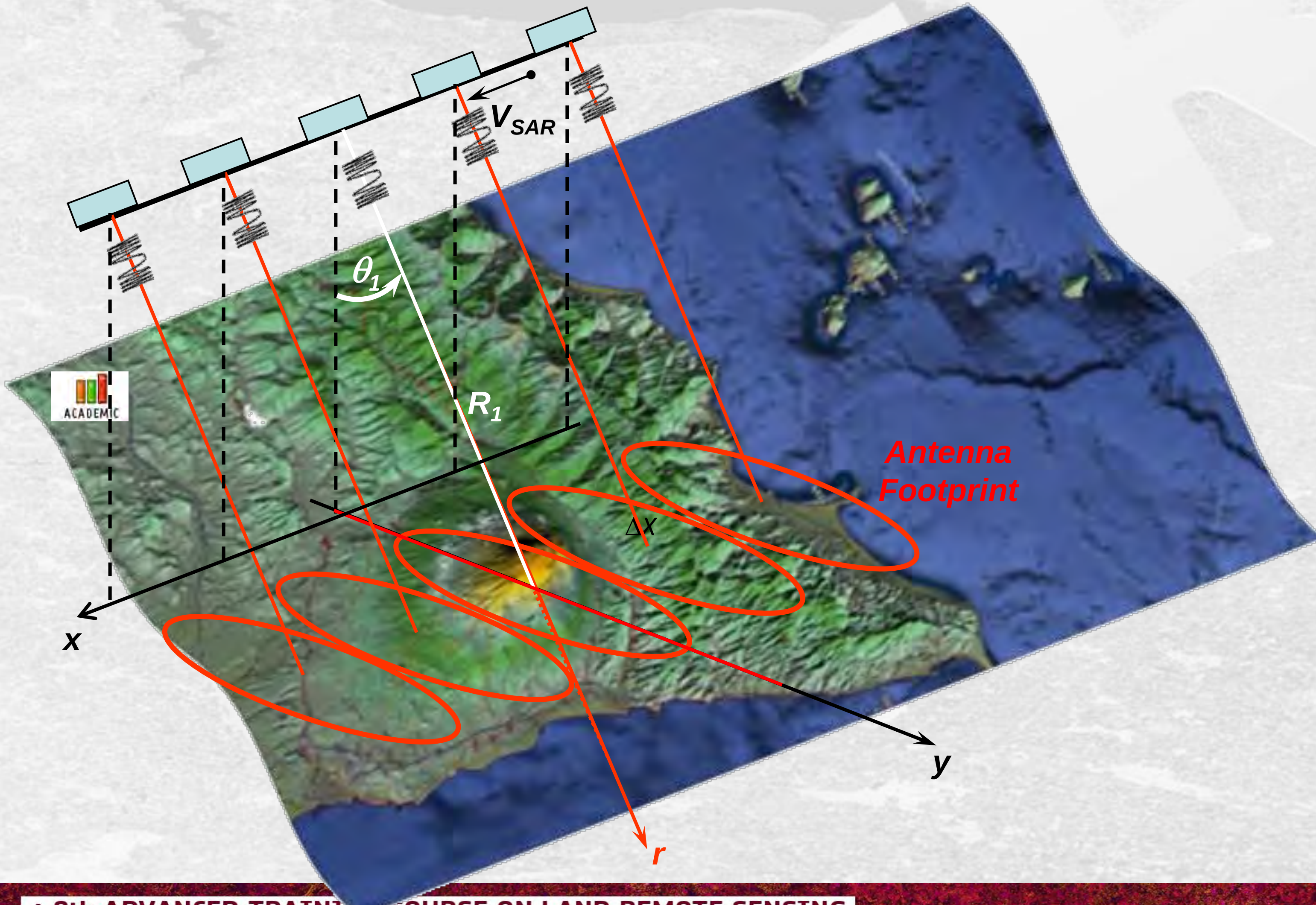
→ **Pol-InSAR**

PART - 1

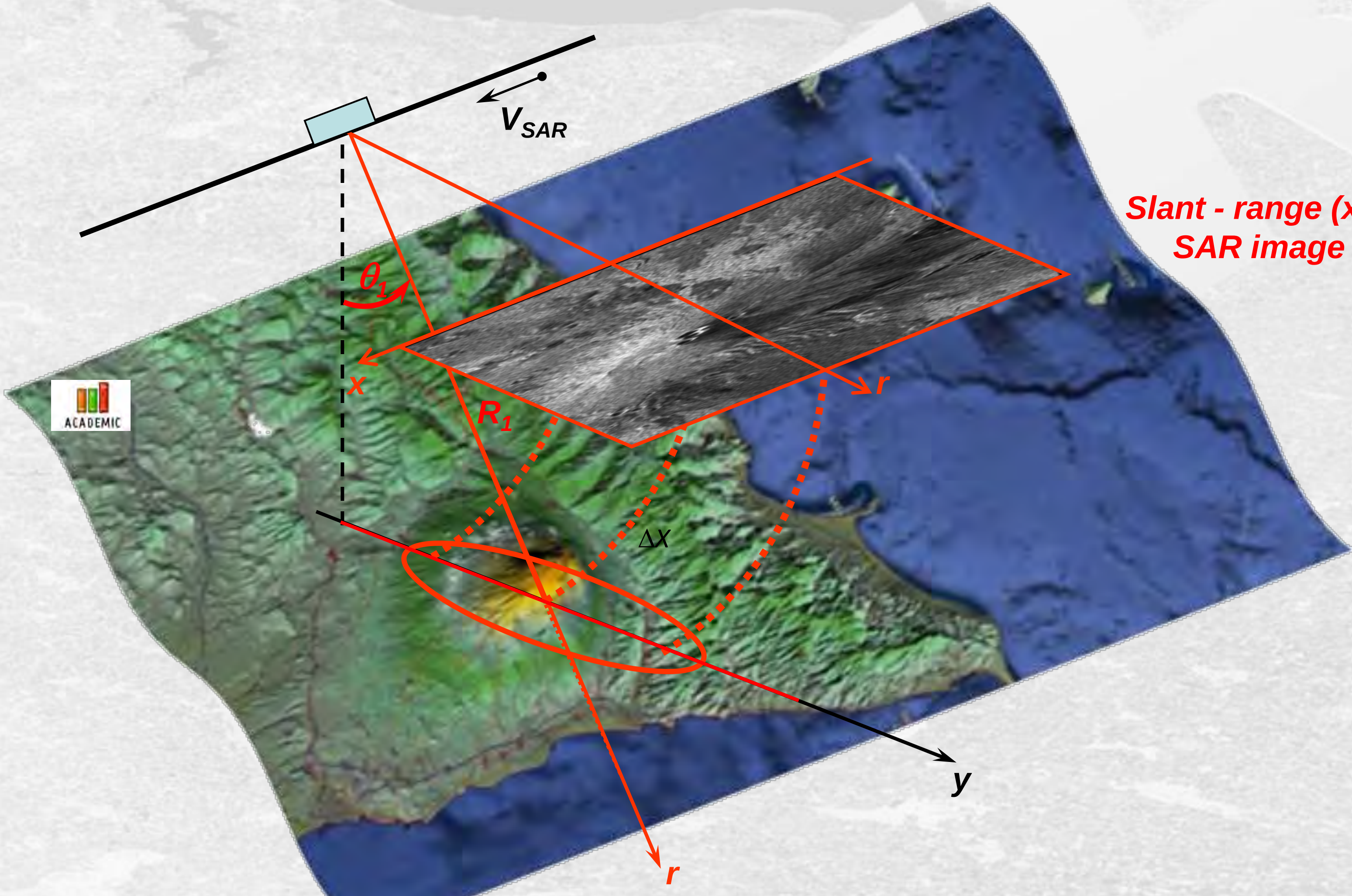
SAR
+
Interferometry

(In-SAR)

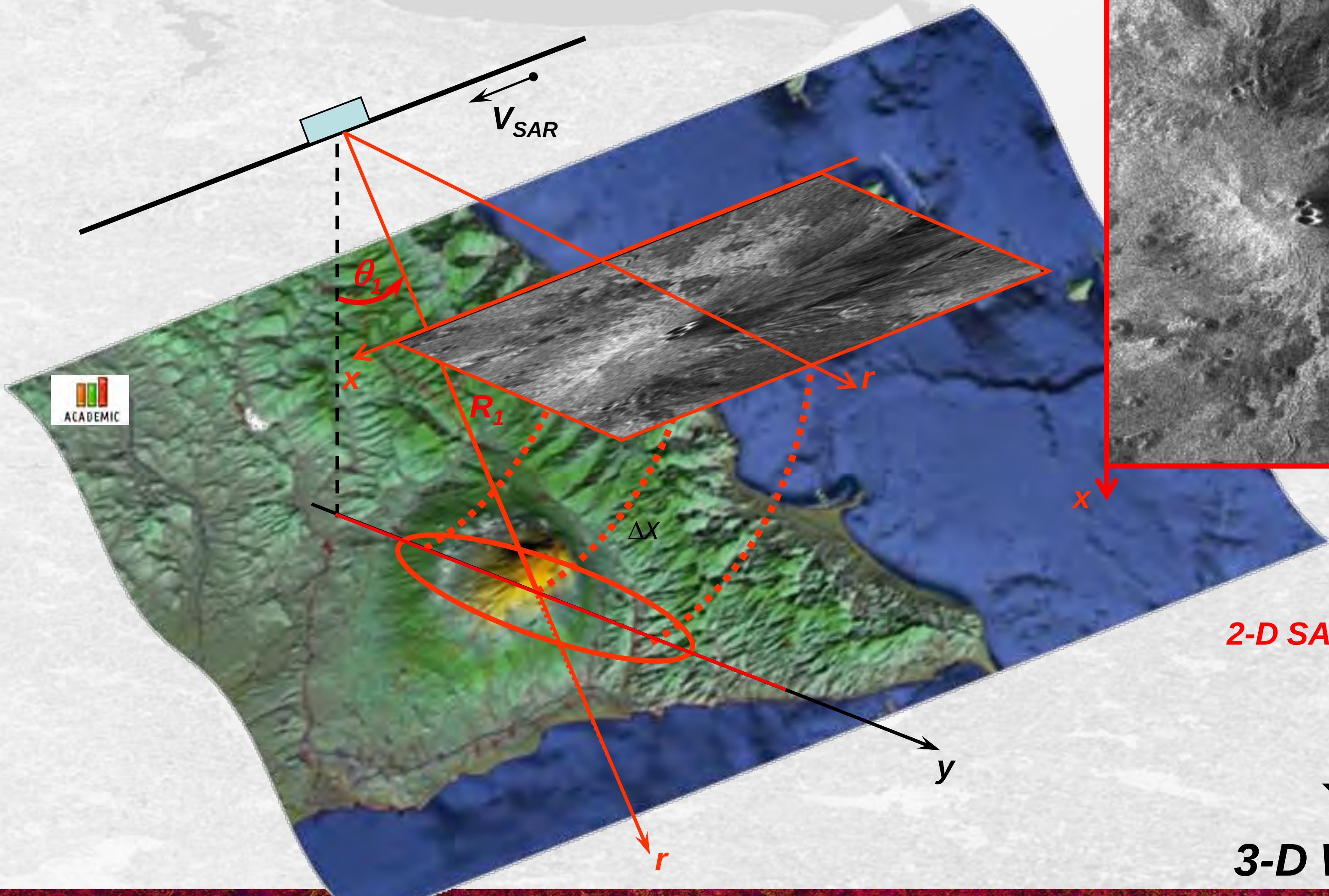
2-D SAR imaging

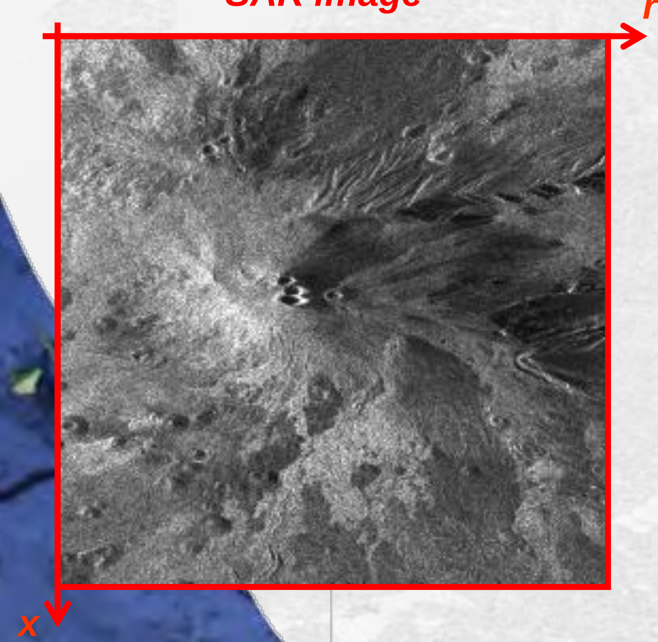


2-D SAR imaging



2-D SAR imaging

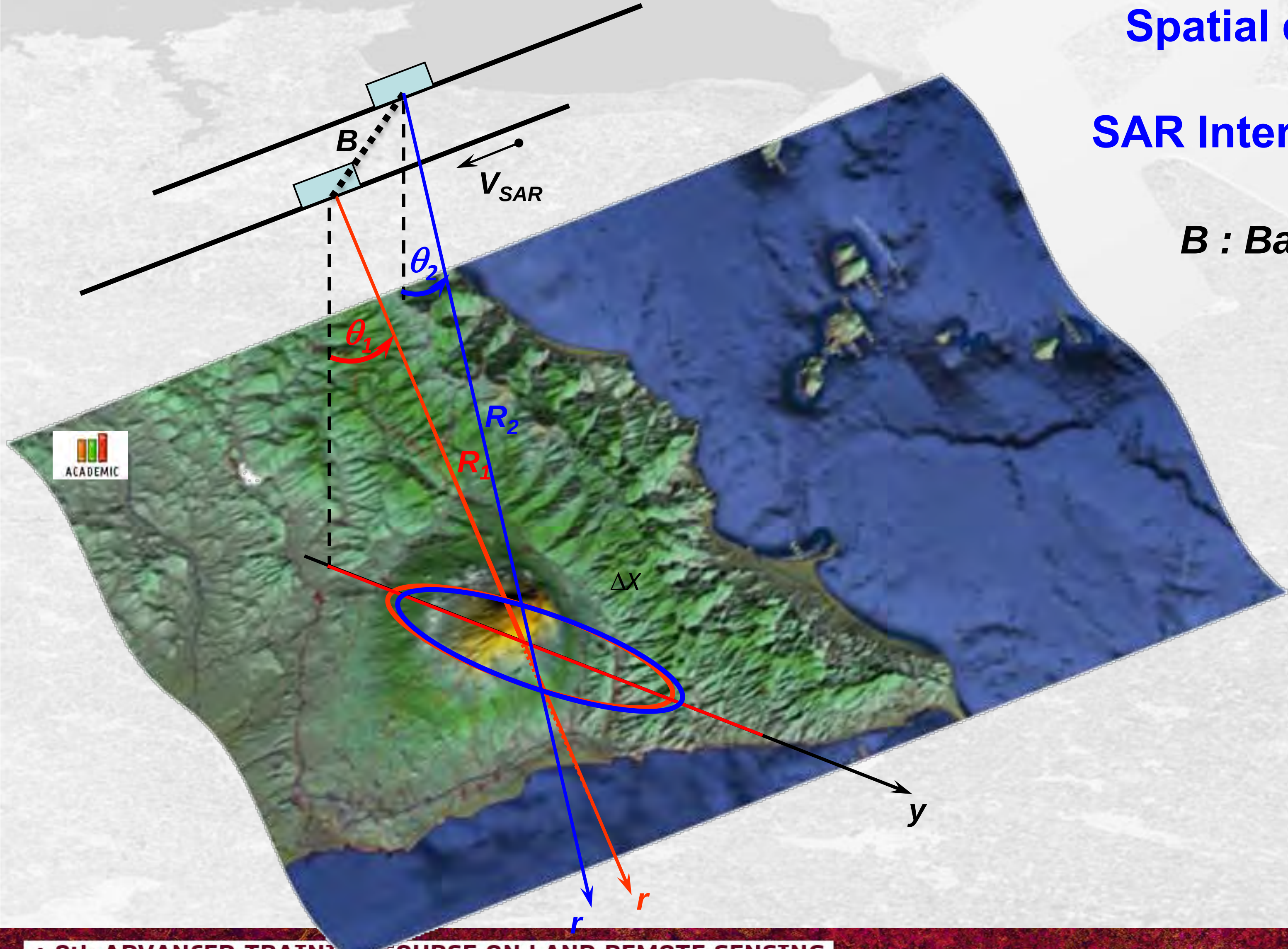




2-D SAR image

3-D World

3-D In-SAR imaging

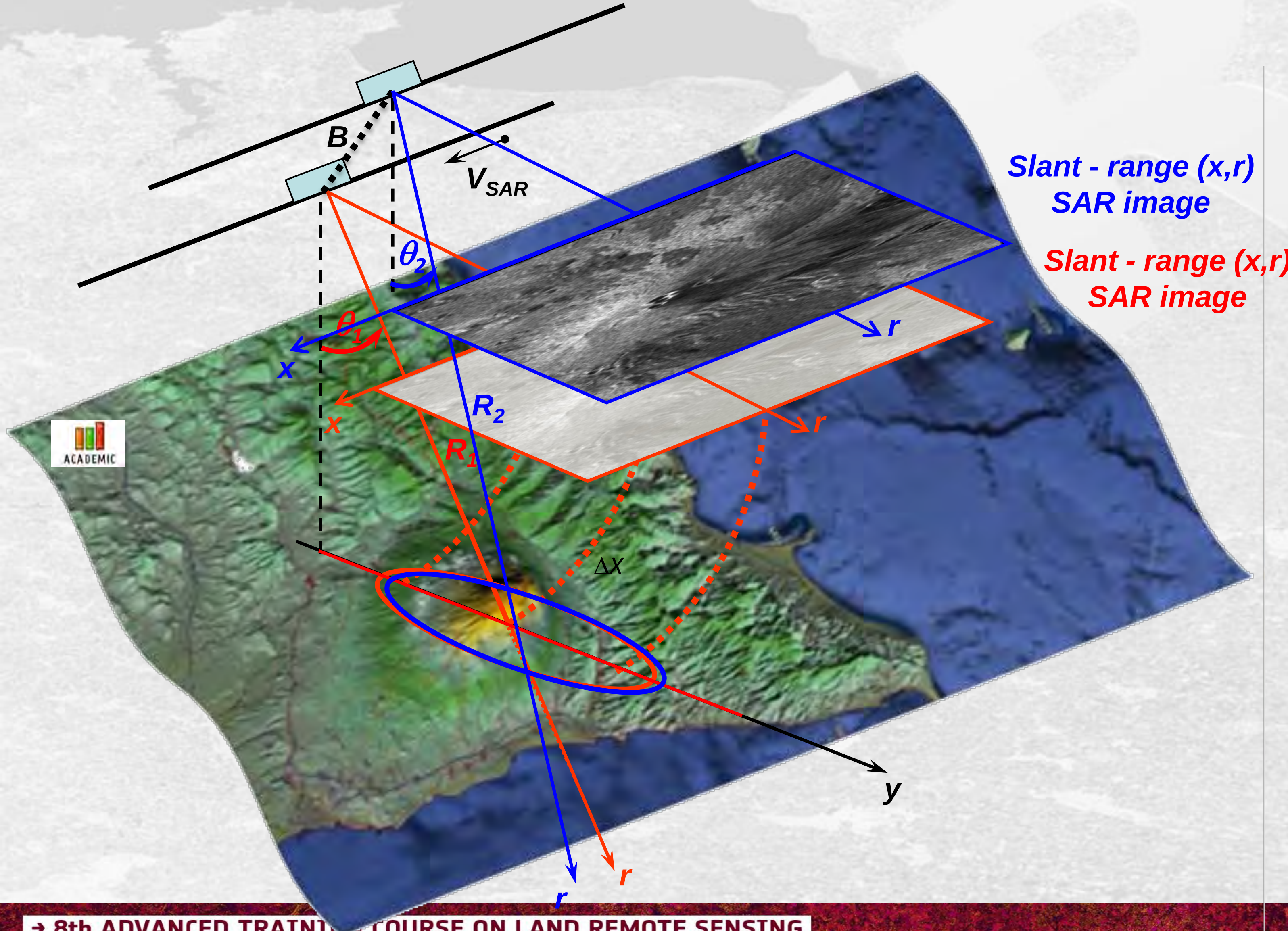


Spatial diversity

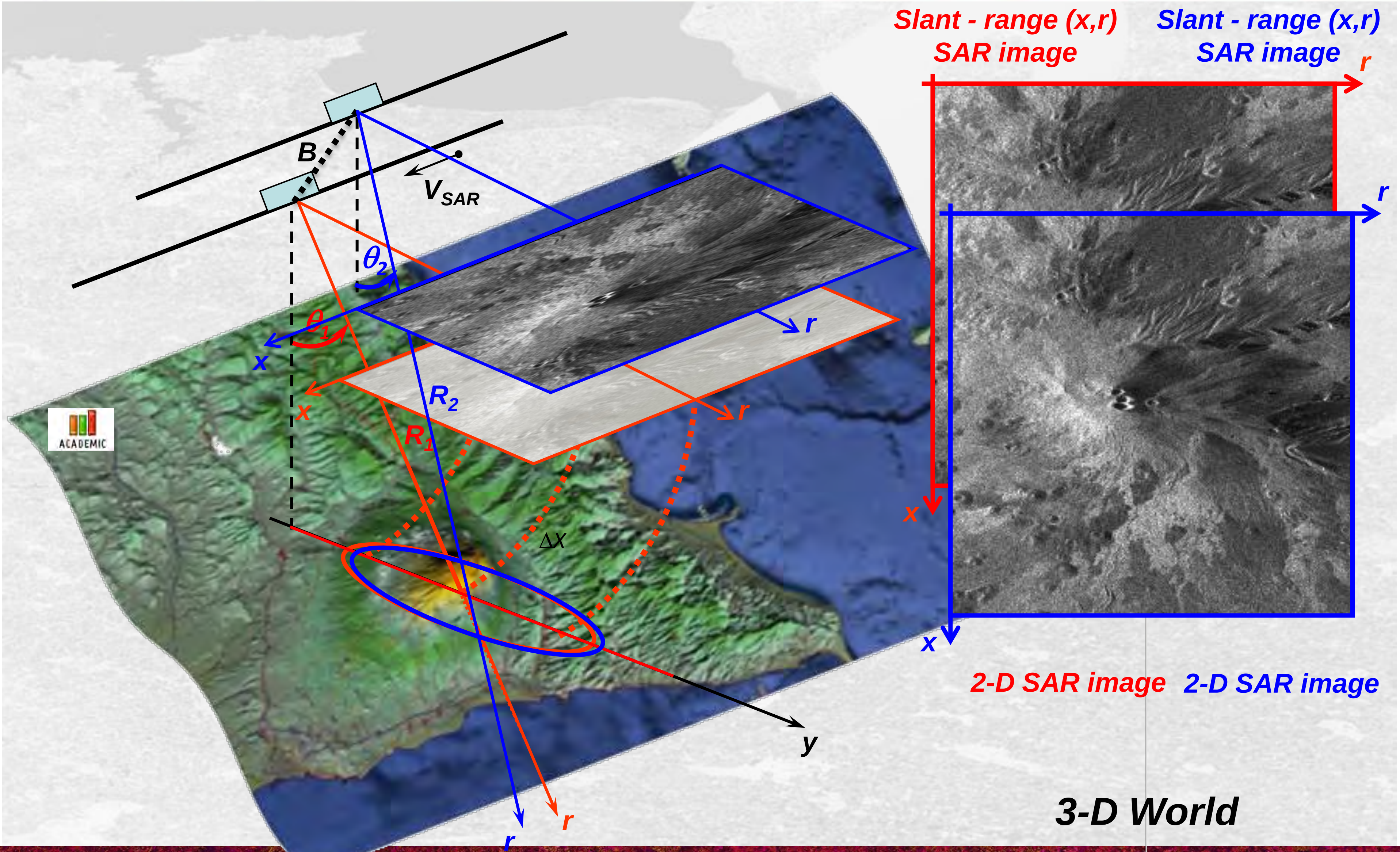
SAR Interferometry

B : Baseline

3-D In-SAR imaging



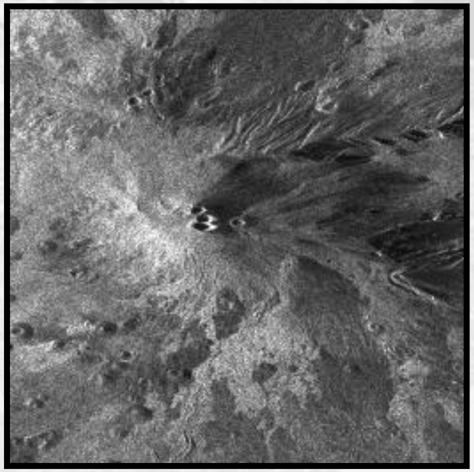
3-D In-SAR imaging



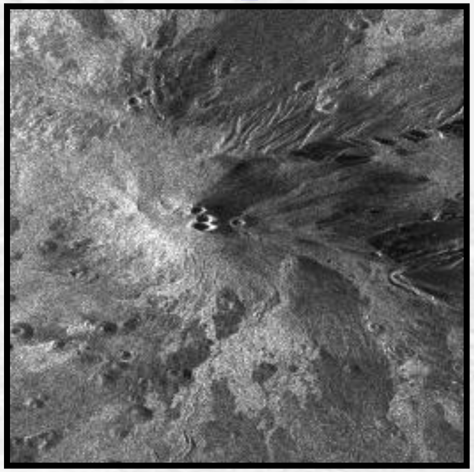
In-SAR data statistics

Interferometric coherence γ

s_1



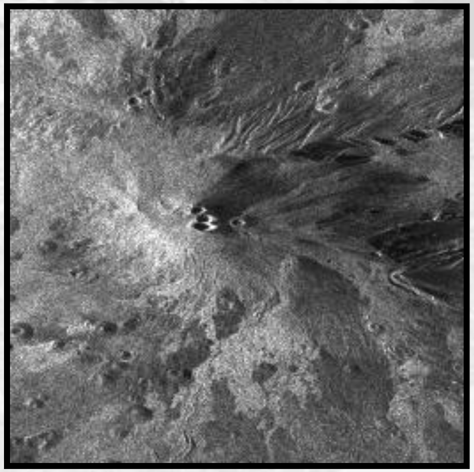
s_2



$$\gamma = \frac{E\left(s_1 s_2^*\right)}{\sqrt{E\left(s_1 s_1^*\right)E\left(s_2 s_2^*\right)}} = \frac{E\left(s_1 s_2^*\right)}{\sqrt{\overline{I}_1 \overline{I}_2}} = |\gamma| e^{j\phi}$$

In-SAR data statistics

s_1



Interferometric coherence γ

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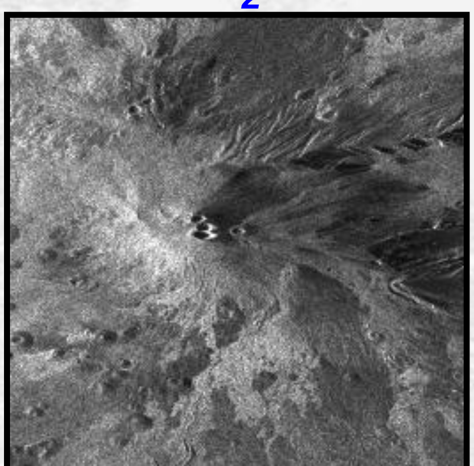
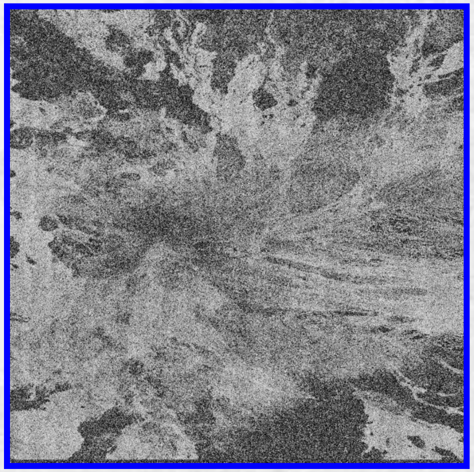
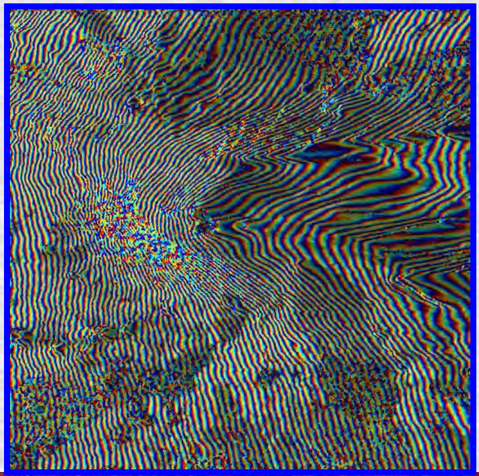
s_2



$|\gamma|$

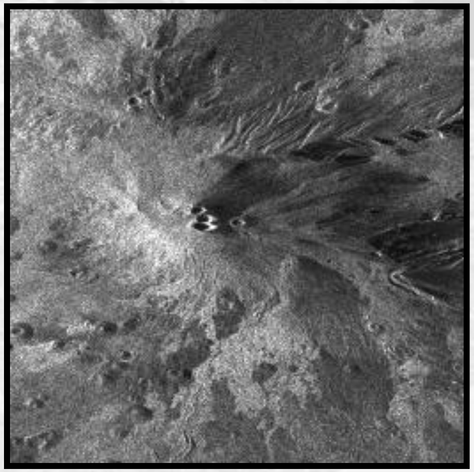


ϕ



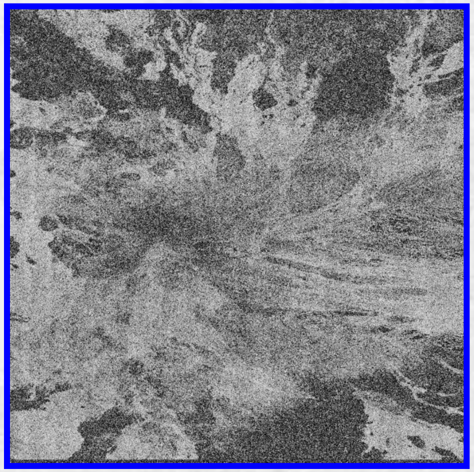
In-SAR data statistics

s_1



Interferometric coherence γ

$|\gamma|$



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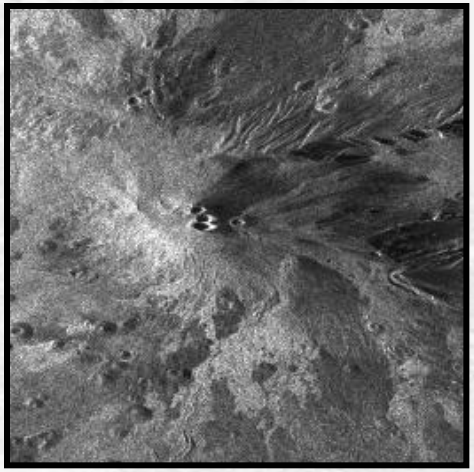
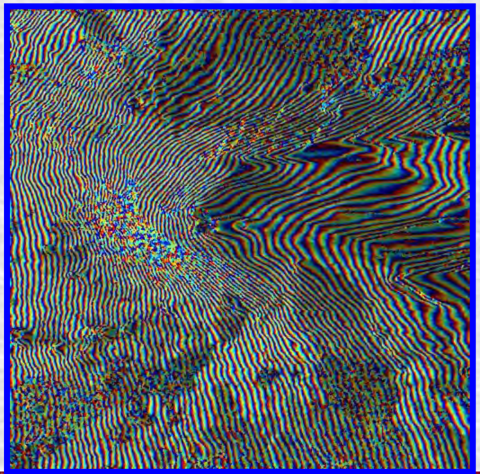
s_2



ϕ



Phase fringes

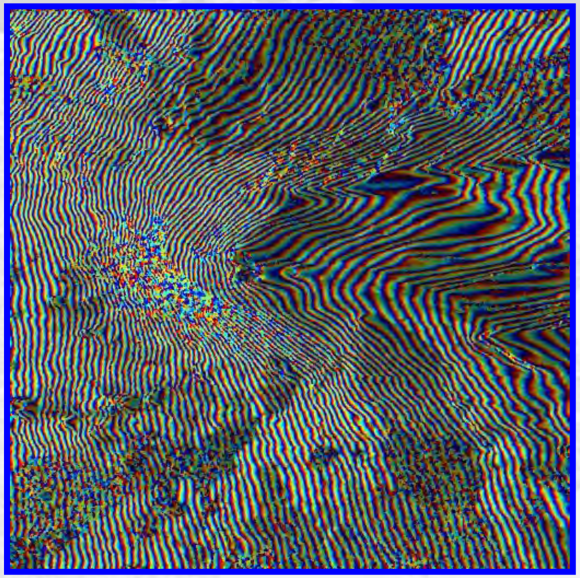
↓

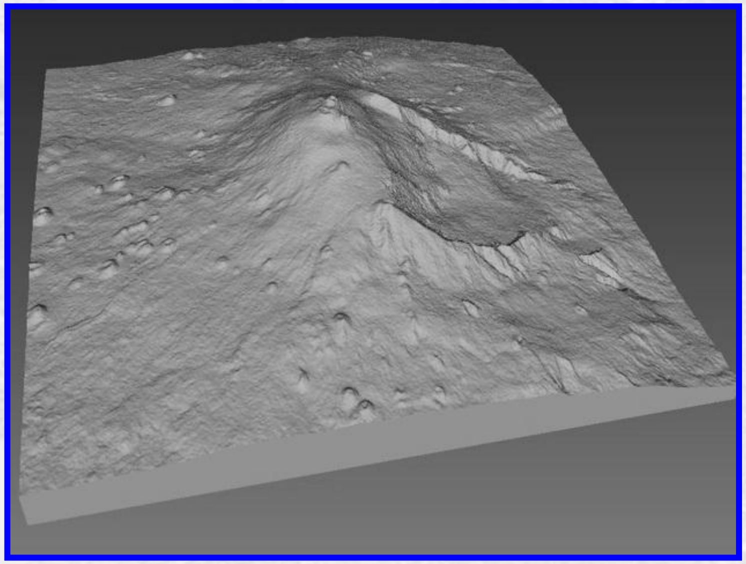
Contour lines

↓

3-D World

Relating In-SAR phase to height



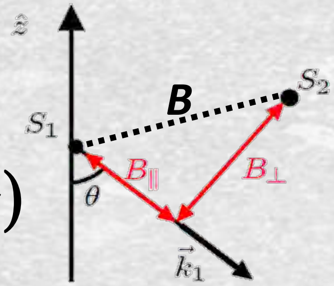


$$\phi = \Delta\phi_{1\cdot 2} \approx \Delta\phi_{topo} + \Delta\phi_{fe}$$

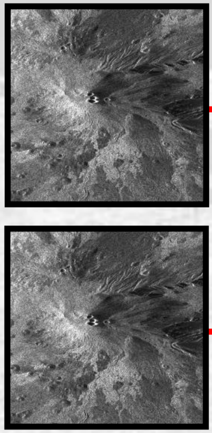
$$\Delta\phi_{topo} \propto \frac{k_c B_\perp}{R_1 \sin(\theta_1)} \Delta h$$

$$k_c = \frac{4\pi f_c}{c} = \frac{4\pi}{\lambda_c}$$

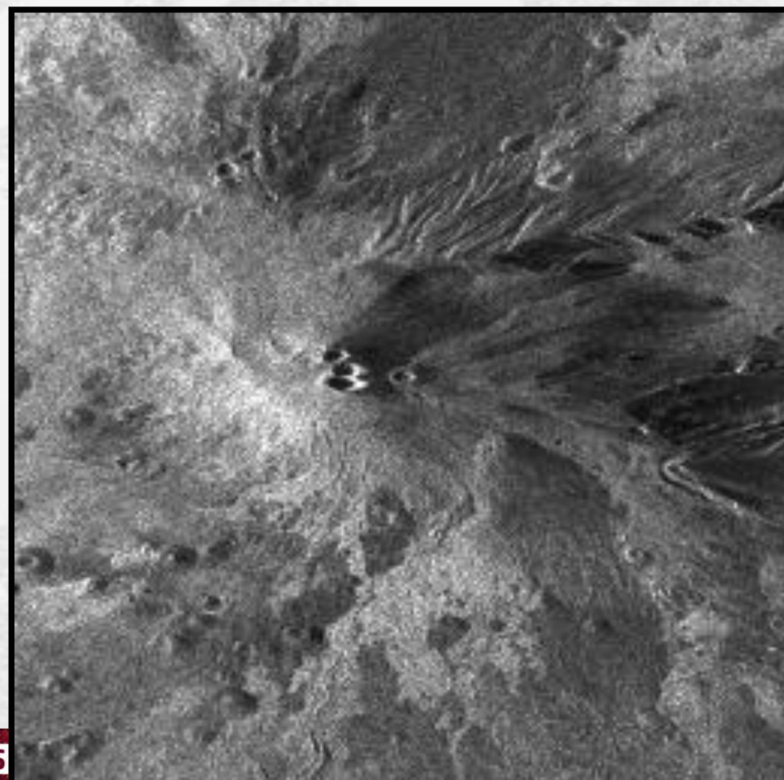
$$B_\perp = B \cos(\theta_1 - \alpha)$$



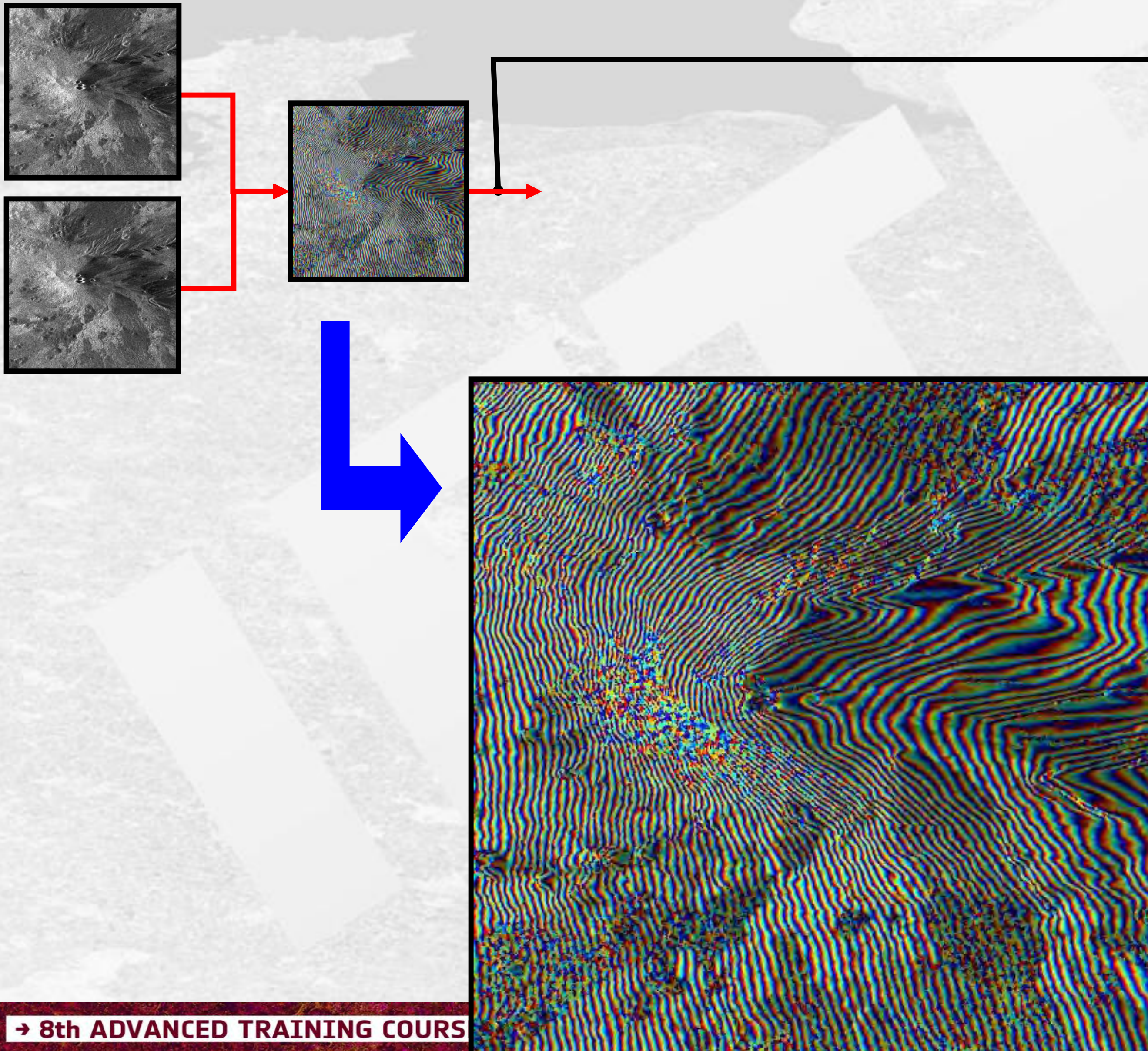
Relating In-SAR phase to height



SAR IMAGES

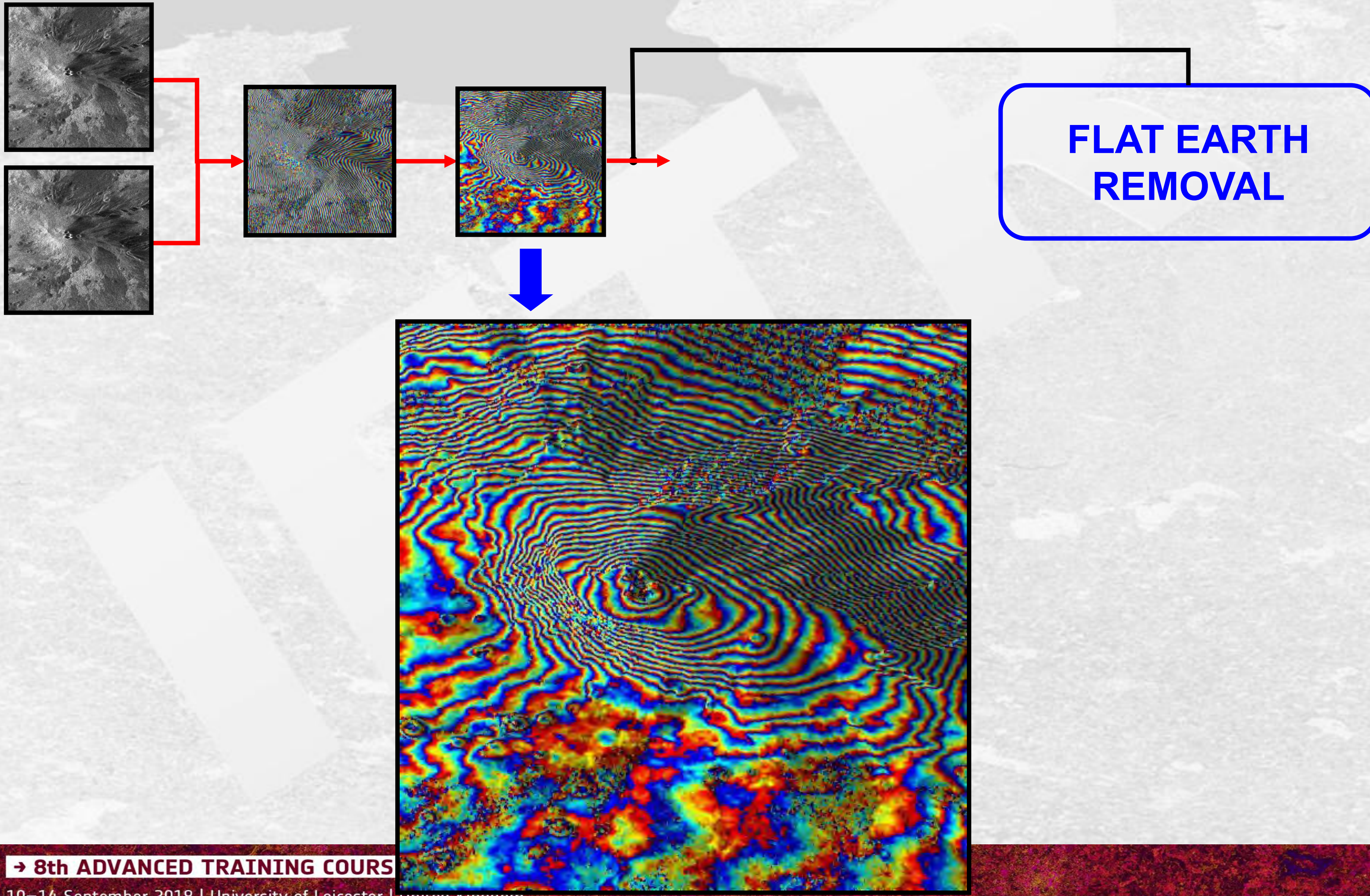


Relating In-SAR phase to height

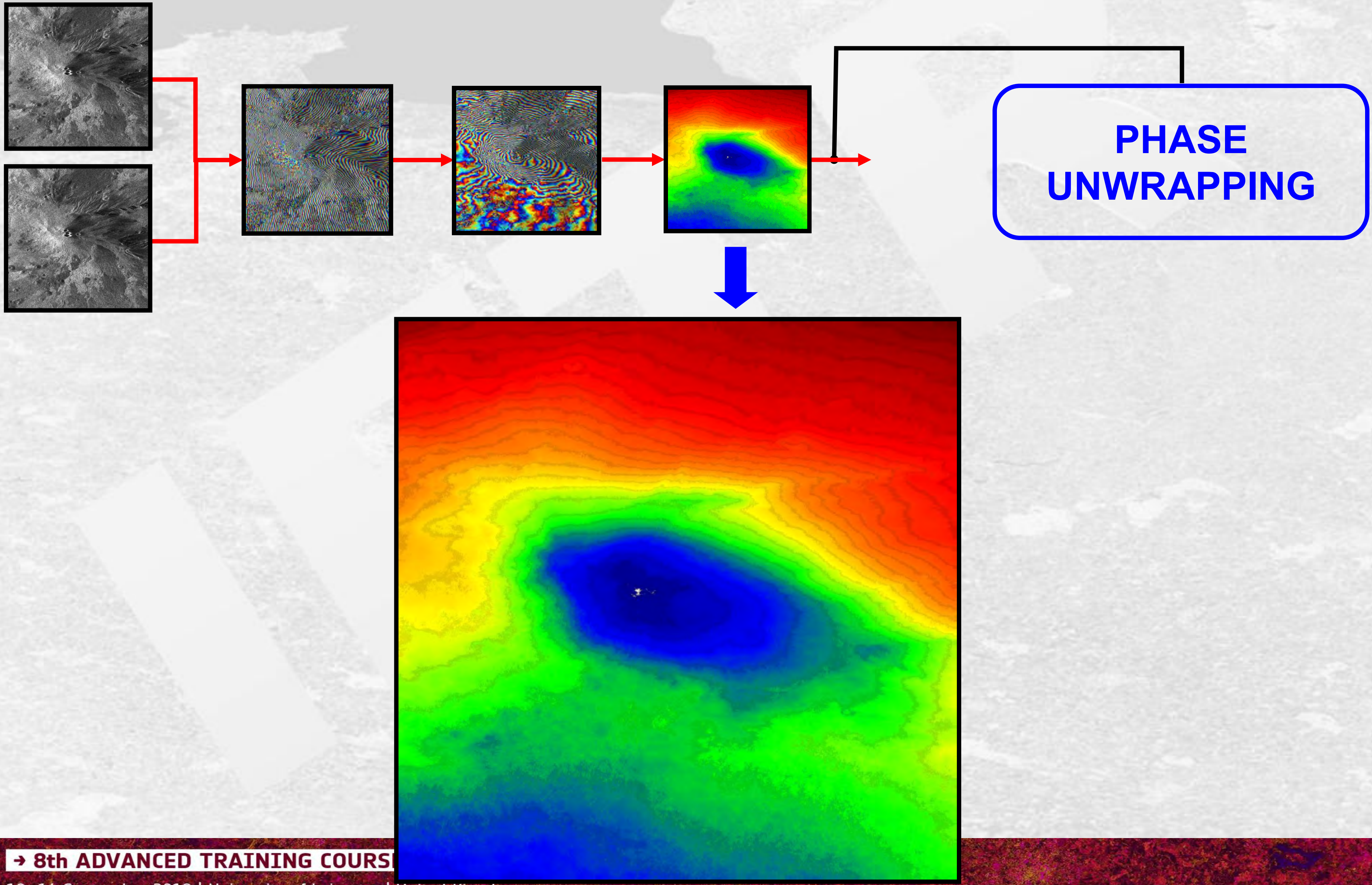


INTERFEROMETRIC PHASE

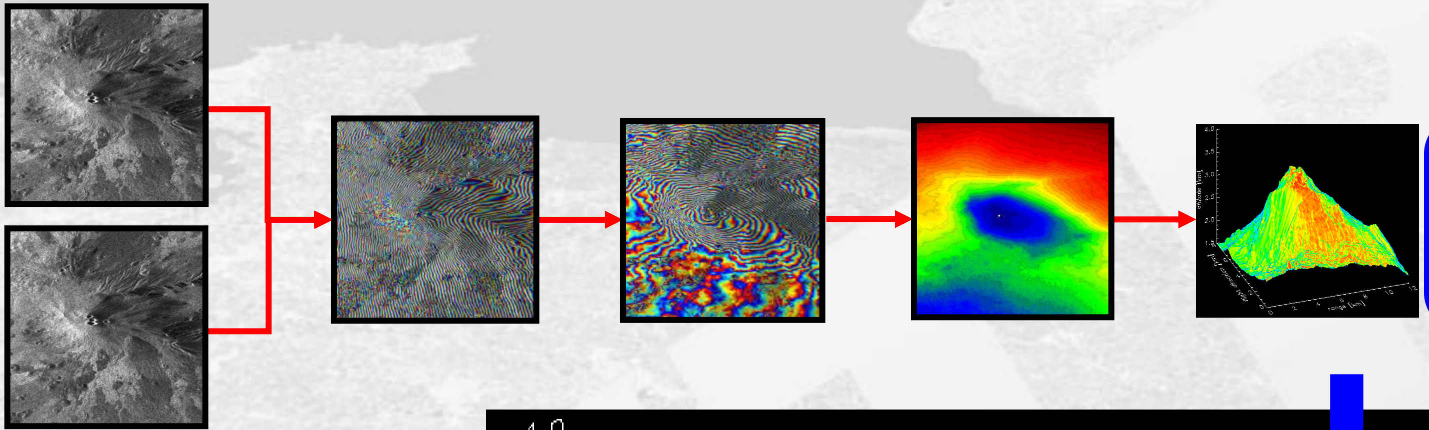
Relating In-SAR phase to height



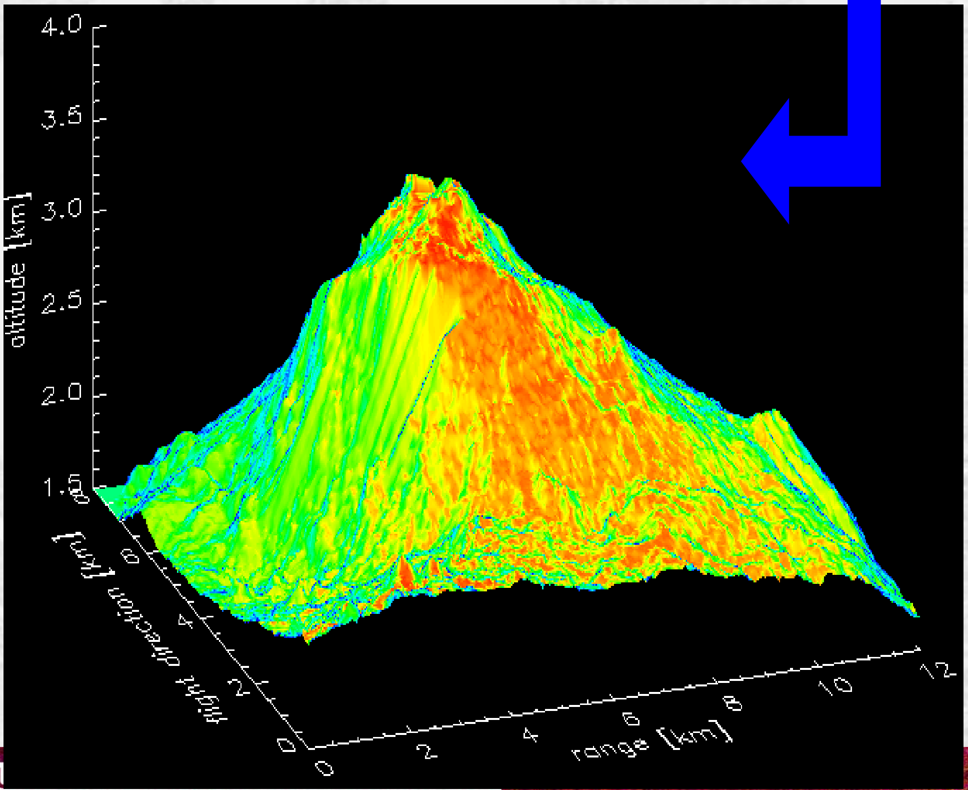
Relating In-SAR phase to height



Relating In-SAR phase to height

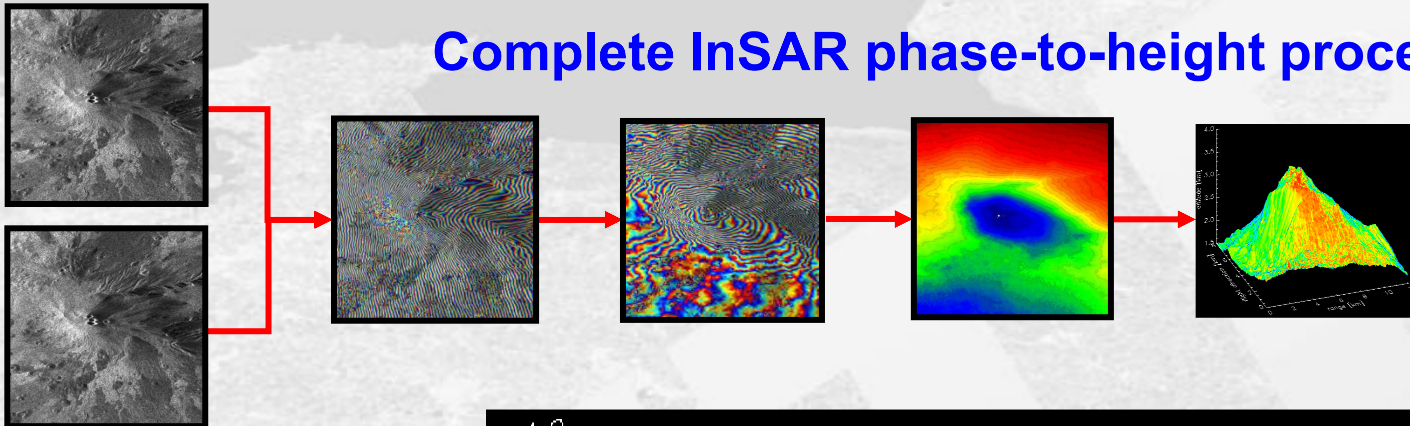


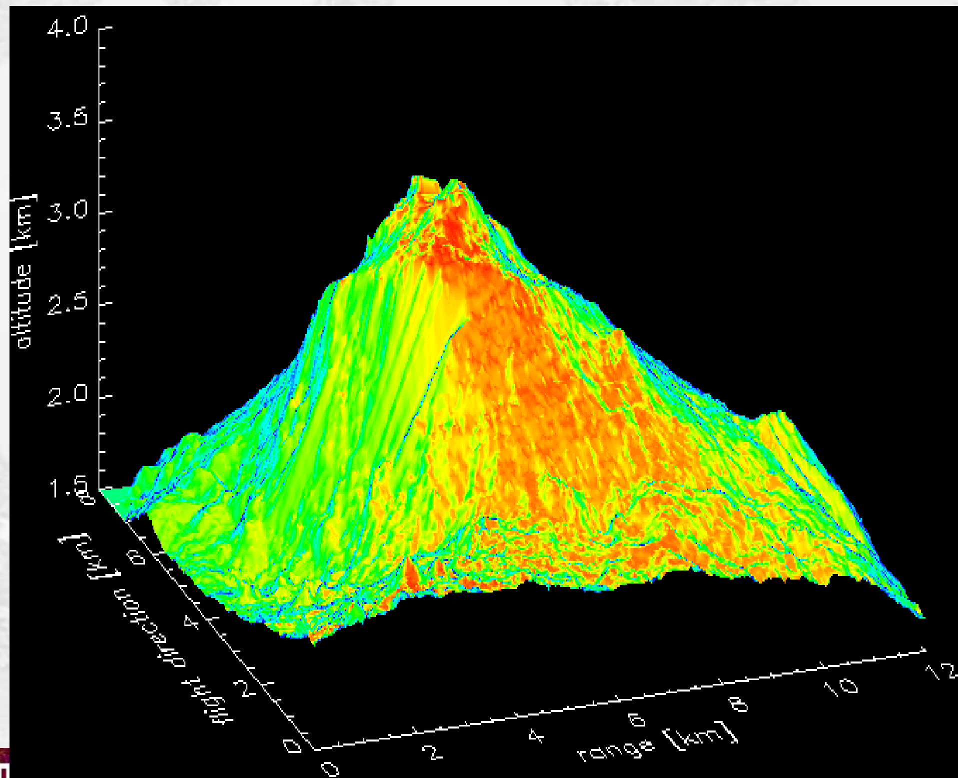
PHASE TO HEIGHT



Relating In-SAR phase to height

Complete InSAR phase-to-height processing chain



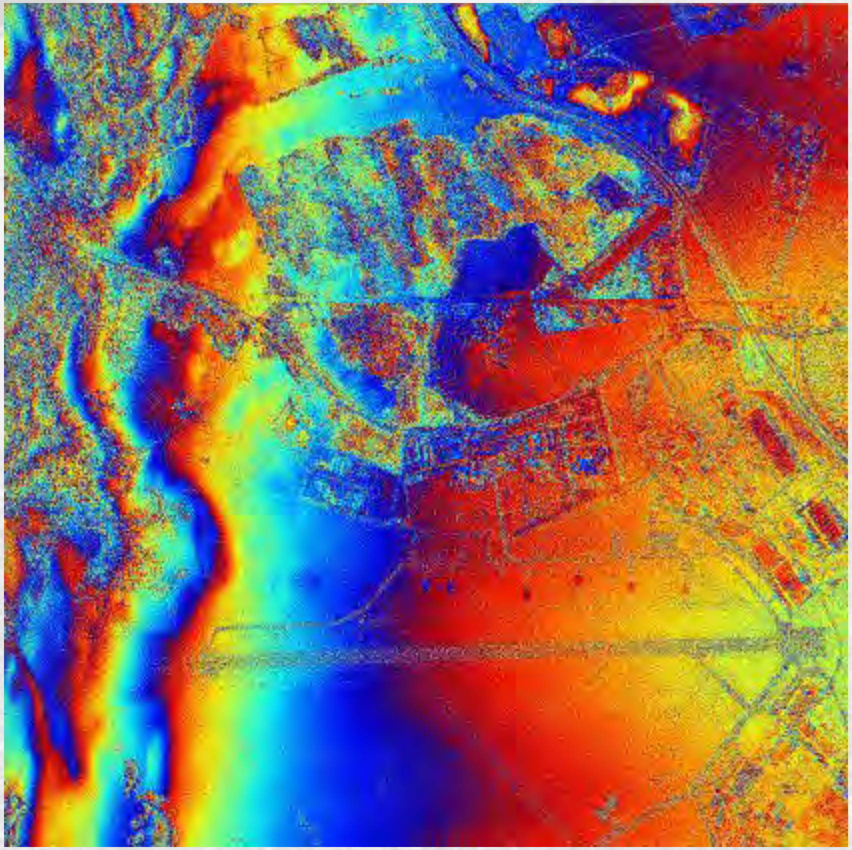


γ

In-SAR data statistics

Interferometric coherence γ

$|\gamma|$



$Arg(\gamma)$

DLR E-SAR L Band

Pol-In SAR (1.5m x 3m) – Baseline 5m

Interferometric coherence γ : decorrelation sources

γ fixed by a set of external sources :

System :

- Thermal or system noise : SAR amplifiers, ADC, antennas …
- Quantization noise
- Geometric decorrelation : Baseline, squint …
- Azimuth : Doppler decorrelation …
- Ambiguities …
- Processing errors : coregistration, interpolation …

Environment :

- Random media : Surface & Volumetric media e.g. forest …
- Temporal variations : wind, flowing or plowing, building …

$$\gamma = \gamma_{SNR} \cdot \gamma_{quant} \cdot \gamma_{amb} \cdot \gamma_{geo} \cdot \gamma_{az} \cdot \gamma_{proc} \cdot \gamma_{media} \cdot \gamma_{temp}$$

Interferometric coherence γ : decorrelation sources

γ fixed by a set of external sources :

System :

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- Processing errors : coregistration, interpolation …

Environment :

- Random media : Surface & Volumetric media e.g. forest …
- Temporal variations : wind, flowing or plowing, building …

γ_{vol} : model ?

$$\gamma = \gamma_{SNR} \cdot \gamma_{quant} \cdot \gamma_{amb} \cdot \gamma_{geo} \cdot \gamma_{az} \cdot \gamma_{proc} \cdot \gamma_{media} \cdot \gamma_{temp}$$

In-SAR data statistics

Interferometric coherence γ

$$\gamma = \frac{E\left(s_1 s_2^*\right)}{\sqrt{E\left(s_1 s_1^*\right)E\left(s_2 s_2^*\right)}} = \frac{E\left(s_1 s_2^*\right)}{\sqrt{\bar{I}_1 \bar{I}_2}} \approx \frac{E\left(s_1 s_2^*\right)}{\bar{I}} = |\gamma| e^{j\phi} \qquad \bar{I}_1 \approx \bar{I}_2 \approx \bar{I}$$

In-SAR signal formulation

$$s_1(x,r) = e^{-jkr_{0_1}} \int_V a_{c_1}(\vec{r}\,') e^{-j\vec{k}_1 \cdot (\vec{r}\,' - \vec{r}_0)} h(x - x', r - r') dv'$$

$$s_2(x,r) = e^{-jkr_{0_2}} \int_V a_{c_2}(\vec{r}\,') e^{-j\vec{k}_2 \cdot (\vec{r}\,' - \vec{r}_0)} h(x - x', r - r') dv'$$

In-SAR data statistics

Interferometric coherence γ

$$\gamma = \frac{E\left(s_1 s_2^*\right)}{\sqrt{E\left(s_1 s_1^*\right)E\left(s_2 s_2^*\right)}} = \frac{E\left(s_1 s_2^*\right)}{\sqrt{\overline{I}_1 \overline{I}_2}} \approx \frac{E\left(s_1 s_2^*\right)}{\overline{I}} = |\gamma| e^{j\phi} \qquad \overline{I}_1 \approx \overline{I}_2 \approx \overline{I}$$

Volume complex reflectivity $a_{c_i}(\vec{r})$

$$\overline{I}_i(x,r) = E\left(s_i(x,r) s_i^*(x,r)\right) = \int_V \sigma_{v_i}(\vec{r}\,') \left| h(x - x', r - r') \right|^2 dv'$$

$$E\left(s_1(x,r) s_2^*(x,r)\right) = \int_V \sigma_{v_e}(\vec{r}\,') e^{-j(\vec{k}_1 - \vec{k}_2)(\vec{r}\,' - \vec{r}_0)} \left| h(x - x', r - r') \right|^2 dv'$$

With :

$$E\left(a_{c_i}(\vec{r}) a_{c_i}^*(\vec{r}\,')\right) = \sigma_{v_i}(\vec{r})\, \delta(\vec{r} - \vec{r}\,')$$ **Reflectivity density**

$$E\left(a_{c_1}(\vec{r}) a_{c_2}^*(\vec{r}\,')\right) = \sigma_{v_e}(\vec{r})\, \delta(\vec{r} - \vec{r}\,')$$ **Effective reflectivity density**

Interferometric coherence γ

$$\gamma = \frac{E\left(s_1 s_2^*\right)}{\sqrt{E\left(s_1 s_1^*\right) E\left(s_2 s_2^*\right)}} = \frac{E\left(s_1 s_2^*\right)}{\sqrt{\bar{I}_1 \bar{I}_2}} \approx \frac{E\left(s_1 s_2^*\right)}{\bar{I}} = |\gamma| e^{j\phi}$$

$$\bar{I}_1 \approx \bar{I}_2 \approx \bar{I}$$

$$\gamma = \frac{\int_V \sigma_{v_e}(\vec{r}\,') e^{-j(\vec{k}_1 - \vec{k}_2)(\vec{r}\,' - \vec{r}_0)} \left| h(x - x', r - r') \right|^2 dv'}{\int_V \sigma_v(\vec{r}\,') \left| h(x - x', r - r') \right|^2 dv'}$$

With :

$$E\left(a_{c_i}(\vec{r}) a_{c_i}^*(\vec{r}\,')\right) = \sigma_{v_i}(\vec{r})\, \delta(\vec{r} - \vec{r}\,')$$ **Reflectivity density**

$$E\left(a_{c_1}(\vec{r}) a_{c_2}^*(\vec{r}\,')\right) = \sigma_{v_e}(\vec{r})\, \delta(\vec{r} - \vec{r}\,')$$ **Effective reflectivity density**

In-SAR coherence decomposition

Interferometric coherence γ

$$\gamma = \frac{\int_V \sigma_{v_e}(\vec{r}')e^{-j(\vec{k}_1-\vec{k}_2)(\vec{r}'-\vec{r}_0)}\left|h(x-x',r-r')\right|^2 dv'}{\int_V \sigma_v(\vec{r}')\left|h(x-x',r-r')\right|^2 dv'}$$

$$\gamma = \gamma_{temp}\cdot\gamma_{media} = \gamma_{temp}\cdot\left(\gamma_{x,y}\cdot\gamma_z\right)$$

Surface / Volume

$$\gamma_{vol} = \gamma_z = \frac{\int_Z \sigma_{v_e}(\vec{r}')\,e^{jk_z(z-z_0)}dz'}{\int_Z \sigma_{v_e}(\vec{r}')\,dz'}$$

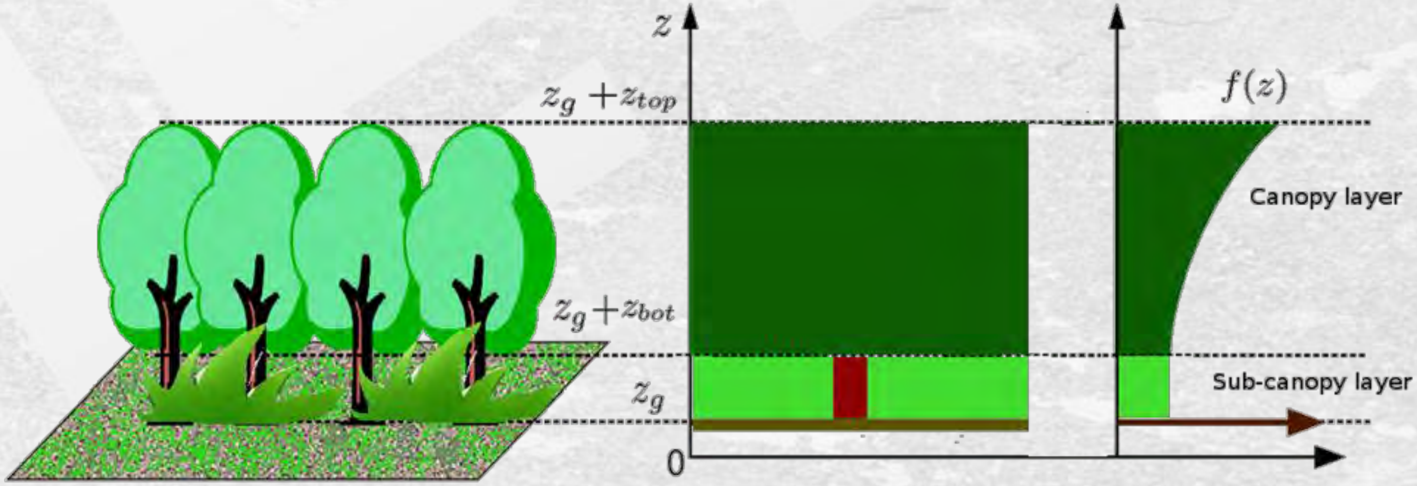
Volumetric / random media decorrelation

In-SAR coherence decomposition

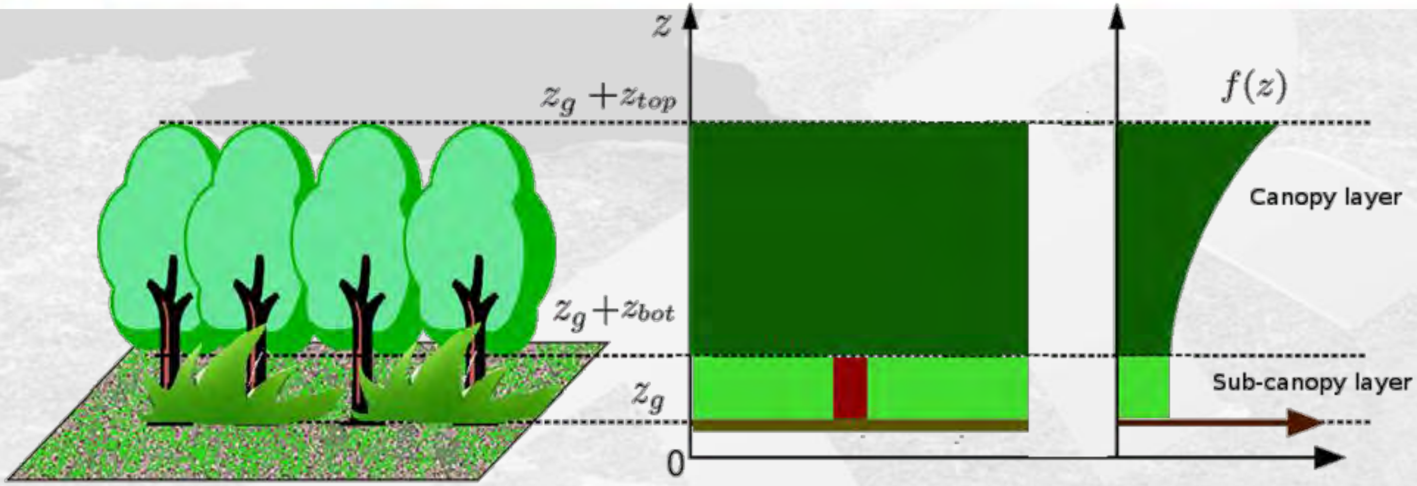
Volume decorrelation

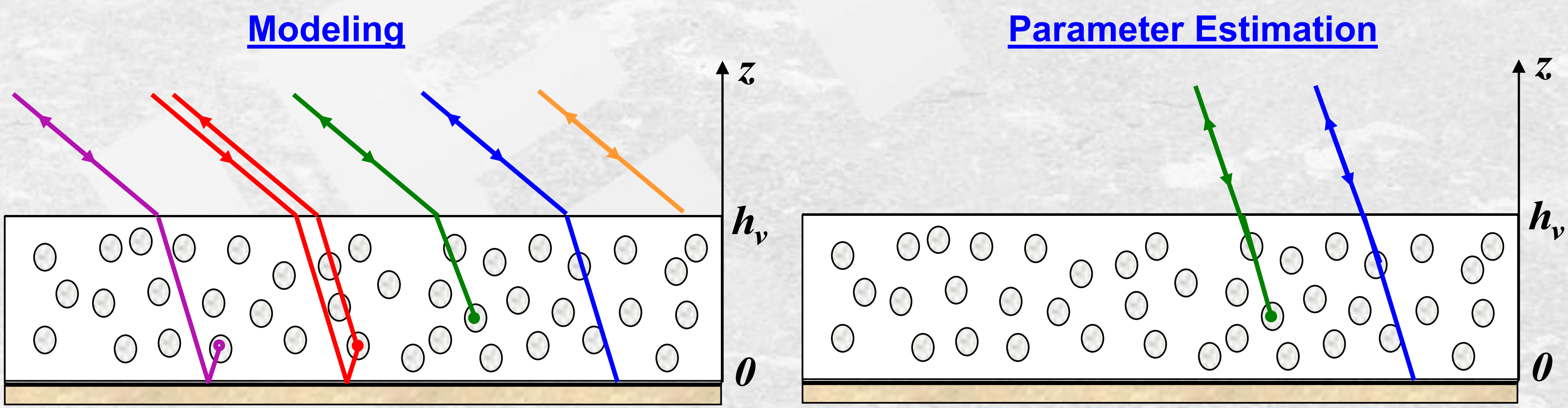
$$\gamma_z = \frac{\int_Z \sigma_{v_e}(z)\, e^{jk_z(z-z_0)}\, dz'}{\int_Z \sigma_{v_e}(z)\, dz'}$$

Decorrelation due to the vertical structure $\sigma_{v_e}(z) = A_{v_e} f(z)$



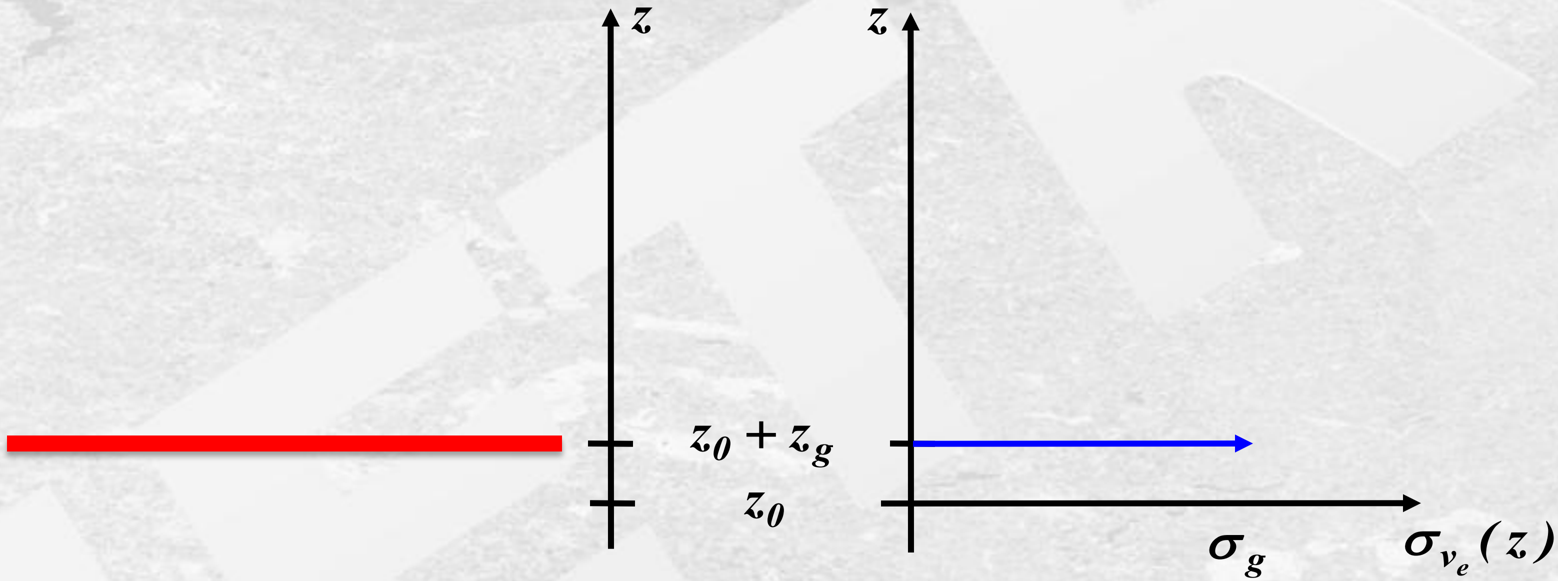
In-SAR coherence decomposition





- 2 significant and uncorrelated mechanisms : volume + underlying ground
- low density medium = No refraction

Ground only



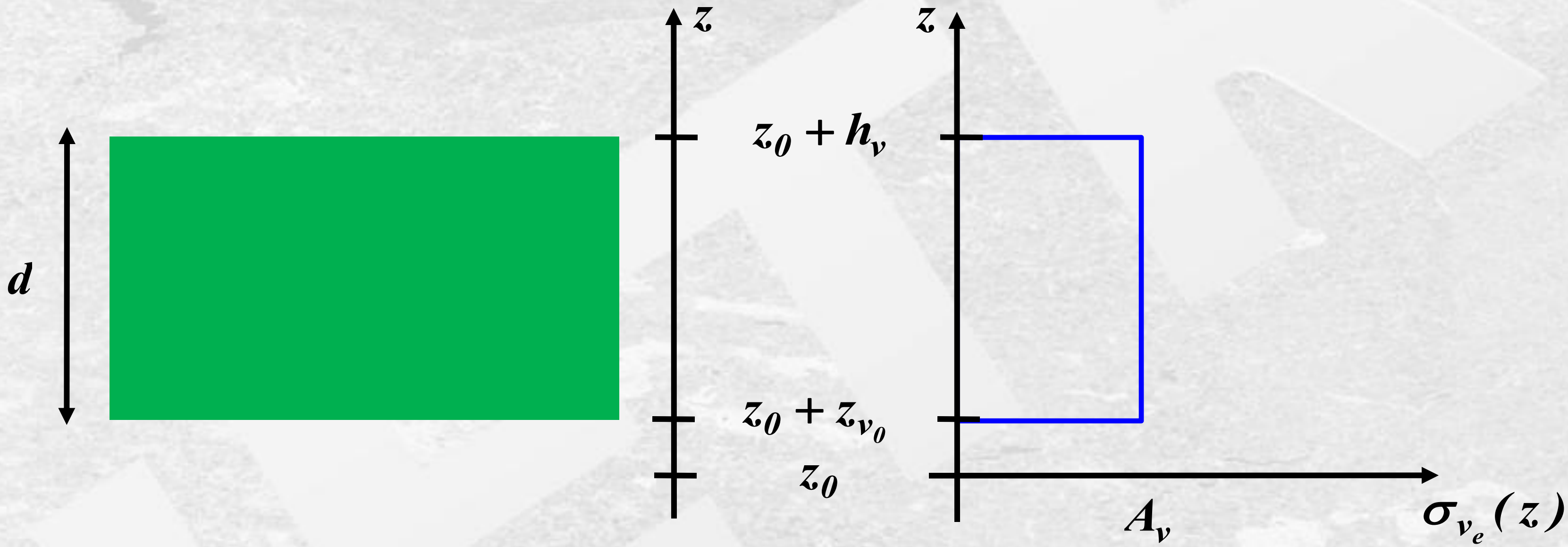
Ground layer $\sigma_{v_e}(z) = \sigma_g \delta(z - z_g)$

No volume

$$\gamma_z = \frac{\int_Z \sigma_{v_e}(z)\, e^{jk_z (z - z_0)} dz'}{\int_Z \sigma_{v_e}(z)\, dz'} = e^{jk_z z_g}$$

In-SAR coherence decomposition

Random volume (RV) with null extinction



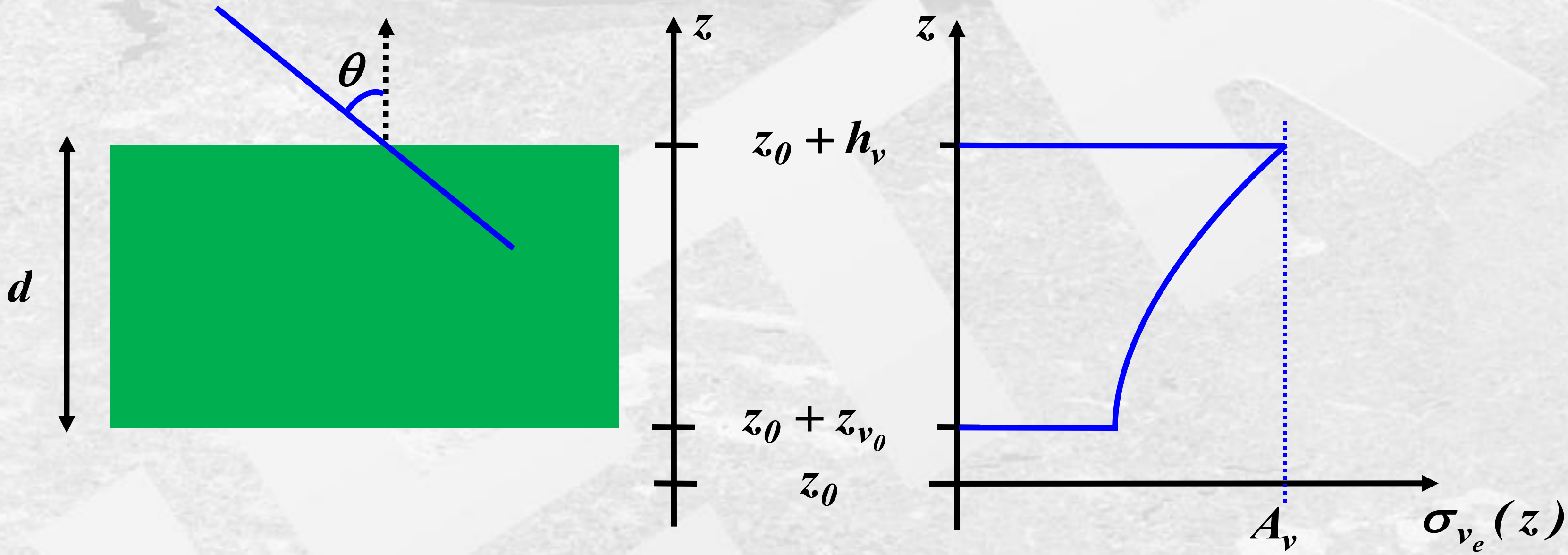
No underlying ground

Homogeneous medium

Null extinction : $\sigma_{v_e}(z) = A_v$

$$\gamma_z = \frac{\displaystyle\int_{z_0+z_{v0}}^{z_0+h_v} \sigma_{v_e}(z)\, e^{jk_z(z-z_0)}\, dz'}{\displaystyle\int_{z_0+z_{v0}}^{z_0+h_v} \sigma_{v_e}(z)\, dz'} = e^{jk_z \frac{(h_v+z_{v0})}{2}}\, sinc\left(\frac{k_z d}{2}\right)$$

Random volume (RV) with non-null extinction

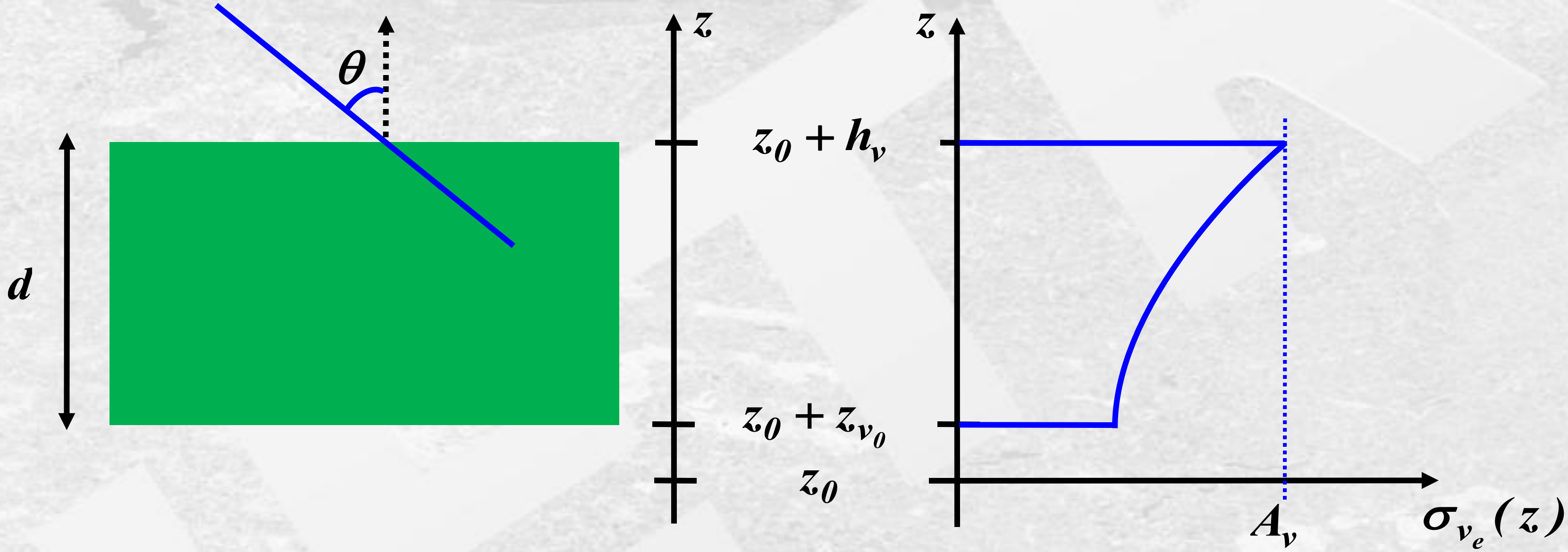


No underlying ground

Non-null extinction : κ_e

Homogeneous medium with elementary reflectivity density $\sigma_{v_e}(z) = A_v e^{\frac{2\kappa_e}{\cos(\theta)}(z-(z_0+h_v))}$

Random volume (RV) with non-null extinction



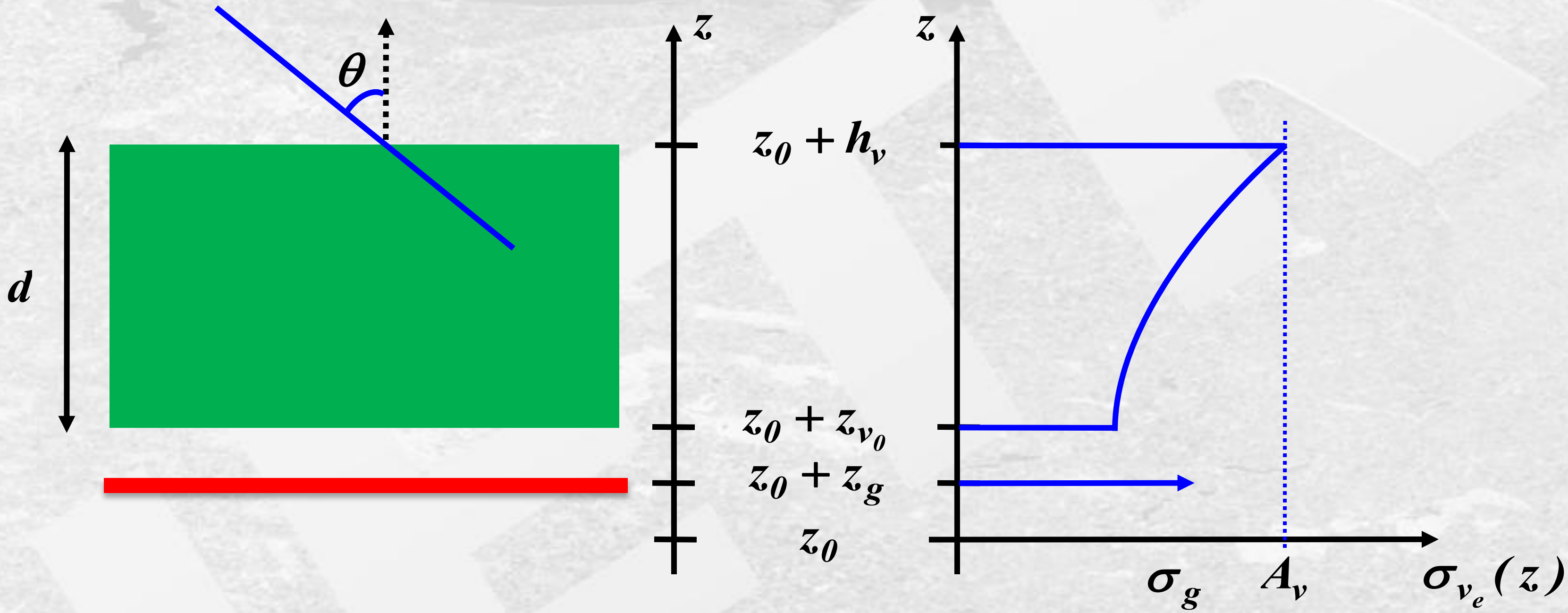
$$\gamma_z = \frac{\int_{z_0+z_{v_0}}^{z_0+h_v} \sigma_{v_e}(z)\, e^{jk_z(z-z_0)} dz'}{\int_{z_0+z_{v_0}}^{z_0+h_v} \sigma_{v_e}(z) dz'} = e^{jk_z z_{v_0}} \frac{p}{p_1} \left(\frac{e^{p_1 d} - 1}{e^{pd} - 1} \right)$$

$$p = \frac{2\kappa_e}{\cos(\theta)}$$

$$p_1 = \frac{2\kappa_e}{\cos(\theta)} + jk_z$$

In-SAR coherence decomposition

Random volume over ground (RVoG)



Non-null extinction : κ_e

Underlying ground : $I_g = \sigma_g e^{-\frac{2\kappa_e d}{\cos(\theta)}} \delta\left(z - \left(z_0 + z_g\right)\right)$

Homogeneous medium with elementary reflectivity density $\sigma_{vol}(z) = A_v e^{\frac{2\kappa_e}{\cos(\theta)}\left(z - \left(z_0 + h_v\right)\right)}$

In-SAR coherence decomposition

Random volume over ground (RVoG)

$$\sigma_{v_e}(z) = I_g + \sigma_{vol}(z)\big|_{z \in [z_0 + z_{v0} \ldots z_0 + h_v]} \Rightarrow \gamma_z = \frac{\int_Z \sigma_{v_e}(z)\, e^{jk_z(z-z_0)} dz'}{\int_Z \sigma_{v_e}(z)\, dz'}$$

$$\gamma_z = \frac{\int_{z_0+z_{v0}}^{z_0+h_v} \sigma_{vol}(z)\, e^{jk_z(z-z_0)} dz' + I_g e^{jk_z z_g}}{\int_{z_0+z_{v0}}^{z_0+h_v} \sigma_{vol}(z) dz' + I_g} = \frac{\int_{z_0+z_{v0}}^{z_0+h_v} \sigma_{vol}(z)\, e^{jk_z(z-z_0)} dz' + I_g e^{jk_z z_g}}{I_v + I_g}$$

$$\gamma_z = \frac{\gamma_{vol} + \frac{I_g}{I_v} e^{jk_z z_g}}{1 + \frac{I_g}{I_v}} = e^{jk_z z_g} \frac{\tilde{\gamma}_{vol} + m}{1 + m}$$

With :

$$\gamma_{vol} = \frac{1}{I_v} \int_{z_0+z_{v0}}^{z_0+h_v} \sigma_{vol}(z)\, e^{jk_z(z-z_0)} dz'$$

In-SAR coherence decomposition

<u>Random volume over ground (RVoG)</u>

$$\gamma_z = e^{jk_z z_g} \frac{\tilde{\gamma}_{vol} + m}{1 + m}$$

$$\tilde{\gamma}_{vol} = e^{-jk_z z_g} \gamma_{vol}$$

$$k_z = \frac{k_c B_\perp}{R_1 \sin(\theta_1)}$$

$$k_c = \frac{4\pi f_c}{c}$$

Ground to volume intensity ratio : $m = \frac{I_g}{I_v}$

Observables (2) : γ_z

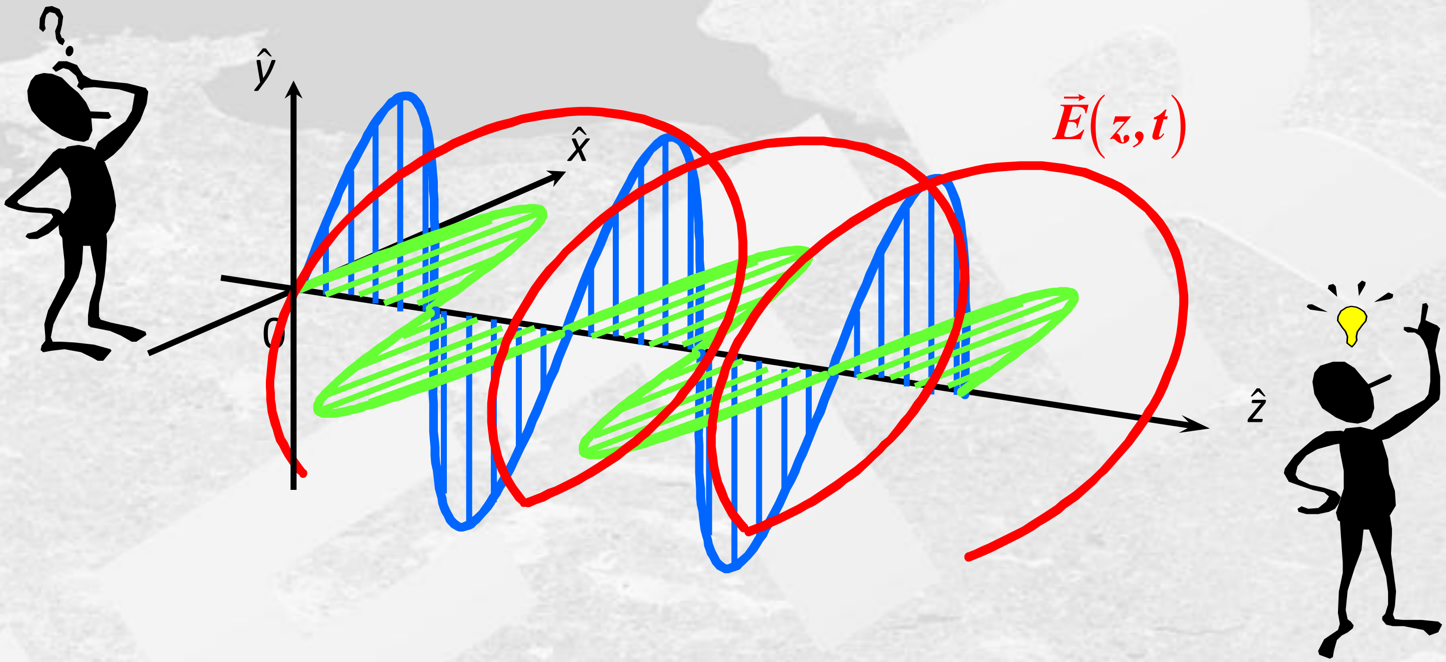
Unknowns (4) : $z_g, m, \gamma_{vol} (2)$

1 In-SAR acquisition vs. Complex RVOG structure : under-determined problem

→ another source of diversity is needed : polarization ?

SAR
+
Polarimetry

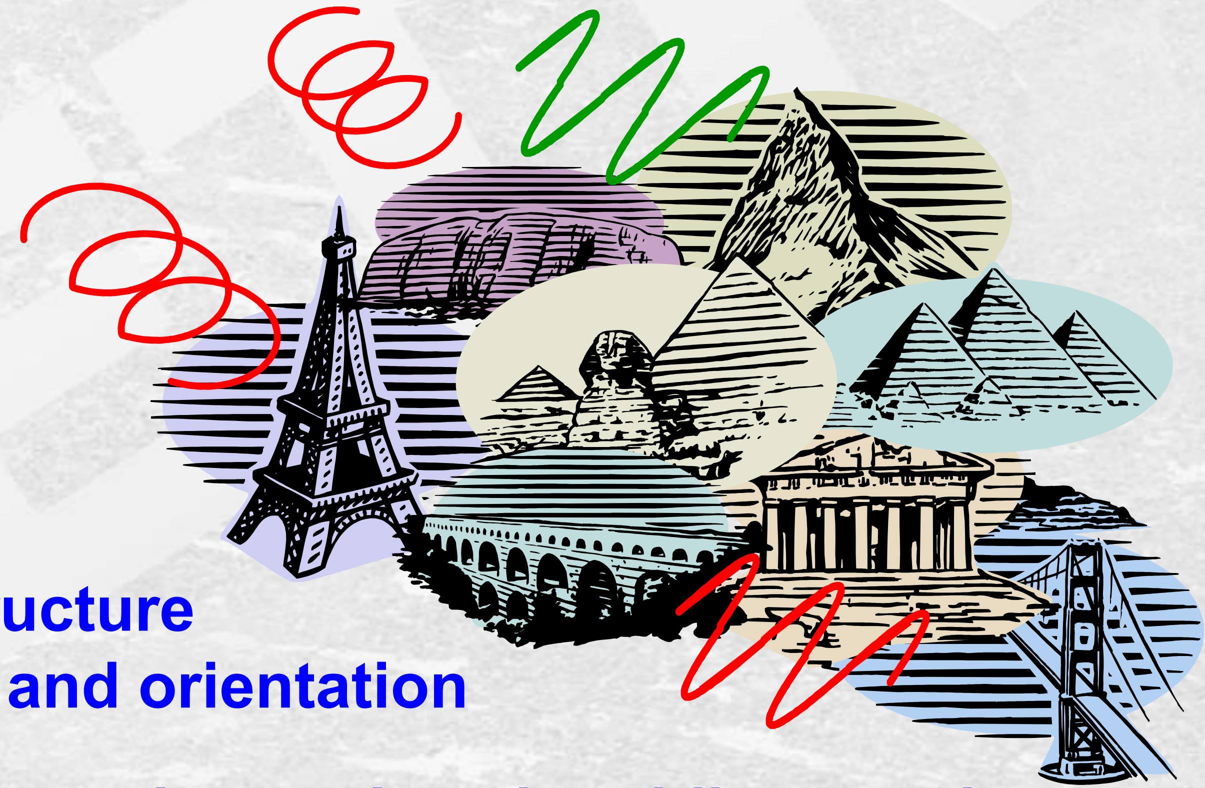
(Pol-SAR)



Radar Polarimetry (Polar : polarisation Metry: measure) is the science of acquiring, processing and analysing the polarization state of an electromagnetic field

Radar Polarimetry deals with the full vector nature of polarized electromagnetic waves

The POLARISATION information Contained in the waves backscattered from a given medium is highly related to:



its geometrical structure reflectivity, shape and orientation

its geophysical properties such as humidity, roughness, …

Radar Polarimetry

Forest Vegetation

- Forest Height
- Forest Biomass
- Forest Structure
- Canopy Extinction
- Underlying Topography

- Forest Ecology
- Forest Management
- Ecosystem Change
- Carbon Cycle

Agriculture

- Soil Moisture Content
- Soil roughness
- Height of Vegetation Layer
- Extinction of Vegetation Layer
- Moisture of Vegetation Layer

- Farming Management
- Water Cycle
- Desretification

Snow and Ice

- Topography
- Penetration Depth / Density
- Snow Ice Layer
- Snow Ice Extinction
- Water Equivalent

- Ecosystem Change
- Water Cycle
- Water Management

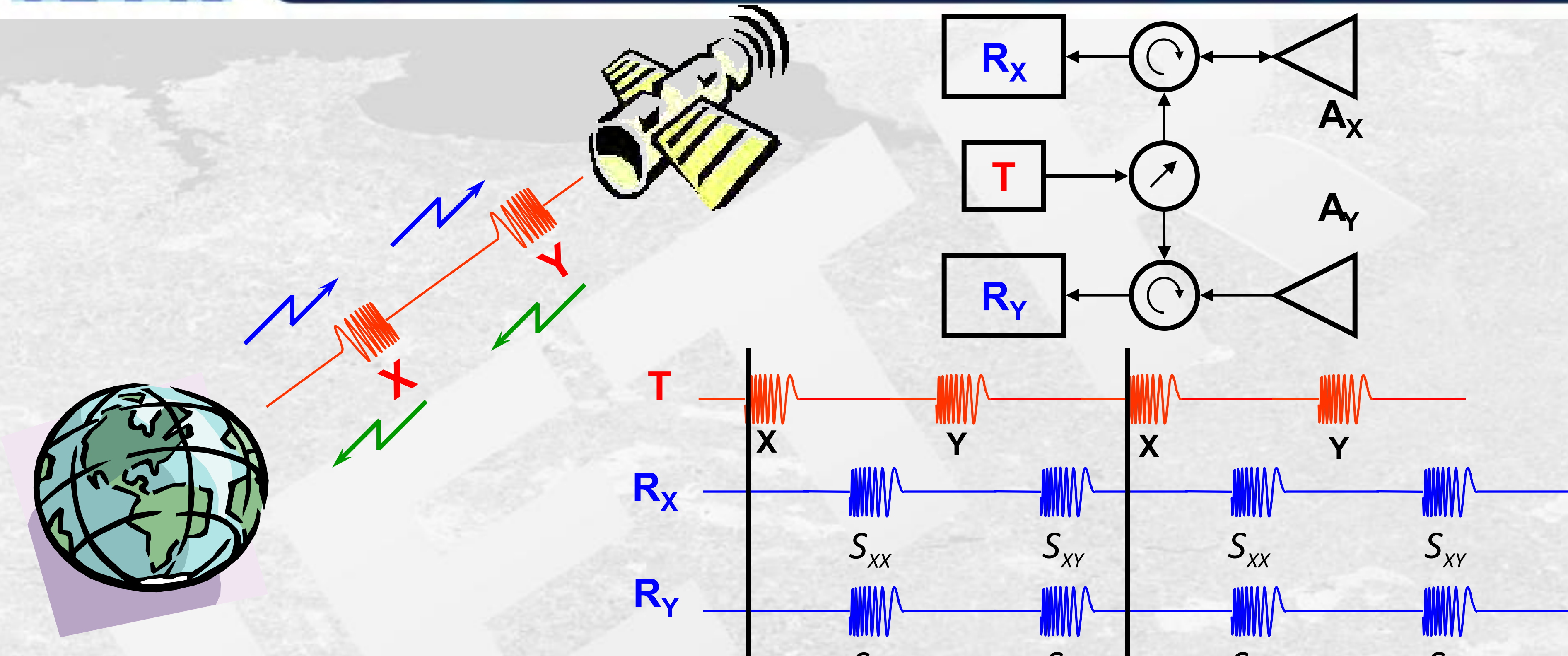
Urban Areas

- Geometric Properties
- Dielectric Properties

- Urban Monitoring

Courtesy of Pr. I. Hajnsek

Scattering Polarimetry

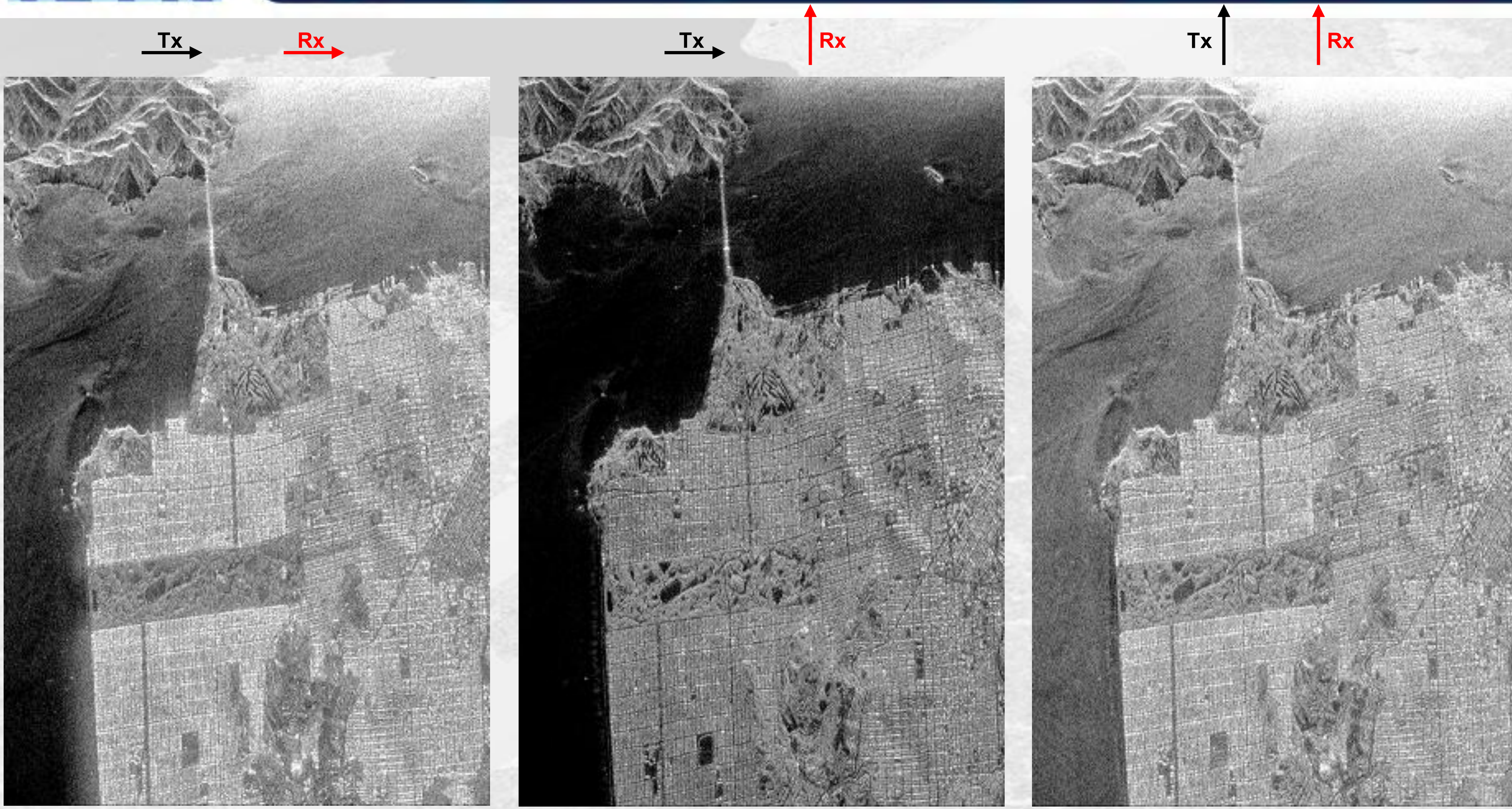


TRANSMITTER: H & V

RECEIVERS: H & V

SINCLAIR MATRICES $\left\{ [S] = \begin{bmatrix} S_{XX} & S_{XY} \\ S_{YX} & S_{YY} \end{bmatrix} \right\}$

Scattering Polarimetry

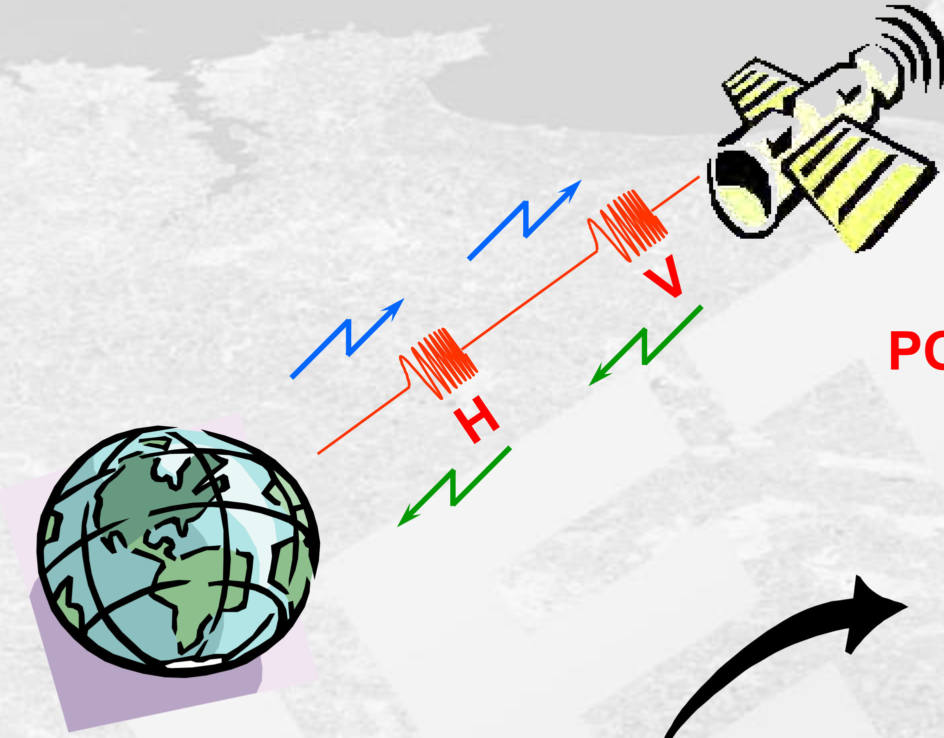


$|HH|_{dB}$ $|HV|_{dB}$ $|VV|_{dB}$

© Google Earth

Sinclair Color Coding

|HH| |HV| |VV|



TRANSMITTER: H & V
RECEIVERS: H & V

POLARIMETRIC DESCRIPTORS

$[S]$ SINCLAIR Matrix

$$[S]=\begin{bmatrix} S_{HH} & S_{HV} \\ S_{VH} & S_{VV} \end{bmatrix}$$

$\underline{k}$ Target Vector

$[T]$ 3x3 COHERENCY Matrix

Coherency Matrix

MONOSTATIC CASE

PAULI SCATTERING VECTOR $\underline{k}$

$$\underline{k} = \frac{1}{\sqrt{2}} \begin{bmatrix} S_{HH} + S_{VV} & S_{HH} - S_{VV} & 2S_{HV} \end{bmatrix}^T$$

↓

COHERENCY MATRIX [*T*]

$$[T] = \underline{k} \cdot \underline{k}^{*T} = \begin{bmatrix} 2A_0 & C - jD & H + jG \\ C + jD & B_0 + B & E + jF \\ H - jG & E - jF & B_0 - B \end{bmatrix}$$

HERMITIAN MATRIX - RANK 1

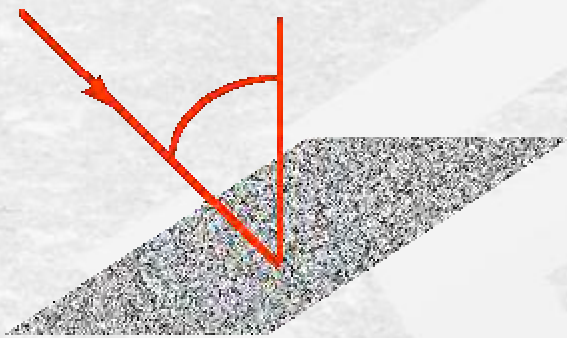
A0, B0+B, B0-B : HUYNEN TARGET GENERATORS

[T]* is closer related to *Physical* and *Geometrical Properties* of the *Scattering Process*, and thus allows a better and direct *physical interpretation

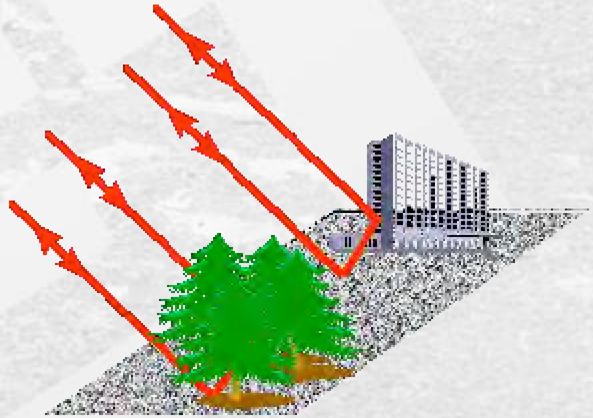
Target Generators

PHYSICAL INTERPRETATION

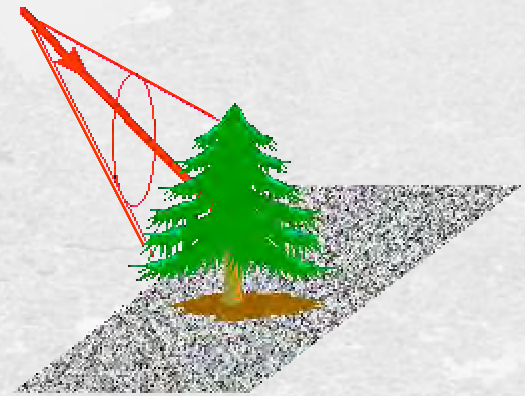
SINGLE BOUNCE SCATTERING
(ROUGH SURFACE)



DOUBLE BOUNCE SCATTERING



VOLUME SCATTERING

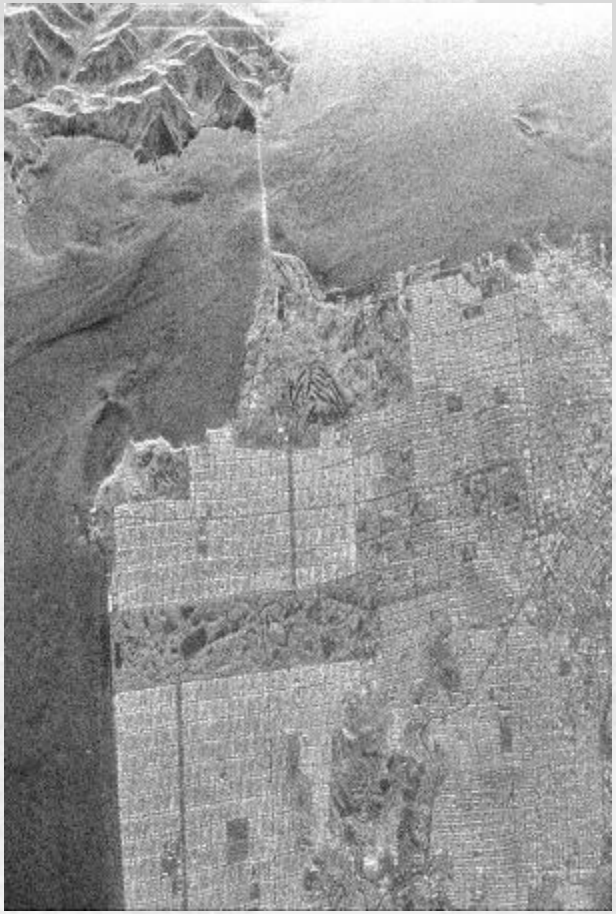


$$T_{11} = 2A_0 = \left|S_{HH} + S_{VV}\right|^2$$

$$T_{33} = B_0 - B = 2\left|S_{HV}\right|^2$$

$$T_{22} = B_0 + B = \left|S_{HH} - S_{VV}\right|^2$$

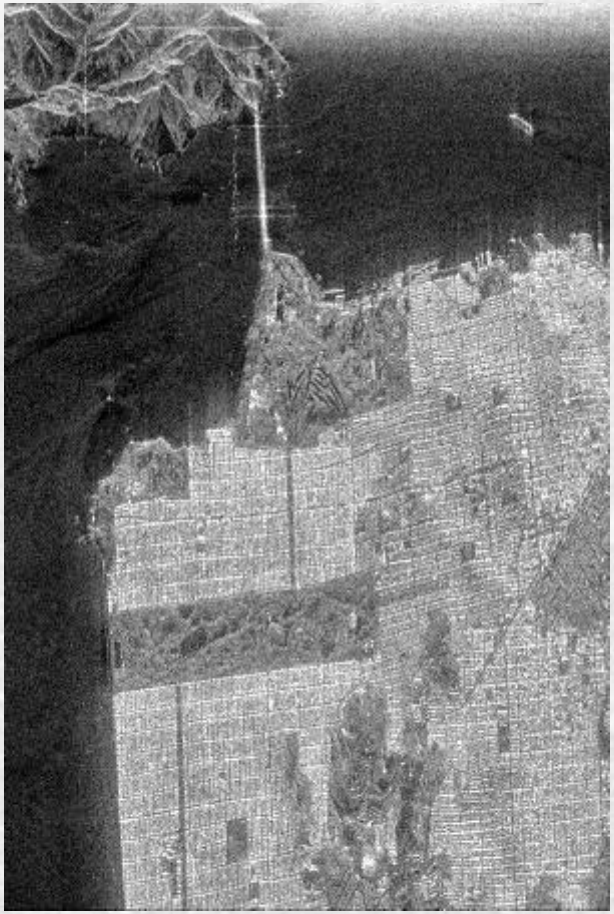
Target Generators



$|HH+VV|_{dB}$

$|HV|_{dB}$

-30dB -15dB 0dB



$|HH-VV|_{dB}$

Target Generators

© Google Earth

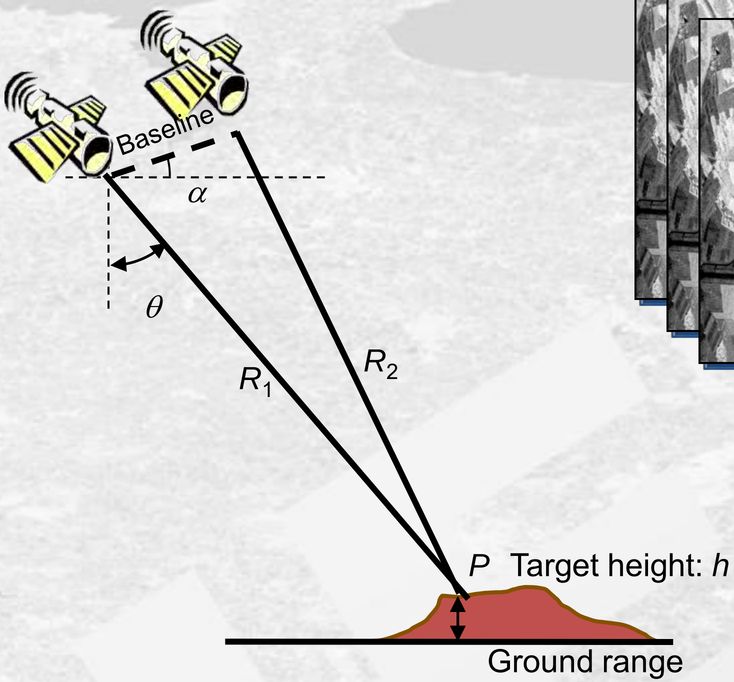
(H,V) POLARISATION BASIS

|HH+VV| |HV | |HH-VV|

PART - 3

SAR
+
Polarimetry
+
Interferometry

(Pol-InSAR)



$$\underline{k}_1 = \frac{1}{\sqrt{2}}\begin{bmatrix} S_{HH_1} + S_{VV_1} \\ S_{HH_1} - S_{VV_1} \\ 2S_{HV_1} \end{bmatrix}$$

$$\underline{\underline{k}} = \begin{bmatrix} \underline{k}_1 \\ \underline{k}_2 \end{bmatrix}$$

POLARIMETRIC INTERFEROMETRIC TARGET VECTOR

$$\underline{k}_2 = \frac{1}{\sqrt{2}}\begin{bmatrix} S_{HH_2} + S_{VV_2} \\ S_{HH_2} - S_{VV_2} \\ 2S_{HV_2} \end{bmatrix}$$

Pol-InSAR

$$\underline{\underline{k}} = \begin{bmatrix} \underline{k}_1 \\ \underline{k}_2 \end{bmatrix}$$

POLARIMETRIC INTERFEROMETRIC TARGET VECTOR

$$\langle [T_6] \rangle = \langle \underline{\underline{k}} \cdot \underline{\underline{k}}^{T*} \rangle = \begin{bmatrix} \langle \underline{k}_1 \cdot \underline{k}_1^{T*} \rangle & \langle \underline{k}_1 \cdot \underline{k}_2^{T*} \rangle \\ \langle \underline{k}_2 \cdot \underline{k}_1^{T*} \rangle & \langle \underline{k}_2 \cdot \underline{k}_2^{T*} \rangle \end{bmatrix} = \begin{bmatrix} \langle [T_1] \rangle & \langle [\Omega_{12}] \rangle \\ \langle [\Omega_{12}]^{T*} \rangle & \langle [T_2] \rangle \end{bmatrix}$$

POLARIMETRIC INTERFEROMETRIC COHERENCY MATRIX (6x6)

$\langle [T_1] \rangle$ HERMITIAN POLARIMETRIC COHERENCY MATRIX (3x3)

$\langle [T_2] \rangle$ HERMITIAN POLARIMETRIC COHERENCY MATRIX (3x3)

$\langle [\Omega_{12}] \rangle$ NON HERMITIAN POLARIMETRIC INTER-COHERENCY MATRIX (3x3)

Pol-InSAR

POLSAR IMAGES $I_1 = \underline{w}_1^{T*} \cdot \underline{k}_1$ and $I_2 = \underline{w}_2^{T*} \cdot \underline{k}_2$

With: $(\underline{w}_1, \underline{w}_2)$ **complex Unitary Vectors**

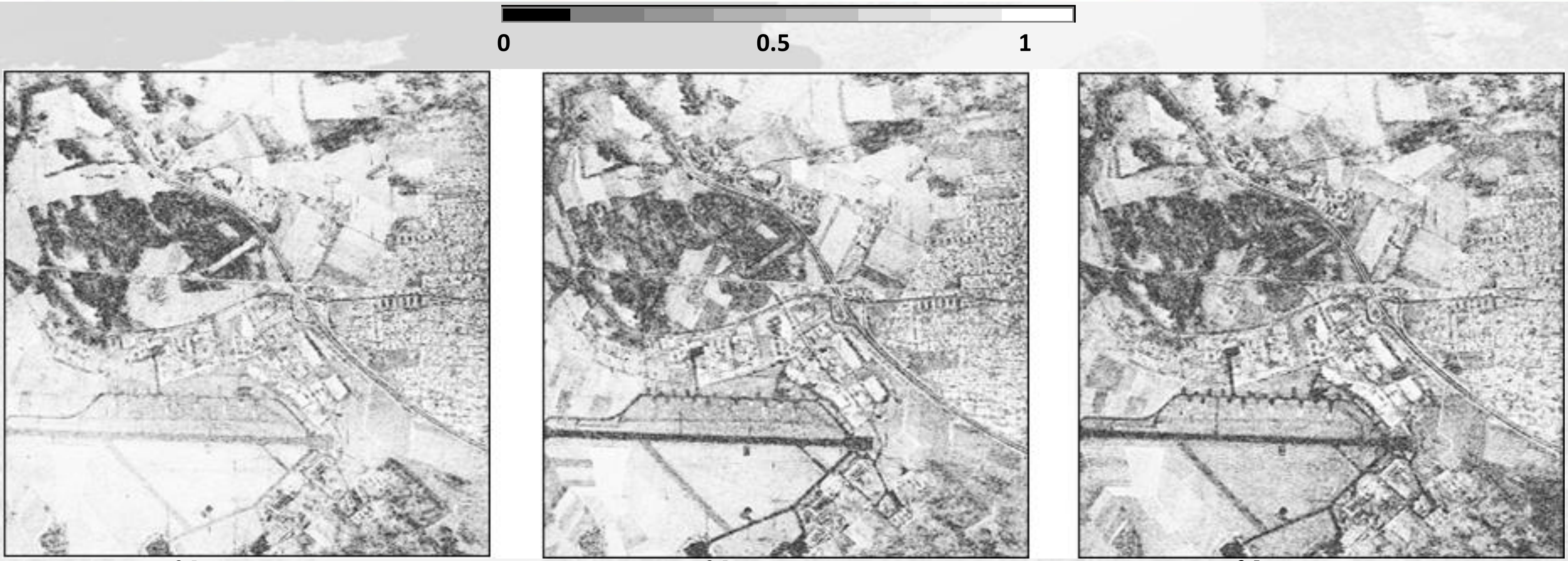
$$\gamma(\underline{w}_1, \underline{w}_2) = \frac{\langle I_1 I_2^* \rangle}{\sqrt{\langle I_1 I_1^* \rangle \langle I_2 I_2^* \rangle}} = \frac{\langle \underline{w}_1 [\Omega_{12}] \underline{w}_2^{T*} \rangle}{\sqrt{\langle \underline{w}_1 [T_1] \underline{w}_1^{T*} \rangle \langle \underline{w}_2 [T_2] \underline{w}_2^{T*} \rangle}}$$

COMPLEX POLARIMETRIC INTERFEROMETRIC COHERENCE

$arg(\gamma)$ **INTERFEROMETRIC PHASE**

$|\gamma|$ **CROSS-CORRELATION COEFFICIENT**

Pol-InSAR

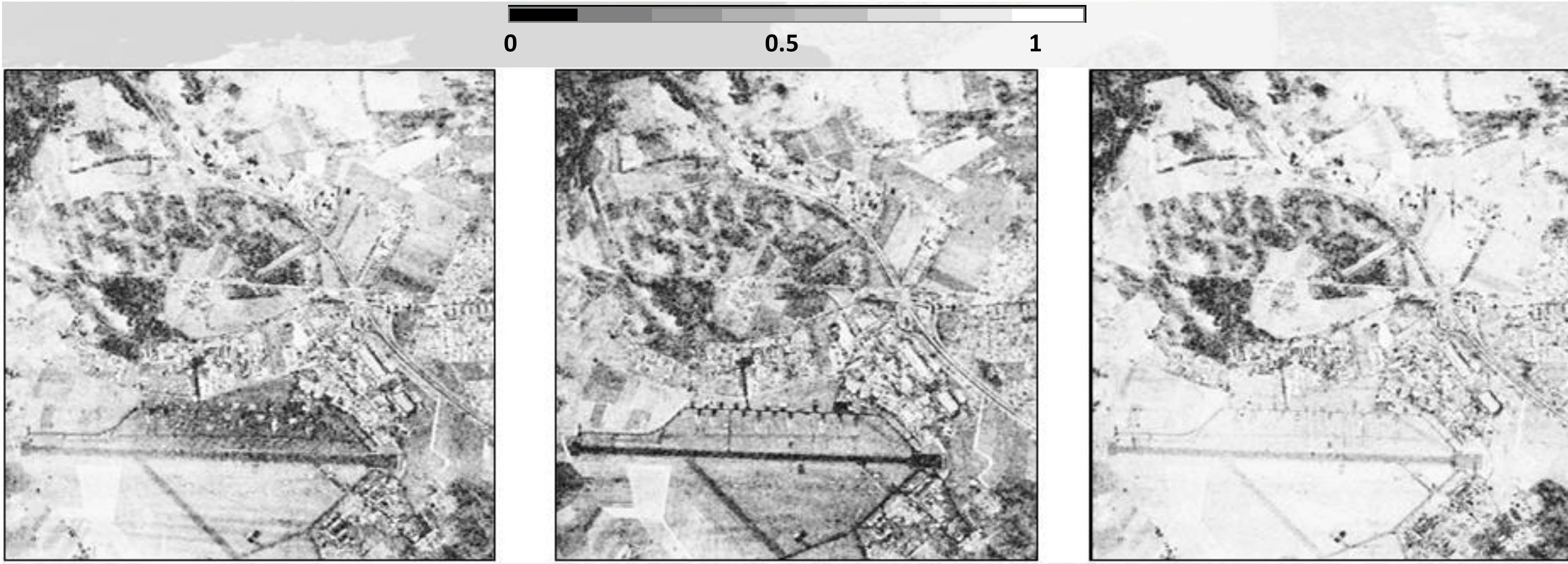


$$\gamma_{HH_1-HH_2} \qquad \gamma_{HV_1-HV_2} \qquad \gamma_{VV_1-VV_2}$$

$$\underline{w}_1 = \underline{w}_2 = \frac{1}{\sqrt{2}}\begin{bmatrix}1\\1\\0\end{bmatrix} \qquad \underline{w}_1 = \underline{w}_2 = \begin{bmatrix}0\\0\\\sqrt{2}\end{bmatrix} \qquad \underline{w}_1 = \underline{w}_2 = \frac{1}{\sqrt{2}}\begin{bmatrix}1\\-1\\0\end{bmatrix}$$

$$\text{if } \underline{w}_1 = \underline{w}_2 \Rightarrow \gamma = \gamma_{INT} \qquad \text{if } \underline{w}_1 \neq \underline{w}_2 \Rightarrow \gamma = \gamma_{INT} \cdot \gamma_{POL}$$

Pol-InSAR Coherence Spectrum



$\gamma_{(HH+VV)_1-(HH+VV)_2}$ ⇓ $\underline{w}_1 = \underline{w}_2 = \frac{1}{\sqrt{2}}\begin{bmatrix}1\\0\\0\end{bmatrix}$

$\gamma_{HV_1-HV_2}$ ⇓ $\underline{w}_1 = \underline{w}_2 = \begin{bmatrix}0\\0\\\sqrt{2}\end{bmatrix}$

$\gamma_{(HH-VV)_1-(HH-VV)_2}$ ⇓ $\underline{w}_1 = \underline{w}_2 = \frac{1}{\sqrt{2}}\begin{bmatrix}0\\1\\0\end{bmatrix}$

$\text{if } \underline{w}_1 = \underline{w}_2 \Rightarrow \gamma = \gamma_{INT} \qquad \text{if } \underline{w}_1 \neq \underline{w}_2 \Rightarrow \gamma = \gamma_{INT} \cdot \gamma_{POL}$

Pol-InSAR Coherence Spectrum

$$\gamma(\underline{w}_1,\underline{w}_2)=\frac{\langle I_1 I_2^*\rangle}{\sqrt{\langle I_1 I_1^*\rangle\langle I_2 I_2^*\rangle}}=\frac{\langle \underline{w}_1[\Omega_{12}]\underline{w}_2^{T*}\rangle}{\sqrt{\langle \underline{w}_1[T_1]\underline{w}_1^{T*}\rangle\langle \underline{w}_2[T_2]\underline{w}_2^{T*}\rangle}}$$

COMPLEX POLARIMETRIC INTERFEROMETRIC COHERENCE

⬇

QUESTION: WHICH POLARISATION COMBINATION LEADS TO THE MAXIMUM POSSIBLE INTERFEROMETRIC COHERENCE ?

⬇

POLARIMETRIC INTERFEROMETRIC COHERENCE OPTIMISATION PROCEDURE

S.R CLOUDE – K. PAPATHANASSIOU (1999)

POLARIMETRIC INTERFEROMETRIC COHERENCE OPTIMISATION PROCEDURE

S.R CLOUDE – K. PAPATHANASSIOU (1999)

$$\gamma(\underline{w}_1,\underline{w}_2)=\frac{\langle I_1 I_2^*\rangle}{\sqrt{\langle I_1 I_1^*\rangle\langle I_2 I_2^*\rangle}}=\frac{\langle \underline{w}_1[\Omega_{12}]\underline{w}_2^{T*}\rangle}{\sqrt{\langle \underline{w}_1[T_1]\underline{w}_1^{T*}\rangle\langle \underline{w}_2[T_2]\underline{w}_2^{T*}\rangle}}$$

Optimum Coherence set (3x3 eigenvector problem) :

$$(\underline{w}_{opt_1},\underline{w}_{opt_2})=\underset{(\underline{w}_1,\underline{w}_2)}{arg\,max}\left(|\gamma(\underline{w}_1,\underline{w}_2)|^2\right)$$

$$\frac{\partial|\gamma(\underline{w}_1,\underline{w}_2)|^2}{\partial\underline{w}_1}=\frac{\partial|\gamma(\underline{w}_1,\underline{w}_2)|^2}{\partial\underline{w}_2}=0$$

POLARIMETRIC INTERFEROMETRIC COHERENCE OPTIMISATION PROCEDURE

S.R CLOUDE – K. PAPATHANASSIOU (1999)

$$\frac{\partial |\gamma(\underline{w}_1,\underline{w}_2)|^2}{\partial \underline{w}_1} = \frac{\partial |\gamma(\underline{w}_1,\underline{w}_2)|^2}{\partial \underline{w}_2} = 0$$

↓

$$[T_1]^{-1}[\Omega_{12}][T_2]^{-1}[\Omega_{12}]^{T*}\underline{w}_{opt_1} = |\gamma_{opt}|^2 \underline{w}_{opt_1}$$

$$[T_2]^{-1}[\Omega_{12}]^{T*}[T_1]^{-1}[\Omega_{12}]\underline{w}_{opt_2} = |\gamma_{opt}|^2 \underline{w}_{opt_2}$$

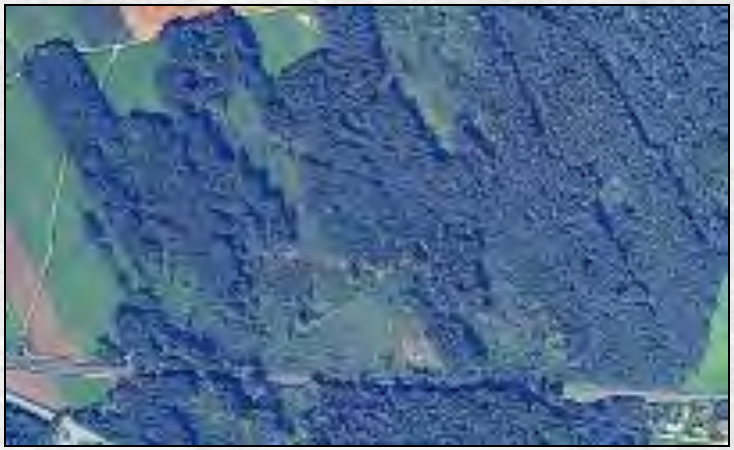
↓

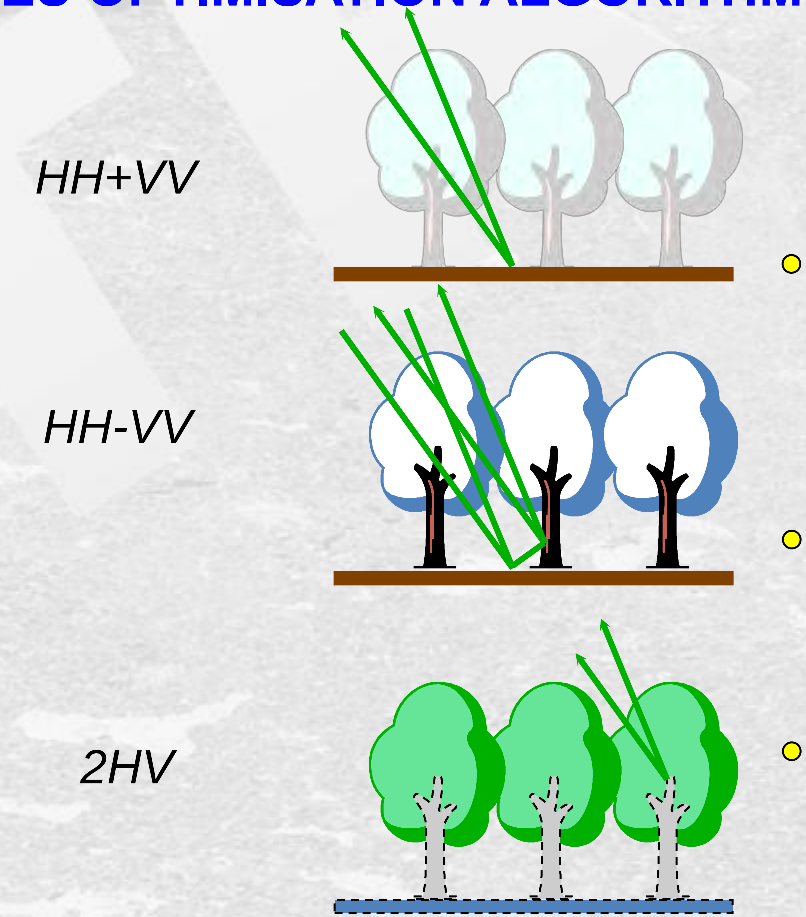
3 Real Eigenvalues (Optimum Coherence Values) : $\gamma_{opt_1} \geq \gamma_{opt_2} \geq \gamma_{opt_3} \geq 0$

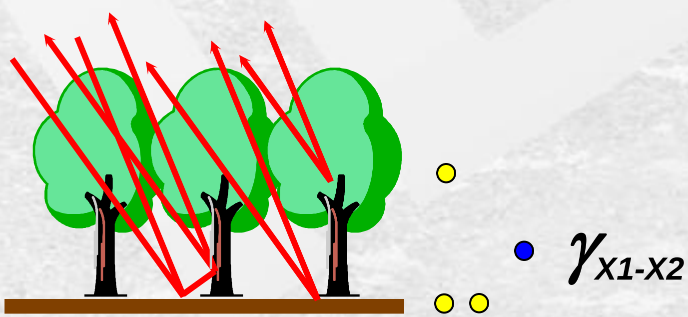
3 Pairs of Eigenvectors (Optimum Scattering Mechanisms) :

$$\{\underline{w}_{opt_{1-1}}, \underline{w}_{opt_{2-1}}\}, \{\underline{w}_{opt_{1-2}}, \underline{w}_{opt_{2-2}}\}, \{\underline{w}_{opt_{1-3}}, \underline{w}_{opt_{2-3}}\}$$

PHYSICAL INTERPRETATION OF POLARIMETRIC INTERFEROMETRIC COHERENCES OPTIMISATION ALGORITHM

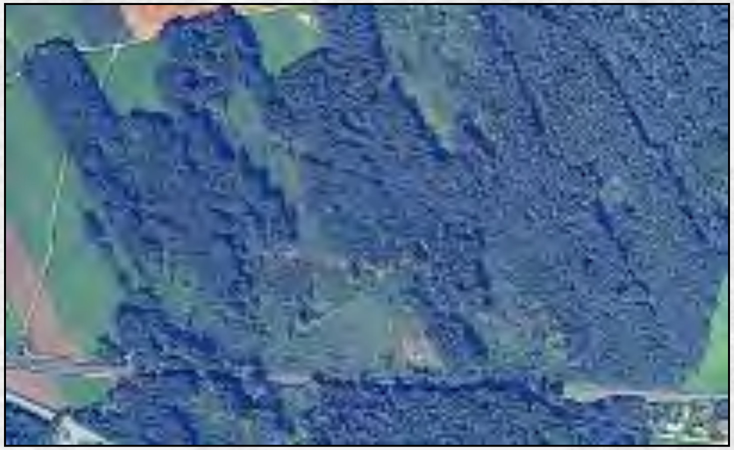


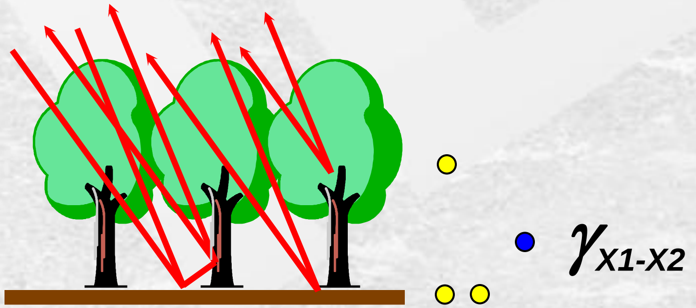


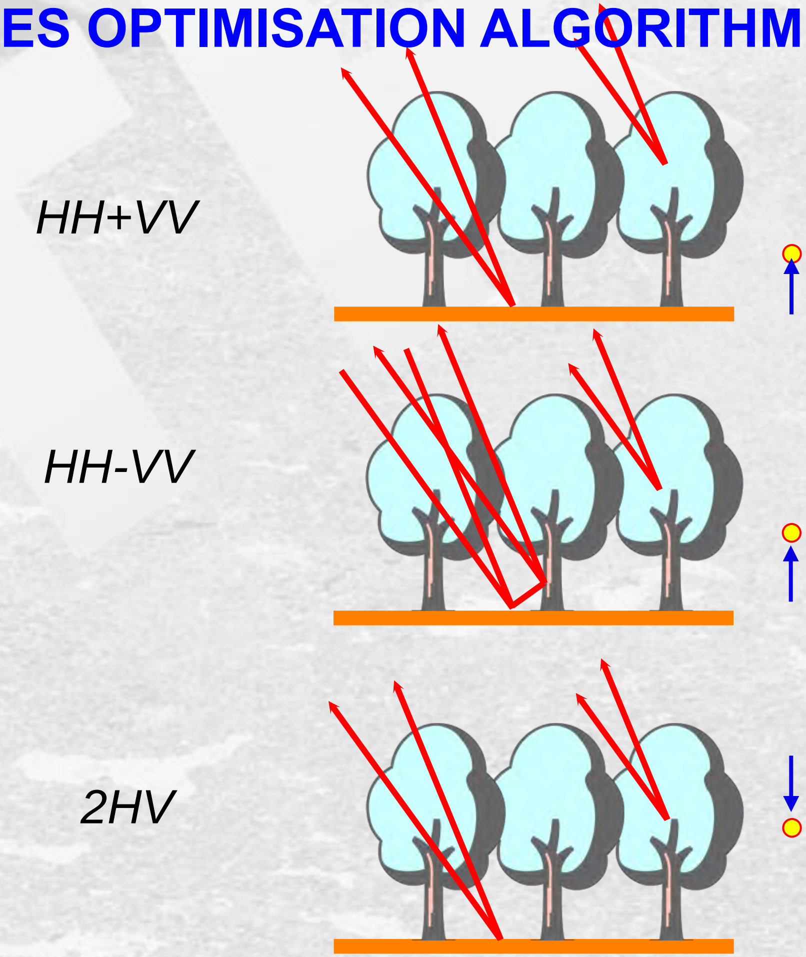


IN A PERFECT WORLD

PHYSICAL INTERPRETATION OF POLARIMETRIC INTERFEROMETRIC COHERENCES OPTIMISATION ALGORITHM

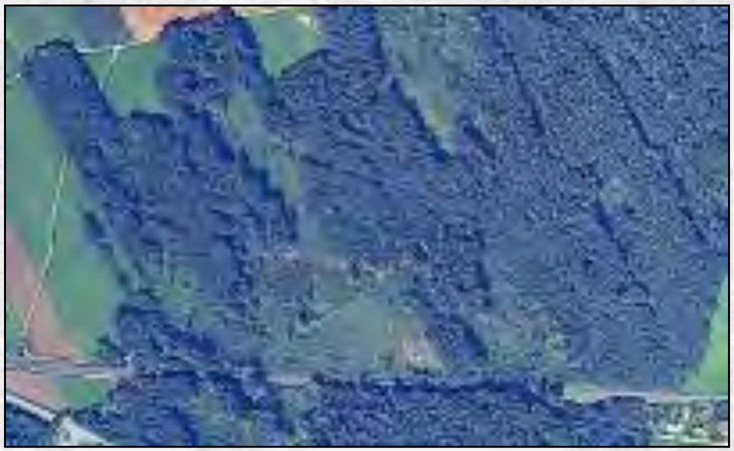






IN A REAL WORLD

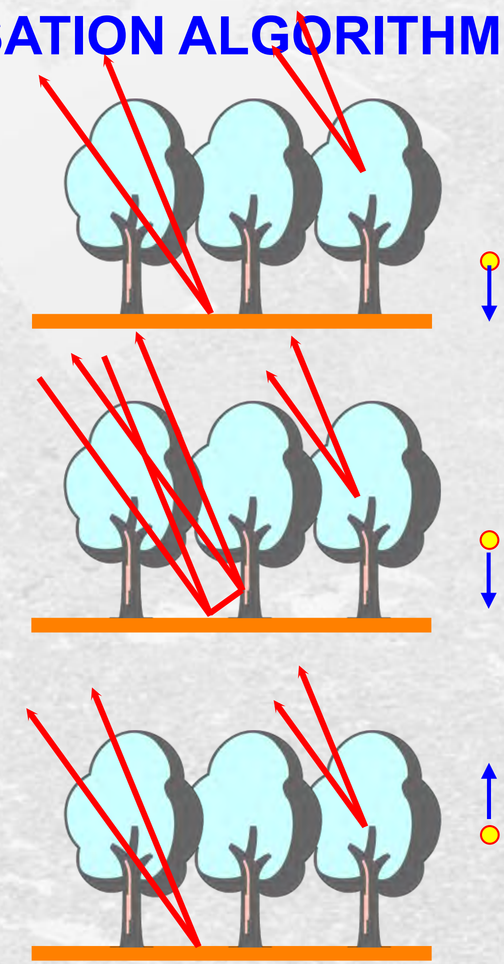
PHYSICAL INTERPRETATION OF POLARIMETRIC INTERFEROMETRIC COHERENCES OPTIMISATION ALGORITHM

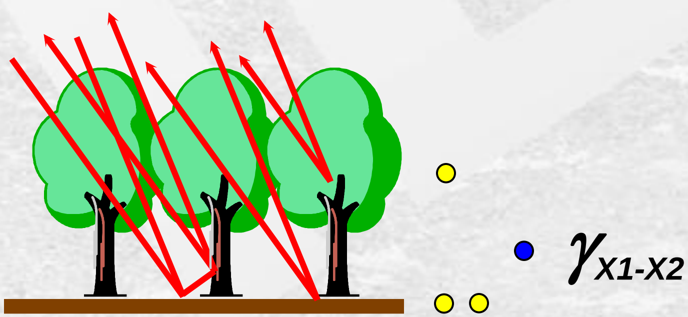


$\{\underline{w}_{11}, \underline{w}_{21}\}$

$\{\underline{w}_{12}, \underline{w}_{22}\}$

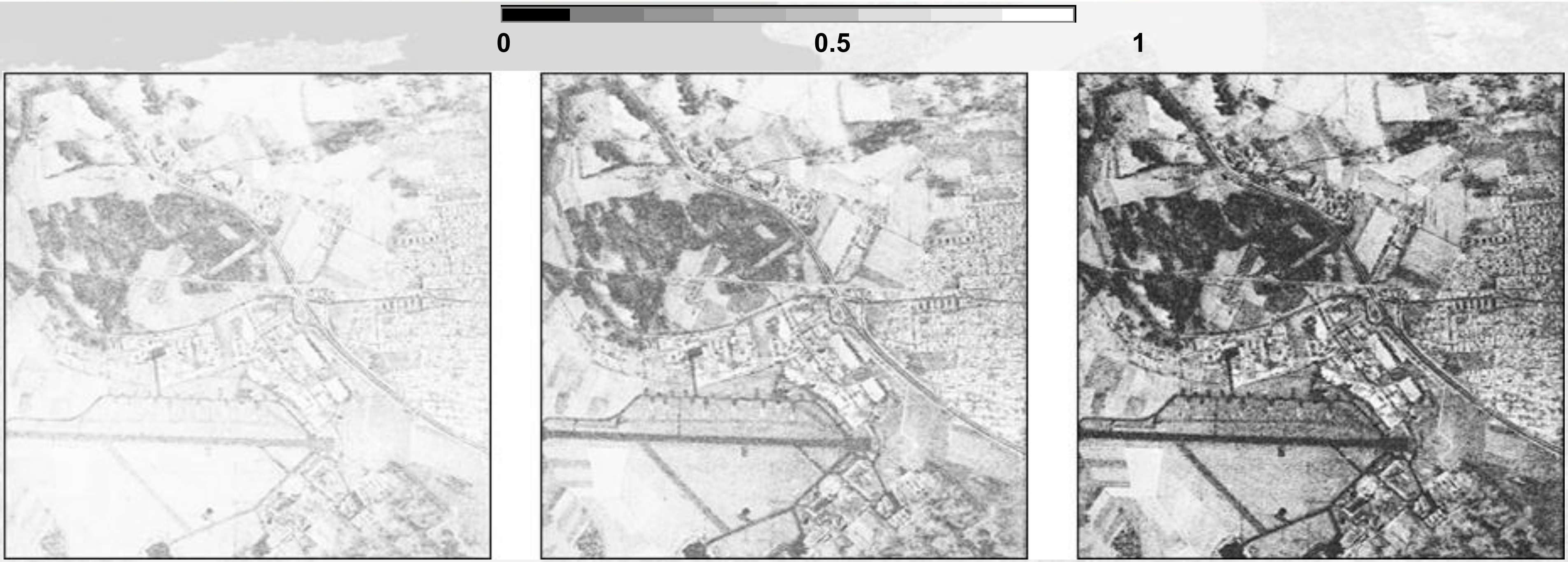
$\{\underline{w}_{13}, \underline{w}_{23}\}$





IN AN OPTIMISED WORLD

Pol-InSAR Coherence Spectrum



$\gamma_{opt\,1}$ → $\{\underline{w}_{11}, \underline{w}_{21}\}$

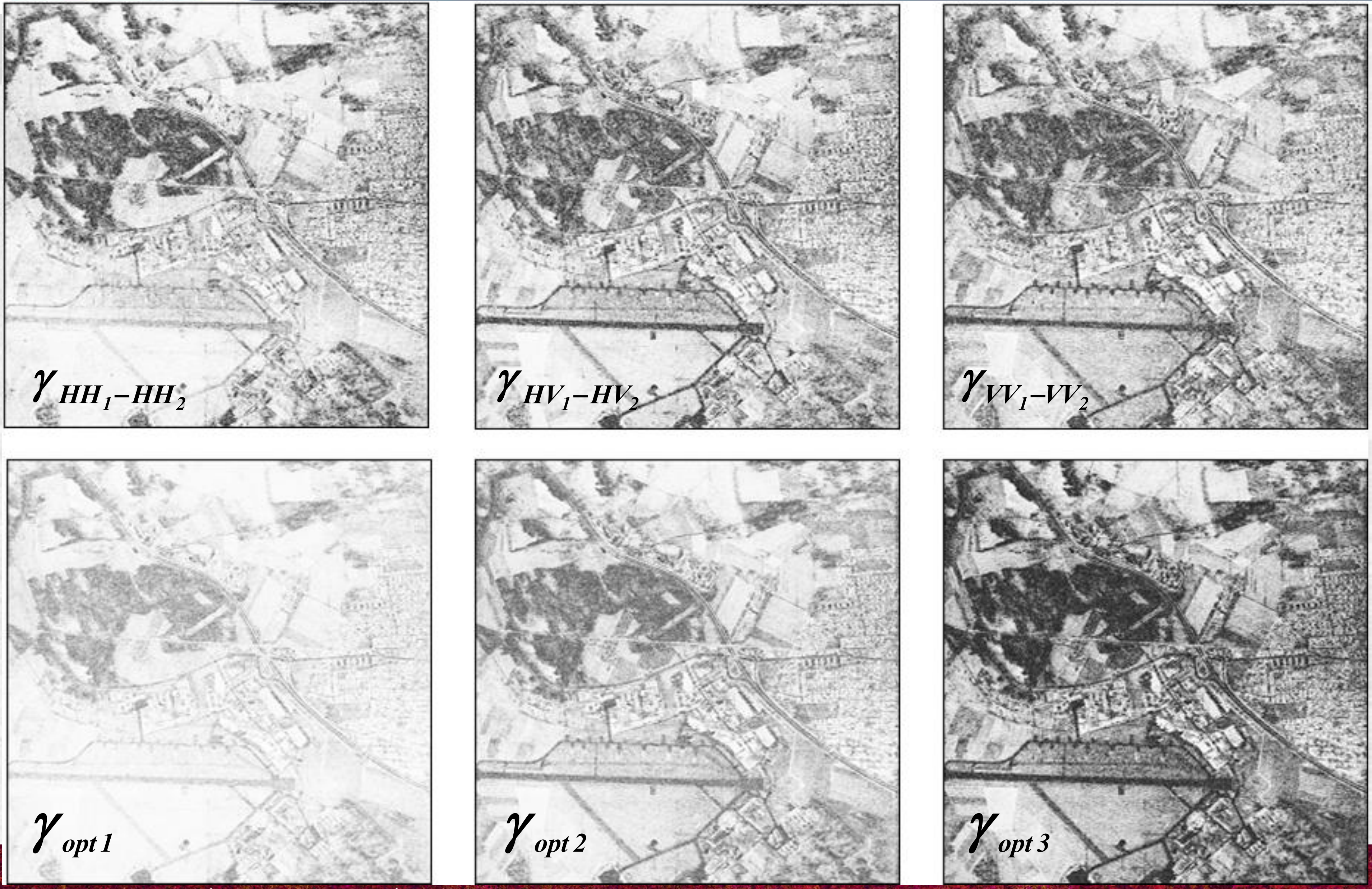
$\gamma_{opt\,2}$ → $\{\underline{w}_{12}, \underline{w}_{22}\}$

$\gamma_{opt\,3}$ → $\{\underline{w}_{13}, \underline{w}_{23}\}$

Optimum coherences spectrum $(\gamma_{opt\,1}, \gamma_{opt\,2}, \gamma_{opt\,3})$

Independent of the radar polarization basis

Pol-InSAR Coherence Spectrum



Forest height estimation

Importance: Key parameter for forest management worldwide

Height as a product itself

- Phase of stand development
- Spatial height distribution (risk assessment, diversity)
- Management with esthetical protection goals
- Change of topography by forests (water runoff, skidding, roads)

Height as an input parameter

- Wood volume / forest biomass
- Site Index (with age and species information)

Height and density determine the microclimate and ecological processes within the forest

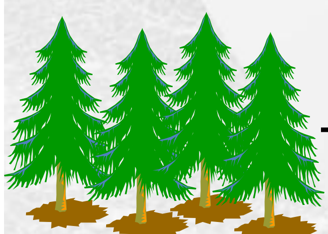
Height is dependent on and therefore reflects the site conditions

Courtesy of DLR

Forest height estimation

Which Height does POLinSAR measure ? H100 (forest standard)

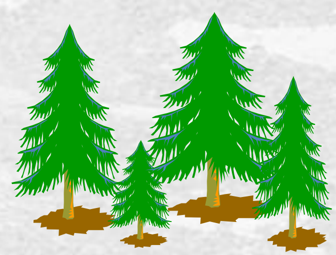
- Most characteristic height in a forest
- Formed by the crown of the trees exposed to the sun light
- Typically concentrate most of the forest biomass
- Simple to measure: it is the intuitive forest height, measurement of few representative tree heights
- Sufficient for a good estimation



Forest Stand Type I

Homogeneous stands

Typical for managed forests



Forest Stand Type II

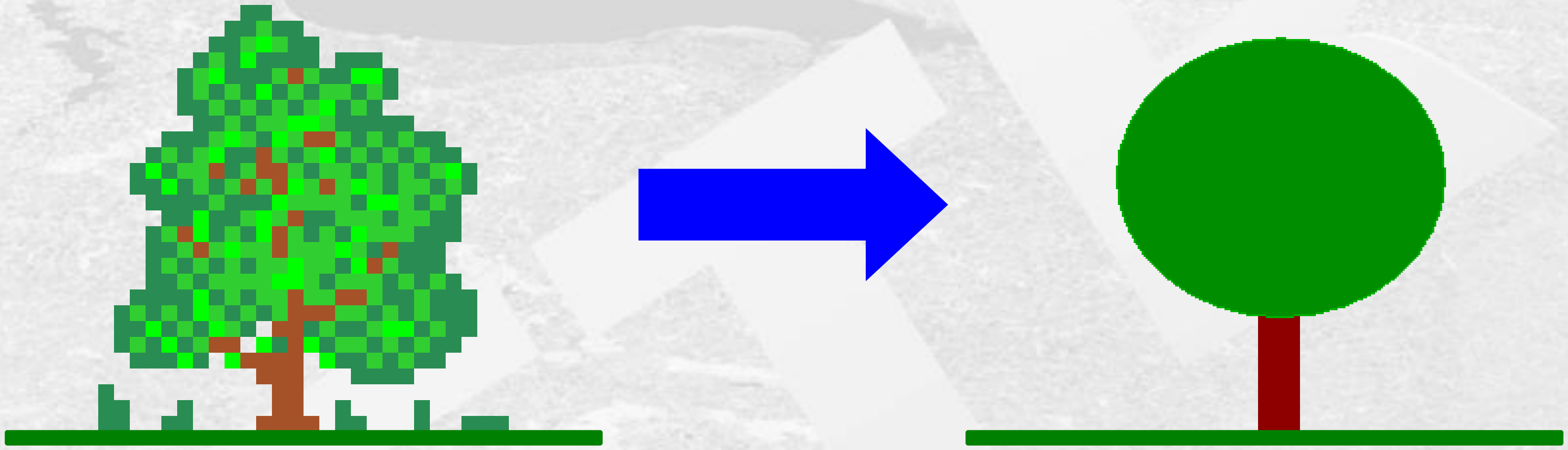
Very heterogeneously structured stands

Large height variations on short distance

Typical for natural uneven-aged forest

Courtesy of DLR

MODELING AND PARAMETER ESTIMATION



Modeling

Establishment of scattering model [M]

$$\begin{bmatrix} \textit{Radar} \\ \textit{Observables} \end{bmatrix} = [M] \begin{bmatrix} \textit{Scatterer} \\ \textit{Parameters} \end{bmatrix}$$

Parameter Estimation

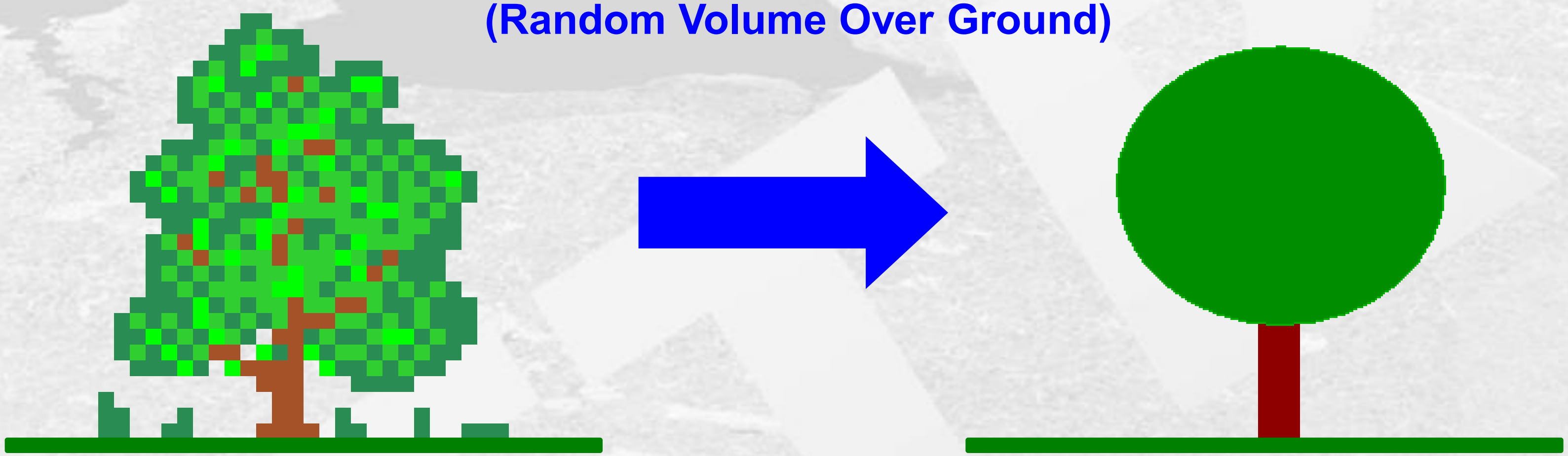
Inversion of the scattering model [M]

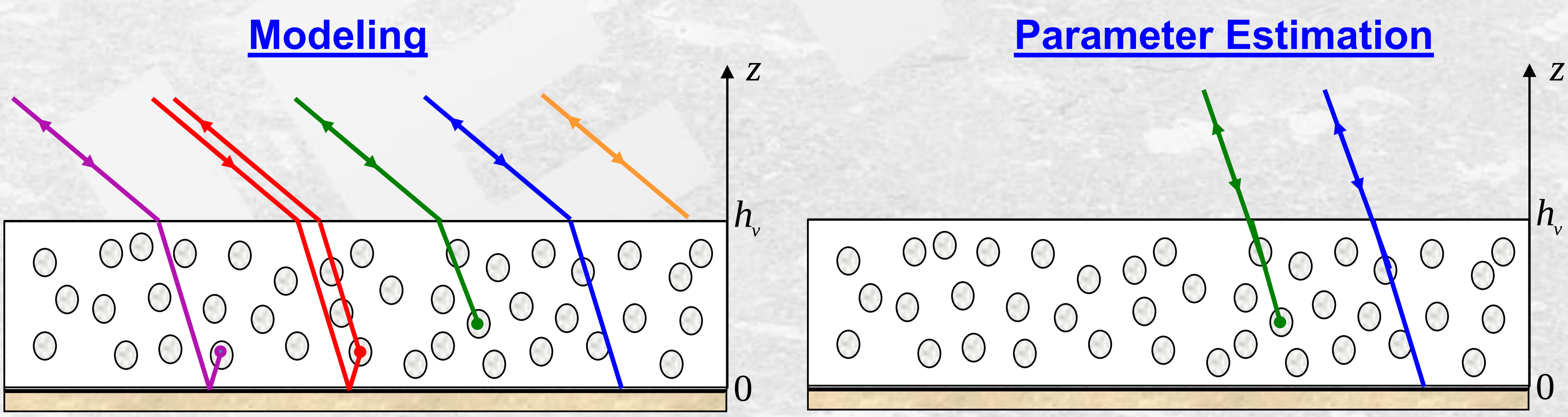
$$\begin{bmatrix} \textit{Scatterer} \\ \textit{Parameters} \end{bmatrix} = [M]^{-1} \begin{bmatrix} \textit{Radar} \\ \textit{Observables} \end{bmatrix}$$

Requirements on [M]: 1. Correctness in Interpretation and prediction of the observables
2. Simplicity in terms of parameters in order to be determined

Forest height estimation

RVOG COHERENCE MODEL
(Random Volume Over Ground)





Simplifications : Only 2 significant mechanisms Low density medium ⇨ No refraction

Interferometric coherence γ : decorrelation sources

γ **fixed by a set of external sources :**

System :

- **Thermal or system noise : SAR amplifiers, ADC, antennas …**
- **Quantization noise**
- **Geometric decorrelation : Baseline, squint …**
- **Azimuth : Doppler decorrelation …**
- **Ambiguities …**
- **Processing errors : coregistration, interpolation …**

Environment :

- **Random media : Surface & Volumetric media e.g. forest …**
- **Temporal variations : wind, flowing or plowing, building …**

$$\gamma = \gamma_{SNR} \cdot \gamma_{quant} \cdot \gamma_{amb} \cdot \gamma_{geo} \cdot \gamma_{az} \cdot \gamma_{proc} \cdot \gamma_{surf} \cdot \gamma_{vol} \cdot \gamma_{temp}$$

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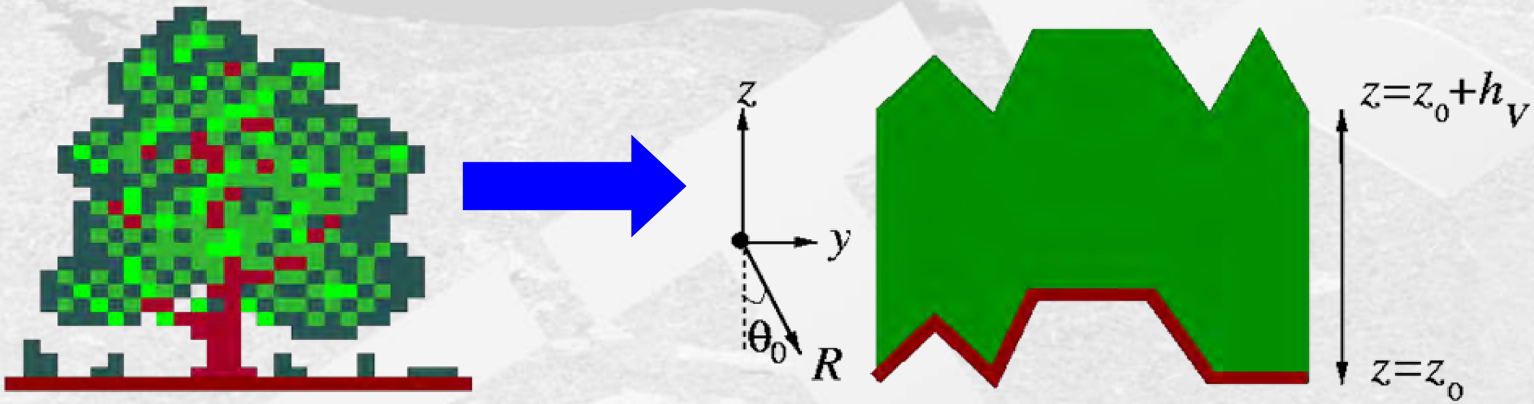


2 Layer Combined Surface and random Volume Scattering

$$\gamma_z(\underline{w}) = e^{j\phi_0} \frac{\tilde{\gamma}_{vol} + m(\underline{w})}{1 + m(\underline{w})}$$

$$m(\underline{w}) = \frac{\text{Surface Scattering Contribution}}{\text{Volume Scattering Contribution}}$$ **G / V ratio**

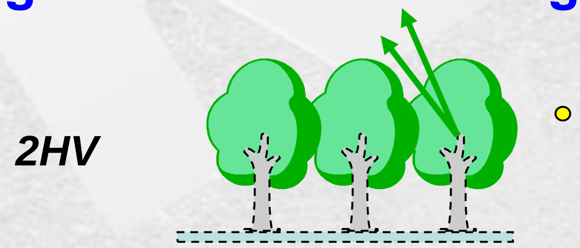
B. Treuhaft (2000), S.R. Cloude (2003)

POLARIZATION DEPENDENT

Forest height estimation

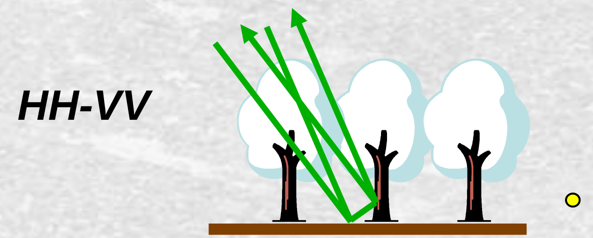
$\underline{w}_v$ **Polarisation Channel corresponding to Volume Scattering**

$$\gamma_z(\underline{w}_v) \underset{m \mapsto 0}{\longmapsto} = e^{j\phi_0}\tilde{\gamma}_{vol}$$



$\underline{w}_s$ **Polarisation Channel corresponding to Surface Scattering**

$$\gamma_z(\underline{w}_s) = e^{j\phi_0}\frac{\tilde{\gamma}_{vol} + m(\underline{w})}{1 + m(\underline{w})} \underset{m \mapsto \infty}{\longmapsto} e^{j\phi_0}$$



Forest height estimation

$$\left.\begin{aligned}\gamma_z(\underline{w}_v) &= e^{j\phi_0}\tilde{\gamma}_{vol}\\ \gamma_z(\underline{w}_s) &= e^{j\phi_0}\frac{\tilde{\gamma}_{vol}+m(\underline{w})}{1+m(\underline{w})}\end{aligned}\right\} \mapsto \begin{bmatrix}\phi_0\\ h_v\\ \kappa_e\\ m\end{bmatrix} = [Model]^{-1}\begin{bmatrix}\gamma_z(\underline{w}_v)\\ \gamma_z(\underline{w}_s)\end{bmatrix}$$

4 Parameters → 4 Observables → INVERSION

DEM Differencing Algorithm

$$\left.\begin{array}{l}\gamma_z(\underline{w}_v) = e^{j\phi_0}\,\tilde{\gamma}_{vol} \\ \gamma_z(\underline{w}_s) \mapsto e^{j\phi_0}\end{array}\right\} \quad \mapsto \quad \gamma_z(\underline{w}_v) = \gamma_z(\underline{w}_s)\,\tilde{\gamma}_{vol} \approx \gamma_z(\underline{w}_s)\,\alpha\, e^{jk_z h_v}$$

$$h_v \approx \frac{arg[\gamma_z(\underline{w}_v)] - arg[\gamma_z(\underline{w}_s)]}{k_z}$$

Coherence Amplitude Inversion Procedure

Assumption : Only volume scattering is present

$$\gamma_z(\underline{w}_v) = e^{j\phi_0}\tilde{\gamma}_{vol} \quad \mapsto \quad |\gamma_z(\underline{w}_v)| = |\tilde{\gamma}_{vol}|$$

$$\arg\min_d \left\| \, |\gamma_z(\underline{w}_v)| - \left| \frac{p}{p_1}\left(\frac{e^{p_1 d}-1}{e^{pd}-1}\right)\right| \, \right\|$$

1-D search procedure with Look-Up-Table (LUT)

Forest height estimation

Topographic Phase Estimation

$$\left.\begin{aligned}\gamma_z(\underline{w}_v) &= e^{j\phi_0}\tilde{\gamma}_{vol}\\ \gamma_z(\underline{w}_s) &= e^{j\phi_0}\frac{\tilde{\gamma}_{vol}+m(\underline{w})}{1+m(\underline{w})}\end{aligned}\right\} \mapsto \quad e^{j\phi_0} = \frac{\gamma_z(\underline{w}_s)-\gamma_z(\underline{w}_v)(1-L)}{L}$$

With : $L = \dfrac{m(\underline{w}_s)}{1+m(\underline{w}_s)}$

$$\hat{\phi}_0 = arg\left[\gamma_z(\underline{w}_s)-\gamma_z(\underline{w}_v)(1-L)\right]$$

Forest height estimation

Estimation of L :

$$e^{j\phi_0} = \frac{\gamma_z(\underline{w}_s) - \gamma_z(\underline{w}_v)(1-L)}{L}$$

$$\left|\frac{\gamma_z(\underline{w}_s) - \gamma_z(\underline{w}_v)(1-L)}{L}\right|^2 = 1 \quad \Rightarrow \quad AL^2 + BL + C = 0$$

With : $A = \left|\gamma_z(\underline{w}_v)\right|^2 - 1 \qquad B = 2\Re\left\{\left(\gamma_z(\underline{w}_s) - \gamma_z(\underline{w}_v)\right)\gamma_z^*(\underline{w}_s)\right\}$

$$C = \left|\gamma_z(\underline{w}_s) - \gamma_z(\underline{w}_v)\right|^2$$

$$L = \frac{-B - \sqrt{B^2 - 4AC}}{2A}$$

Topographic Phase Estimation

$$\left\{\gamma_z(\underline{w}_s), \gamma_z(\underline{w}_v)\right\} \Rightarrow \begin{aligned} A &= \left|\gamma_z(\underline{w}_v)\right|^2 - 1 \\ B &= 2\Re\left\{\left(\gamma_z(\underline{w}_s) - \gamma_z(\underline{w}_v)\right)\gamma_z^*(\underline{w}_s)\right\} \\ C &= \left|\gamma_z(\underline{w}_s) - \gamma_z(\underline{w}_v)\right|^2 \end{aligned}$$

$$\Downarrow$$

$$L = \frac{-B - \sqrt{B^2 - 4AC}}{2A}$$

$$\Downarrow$$

$$\hat{\phi}_0 = arg\left[\gamma_z(\underline{w}_s) - \gamma_z(\underline{w}_v)(1 - L)\right]$$

Forest height estimation

Random Vegetation Over Ground (RVoG) inversion procedure

$$\underset{d,\kappa_e}{\arg\min} \left\| \gamma_z(\underline{w}_v) - e^{j\hat{\phi}_0} \frac{p}{p_1} \left(\frac{e^{p_1 d} - 1}{e^{pd} - 1} \right) \right\|$$

Expensive 2-D search procedure

$$d \approx \frac{\arg[\gamma_z(\underline{w}_v)] - \hat{\phi}_0}{k_z} + \varepsilon \frac{2\,\mathrm{sinc}^{-1}\left(|\gamma_z(\underline{w}_v)| \right)}{k_z}$$

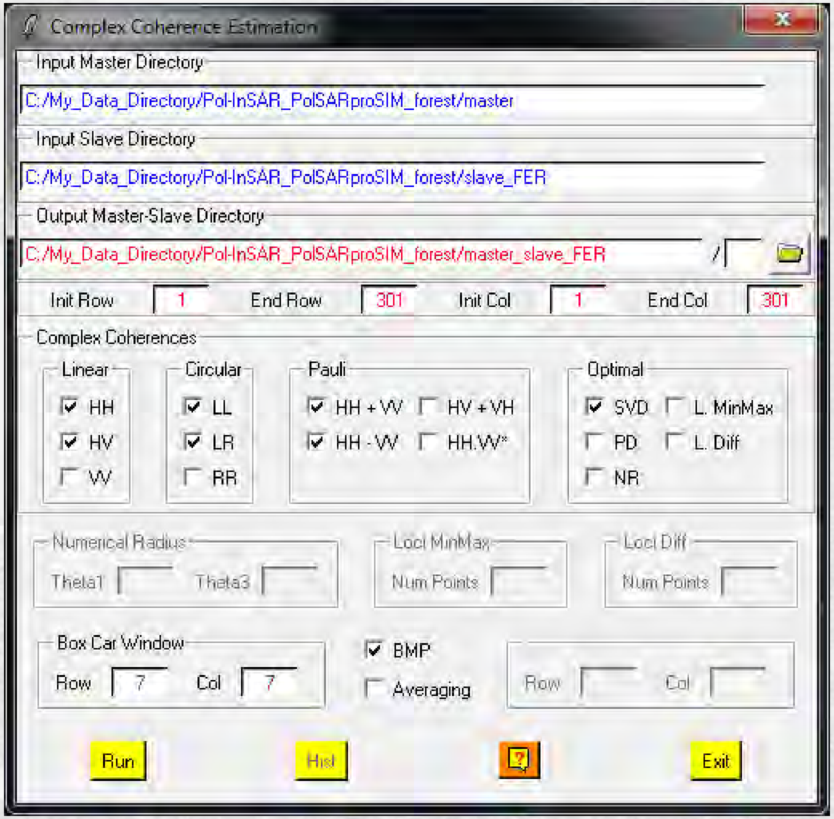
$0.3 \leq \varepsilon \leq 0.5$

Suitable Compromise

DEM Differencing Inversion

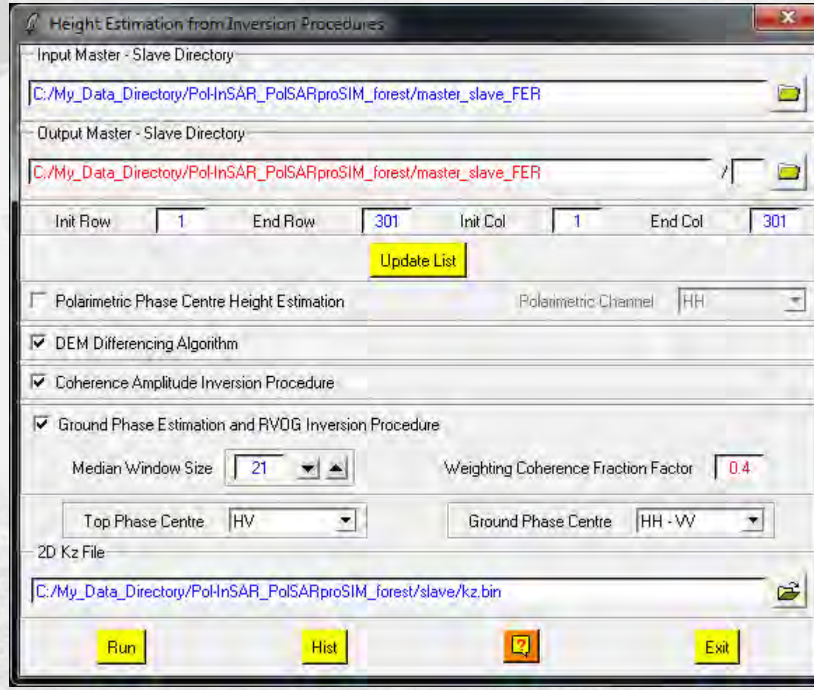
Coherence Amplitude Inversion

PolSARpro - practicals



Complex Coherence Estimation

PolSARpro - practicals



Height estimation
Inversion procedures

Questions ?