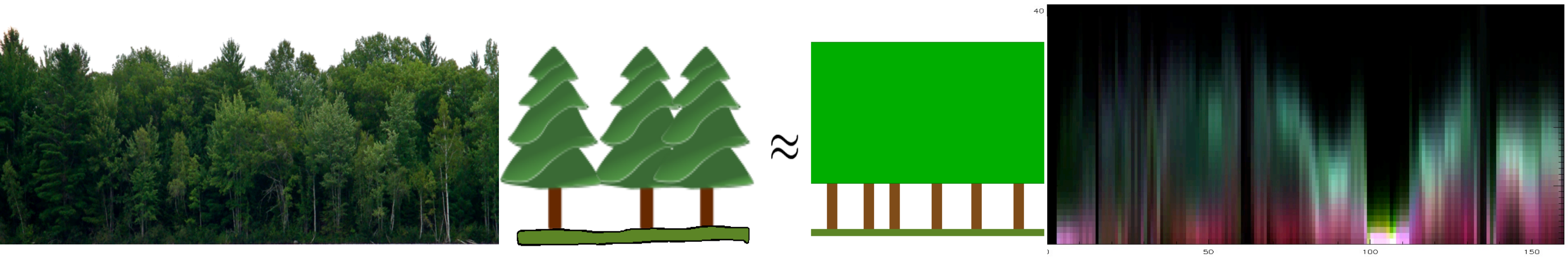
Forest Structure Characterization using UAVSAR PolInSAR and Tomography



Maxim Neumann

UAVSAR Team: Scott Hensley, Marco Lavalle, Razi Ahmed, Thierry Michel, Ron Muellerschoen, . . .

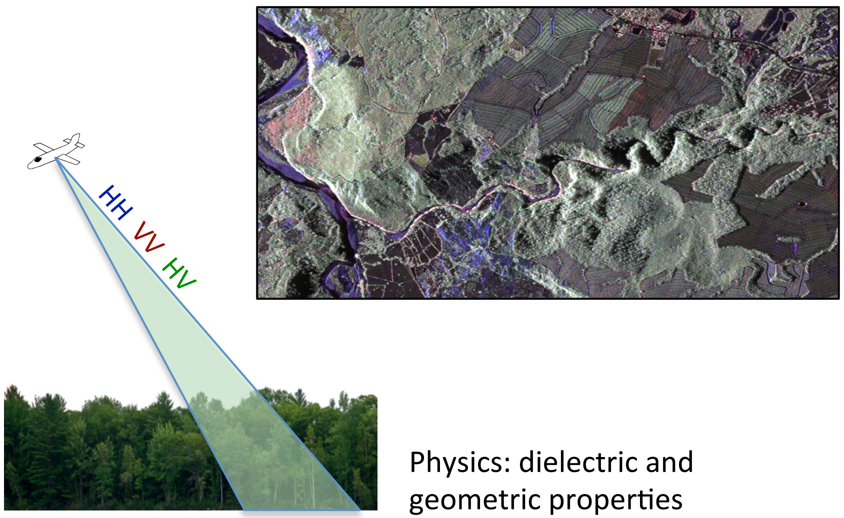
Jet Propulsion Laboratory, California Institue of Technology

UAVSAR Workshop

03/27/2012 – Pasadena

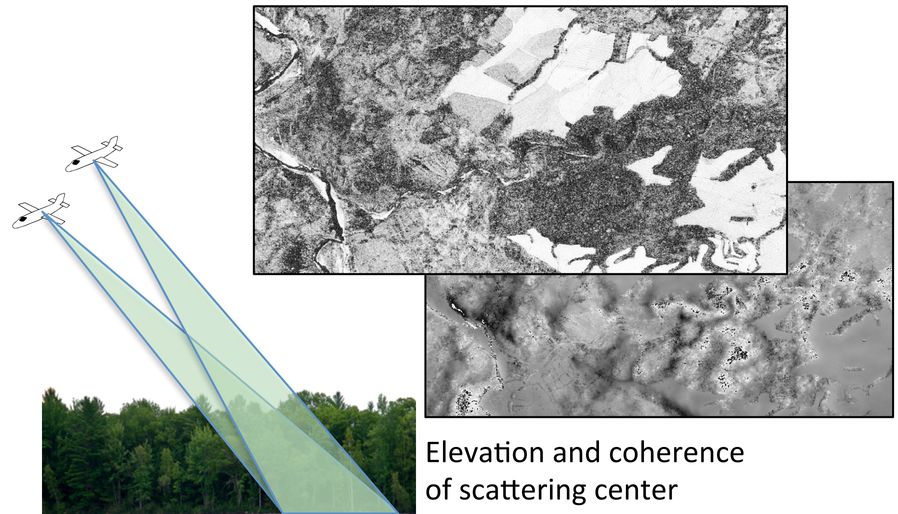
Basic Principles

Polarimetry



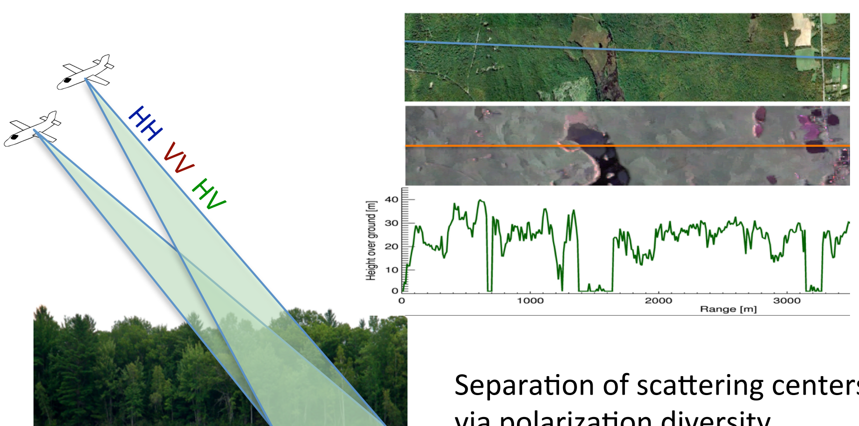
Physics: dielectric and
geometric properties

Interferometry



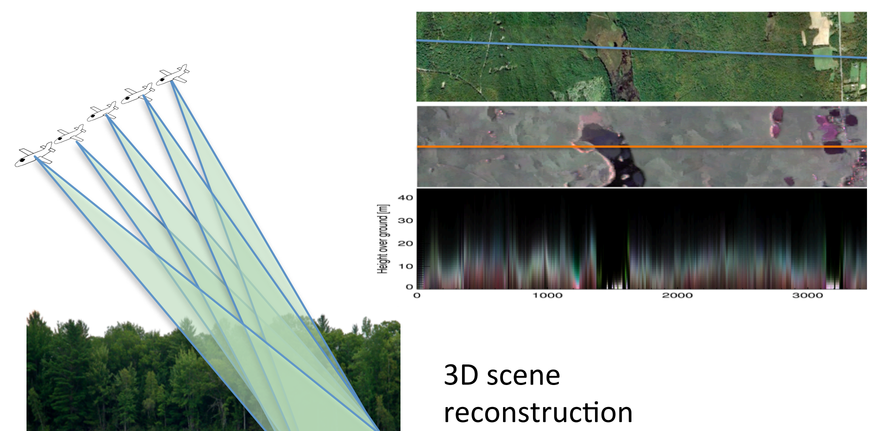
Elevation and coherence
of scattering center
Volumetric and temporal properties

Polarimetric Interferometry



Separation of scattering centers
via polarization diversity

Tomography



3D scene
reconstruction

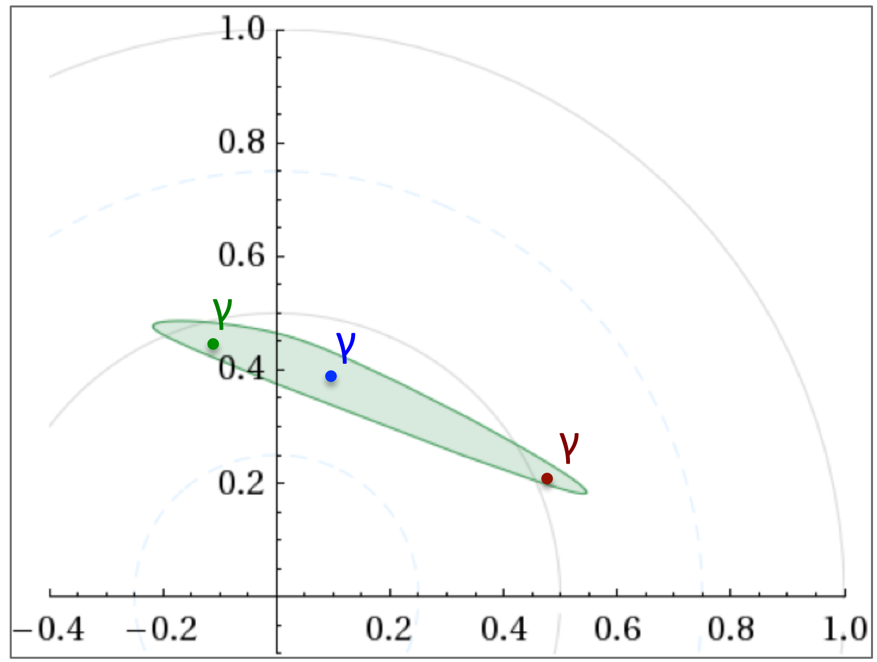
PolInSAR Intro

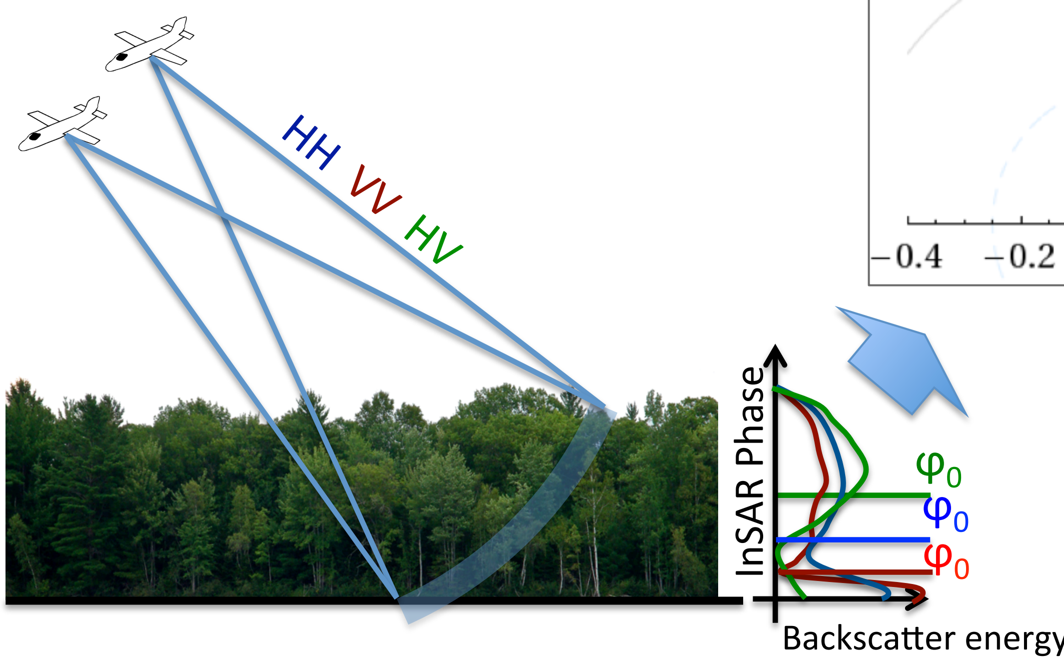
Polarimetric SAR Interferometry

$$\mathbf{T}_6 = \left\langle \boldsymbol{k}\boldsymbol{k}^{\dagger} \right\rangle = \begin{bmatrix} \mathbf{T}_{11} & \boldsymbol{\Omega}_{12} \\ \boldsymbol{\Omega}_{12}^{\dagger} & \mathbf{T}_{22} \end{bmatrix} \qquad \boldsymbol{k}_i = \begin{bmatrix} HH_i \\ HV_i \\ VV_i \end{bmatrix}$$

$$\boldsymbol{k} = \begin{bmatrix} \boldsymbol{k}_1 \\ \boldsymbol{k}_2 \end{bmatrix}, \quad \gamma_{12(\boldsymbol{\omega})} = \frac{\boldsymbol{\omega}^{\dagger}\boldsymbol{\Omega}_{12}\boldsymbol{\omega}}{\sqrt{\boldsymbol{\omega}^{\dagger}\mathbf{T}_{11}\boldsymbol{\omega}\boldsymbol{\omega}^{\dagger}\mathbf{T}_{22}\boldsymbol{\omega}}}$$

Coherence Unitary Circle (CUC)

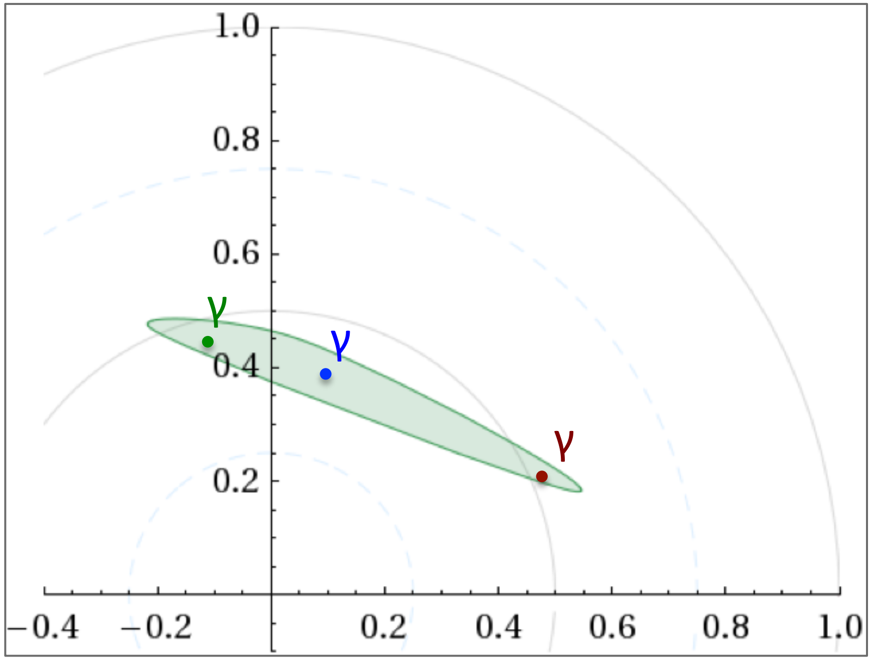


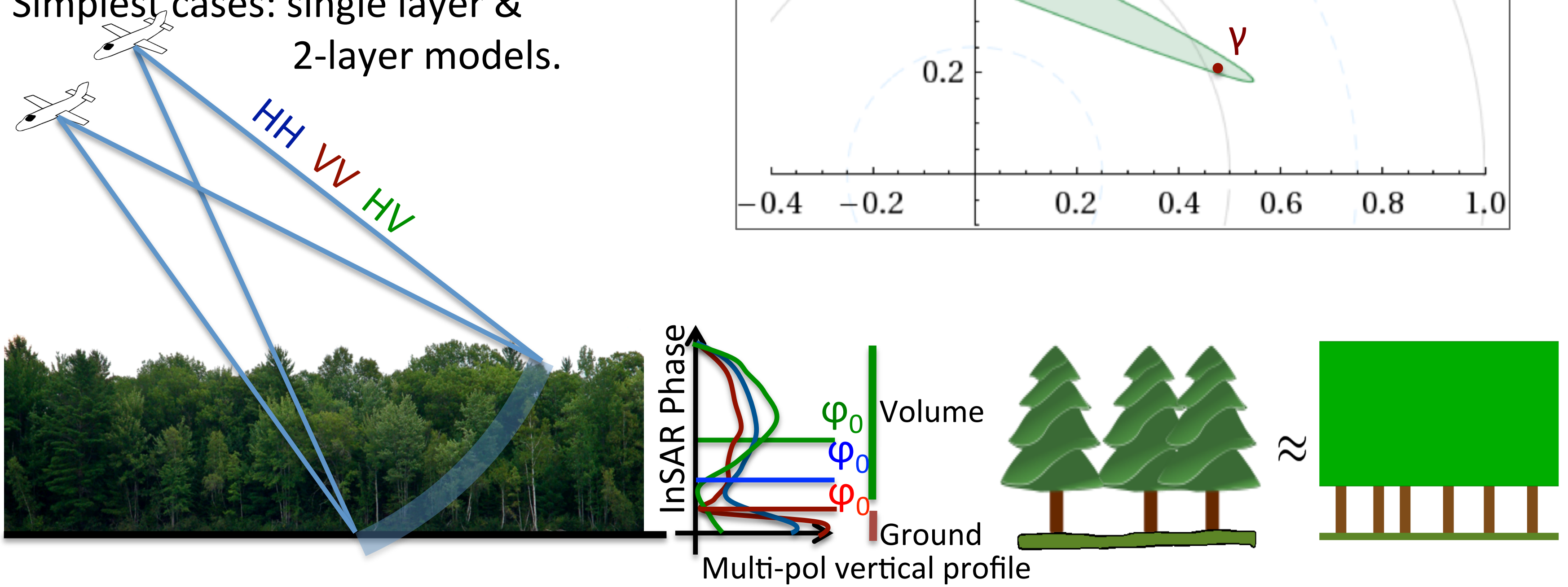


PolInSAR Vegetation Model

- Multi-layer model: $\mathbf{T} = \sum \mathbf{T}_i$
- Possible layer separation due to
  - vertical structure
  - temporal behavior
  - polarimetric characteristics
- Every medium can be characterized with $i \to \infty$ → unpractical!
- Simplest cases: single layer & 2-layer models.

Coherence Unitary Circle (CUC)





2-Layer PolInSAR Vegetation Model

Assumptions:

- Ground and volume components not correlated
- Polarimetric stationarity
- No refraction effects and no differential extinction
- Volume and ground components homogeneous

Model: Ground + Volume Layers

$$\mathbf{T}_6 = \begin{bmatrix} \mathbf{T} & \mathbf{\Omega} \\ \mathbf{\Omega}^\dagger & \mathbf{T} \end{bmatrix} \begin{cases} \mathbf{T} = \mathbf{T}_g + \mathbf{T}_v \\ \mathbf{\Omega} = \gamma_g \mathbf{T}_g + \gamma_v \mathbf{T}_v \end{cases}$$

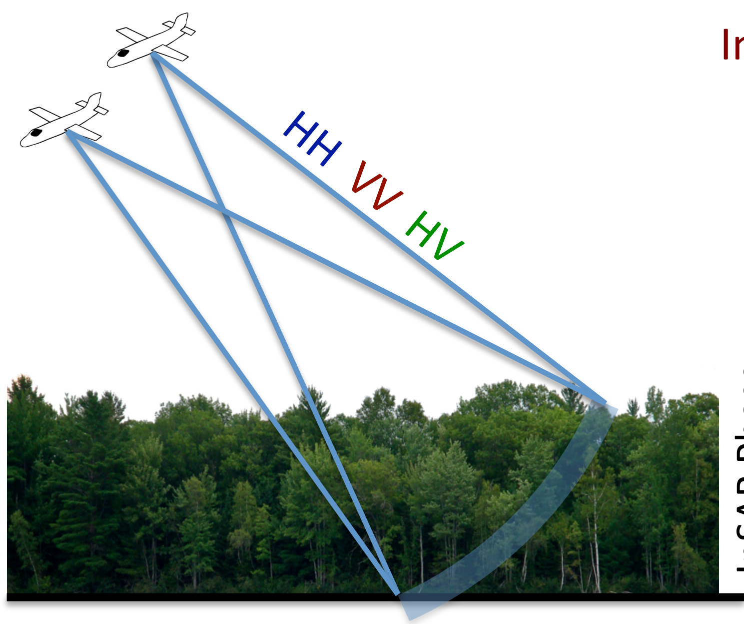
$$= \mathbf{R}_g \otimes \mathbf{T}_g + \mathbf{R}_v \otimes \mathbf{T}_v \text{ with } \mathbf{R}_{g/v} = \begin{bmatrix} 1 & \gamma_{g/v} \\ \gamma^*_{g/v} & 1 \end{bmatrix}$$

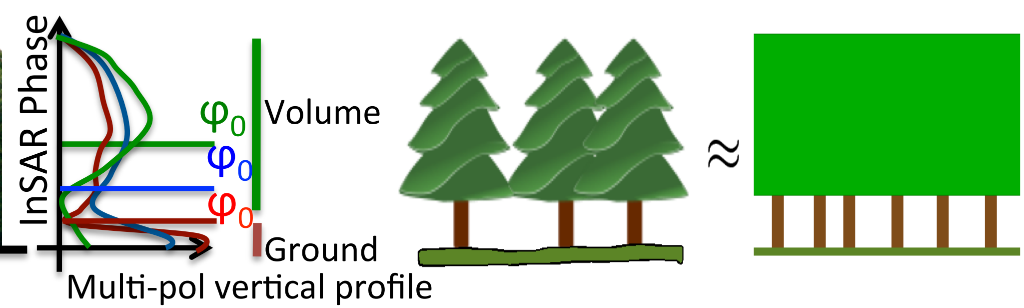
T_g/T_v: ground and volume PolSAR cov matrices
γ_g/γ_v: ground and volume InSAR coherences

Interferometric coherence model

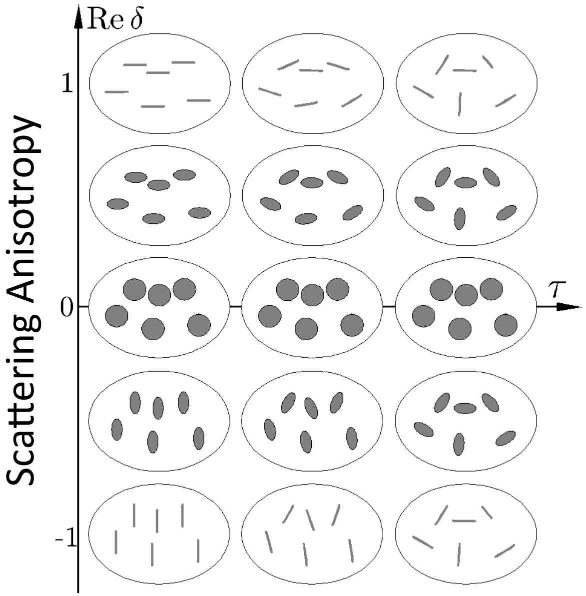
$$\gamma \approx \gamma_{sys}\gamma_{geom}\gamma_z\gamma_{temp}$$

$$\gamma_z = e^{i\phi_0}\int f_0(z)e^{ik_z z}dz, \quad f_0(z) = \frac{e^{\frac{2\sigma}{\cos\theta_0}z}}{\int e^{\frac{2\sigma}{\cos\theta_0}z'}dz'}$$





Polarimetric Homogeneous Medium Model



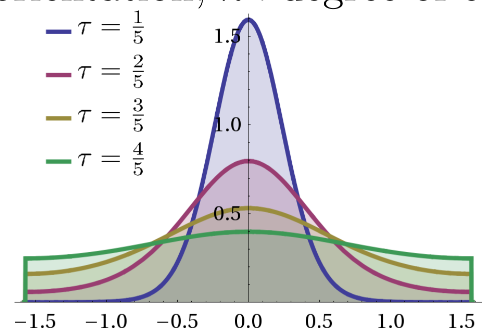
Orientation Randomness

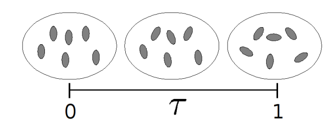
Orientation Randomness

Circular normal distribution of orientation angles:

$$p(\psi|\widetilde{\psi},\kappa_\psi) = \frac{e^{\kappa_\psi \cos(2(\psi-\widetilde{\psi}))}}{\pi I_0(\kappa_\psi)} \qquad \tau = \frac{\int p(\psi-\widetilde{\psi})d\psi}{\pi \max p(\psi)} = I_0(\kappa)e^{-\kappa}$$

$\widetilde{\psi}$: main orientation, κ : degree of concentration





General formulation:

$$\mathbf{T} = \mathbf{R}_{T(2\widetilde{\psi})} \begin{bmatrix} 1 & g_c\delta^* & 0 \\ g_c\delta & \frac{(1+g)}{2}|\delta|^2 & 0 \\ 0 & 0 & \frac{(1-g)}{2}|\delta|^2 \end{bmatrix} \mathbf{R}^{\mathrm{T}}_{T(2\widetilde{\psi})}$$

$\mathbf{R}_{T(2\widetilde{\psi})}$: Rotation to main orientation

$$g = \frac{I_2(\kappa)}{I_0(\kappa)},\quad g_c = \frac{I_1(\kappa)}{I_0(\kappa)},\quad \tau = I_0(\kappa)e^{-\kappa}$$

* assumption: δ and τ uncorrelated.

Scattering Anisotropy: Spheroidal Particles

Physical Aspect ratio:

$$r \approx \frac{b}{a} \begin{cases} < 1 & \text{prolate particles} \\ = 1 & \text{spherical particles} \\ > 1 & \text{oblate particles.} \end{cases}$$

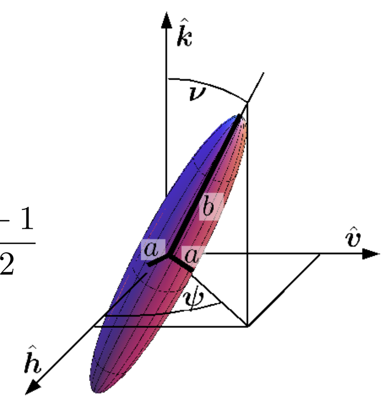
Polarizability Ratio: $\alpha_r = \dfrac{\alpha_a}{\alpha_b} = \dfrac{r+\epsilon_r+1}{r\epsilon_r+2}$

Particle Scattering Anisotropy

$$\delta_{s(\nu,\alpha_r)} = \frac{\alpha_r - 1}{\alpha_r + 1 + 2\cot^2\nu}$$

Effective Scattering Anisotropy

$$\delta = \iint \delta_{s(\nu,\alpha_r)} p(\nu) p(\alpha_r)\, d\nu\, d\alpha_r$$



2-Layer PolInSAR Vegetation Model

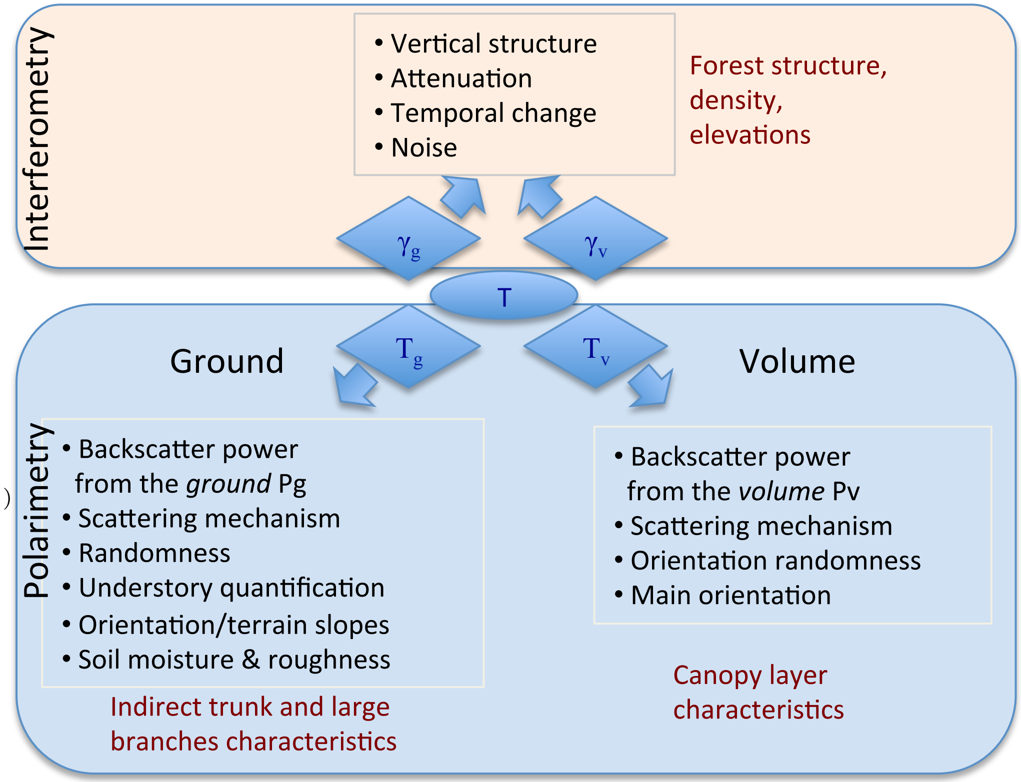
Single baseline PolInSAR:

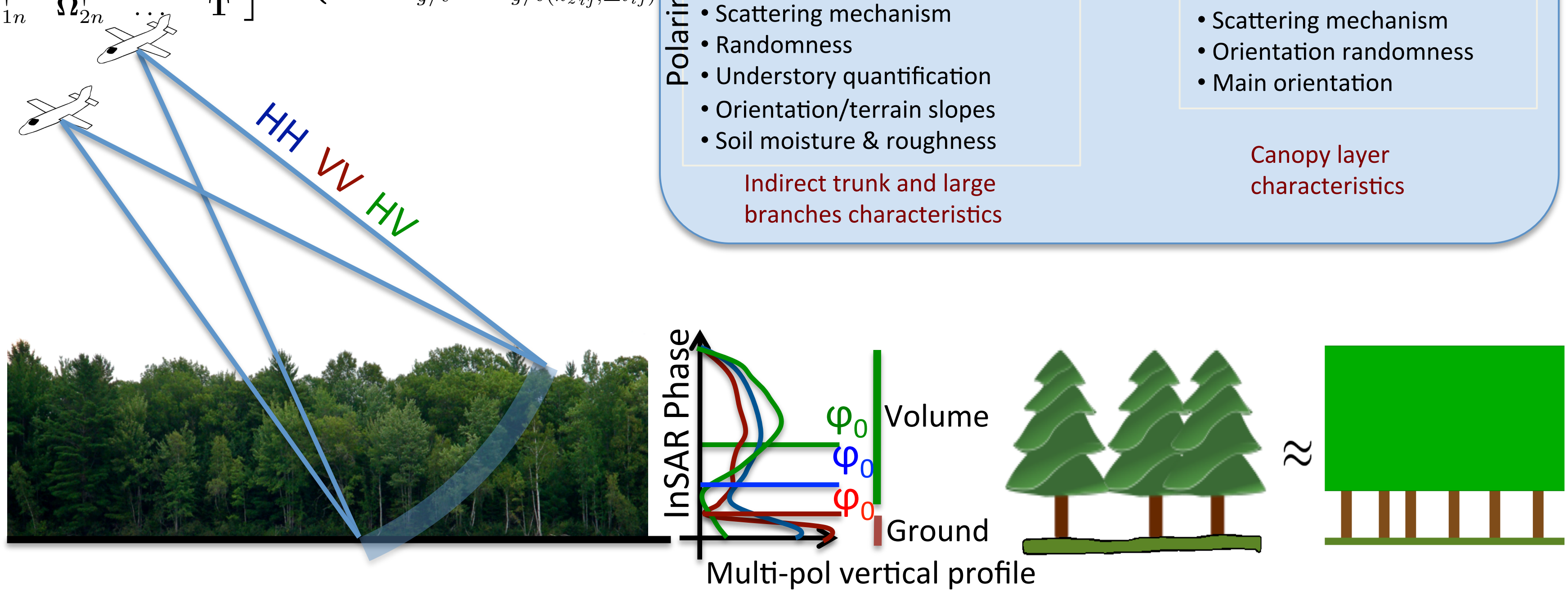
$$\mathbf{T}_6 = \begin{bmatrix} \mathbf{T} & \mathbf{\Omega} \\ \mathbf{\Omega}^\dagger & \mathbf{T} \end{bmatrix} \begin{cases} \mathbf{T} = \mathbf{T}_g + \mathbf{T}_v \\ \mathbf{\Omega} = \gamma_g \mathbf{T}_g + \gamma_v \mathbf{T}_v \end{cases}$$

$$= \mathbf{R}_g \otimes \mathbf{T}_g + \mathbf{R}_v \otimes \mathbf{T}_v \text{ with } \mathbf{R}_{g/v} = \begin{bmatrix} 1 & \gamma_{g/v} \\ \gamma^*_{g/v} & 1 \end{bmatrix}$$

Multi-baseline PolInSAR:

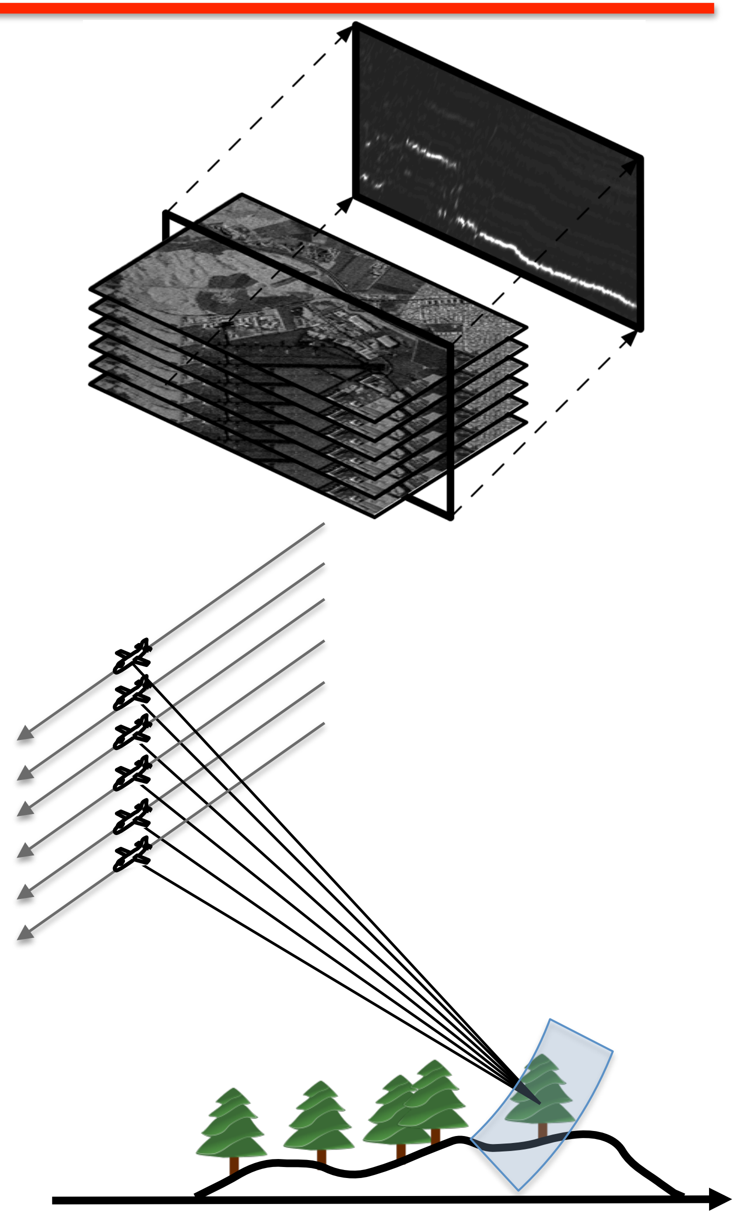
$$\mathbf{T}_{MB} = \begin{bmatrix} \mathbf{T} & \mathbf{\Omega}_{12} & \dots & \mathbf{\Omega}_{1n} \\ \mathbf{\Omega}^\dagger_{12} & \mathbf{T} & \dots & \mathbf{\Omega}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{\Omega}^\dagger_{1n} & \mathbf{\Omega}^\dagger_{2n} & \dots & \mathbf{T} \end{bmatrix} \rightarrow \begin{cases} \mathbf{T} & = \mathbf{T}_g + \mathbf{T}_v \\ \mathbf{\Omega}_{ij} & = \gamma_g^{ij} \mathbf{T}_g + \gamma_v^{ij} \mathbf{T}_v \\ & \gamma_{g/v}^{ij} \leftarrow \gamma_{g/v(k_{z_{ij}}, \Delta t_{ij})} \end{cases}$$





SAR Tomography

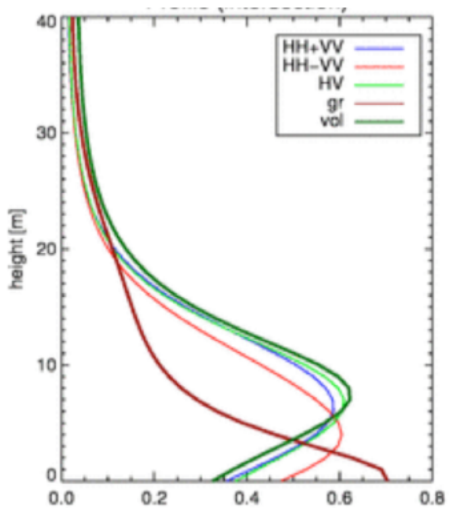
- SAR Interferometry and SAR Polarimetry:
  - Largely developed at JPL (15-25y ago)
- SAR Tomography:
  - Mainly in Europe (last 10-15y)
  - Initial demonstrations: 10 years ago using airborne (ESAR) and space-borne sensors (ERS-1/2)
  - Potentially high resolution
  - Independent of solar illumination
  - High coverage

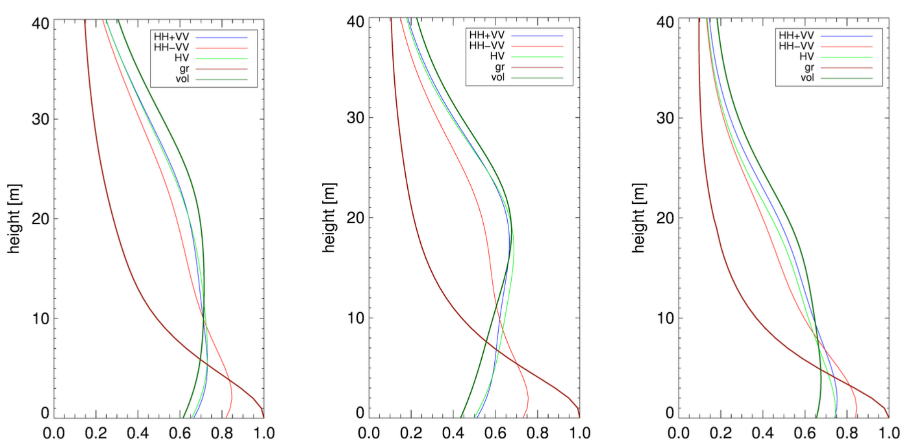


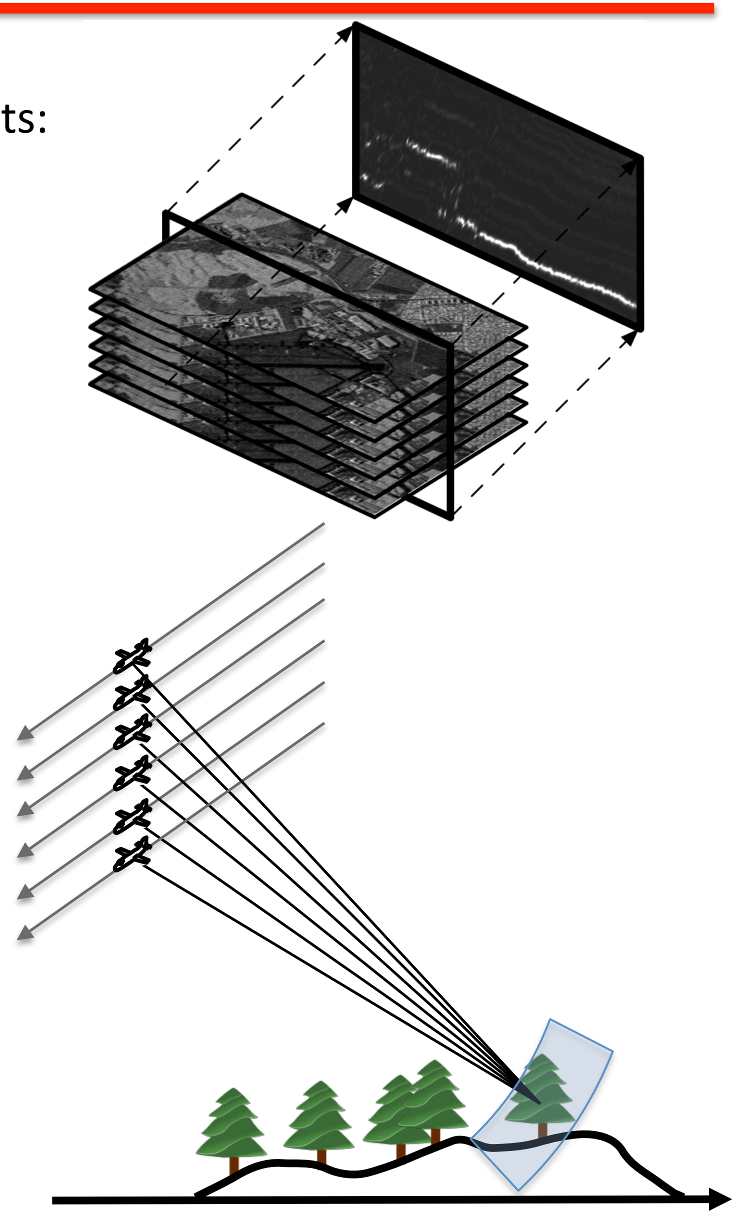
- Tomography offers the capability to sense vertically distributed information, e.g., vegetation and ice structure or deformation signals.
  - Extension of 2d SAR imaging to 3d and 4d (space-time).
  - Formation of an additional synthetic aperture in elevation.

SAR Tomography

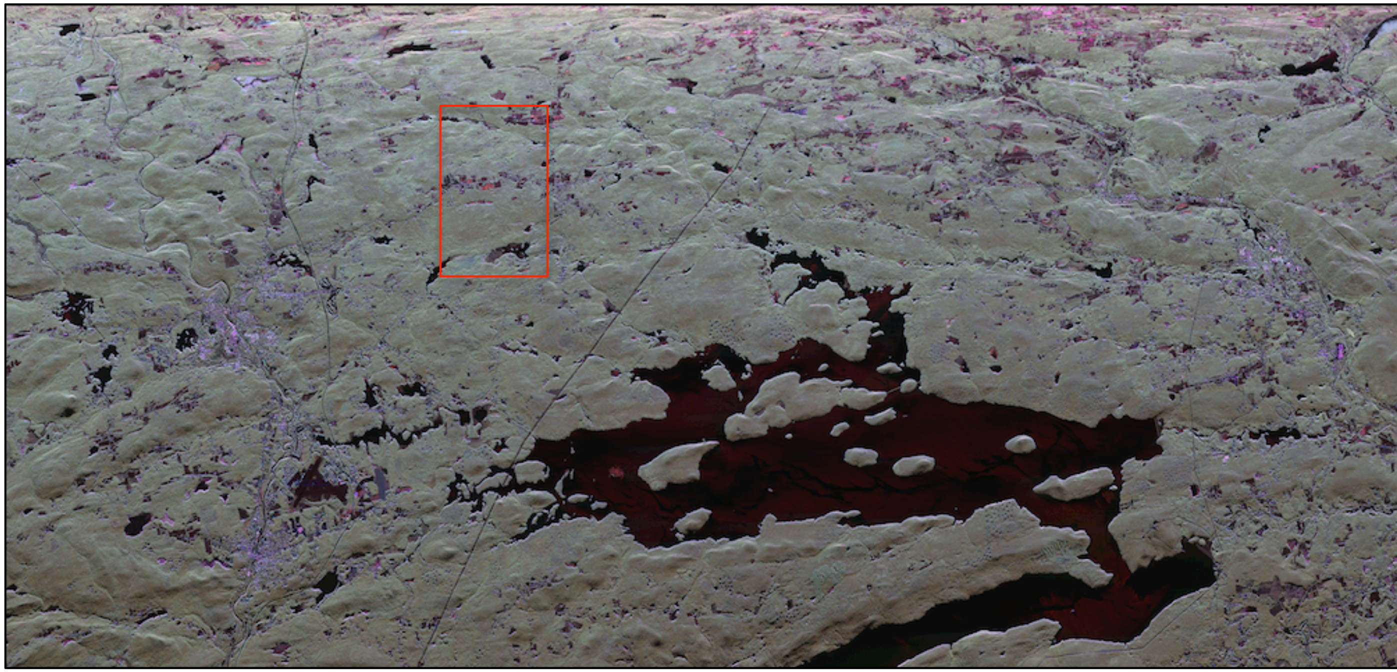
Interpreting Polarimetric SAR Tomography over forests:
- vertical distribution of backscattered energy in dependence of polarization







Experimental Results



Harvard Forest

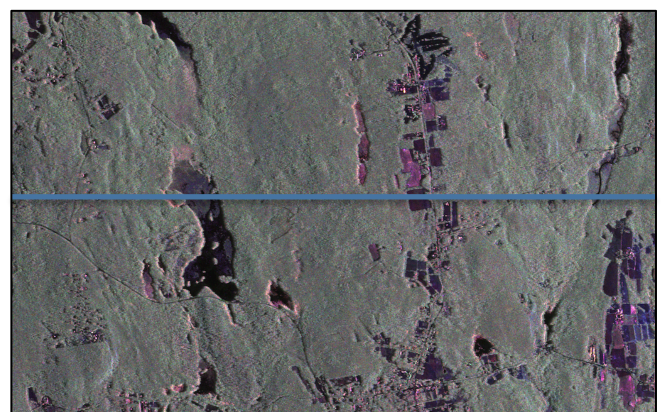
JPL's UAVSAR

L-band

13 tracks

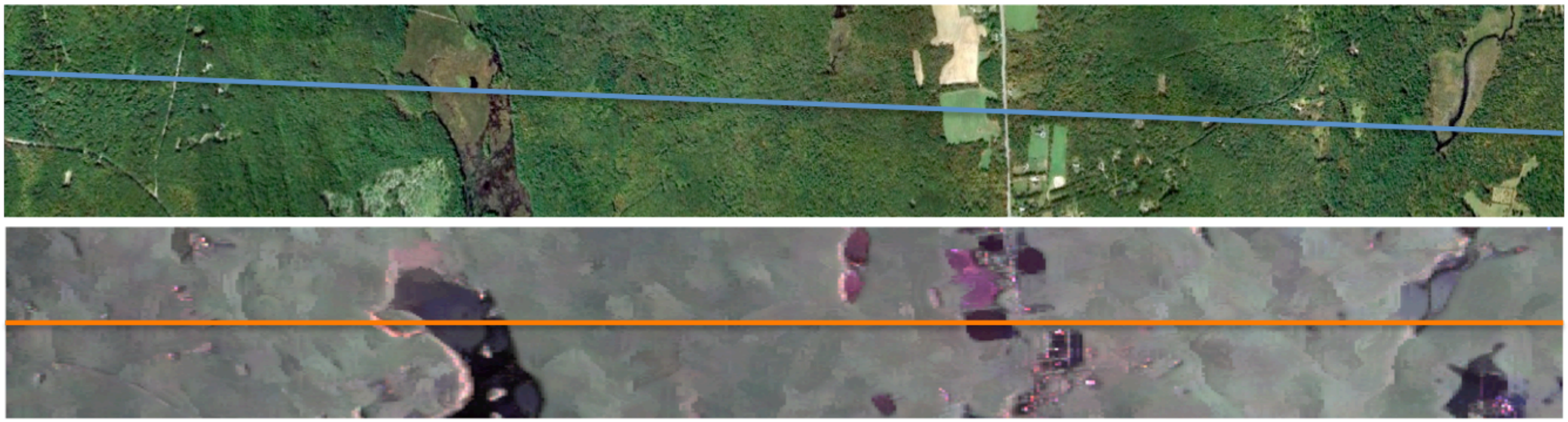
Spatial baselines: 5m – 125m

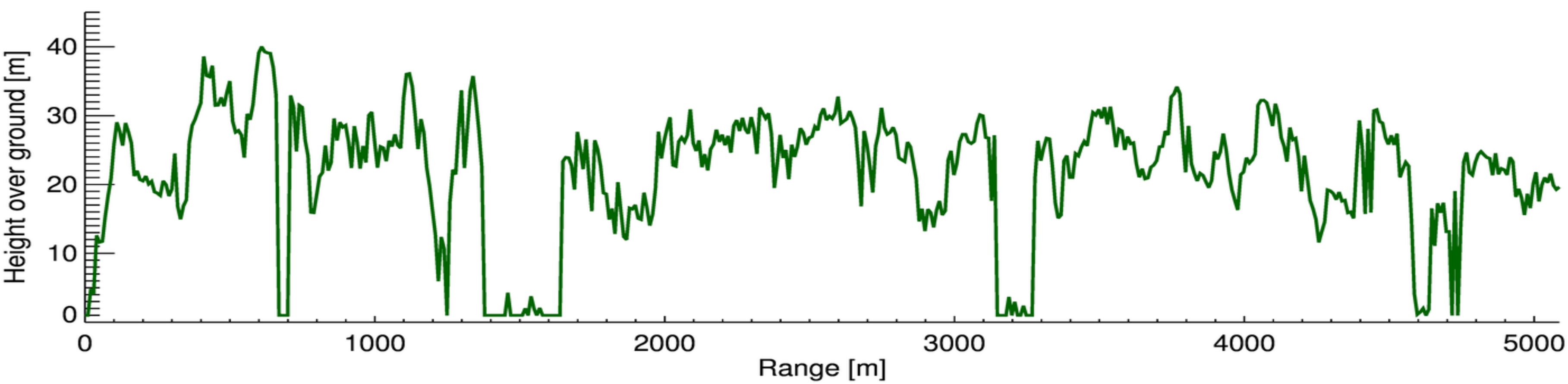
Temporal separation: 30 min – 11 days



Experimental Results

JPL's UAVSAR sensor – Harvard Forest dataset – L-band

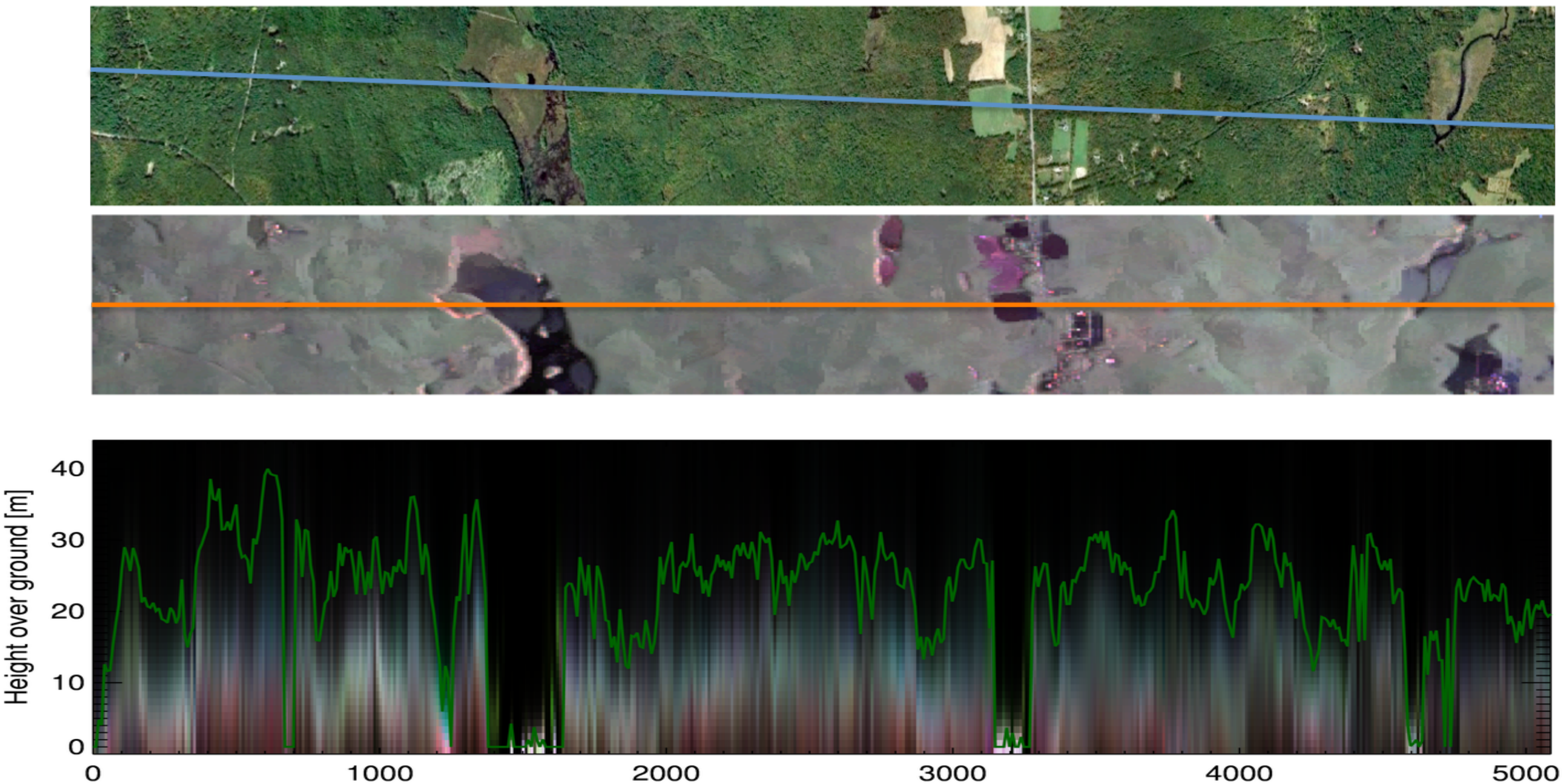




PolInSAR Height Estimate

Experimental Results

JPL’s UAVSAR sensor – Harvard Forest dataset – L-band

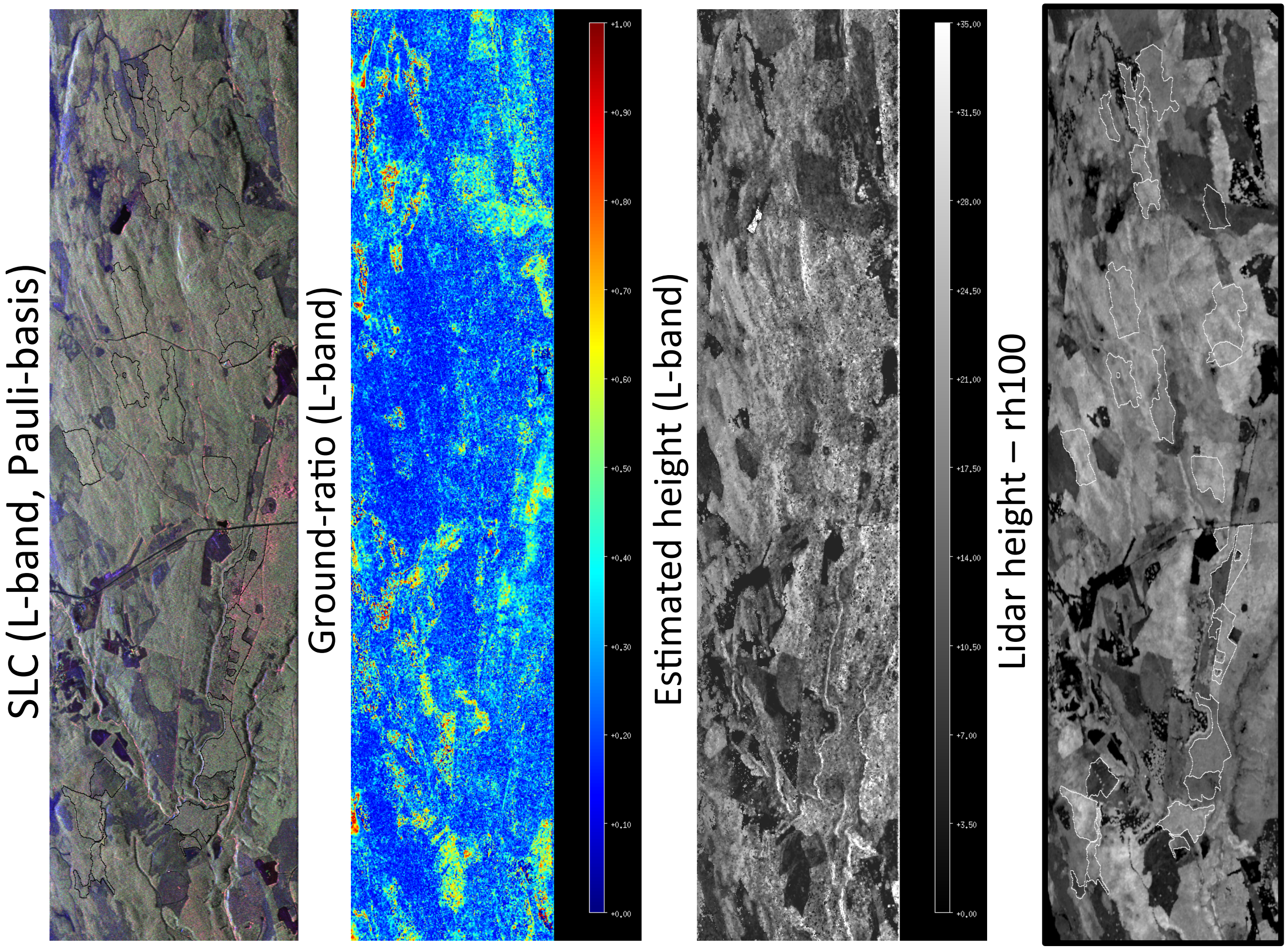


Overlaying PolInSAR Estimate and Pol-Tomogram

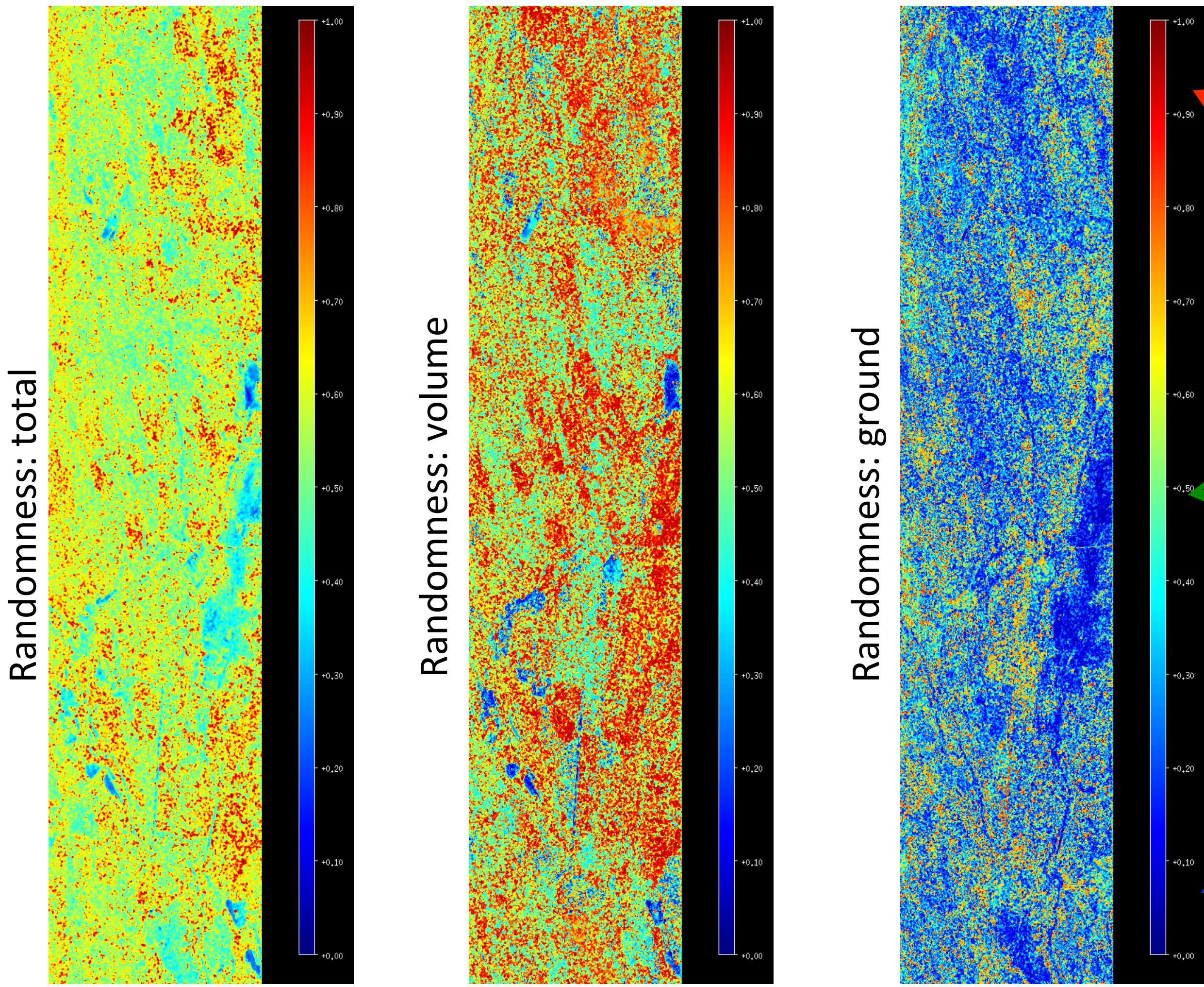
Experimental Results

- **Krycklan Catchment**
- Northern Sweden Boreal forest
- BioSAR II campaign 2008
- ESA-DLR-FOI-SLU
- DLR's E-SAR sensor

- ascending/descending paths
- 6 tracks, respectively
- L- and P-bands
- 2*27 forest plots



Experimental Results

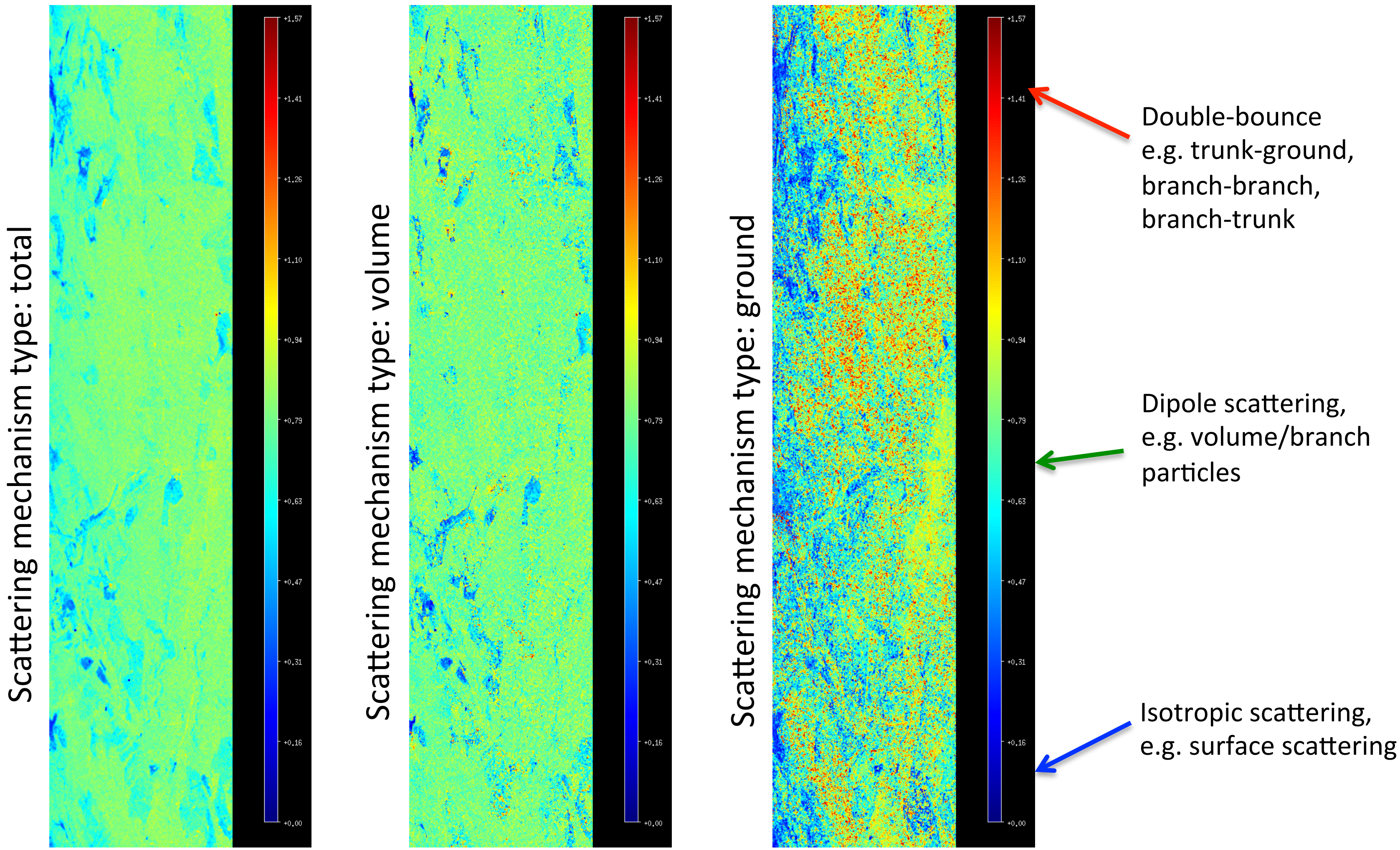


Diffuse scattering, random orientations, high entropy

Partially randomly oriented, but with preferred direction

Deterministic scattering, uniformly aligned, e.g. only surface, or only double bounce

Experimental Results

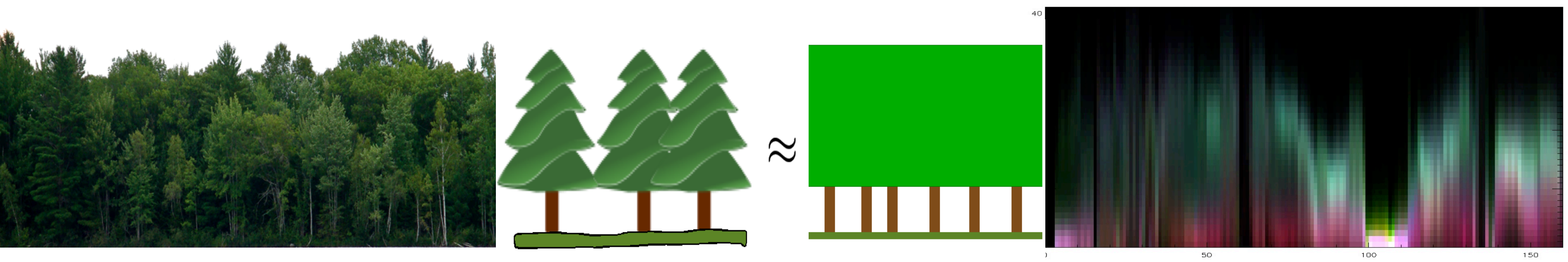


Conclusion

- Potential of Polarimetric SAR Interferometry and SAR Tomography for
  - vertical forest structure characterization
  - vegetation and scattering type characterization
- Observations from data:
  - No definitive model which would work for all forests
  - Temporal decorrelation - potentially large error source
  - Strong baseline choice dependence
  - Multiple baselines improve the estimation (*requires accurate processing & calibration)
  - Performance depends on forest and tree species type
  - L-band: no ground for dense forests, slopes, insufficient double-bounce
- Challenges:
  - Data processing and calibration
  - Long baselines processing for improved height resolution
  - Error analysis

Forest Structure Characterization using UAVSAR PolInSAR and Tomography

Thank you for your attention!



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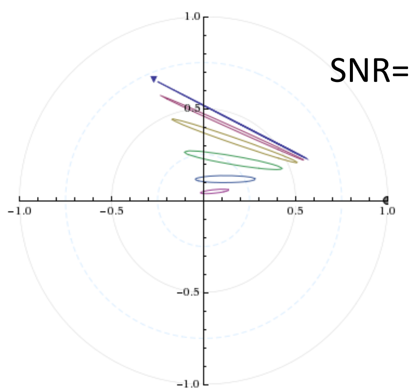
PolInSAR Coherence Set Distributions

- Example scenario:

  hv=20m, extinction=0.3dB/m, ground phase=0 degree

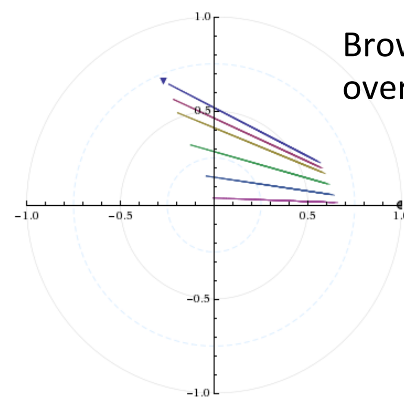
  SNR: [9dB, 15dB], Temporal Brownian motion: 24h with sdev=2mm/h

Thermal decorrelation effects:



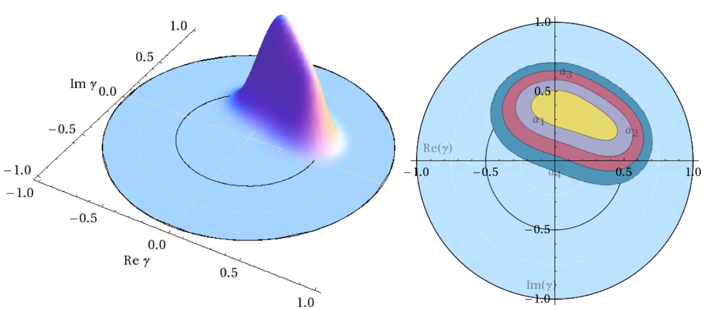
SNR=[∞,15,10,5,0,-5]dB

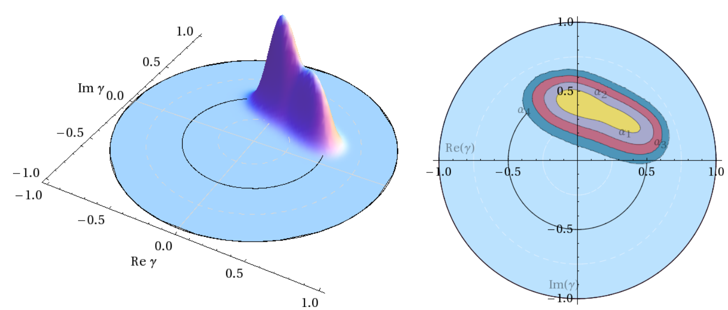
Temporal decorrelation effects:



Brownian motion with sdev=2mm/h
over 0,1,2,5,10,20 days

A-posteriori cohset PDF's and Confidence regions for 49 and 100 looks:





Confidence levels: 68%, 95.5%, 99.7%, 99.994%

Non-modeled Variability

- Example PolInSAR height estimation errors due to model simplification. Induced non-modeled coherence magnitude and phase offsets or variabilities, and the resulting height estimation errors, if not compensated.
- Model: simple RVoG
- Example scenario:

  hv=25m, incidence angle=45 degrees,

  kz=0.15, extinction=0dB.

Error Source	$\Delta\|\gamma\|$	$\Delta \arg\gamma$	$\Delta h_v(\|\gamma\|)$	$\Delta h_v(\arg\gamma)$
γ_{temp} of 0.8	-0.10	0°	3.12m	0m
$\sigma_{\gamma_{temp}}$ of 50%	±0.05	0°	±1.58m	0m
Min(c_g) of 15%	-0.10	-20.3°	2.94m	-4.72m
Canopy 75%	0.19	13.4°	-6.25m	3.12m
Extinction 0.2dB/m	0.07	35.4°	-2.16m	8.23m
$\sigma_\phi, \sigma_\gamma$ (# looks =25)	± 0.10	±13.7°	±3.26m	±3.19m
$\sigma_\phi, \sigma_\gamma$ (# looks =100)	±0.05	±6.85°	±1.61m	±1.60m