Polarimetric SAR Interferometry: Status and Future Trends

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Summary

"POLInSAR involves the combination of multiple interferograms in different polarisation channels for the purposes of studying vertical structure and problems involving combined surface and volume scattering"

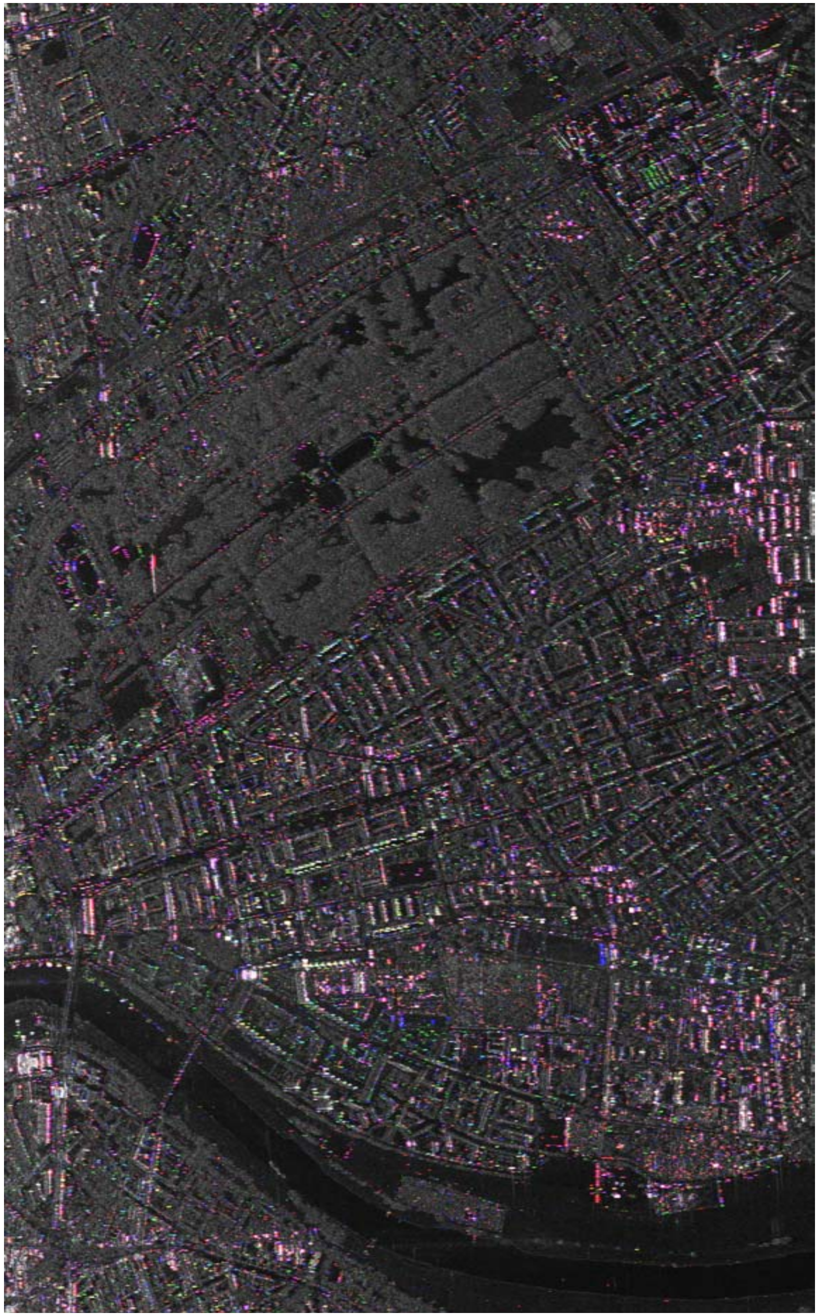
Primary Application Area

- Forestry (mainly L and some P band studies)
  Tree Height/Biomass

- Future Research Trends (P,L,C,X….)
  - Urban applications (PPS)
  - Concealed Target Detection
  - Snow/Ice Studies (thickness/SWE etc)
  - Multi-baseline techniques:
    a) Vertical Structure Mapping
    b) Temporal Decorrelation
  - Agriculture
    a) Plant Water Content
    b) Sub-Canopy Moisture

Polarisation Dependence
Of Candidate
Permanent Scatterers

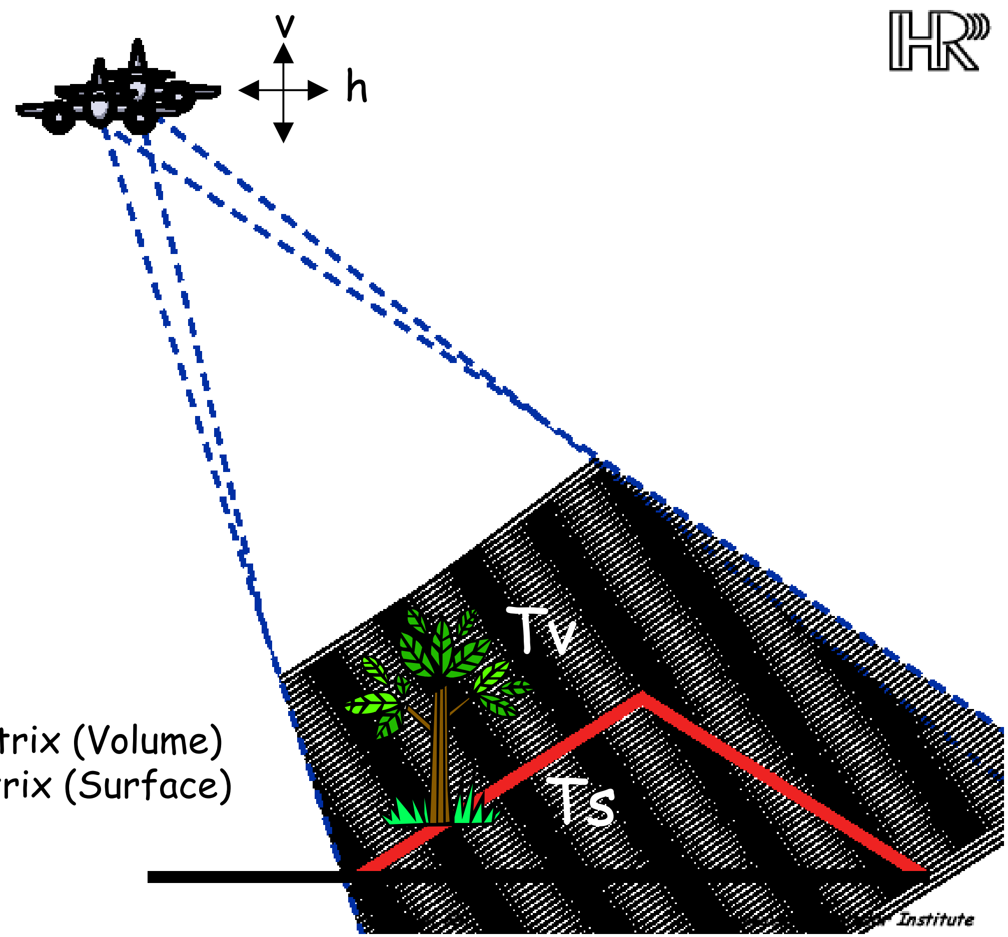
E-SAR L band Data,
City of Dresden



…but vegetated areas show poor polarimetric phase stability due to depolarisation (high entropy)..

…one possible solution…
combine polarimetry with interferometry

Polarimetric Radar Interferometry



$$T = T_v + T_s$$

T_v = Polarimetric Coherency matrix (Volume)
T_s = Polarimetric Coherency matrix (Surface)

German Aerospace Center

..provides Entropy Control…via (user) choice of baseline
…measure phase ϕ with high coherence, even for vegetation

Coherent Vegetation Mapping
Method 1: DEM Differencing Algorithms

Stage 1 : Surface Topography Estimation

$$\hat{\phi} = \arg(\tilde{\gamma}_{rs})$$

- Coherence Optimisation
- Coherence Region Analysis
- ESPRIT Superesolution
- Sub-space coherence analysis

Stage 2 : Height Estimation

pq - polarisation 1

rs - polarisation 2

$$h_v = \frac{\arg(\gamma_{pq}) - \hat{\phi}}{k_z}, \quad k_z = \frac{4\pi\Delta\theta}{\lambda\sin\theta} \approx \frac{4\pi B_n}{\lambda R\sin\theta}$$

Stage 3 : Volume/Surface scattering separation

$$s(\underline{w}) = \underline{w}^{*T} T_V \underline{w} + \underline{w}^{*T} T_s \underline{w}$$

Coherent Vegetation Mapping
Method 2 : 2-layer coherence model inversion

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Stage 1 : Surface Topography Estimation

$$\hat{\phi} = \arg(\tilde{\gamma}_{pq} - \tilde{\gamma}_{rs}(1 - L_{pq})) \quad 0 \le \mathrm{L}_{\mathrm{pq}} \le 1$$

$$AL_{pq}^2 + BL_{pq} + C = 0 \Rightarrow L_{pq} = \frac{-B - \sqrt{B^2 - 4AC}}{2A}$$

$$A = |\tilde{\gamma}_{rs}|^2 - 1 \quad B = 2\mathrm{Re}((\tilde{\gamma}_{pq} - \tilde{\gamma}_{rs}).\tilde{\gamma}_{rs}^*) \quad C = |\tilde{\gamma}_{pq} - \tilde{\gamma}_{rs}|^2$$

Stage 2 : Height Estimation…with regularisation parameter λ

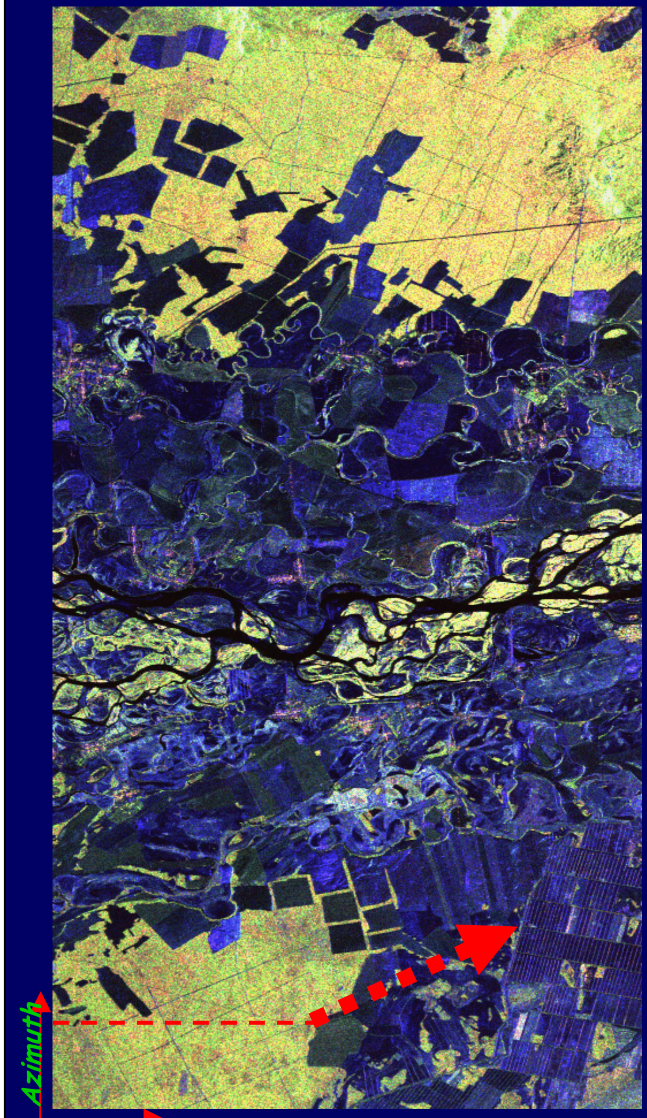
$$\min_{h_v, \sigma} L_1(\lambda) = \left\| \tilde{\gamma}_{rs} + \lambda\left(e^{i\hat{\phi}_2} - \tilde{\gamma}_{rs}\right) - e^{i\hat{\phi}} \frac{p}{p_1} \frac{e^{p_1 h_v} - 1}{e^{p h_v} - 1} \right\| \quad \text{where} \begin{cases} p = \dfrac{2\sigma}{\cos\theta} \\ p_1 = p + ik_z \\ \hat{\phi}_2 = \arg(\tilde{\gamma}_{rs} - \tilde{\gamma}_{pq}(1 - L_{rs})) \end{cases}, k_z = \frac{4\pi\Delta\theta}{\lambda \sin\theta} \approx \frac{4\pi B_n}{\lambda R \sin\theta}$$

Stage 3 : Volume/Surface scattering separation

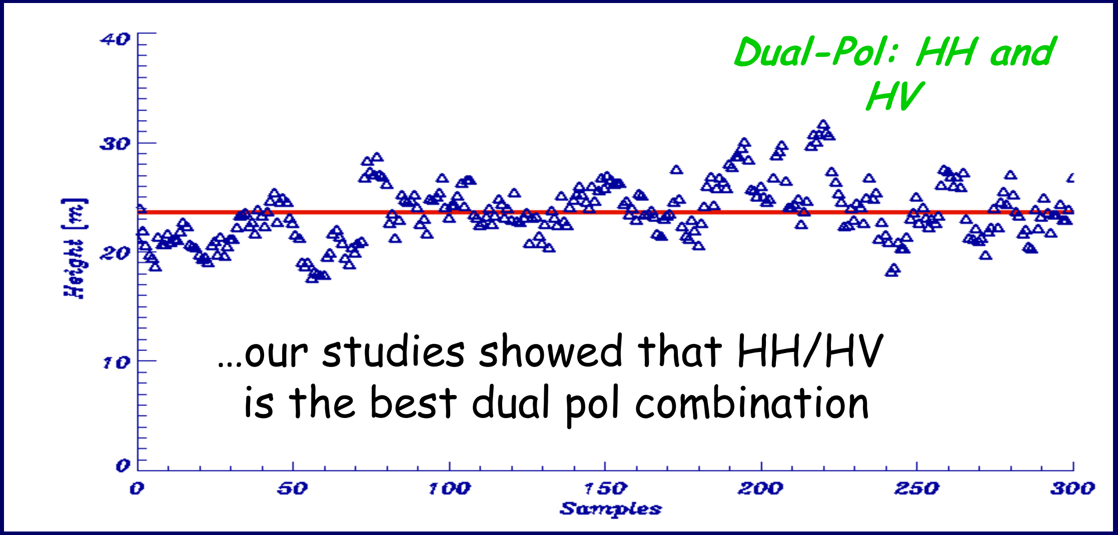
$$s(\underline{w}) = \underline{w}^{*T} T_V \underline{w} + \underline{w}^{*T} T_s \underline{w}, \qquad 0 \le L(\underline{w}) = \frac{\dfrac{\hat{p}}{\hat{p}_1} \dfrac{e^{\hat{p}_1 \hat{h}_v} - 1}{e^{\hat{p}\hat{h}_v} - 1} - e^{-i\hat{\phi}} \hat{\gamma}(\underline{w})}{\dfrac{\hat{p}}{\hat{p}_1} \dfrac{e^{\hat{p}_1 \hat{h}_v} - 1}{e^{\hat{p}\hat{h}_v} - 1} - 1} \le 1 \Rightarrow \begin{cases} \underline{w}^{*T} T_s \underline{w} = e^{\frac{2\sigma h_v}{\cos\theta_0}} L(\underline{w}) s(\underline{w}) \\ \underline{w}^{*T} T_V \underline{w} = s(\underline{w}) - \underline{w}^{*T} T_s \underline{w} \end{cases}$$

Forest Height Estimation: Quad-Pol vs.Dual-Pol

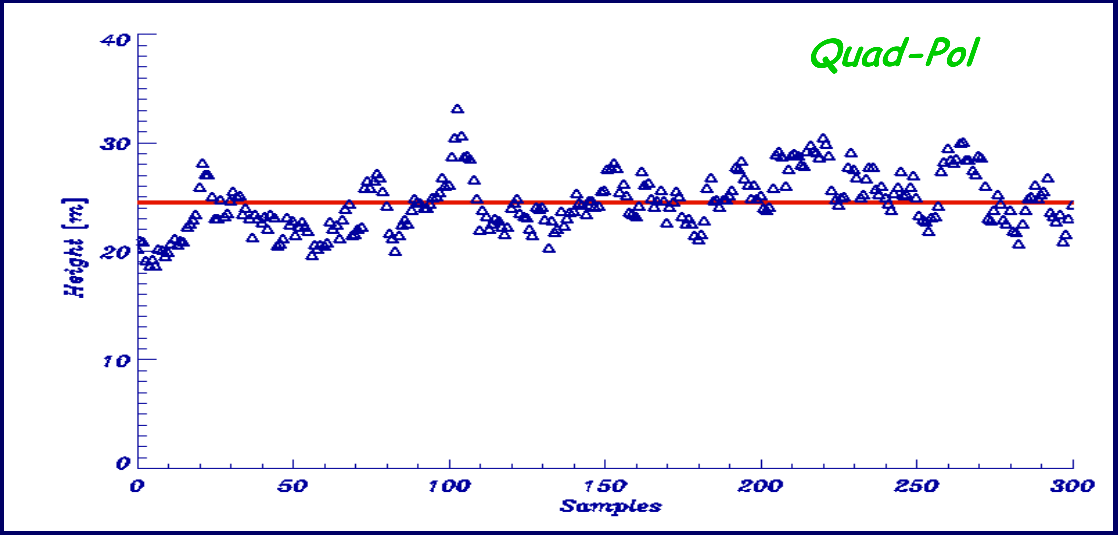
SIR-C / Test Site: Kudara,Russia



L-band



...our studies showed that HH/HV is the best dual pol combination



Temporal Baseline: 48 Hours

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POlInSAR Coherence : The 'rvog' model

$$\gamma(\underline{w}) = e^{i\phi} \frac{\frac{p}{p_1}\frac{e^{p_1 h_v}-1}{e^{p h_v}-1} + \mu(\underline{w})}{1+\mu(\underline{w})} \qquad \text{where} \begin{cases} p = \dfrac{2\sigma}{\cos\theta} \\ p_1 = p + ik_{z1} \end{cases}$$

μ = surface-to-volume scattering ratio

Extinction dB/m + 'effective' surface scattering + volume scattering

'effective' =

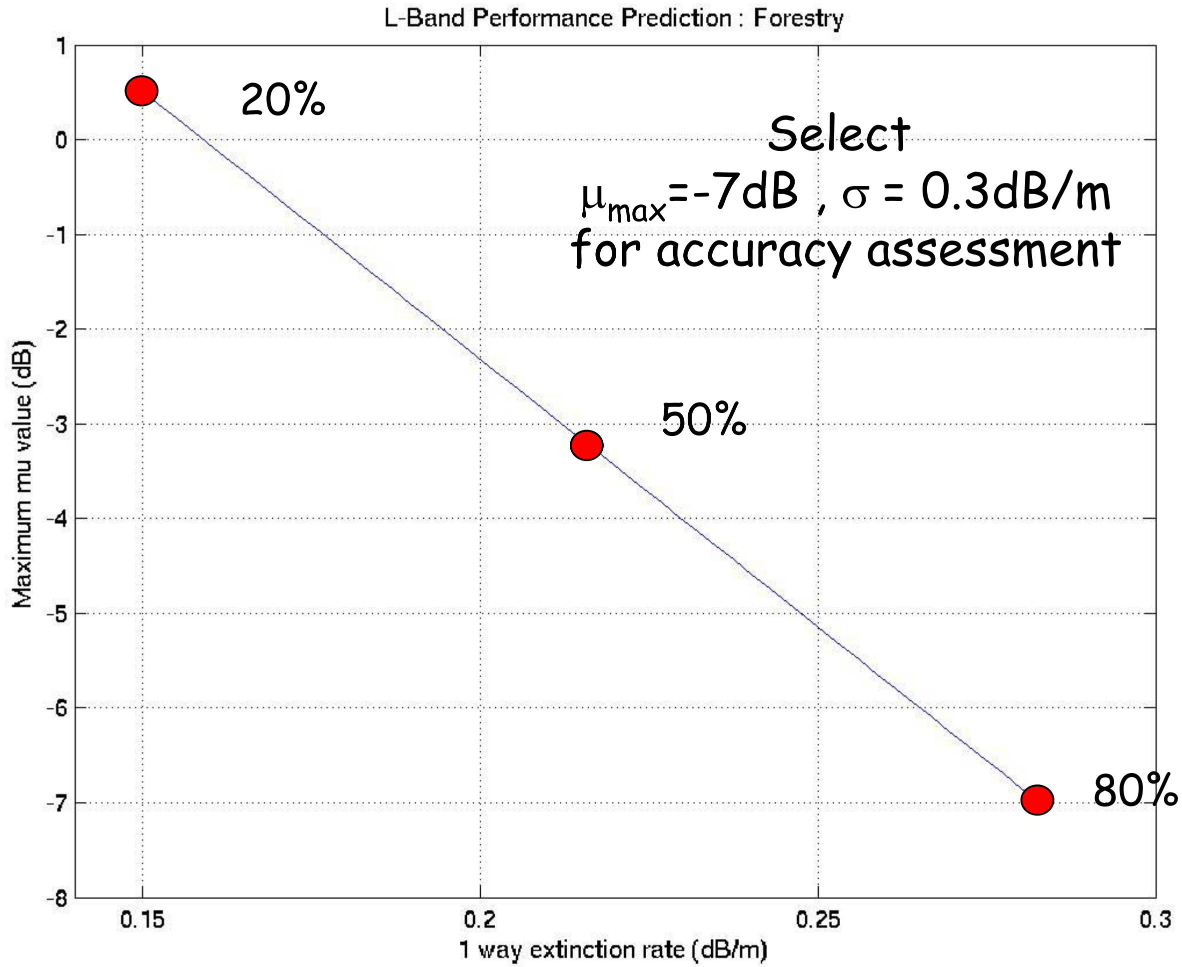
- attenuated by wave extinction
- includes direct surface and dihedral returns

2 issues of importance:

1. Must assume that for at least one polarisation $\mu = 0$ but…
2. If $\mu(\underline{w}) = 0$ ….inversion collapses …$\gamma_{pq} = \gamma_{rs}$ for all polarisations

   …so what is a typical range of μ_{min} to μ_{max}?

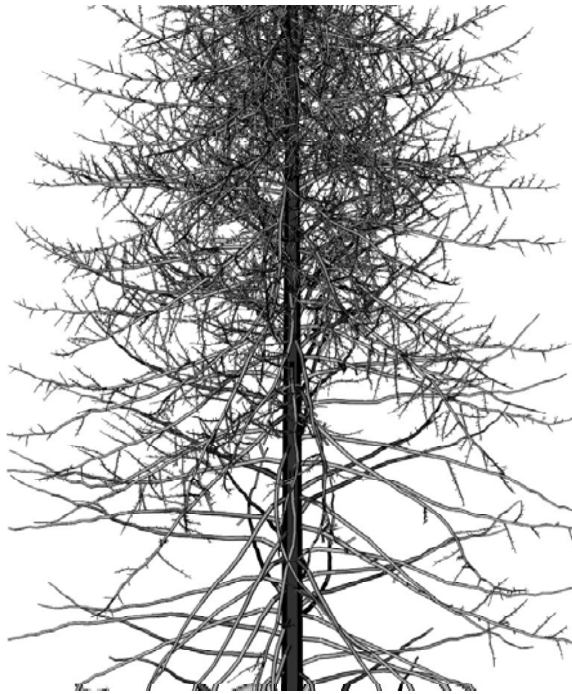
Summary : Parameters used for L-band Forestry Product Accuracy assessment

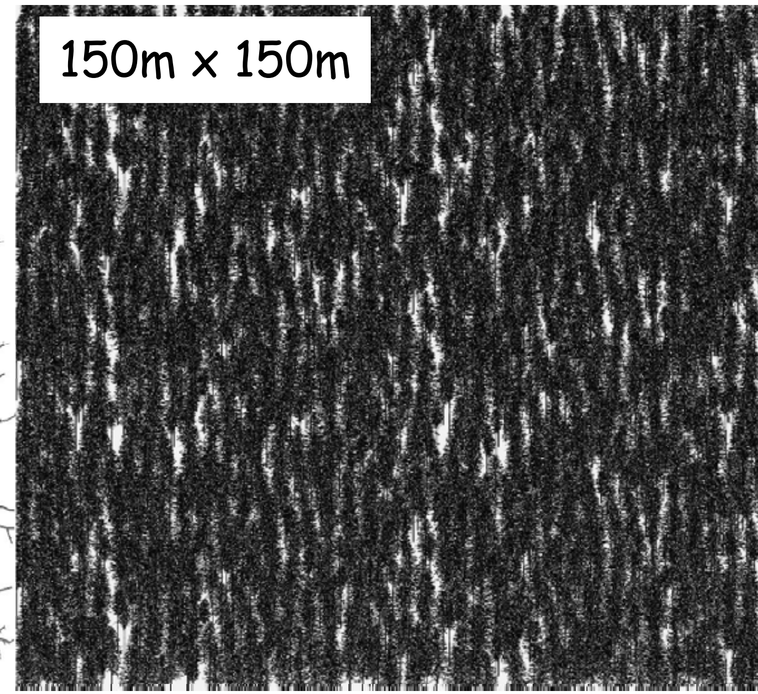


This allows us to estimate μ_{max} ...but what about μ_{min}?

Scots Pine Forest POLInSAR Simulation

Architectural tree model courtesy of University of Joensuu, Finland
Simulations Carried out by Dr Mark Williams, DSTO

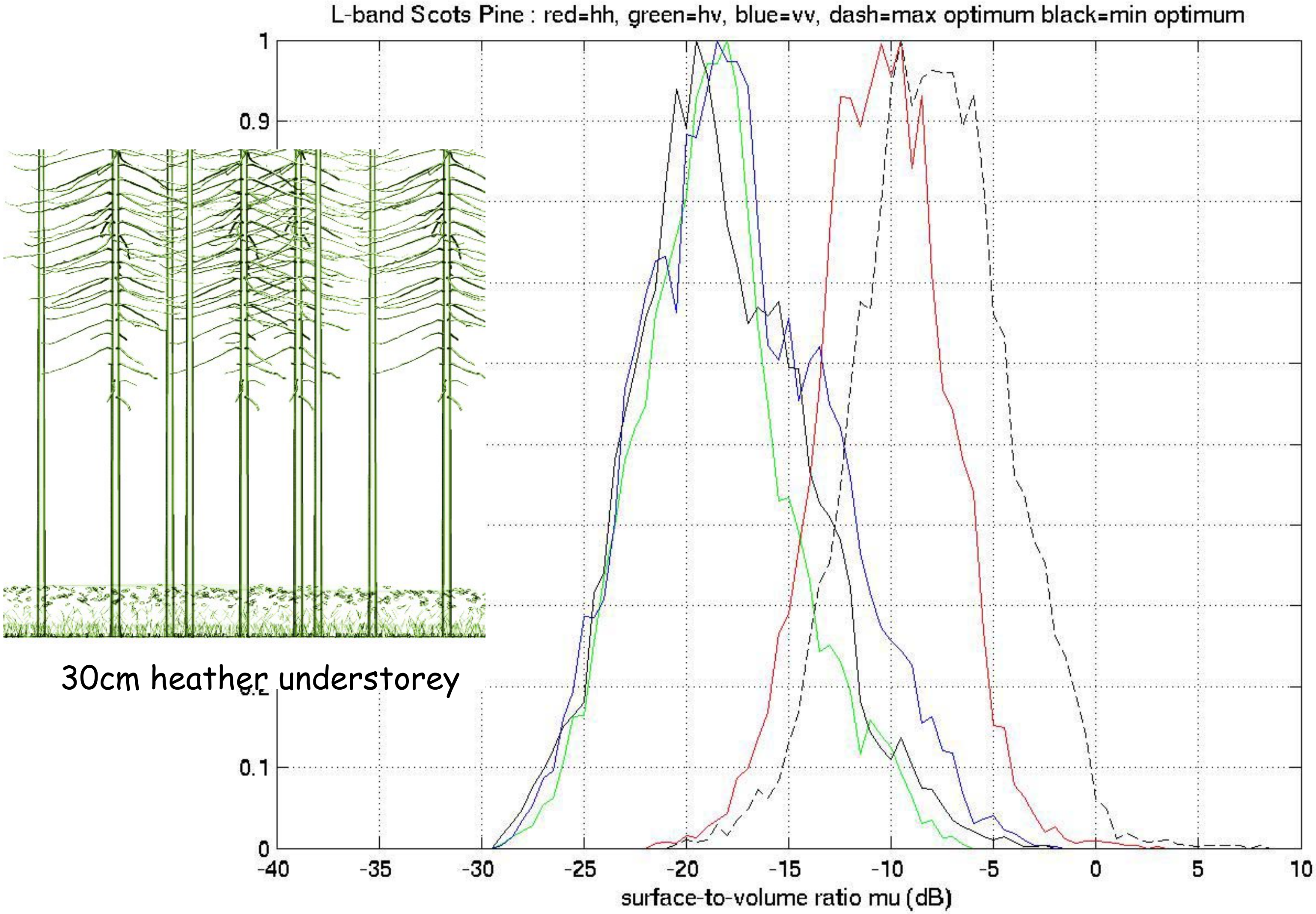




Stand density = 0.055 stems/m^2
Mean height = 18m…std = 0.6m

L-band θ=45 degrees…can be used to calculate extinction and μ values ..
…Mean extinction = 0.28 dB/m..μ depends on polarisation as..

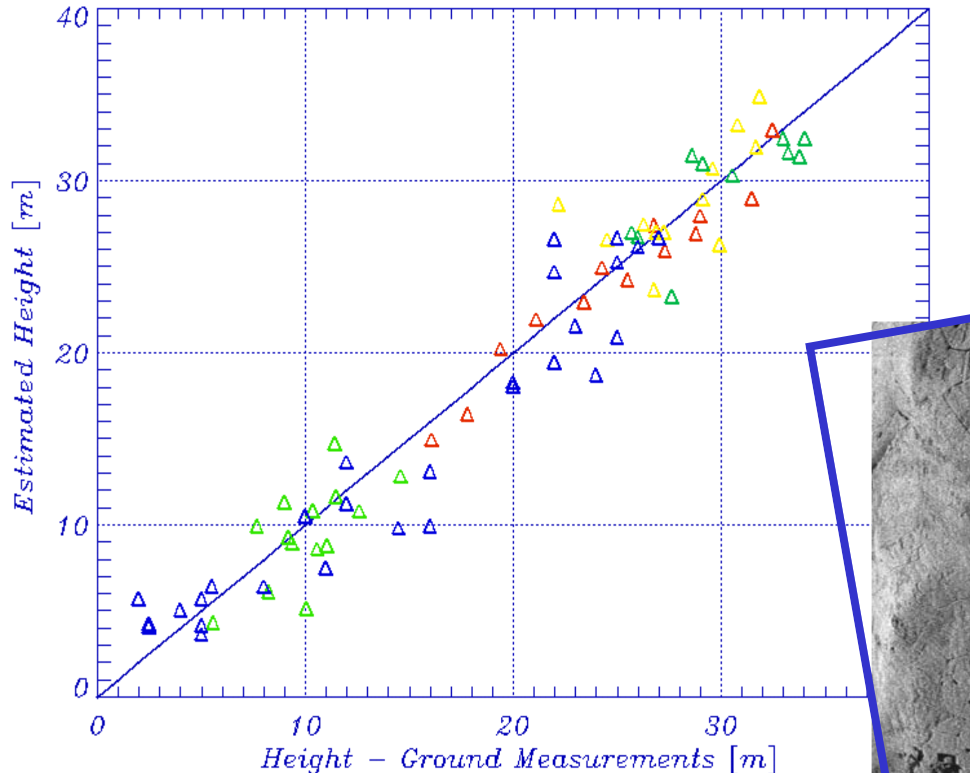
4-layer Understorey Models



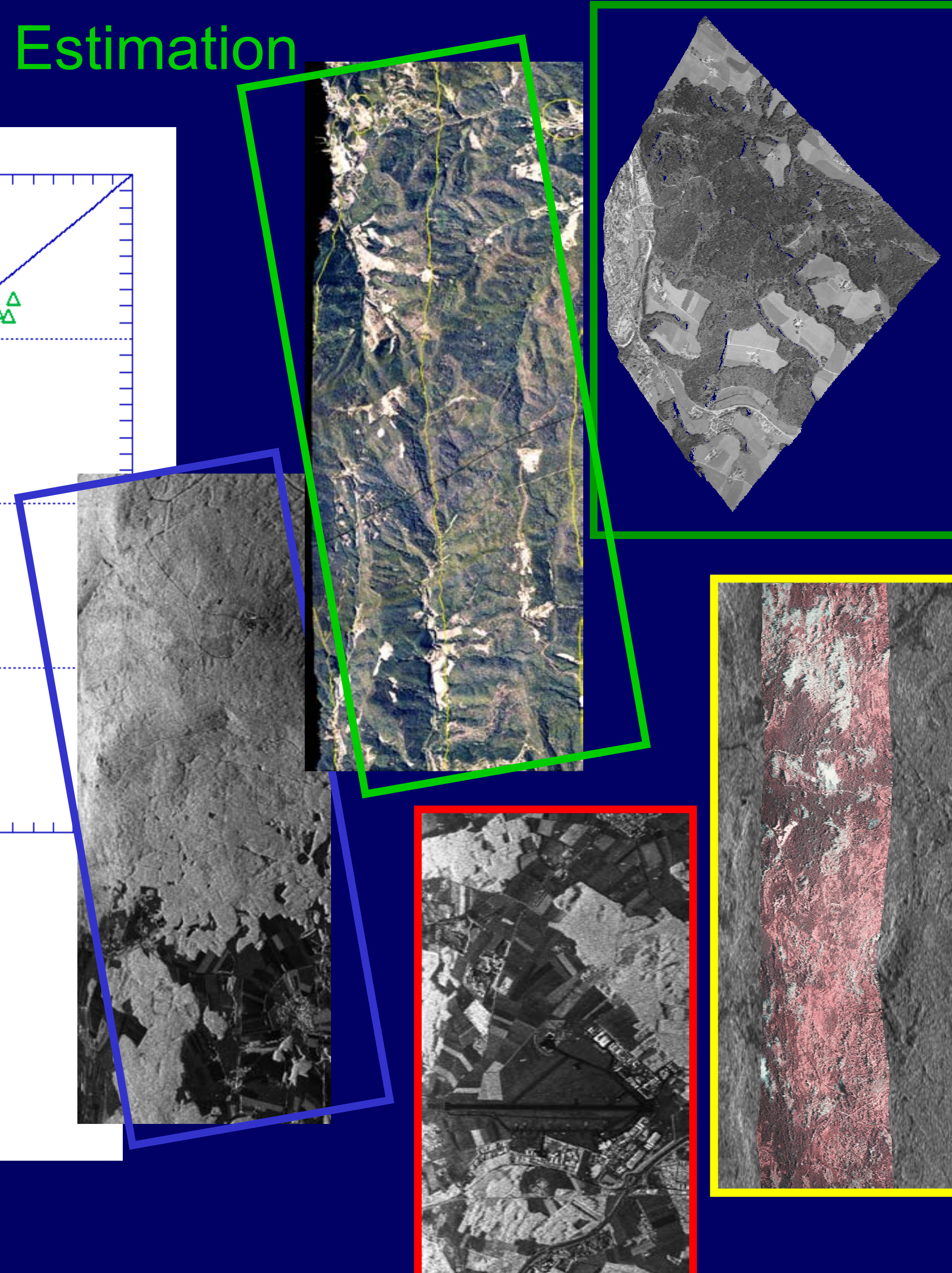
30cm heather understorey

Can use the dynamic range of μ with polarisation to assess system performance (the phase tube)

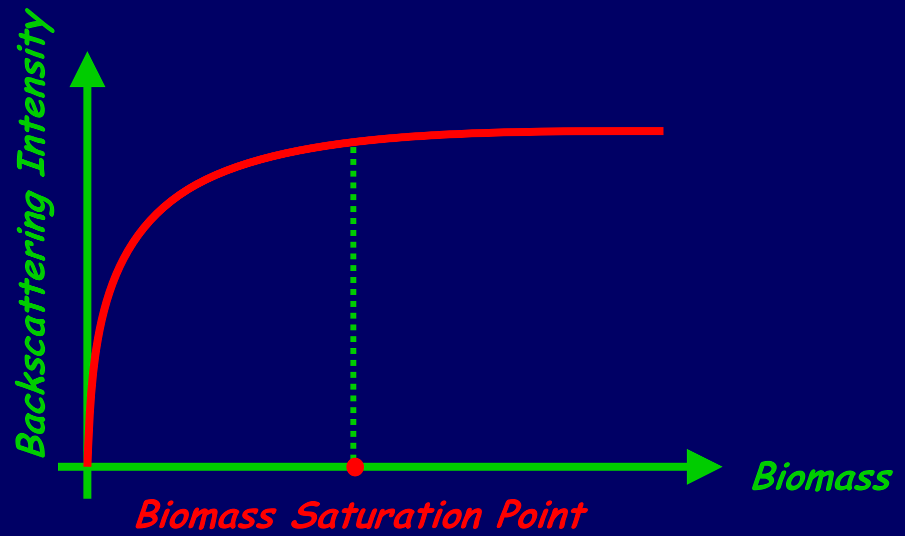
Summary: POlInSAR Height Estimation



Fichtelgebirge / Germany
Corridor / Spain
Bayrischer Wald / Germany
Traunstein / Germany
Oberpfaffenhofen / Germany



Biomass Estimation from Radar Remote Sensing Data



Backscatter Saturation:

	Biomass Saturation Limit [T/ha]	[Kg/(m^2)]	% of Earths Vegetated Area	% of Total Biomass Stock
C-band	20*	2	25%	4%
L-band	40*- 60	4 - 6	35%	8%
P-band	100*-150	10 -15	60-65%	20-25%

* M. L. Imhoff, "Radar Backscatter and Biomass Saturation: Ramifications for Global Biomass Inventoty ",IEEE TGARS, Vol. 33, No. 2, Ma

West, Brown and Enquist (WBE) General forest structure model

Self-similar 3 parameter model for forests in equilibrium with resources

Example Biomass-Height Relationship :

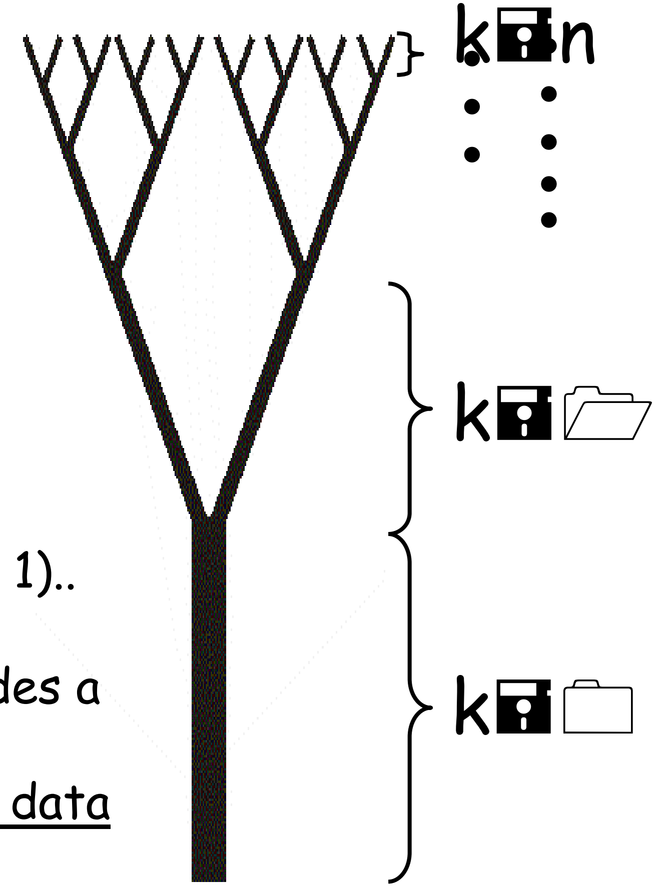
$$\left.\begin{array}{r} M \propto h^{4} \\ N \propto M^{-\frac{3}{4}} \end{array}\right\} \Rightarrow \overline{M} = M * N \propto \overline{h}$$

More detailed analysis shows that $\overline{M} \propto h^{\alpha}$

Where α depends on latitude (for tropical forest α = 1)..

These results indicate that height measurement provides a non-saturating robust estimate of biomass..

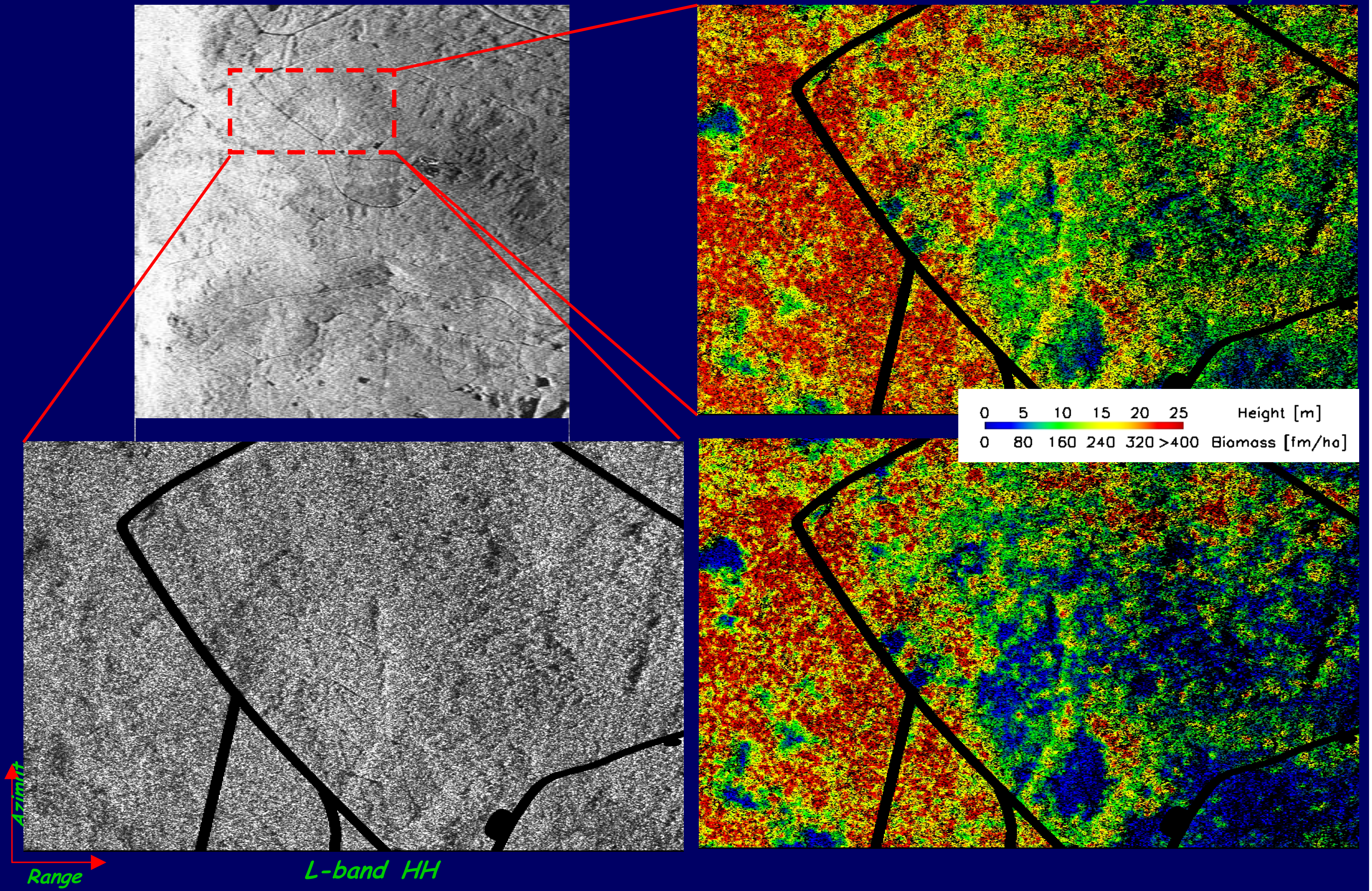
...but need to reliably estimate <u>tree height</u> from <u>radar data</u>



G.B West, J.H.Brown,B.J.Enquist, "A General Model For the Structure and Allometry of Plant Vascular Systems", NATURE, Vol. 400, 12 August 1999

Forest Height & Biomass Maps : Airborne Sensors

ESAR / Test Site: Fichtelgebirge, Germany




AIRBORNE SAR CAMPAIGN OVER TROPICAL FOREST
D-CFFU
INDREX 2
INDONESIA RADAR EXPERIMENT
Mawas-Gunung Meratus-Sungai Wain-Balikpapan Bay Mangrove-Samboja Lestari
NOVEMBER, 2004
esa
DLR
BOS
SarVision
AIRBORNE SAR CAMPAIGN OVER TROPICAL FOREST IN P-L-C and X-BAND
SAR: Synthetic Aperture Radar
European Space Agency-ESA ~ German Aerospace Centre-DLR ~ Wageningen University-WUR ~ Ministry of Foresty-MoF
Borneo Orangutan Survival Foundation-BOS ~ Sarvision The Netherlands-SVBV and Sarvision Indonesia-SVI

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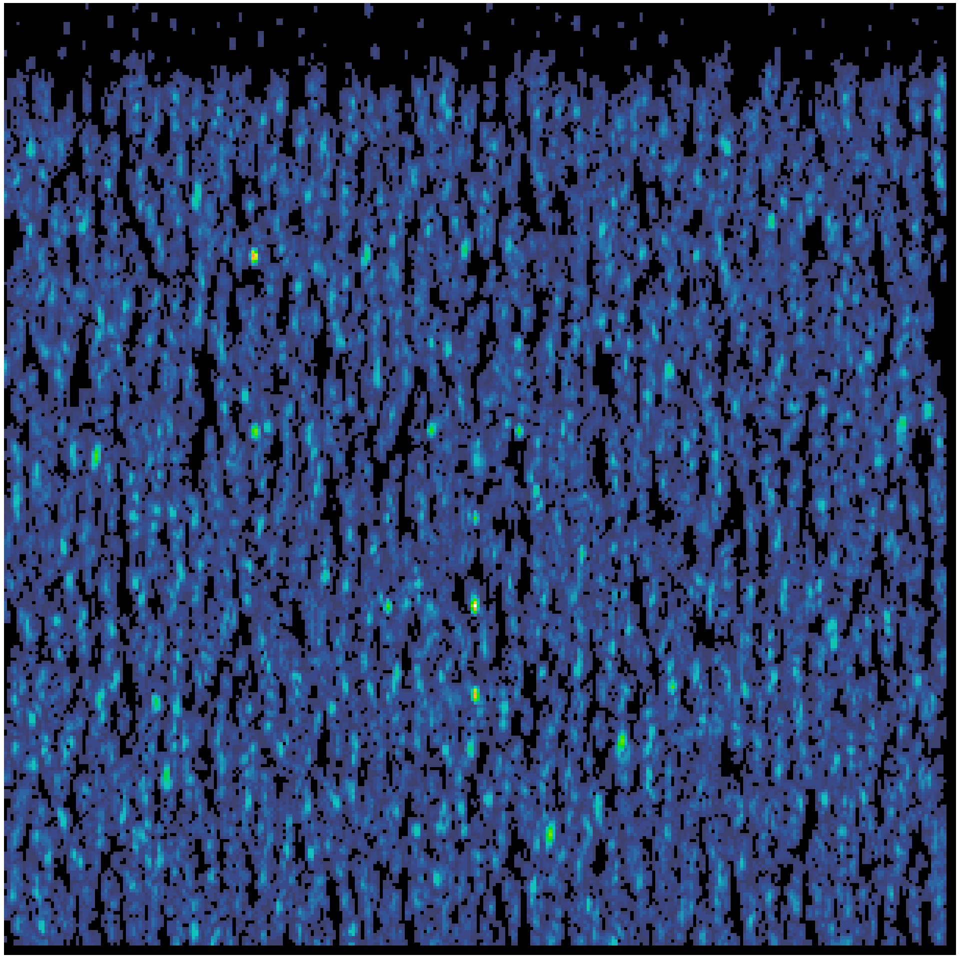
Future POLInSAR Application Developments:

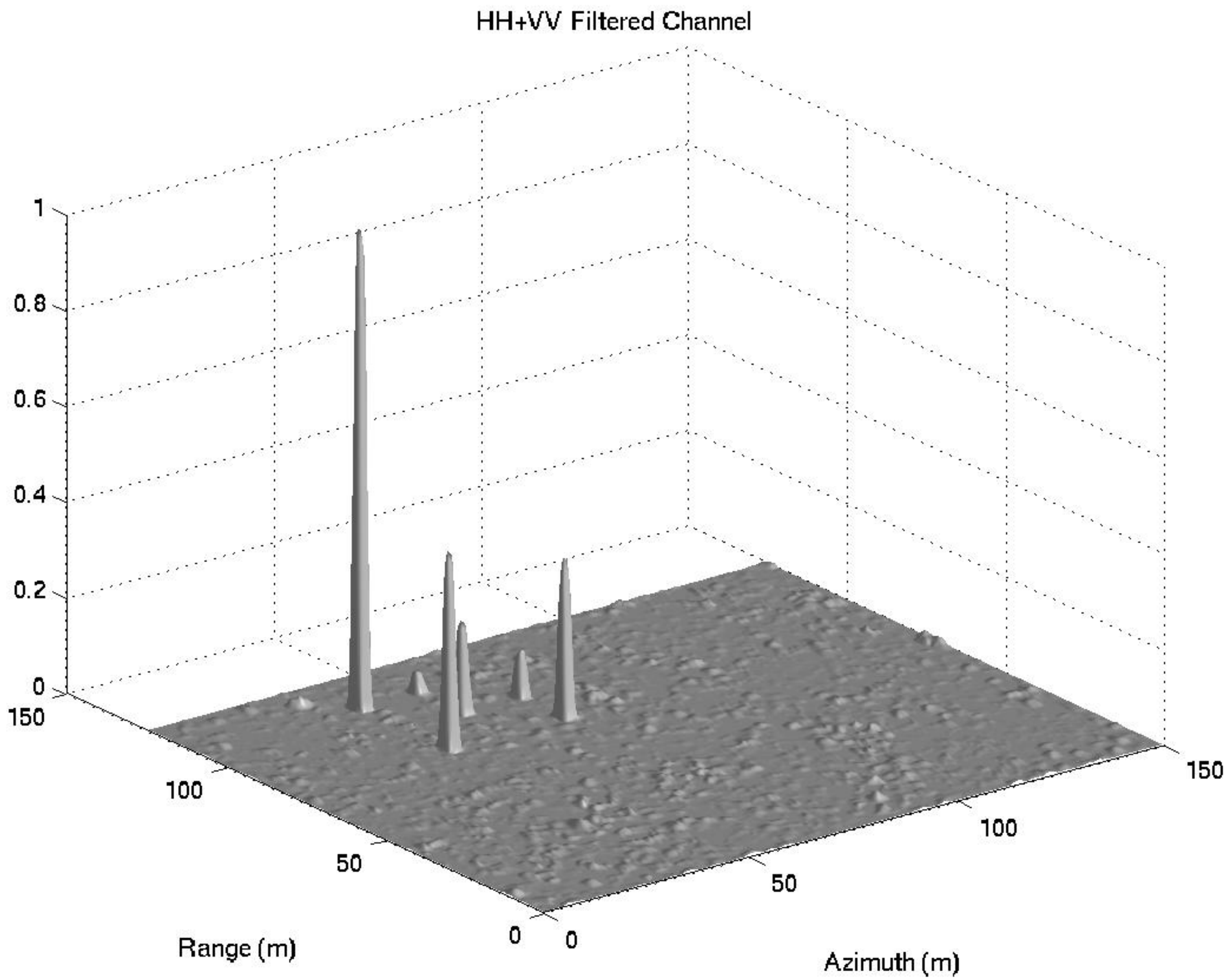
- Concealed Target Detection (FOPEN)

POLInSAR can be used to separate surface and volume contributions..with applications in target detection



L-Band FOPEN Simulations: Corner Reflectors in Scots Pine Forest
Courtesy of Dr. Mark Williams, DSTO, Australia

Detection of Obscured Corner Reflectors using POLInSAR



S.R. Cloude, D.G. Corr, M.L. Williams, "Target Detection Beneath Foliage Using Polarimetric SAR Interferometry", Waves in Random Media, volume 14, issue 2, pages S393 - S414., 2004

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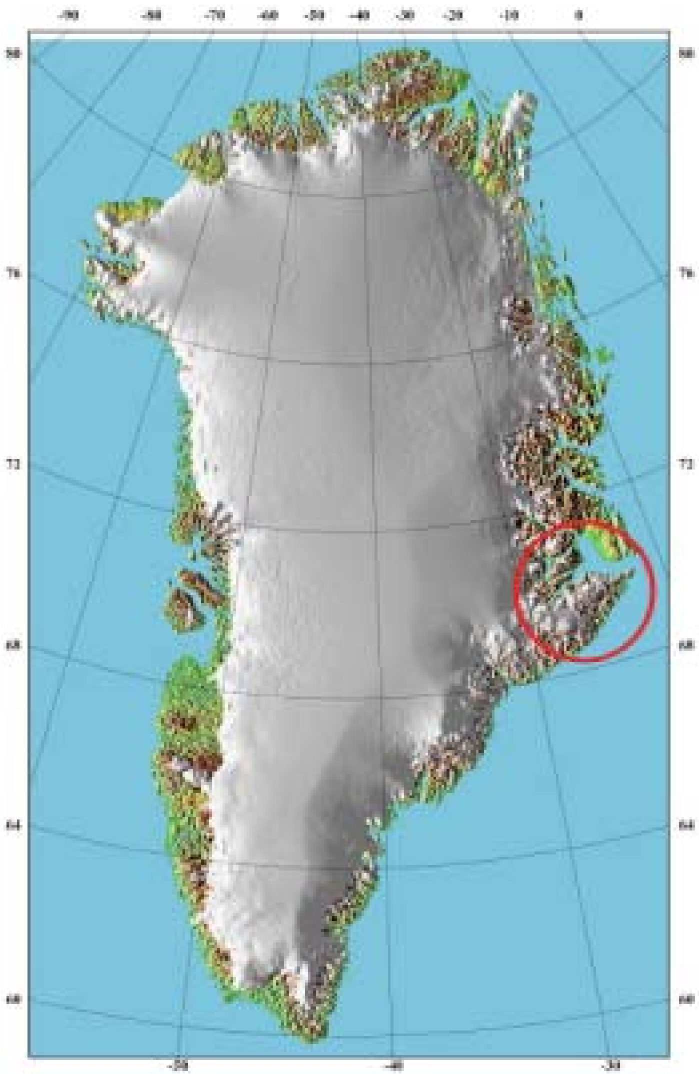
Land Ice and Snow Applications

Land ice site



Geikie ice cap, Greenland

Ice zones:	percolation, (wet-snow)
Penetration:	up to 13 m at C-band
Accumulation:	2 – 3 m per year
Elevation:	1600 – 2300 m
Latitude:	69°56' N
Size:	80 km (east-west)
	15 km (north-south)
SAR mapping:	Aug. 1997 and 1998

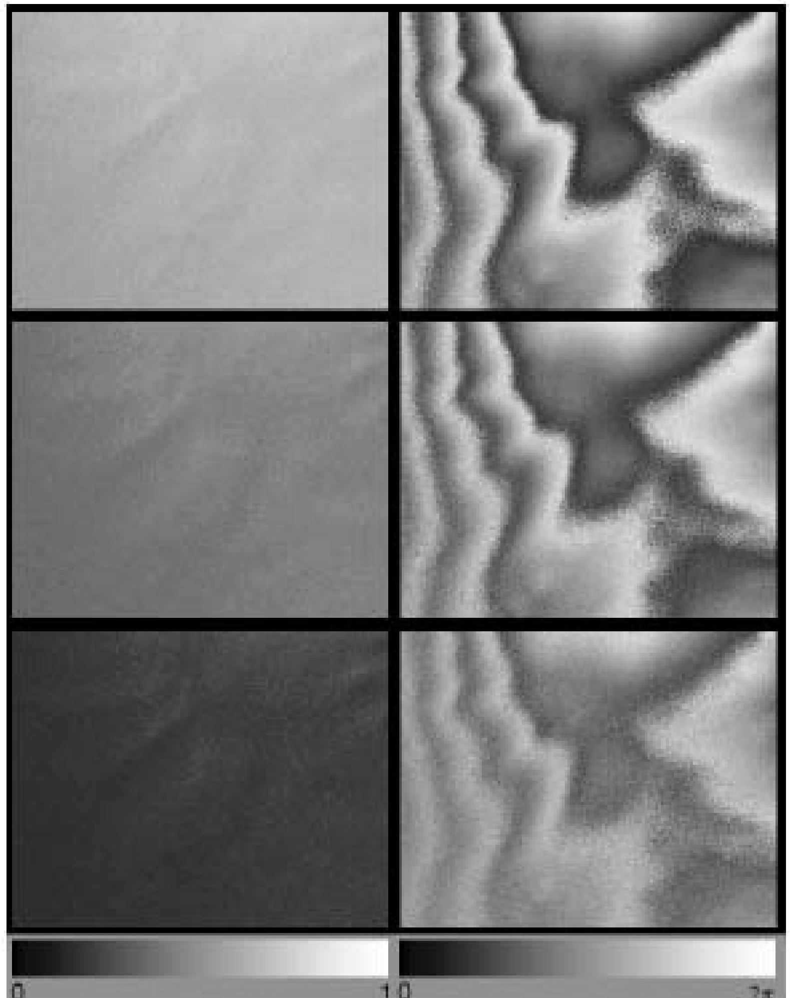
Optimization

amplitude | phase

$|\gamma_{opt1}|$ $\angle\gamma_{opt1}$

$|\gamma_{opt2}|$ $\angle\gamma_{opt2}$

$|\gamma_{opt3}|$ $\angle\gamma_{opt3}$

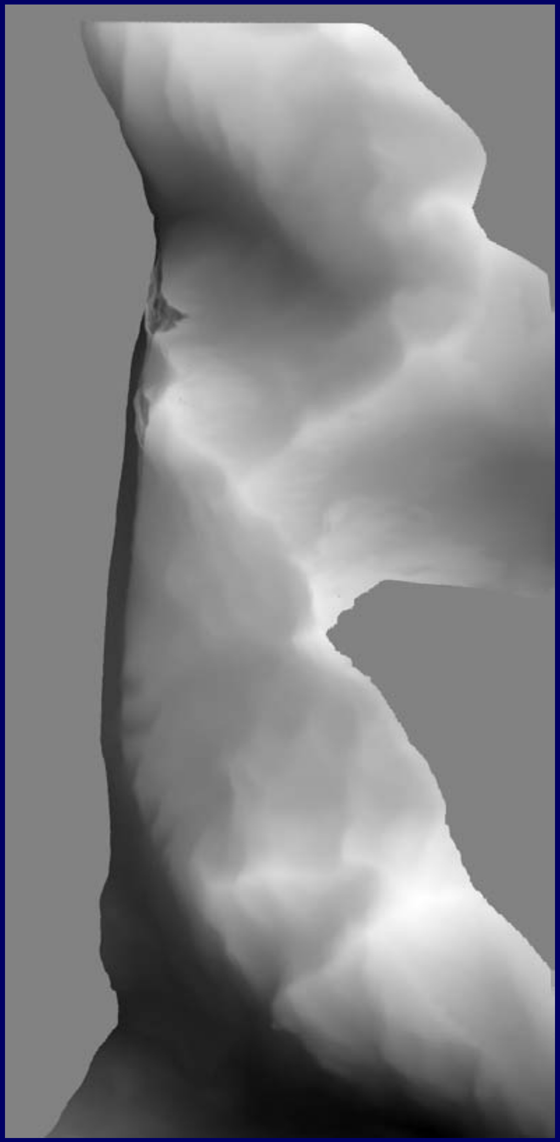


…need new model developments for interpretation of data

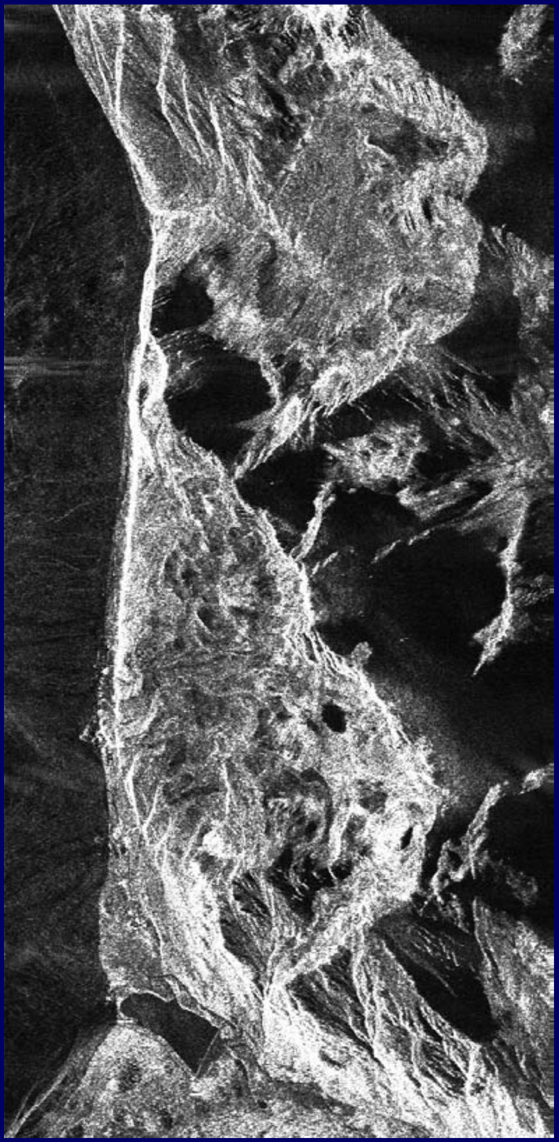
Kühtai Test Site

L-band

E-SAR / Test Site: Kuehtai / Austria



X-band DEM



HV

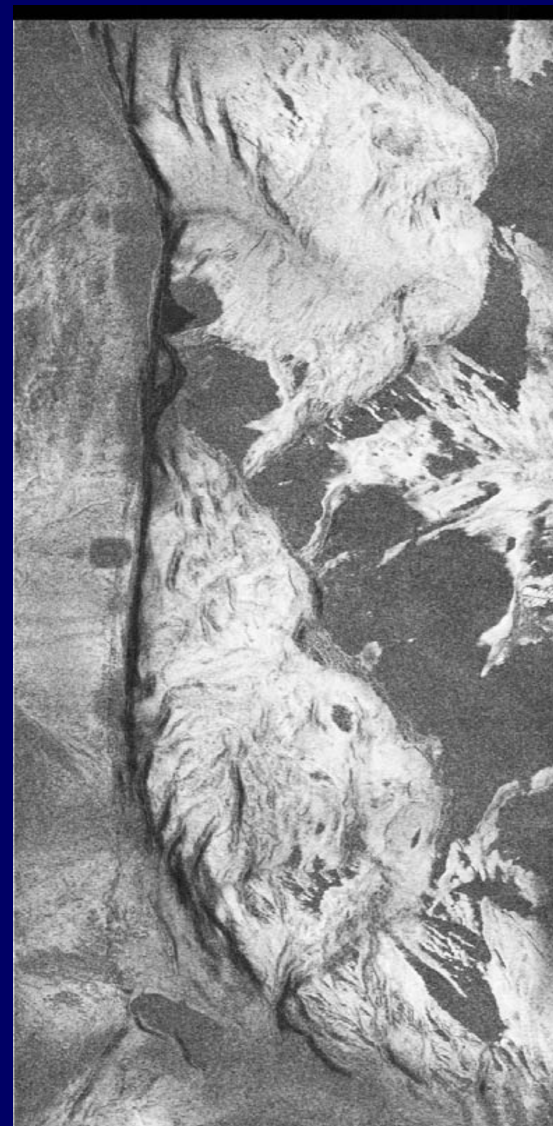
Interferometric Coherence Images

L-band

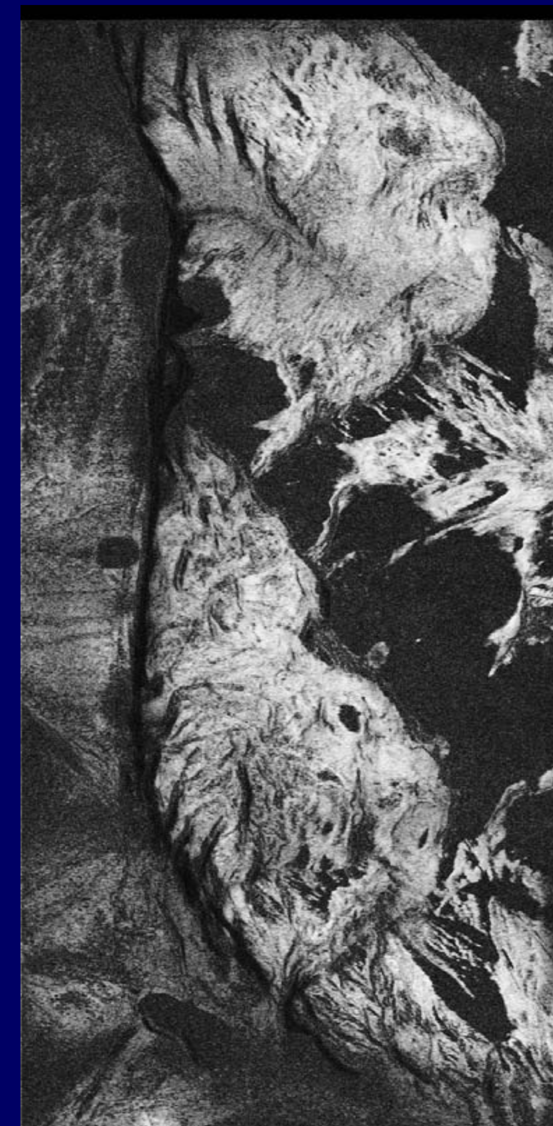
E-SAR / Test Site: Kuehtai / Austria

Baseline=20m

Opt 1



Opt 2

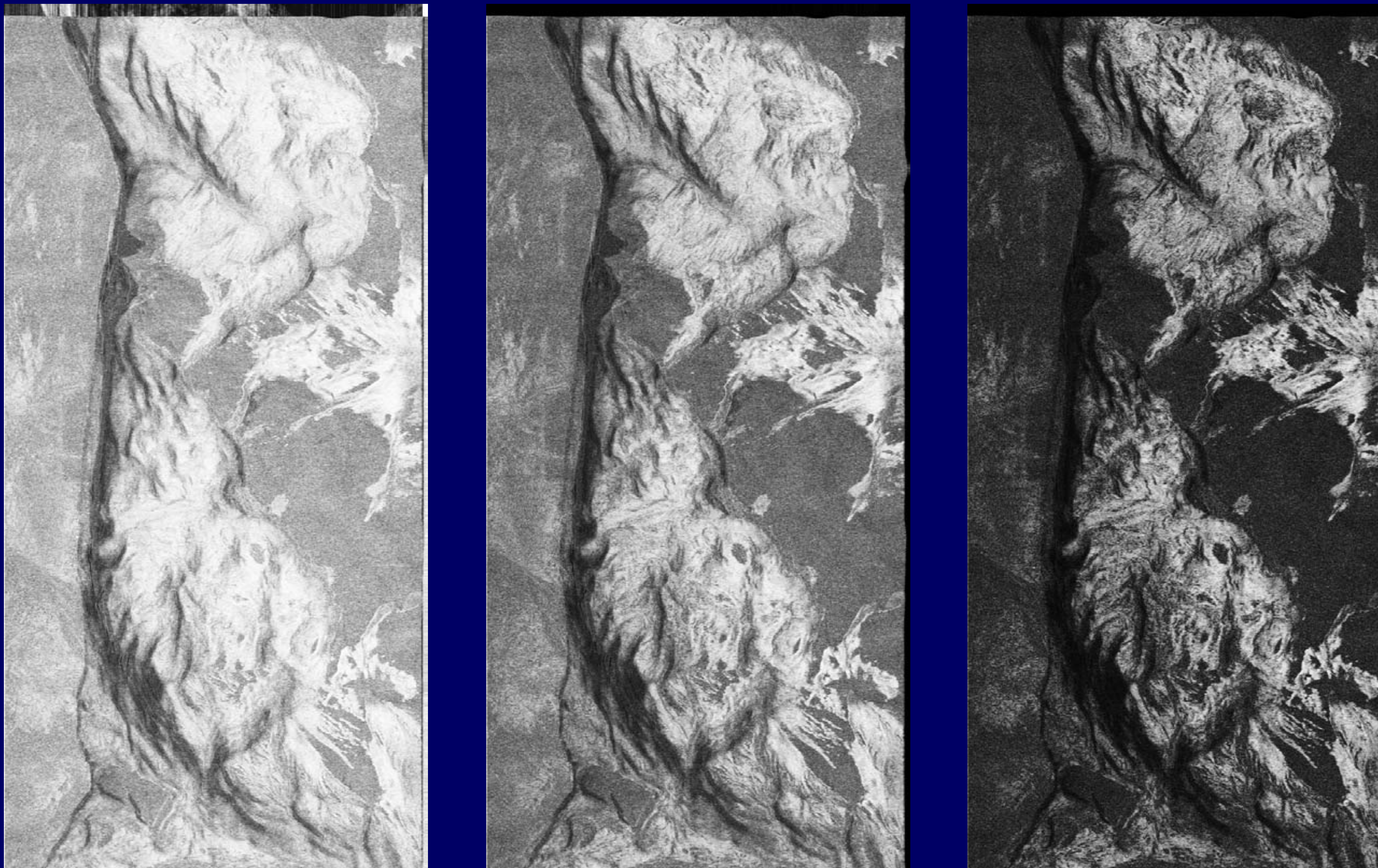


Opt 3

Interferometric Coherence Images

L-band

E-SAR / Test Site: Kuehtai / Austria



Baseline=40m *Opt 1* *Opt 2* *Opt 3*

Multi-Baseline Techniques:

a) Vertical Structure

Structural Ambiguity in Single Baseline Interferometry (SBPI)

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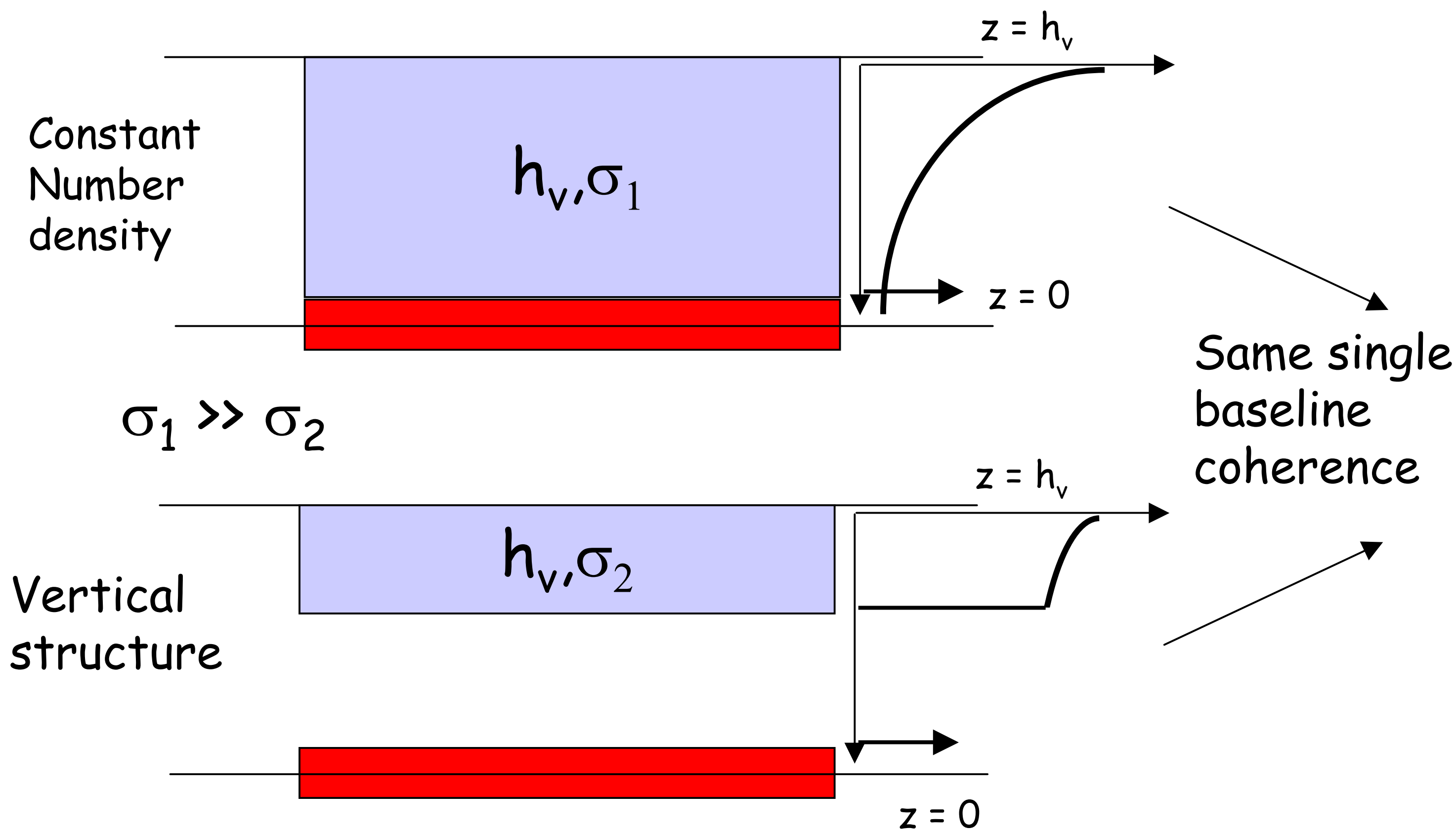
e.g Scots Pine



…need multi-baseline interferometry to resolve this ambiguity

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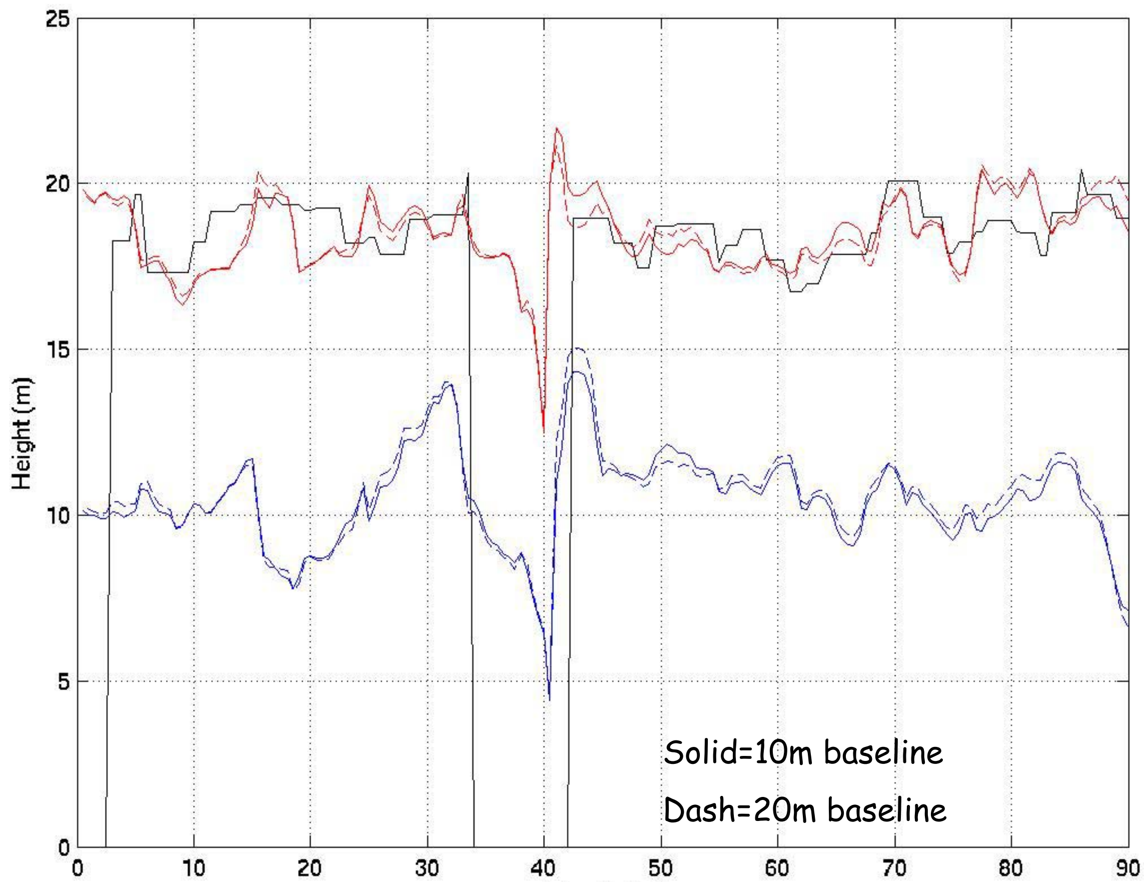
The solution….dual baseline interferometry

…leads to better height estimation (red)

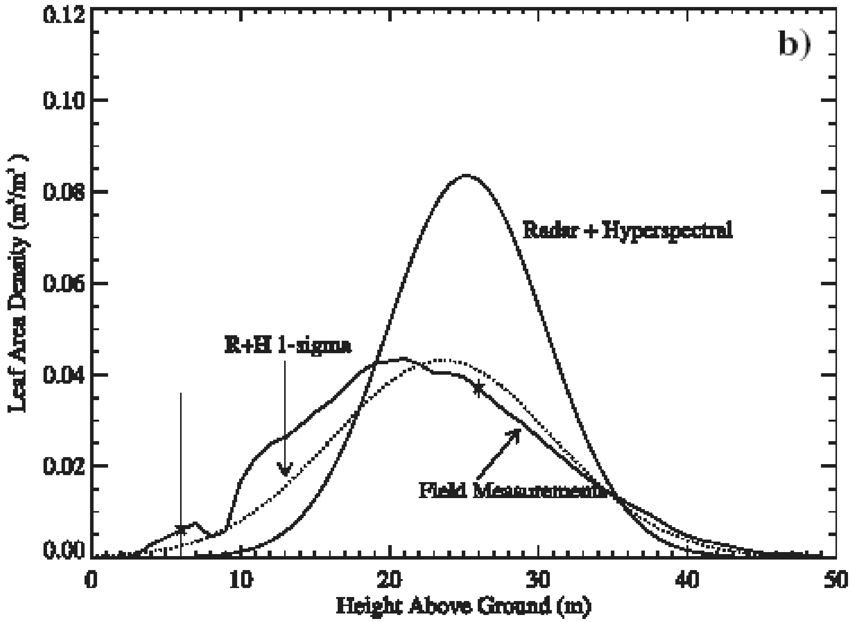
+ an estimate of crown depth (blue)



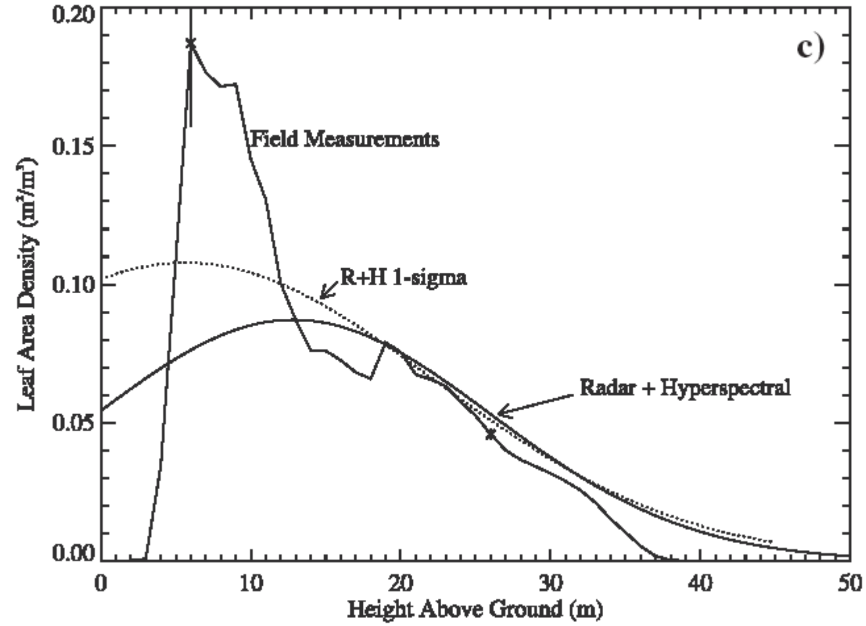
..Natural extension is to consider multiple baselines..

Example of LAD estimates using multi-baseline Interferometry + hyperspectral data

good fit…



…bad fit



R.N. Treuhaft, G.P.Asner, B.E. Law, S. Van Tuyl, "Forest Leaf Area Density Profiles from the quantitative fusion of radar and hyperspectral data", J. Geophys. Res., 107(D21), 4568, 2002

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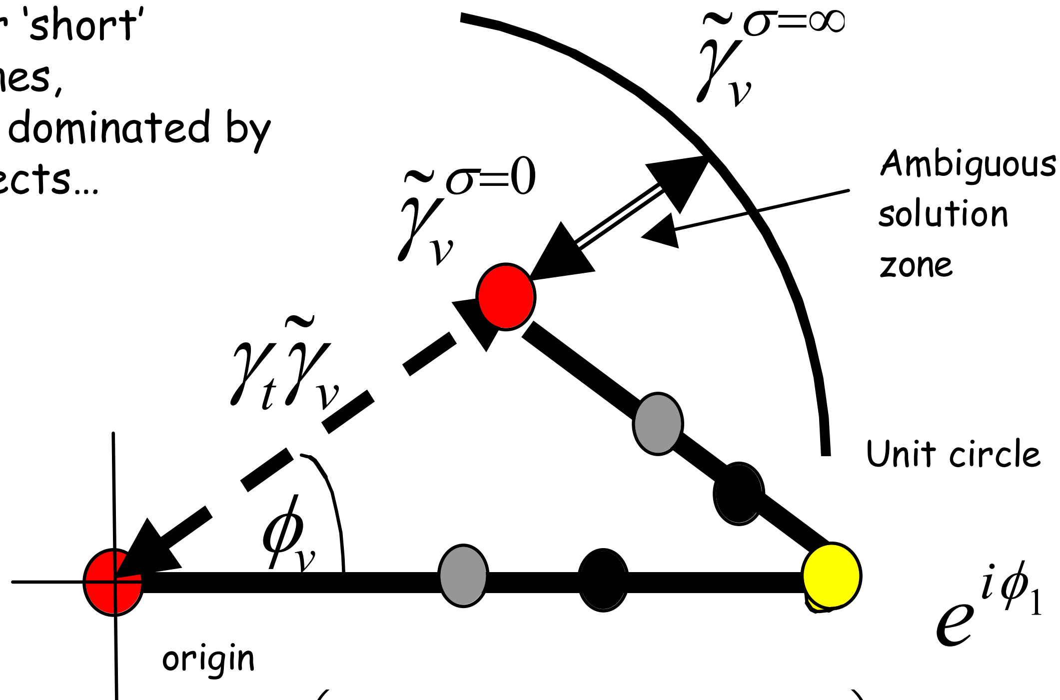
Multi-Baseline Techniques:

b) Temporal Decorrelation

Geometrical model for temporal decorrelation

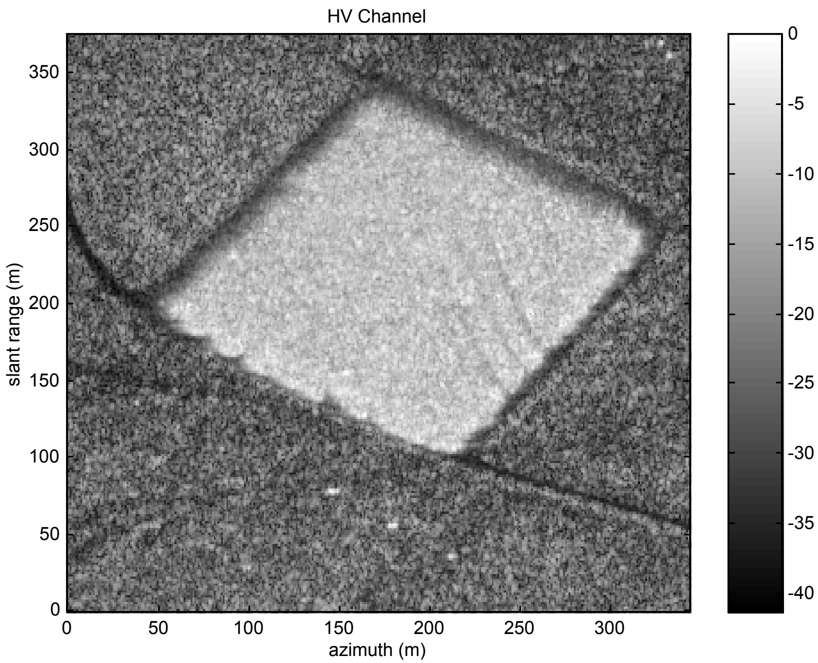
Assume that for 'short' temporal baselines, decorrelation is dominated by wind driven effects…

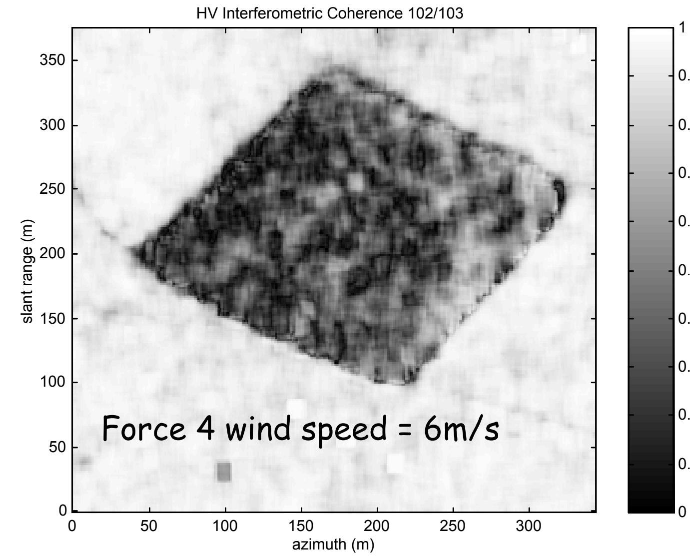


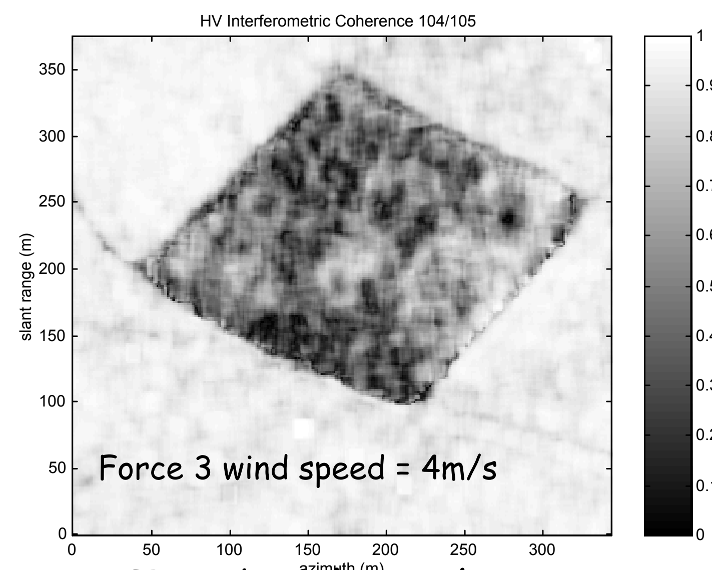
$$\tilde{\gamma} = e^{i\phi}\left(\gamma_t \tilde{\gamma}_v - \frac{\mu}{1+\mu}\left(1 - \gamma_t \tilde{\gamma}_v\right)\right)$$

Temporal decorrelation changes the observed coherence variation with polarisation but maintains the line model and causes an unknown rotation about the ground topography point…to test this model we use E-SAR/SIR-C data

Fox Covert, England, L-Band ESAR Data







Zero baseline coherence

Uniform Birch stand

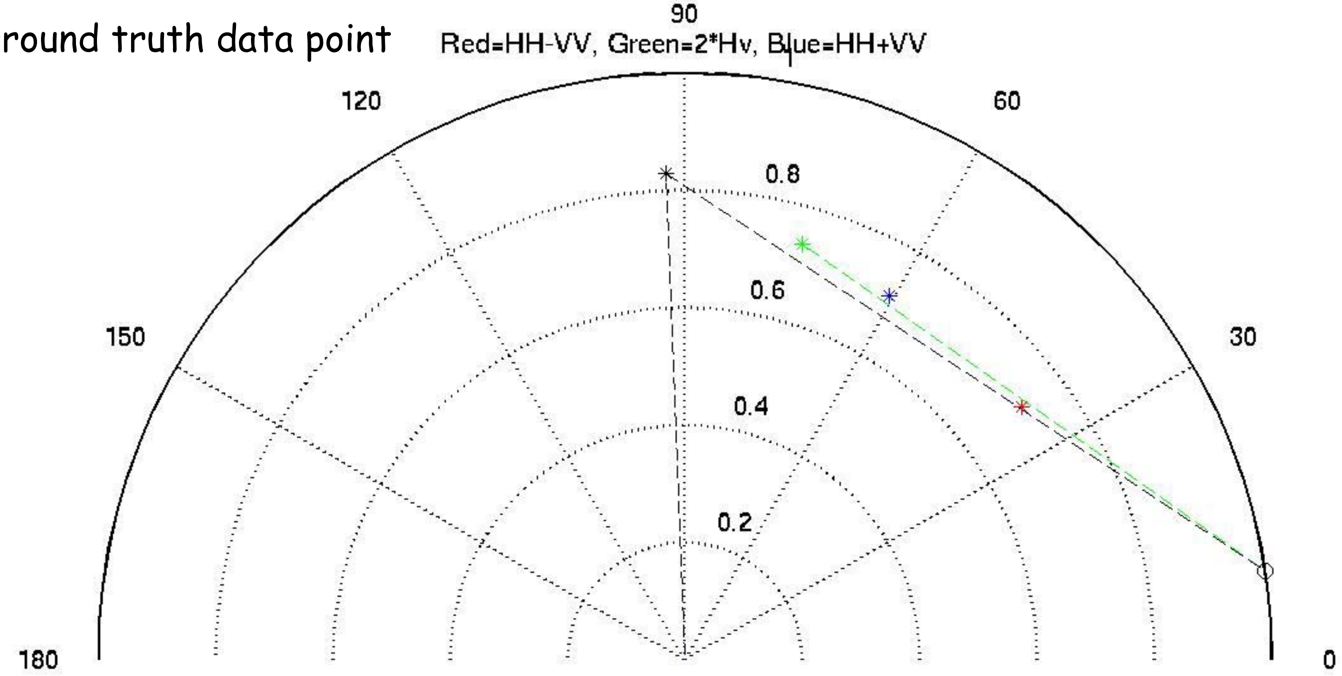
Mean tree height = 17.4m

May 2002

Weather conditions, dry/ gusting force 3-5

POLInSAR Coherence Loci: 8m baseline using known tree height and ground phase

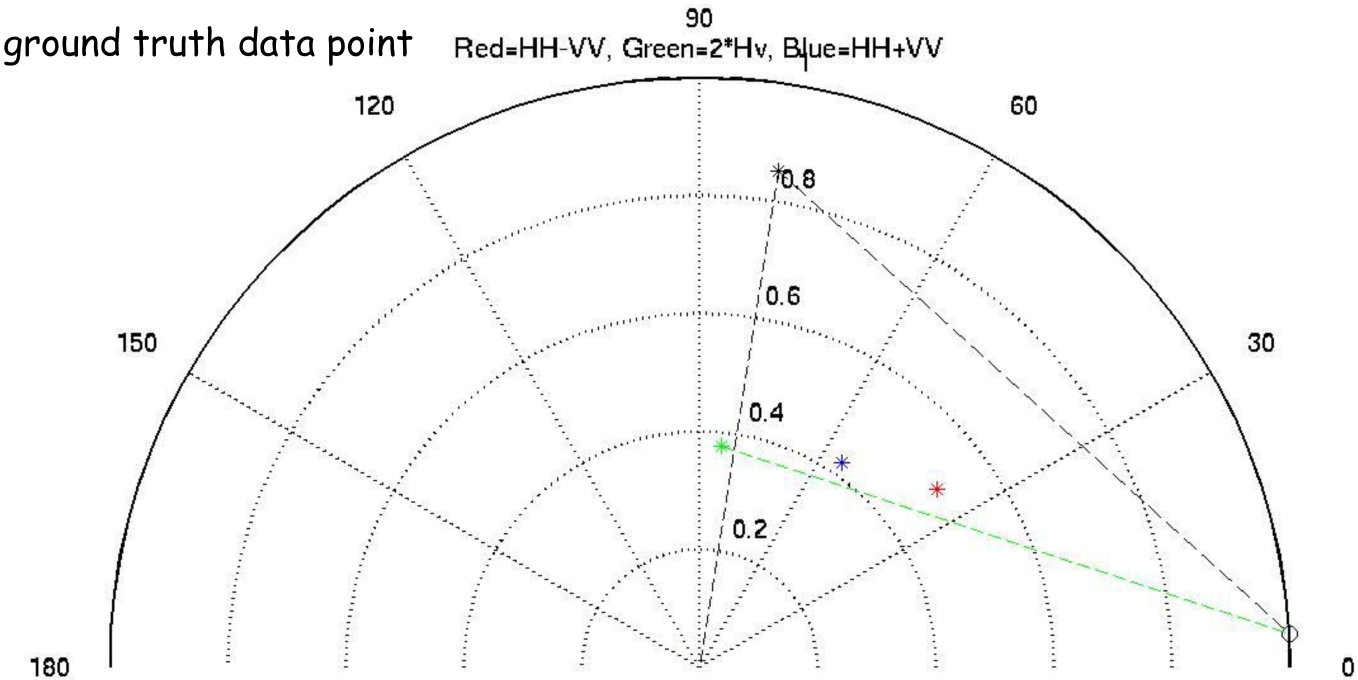
black star = ground truth data point



Fox Covert data point : zero temporal effect, $\mu_{min} > 0$

POLInSAR Coherence Loci: 8m baseline using known tree height and ground phase

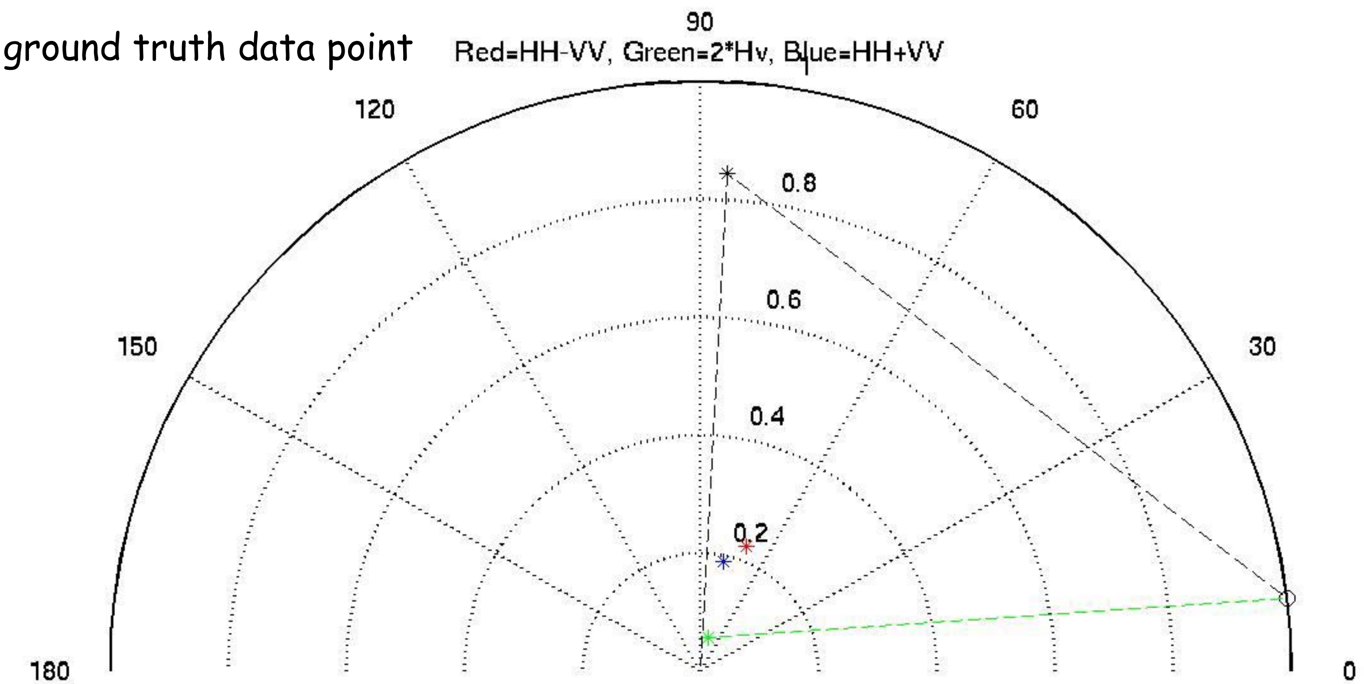
black star = ground truth data point



Fox Covert data point : moderate temporal effect, μ_{min} = 0

POLInSAR Coherence Loci: 8m baseline using known tree height and ground phase

black star = ground truth data point



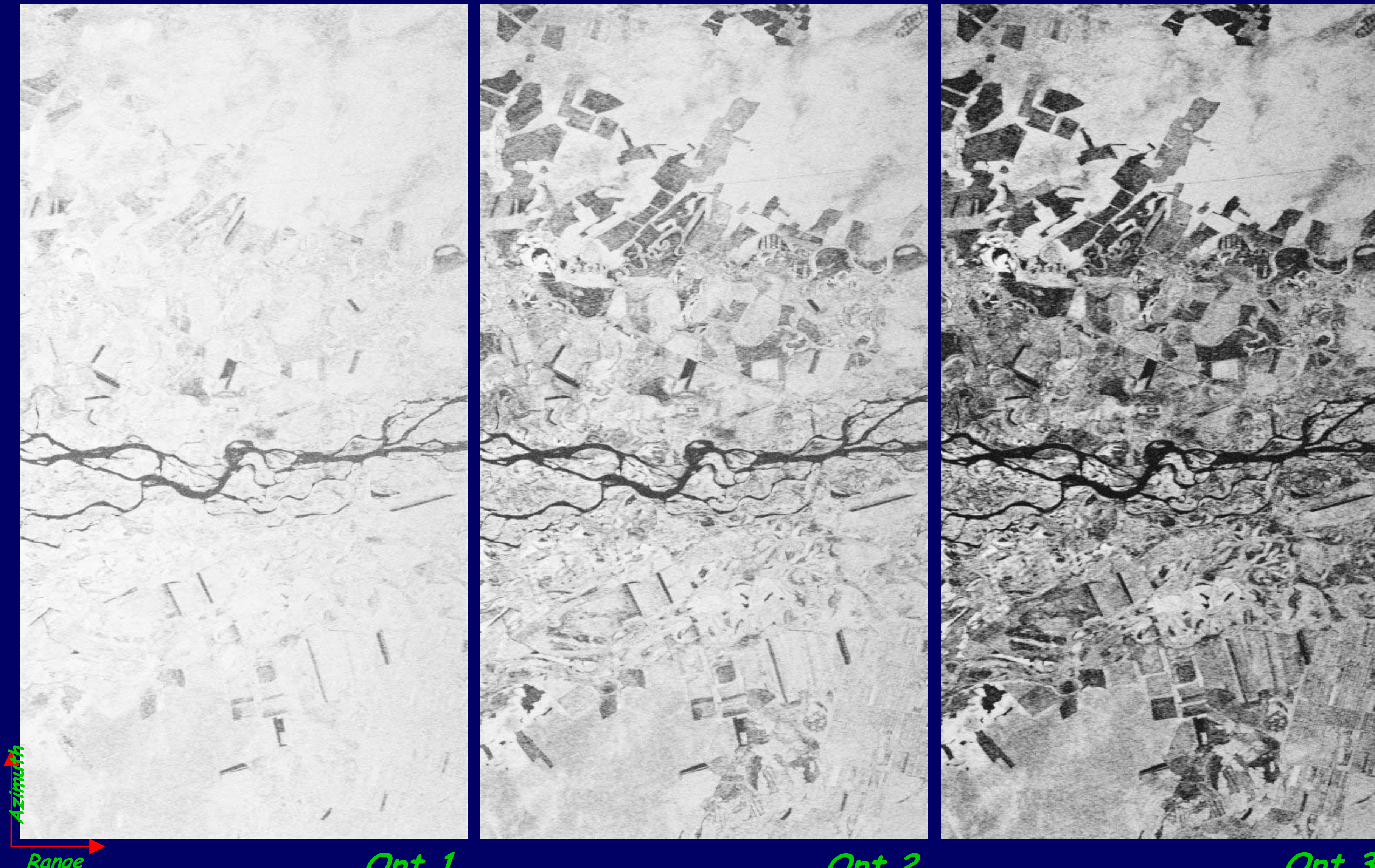
Fox Covert data point : strong temporal effect, μ_{min} = 0

Test Data : SIR-C L-Band

DLR

L-band

SIR-C / Test Site: Kudara,Russia

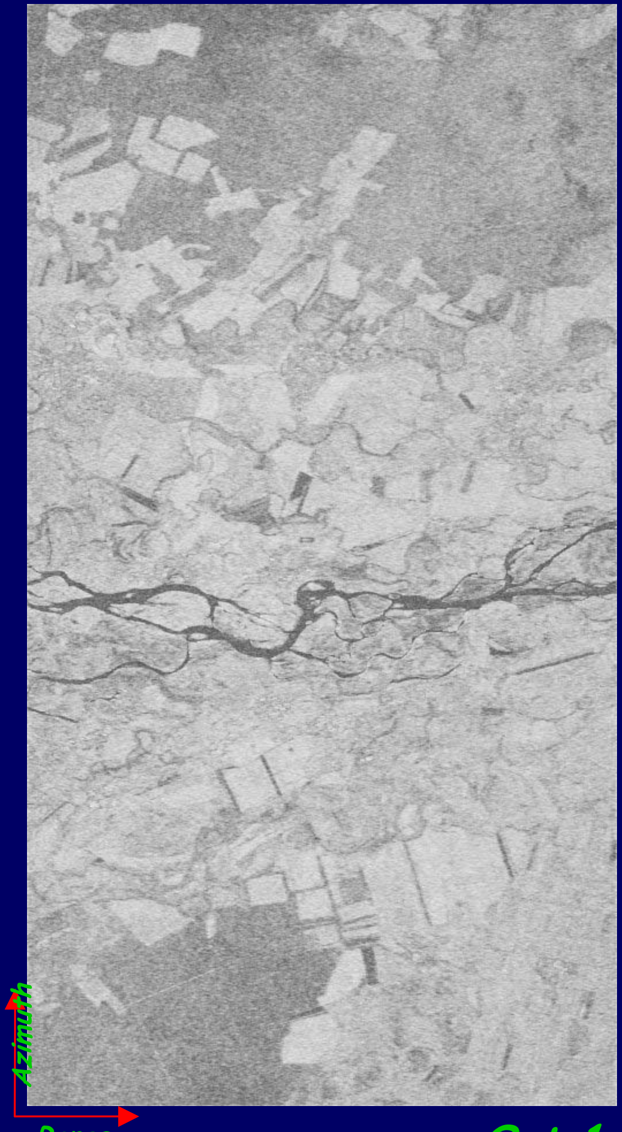


Opt 1 *Opt 2* *Opt 3*

Test Data : SIR-C C-Band

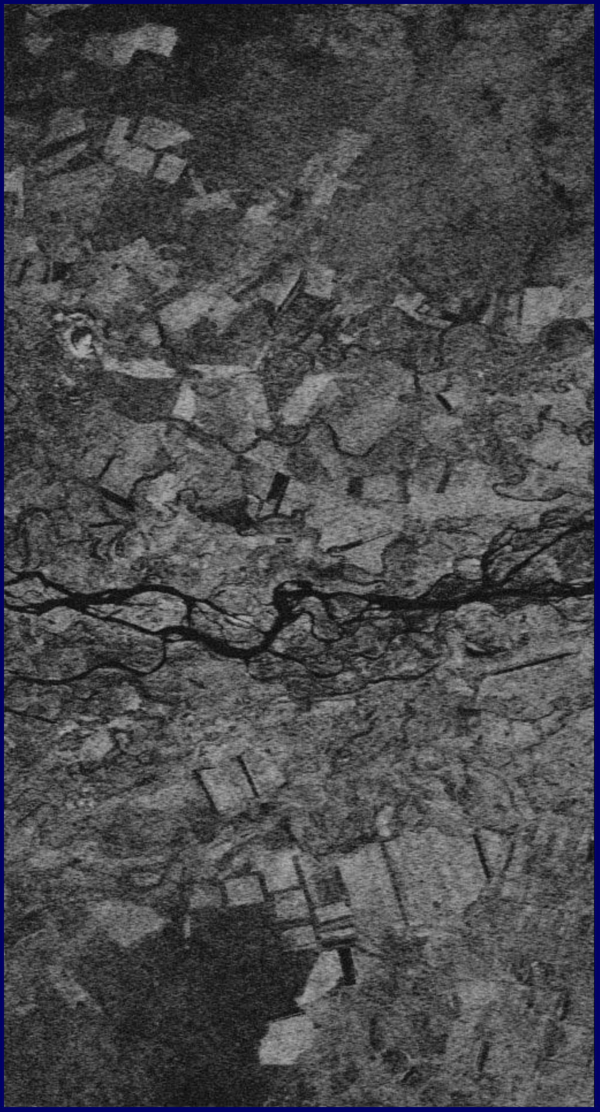
C-band

SIR-C / Test Site: Kudara,Russia



Opt 1

Opt 2

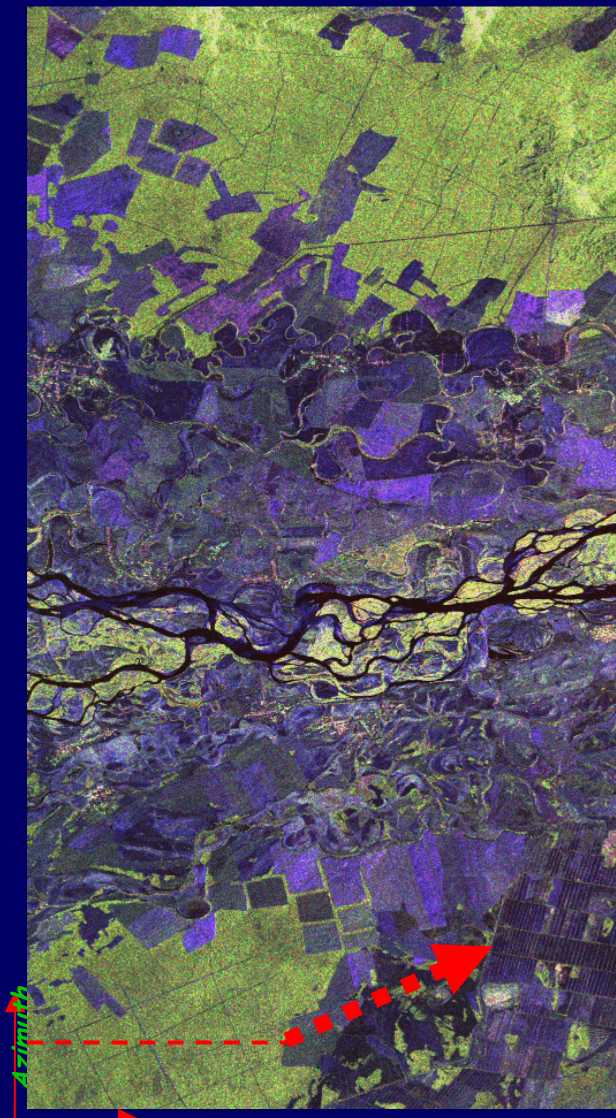


Opt 3

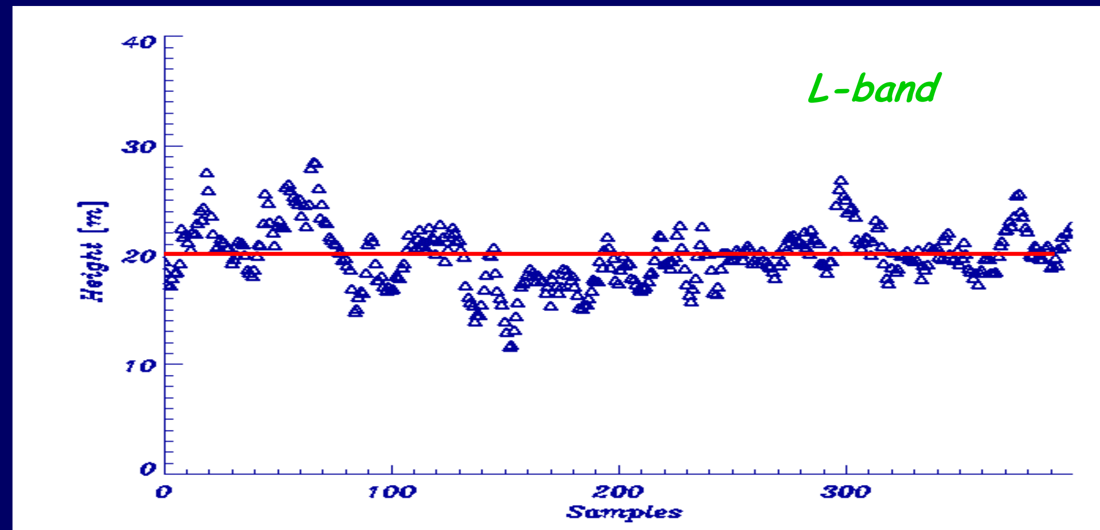
Tree Height Estimation

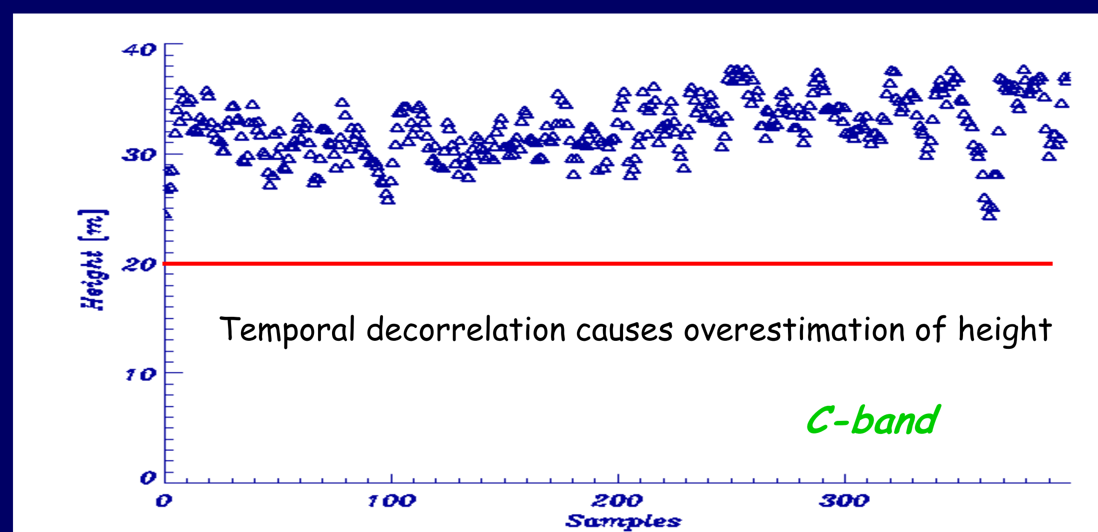
Temporal Baseline: 48 Hours

SIR-C / Test Site: Kudara,Russia



Pauli RGB Image

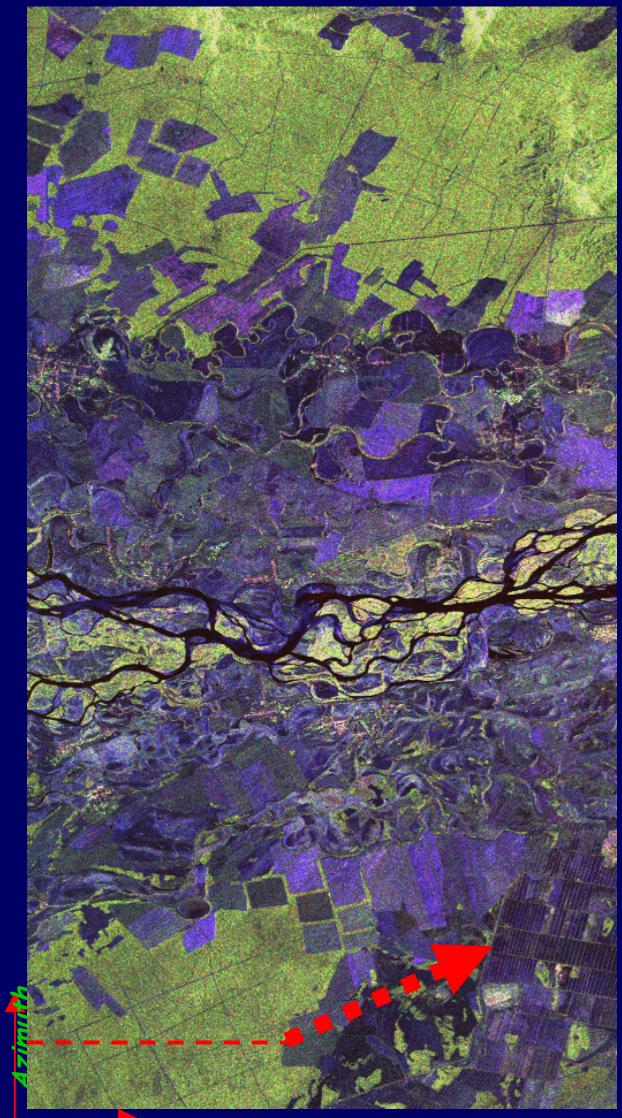




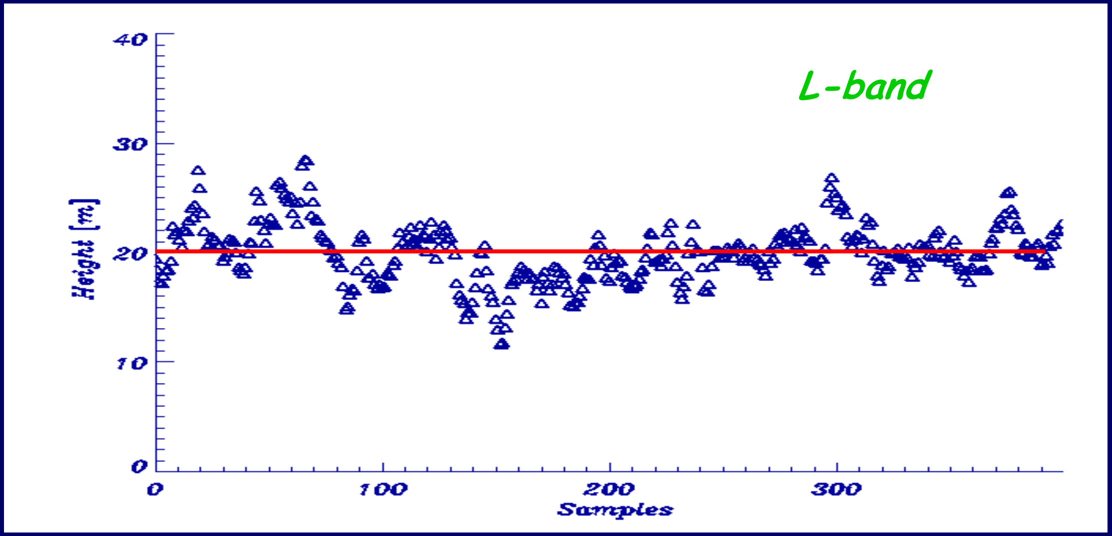
Dual Frequency Compensation for Temporal Effects

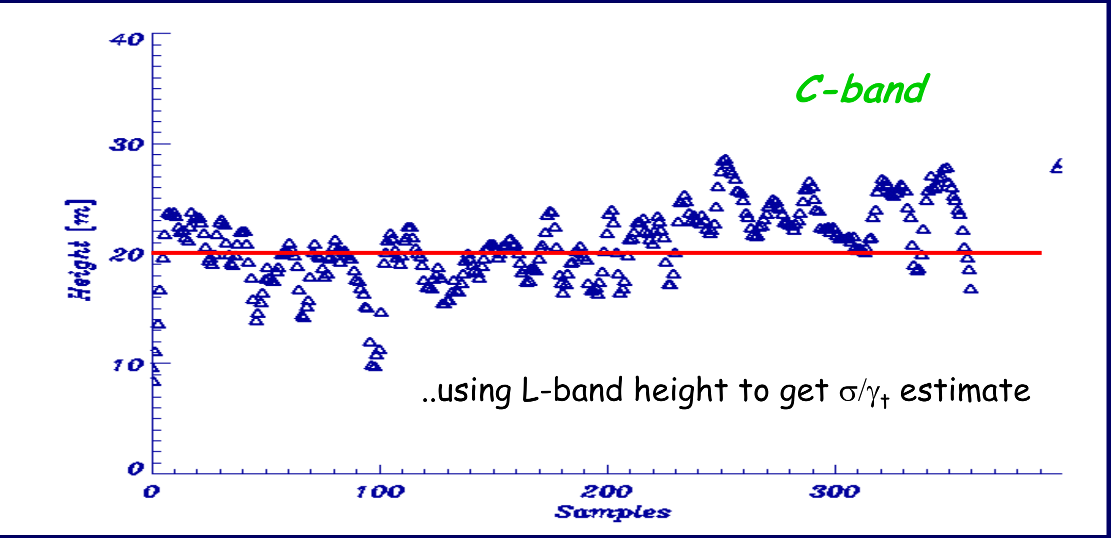
Temporal Baseline: 48 Hours

SIR-C / Test Site: Kudara,Russia



Pauli RGB Image





Agriculture:

Plant Water Content

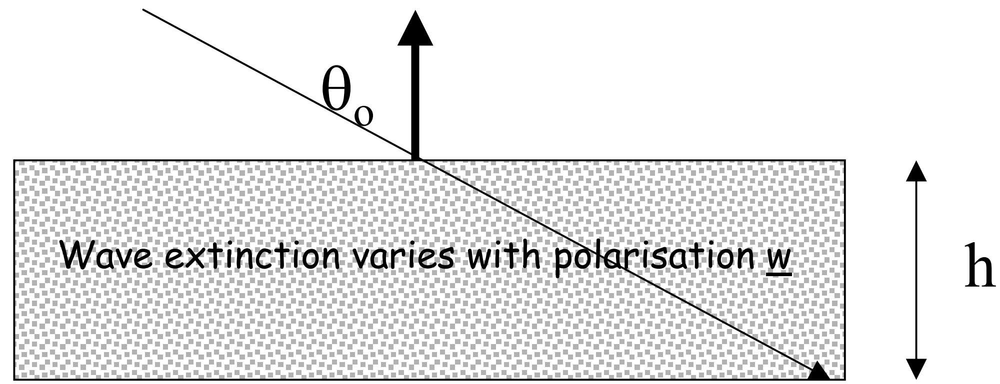
Ulaby Uniaxial Vegetation Model

x and y are the eigenpolarisations: typically h and v

Mixture of 2 components:

Leaf (L) + Stalks (S)

↓	↘
Azimuthal Symmetry	uniaxial crystal



$$L(\underline{w}) = L_L + L_S(\underline{w})$$

where

$$L_L \approx \exp\left(-\frac{4\pi v_L \varepsilon_L'' h}{3\lambda\cos\theta_o}\right) \Rightarrow h v_L = LAI.\bar{t}$$

..in small albedo regime absorption loss >> scattering loss

$$L_s \Rightarrow \begin{cases} L_{xx} \approx \exp\left(-\dfrac{4\pi n_o'' h}{\lambda\cos\theta_o}\right) & n_o'' = \mathrm{Im}(\sqrt{\varepsilon_o}) \quad \varepsilon_o \approx (1+2v_s) - i\left(\dfrac{4 v_s \varepsilon_s''}{(\varepsilon_s'')^2 + (\varepsilon_s')^2}\right) \\ L_{yy} \approx \exp\left(-\dfrac{4\pi(\cos^2\theta_o n_o'' + \sin^2\theta_o n_e'')h}{\lambda\cos\theta_o}\right) & n_e'' = \mathrm{Im}(\sqrt{\varepsilon_e}) \quad \varepsilon_e \approx (1 + v_s(\varepsilon_s' - 1)) - i v_s \varepsilon_s'' \end{cases}$$

L component matches the random volume assumption..

.. but the S component requires a multi-channel coherence description

…the oriented volume of 'ov' model.. When S >> L

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Differential Extinction and Oriented Volume (OV) Model

If $\sigma_y \gg \sigma_x$ (strong uniaxial component) then $|\tilde{\gamma}_1| > |\tilde{\gamma}_2| > |\tilde{\gamma}_3| \geq 0$

..so we get a measurable difference between the coherences in different polarisations which in turn can be related to physical parameters as:

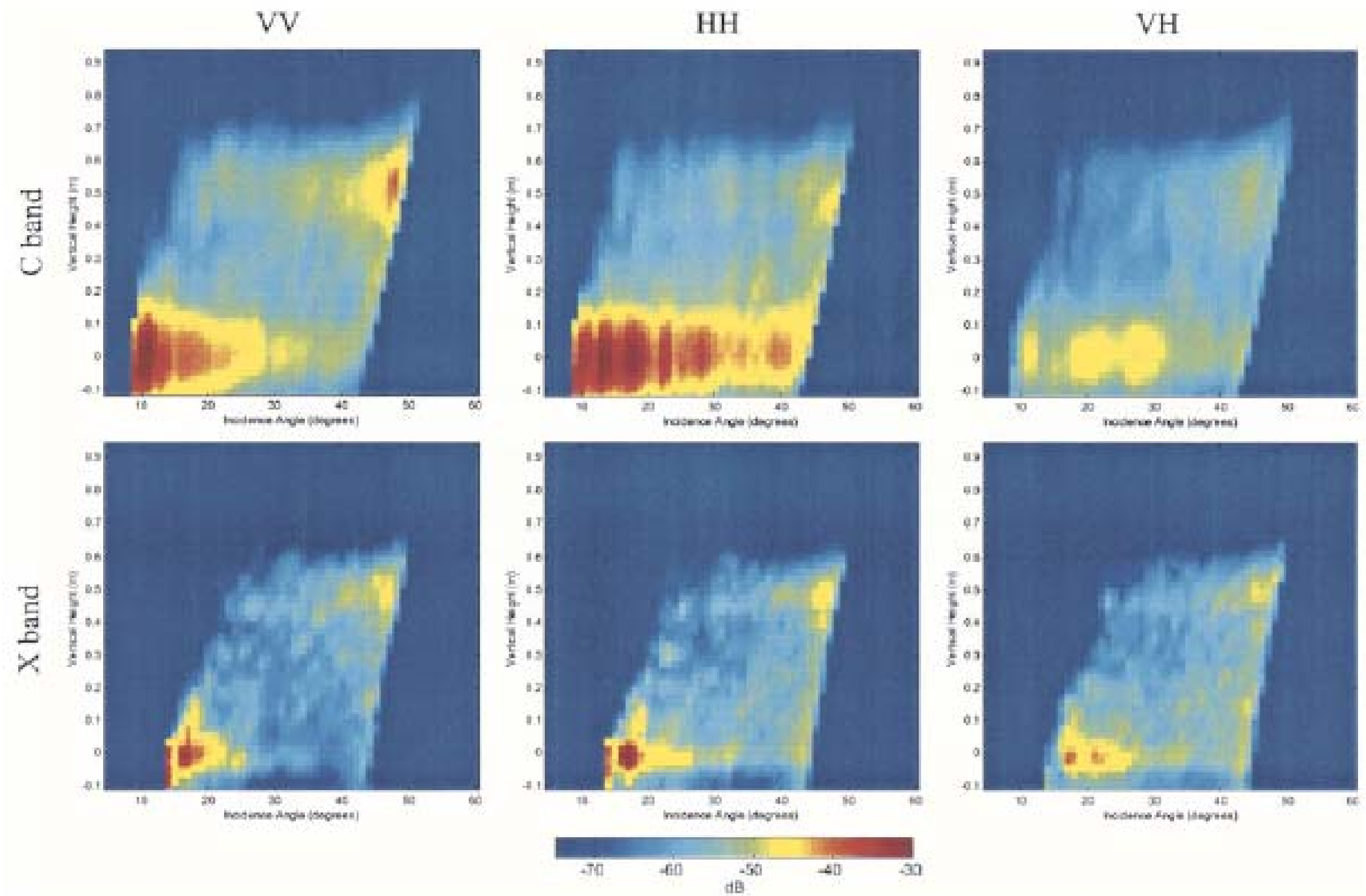
$$\tilde{\gamma}_3 = \frac{2\sigma_x\, e^{i\phi(z_o)}}{\cos\theta_o(e^{2\sigma_x h_v/\cos\theta_o} - 1)} \int_0^{h_v} e^{ik_z z'} e^{\frac{2\sigma_x z'}{\cos\theta_o}} dz'$$

$$\tilde{\gamma}_2 = \frac{\sigma_x + \sigma_y\, e^{i\phi(z_o)}}{\cos\theta_o(e^{(\sigma_x+\sigma_y)h_v/\cos\theta_o} - 1)} \int_0^{h_v} e^{ik_z z'} e^{\frac{(\sigma_x+\sigma_y) z'}{\cos\theta_o}} dz'$$

$$\tilde{\gamma}_1 = \frac{2\sigma_y\, e^{i\phi(z_o)}}{\cos\theta_o(e^{2\sigma_y h_v/\cos\theta_o} - 1)} \int_0^{h_v} e^{ik_z z'} e^{\frac{2\sigma_y z'}{\cos\theta_o}} dz'$$

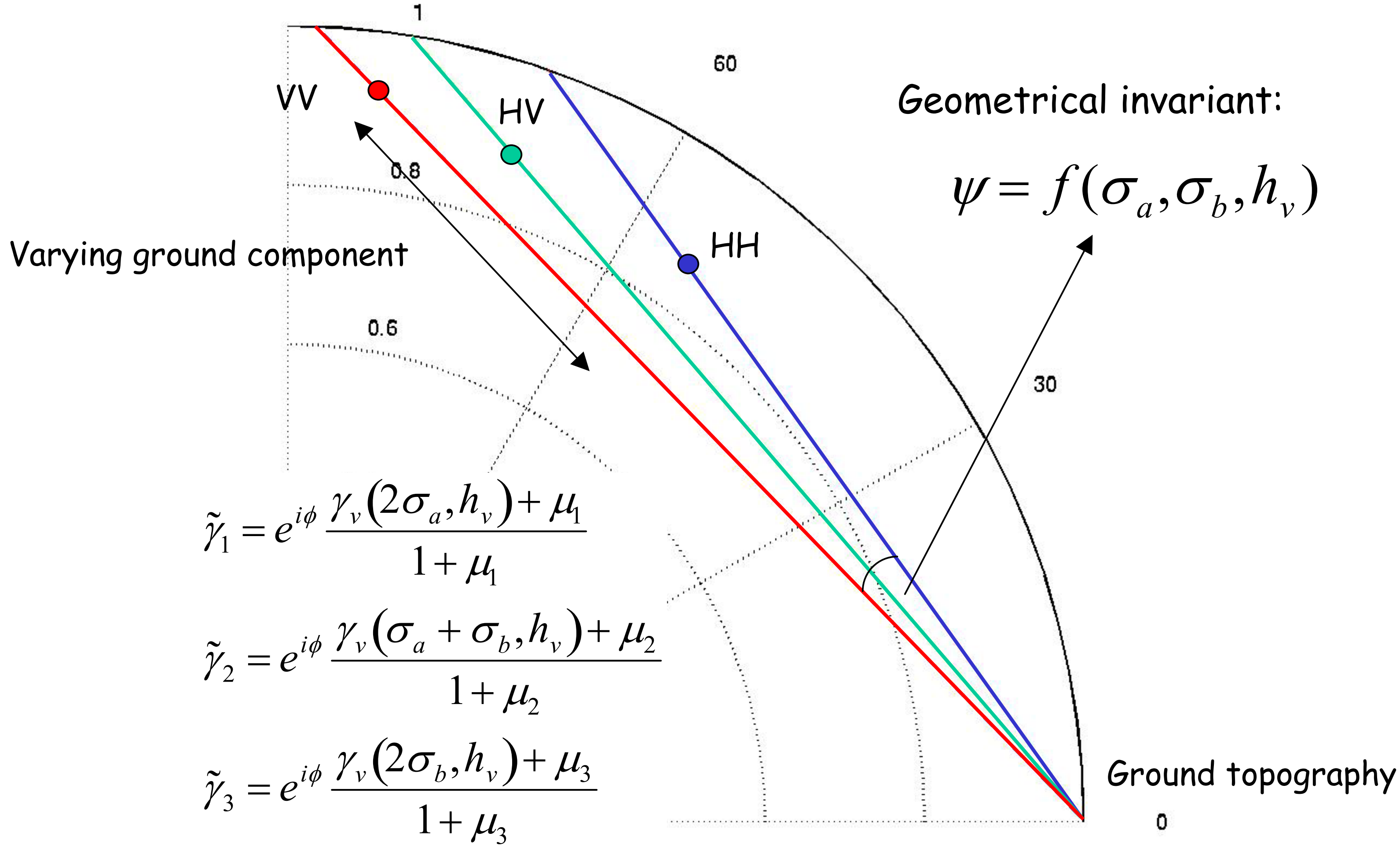
…now 6 observations with 4 unknowns (σ_x, σ_y, h_v, ϕ)..can be inverted..but..
…need to consider the influence of surface scattering
..leads to oriented volume over a ground (ovog) model

Example : Ground Effects in Wheat Scattering



S.C.M. Brown, S Quegan, K Morrison, J Bennett, G Cookmartin,
"High Resolution Measurements of Scattering in Wheat Canopies-Implications for Crop Parameter Retrieval",
IEEE Trans GRS 41 (7), July 2003, pp 1602-1610

Geometry of the oriented-volume-over-ground or'ovog' model



Geometrical invariant:

$$\psi = f(\sigma_a, \sigma_b, h_v)$$

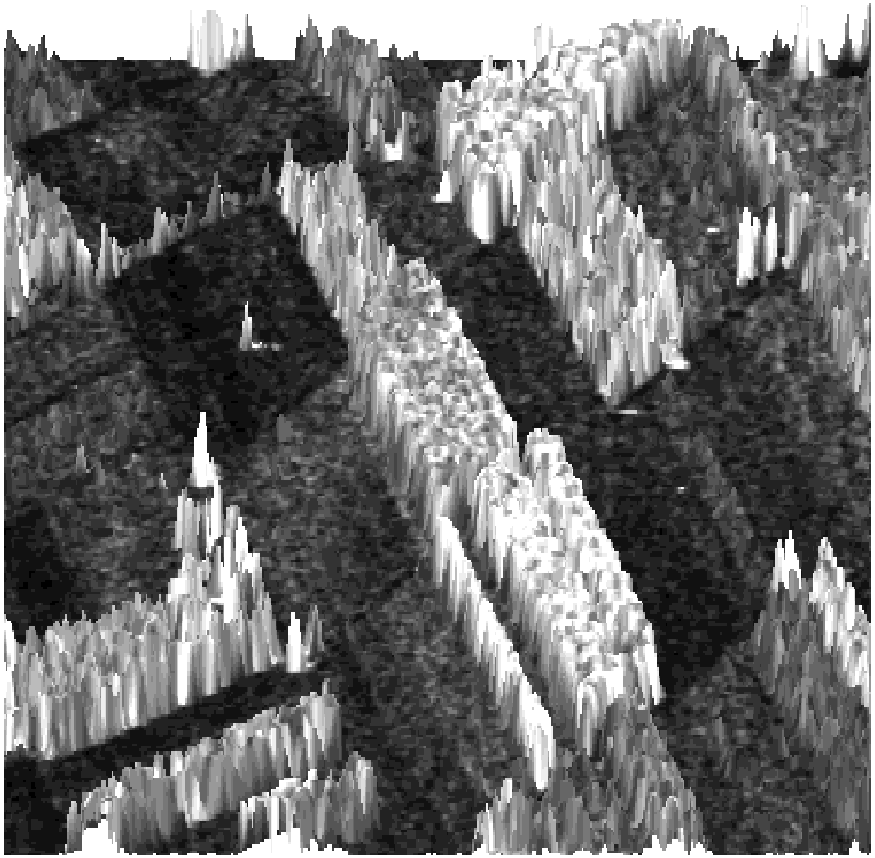
$$\tilde{\gamma}_1 = e^{i\phi}\frac{\gamma_v(2\sigma_a, h_v) + \mu_1}{1+\mu_1}$$

$$\tilde{\gamma}_2 = e^{i\phi}\frac{\gamma_v(\sigma_a + \sigma_b, h_v) + \mu_2}{1+\mu_2}$$

$$\tilde{\gamma}_3 = e^{i\phi}\frac{\gamma_v(2\sigma_b, h_v) + \mu_3}{1+\mu_3}$$

POLInSAR Agricultural Applications

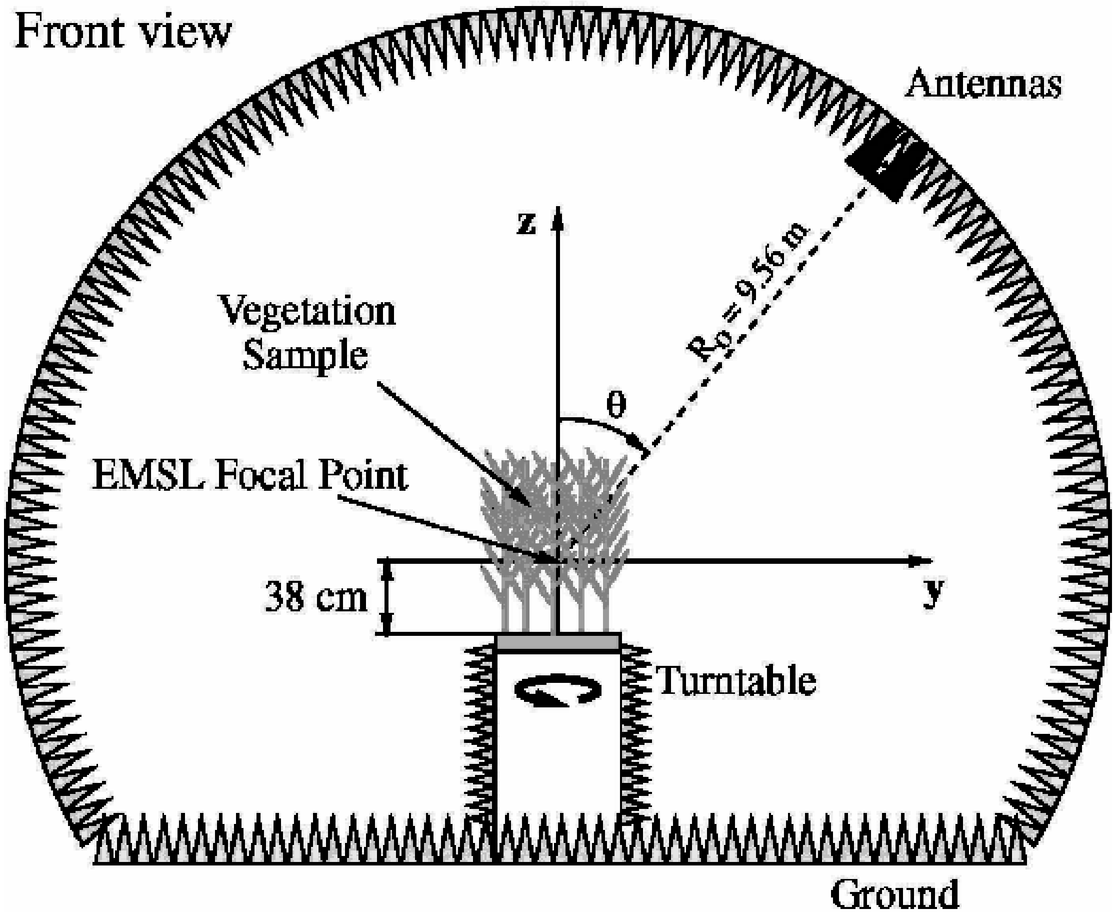
..using volume only 'ovog' inversion

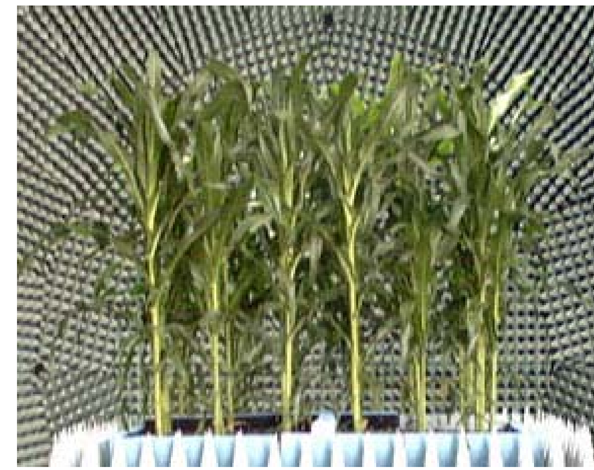


…potentially Crop Height, Vegetation Moisture Content, Surface Moisture..

…use GB-POLInSAR and Coherent EM Modelling to investigate..

EMSL POlInSAR Maize Experiment





6 x6 maize plants (2m x 2m)

hv = 1.8m

1.5 - 9.5 GHz (10MHz steps)

θ= 44:0.25:45 degrees

ϕ= 0:5:360 degrees

GB-POLInSAR Processing

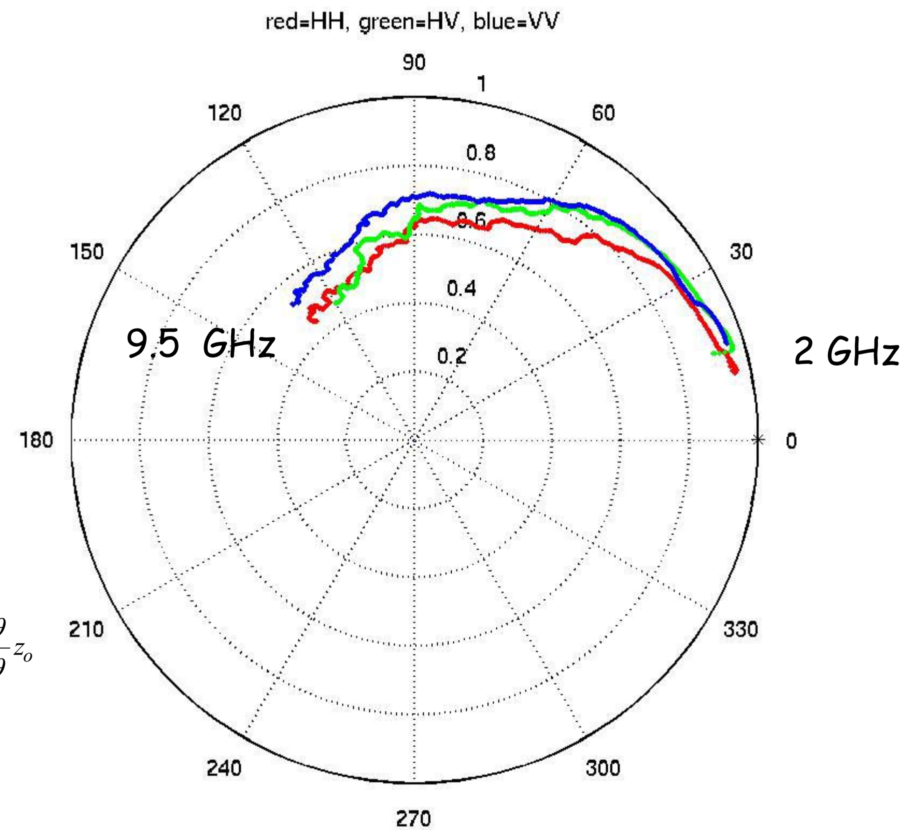
$$E_{\theta}^{pq}(f) \qquad E_{\theta+\Delta\theta}^{pq}(f)$$

$$f \rightarrow f(1 - \frac{\Delta\theta}{\tan\theta})$$

$$k_z = \frac{4\pi f \Delta\theta}{c.\sin\theta}$$

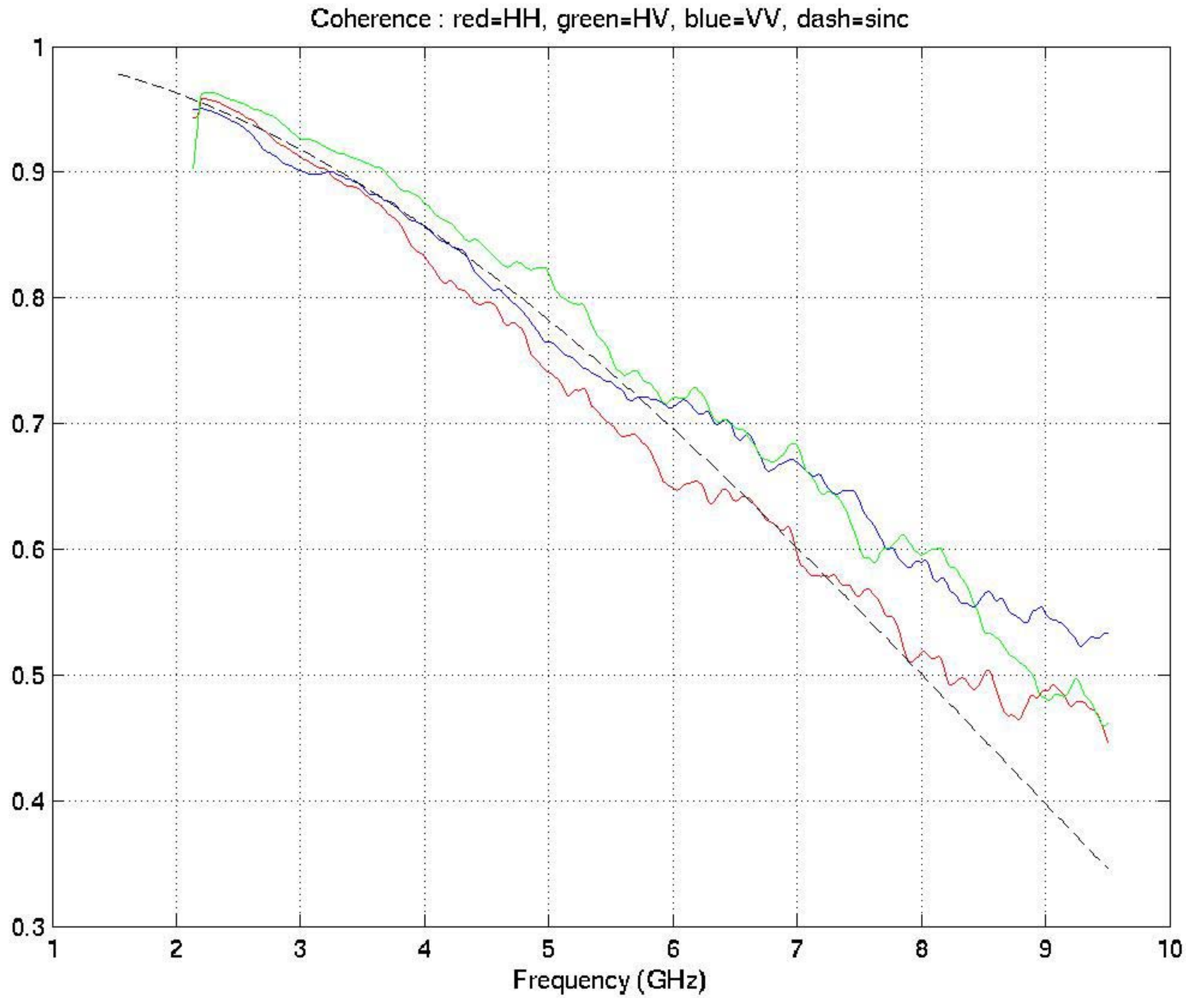
$$s_1.s_2^* = E_{\theta}^{pq}(f).conj(E_{\theta+\Delta\theta}^{pq}\left(f - \frac{f\Delta\theta}{\tan\theta}\right))e^{-i\frac{4\pi f\Delta\theta}{c\sin\theta}z_o}$$

$$\tilde{\gamma}_{pq}(f) = \frac{\langle s_1 s_2^* \rangle}{\sqrt{\langle s_1 s_1^* \rangle \langle s_2 s_2^* \rangle}}$$

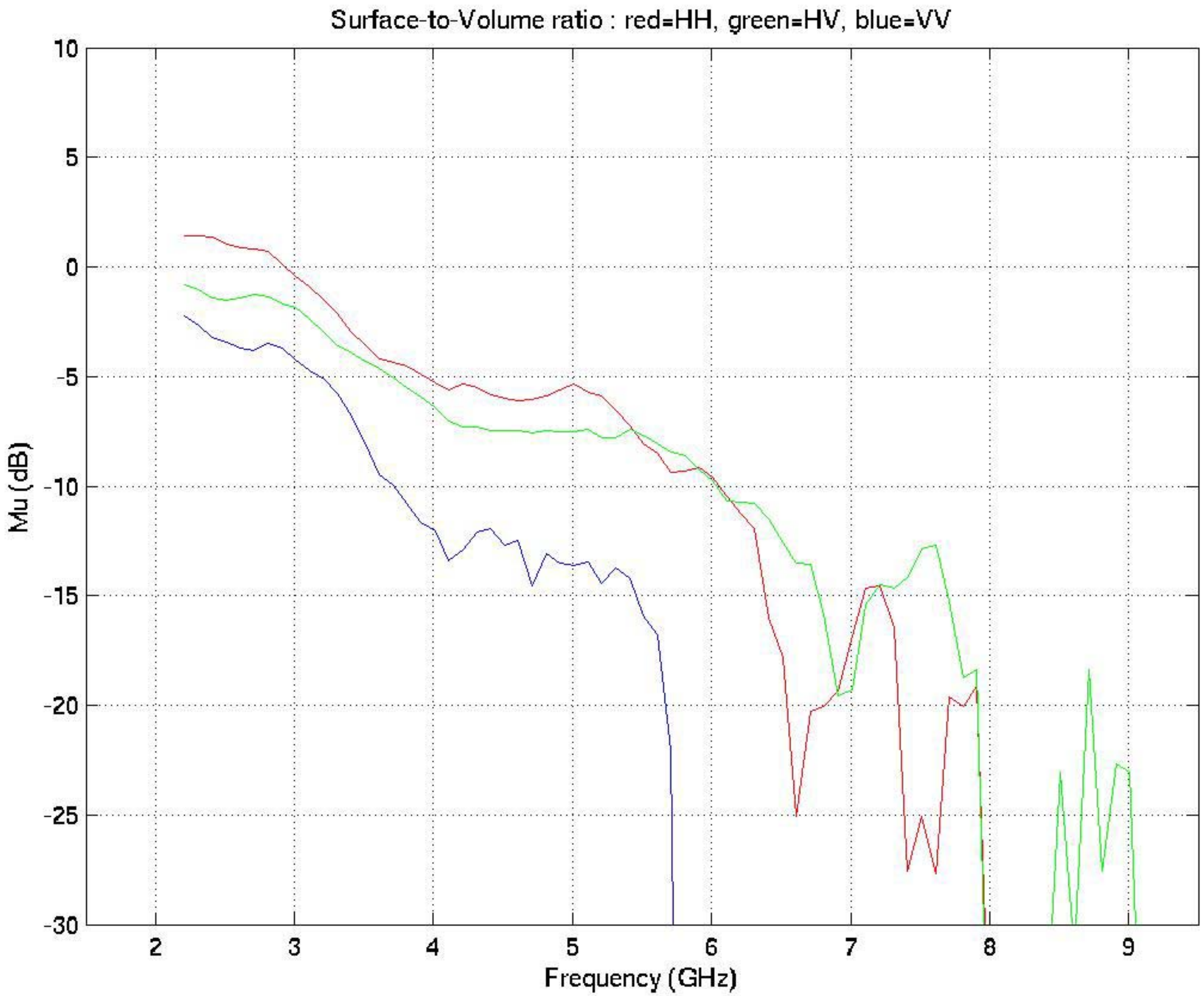


Complex coherence loci for 3 polarisations

Coherence Amplitude vs. Sinc Coherence Prediction

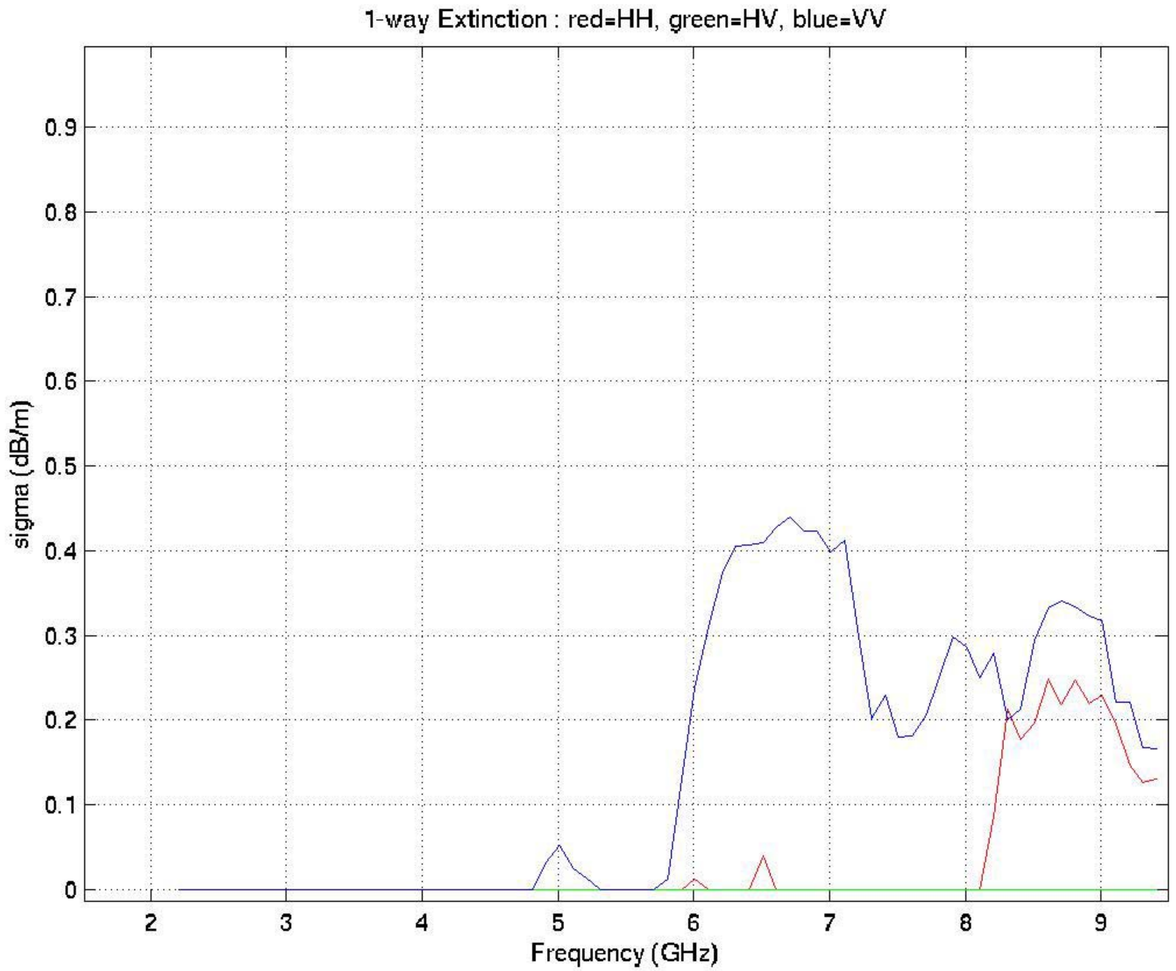


Estimate of μ vs Frequency



Can be used to help design air and space borne POLInSAR sensors
…e.g. Terrasar X, radarsat 2

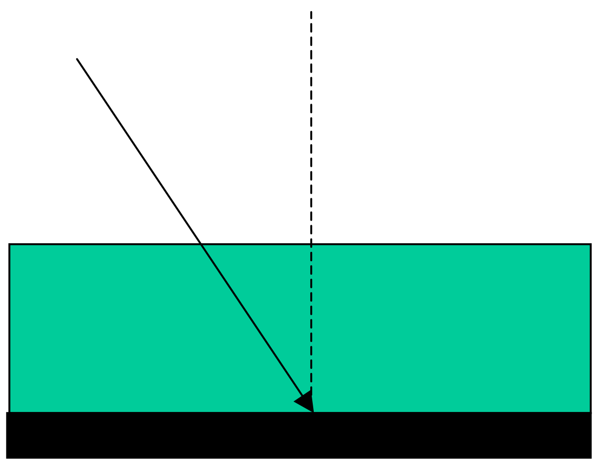
Estimate of extinction vs Frequency



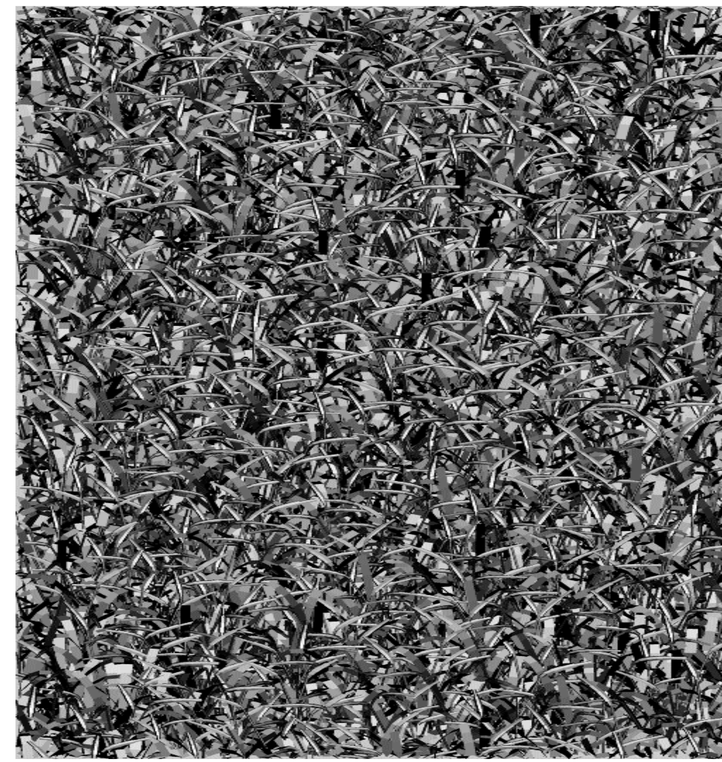
Can be used to select best frequency for studying vegetation effects

Simulated Wheat+Surface Scattering

Coherent wave propagation and scattering:
- Wave extinction
- Direct volume+
- Direct ground+
- Ground-volume and volume-ground+
- Ground-volume-ground..

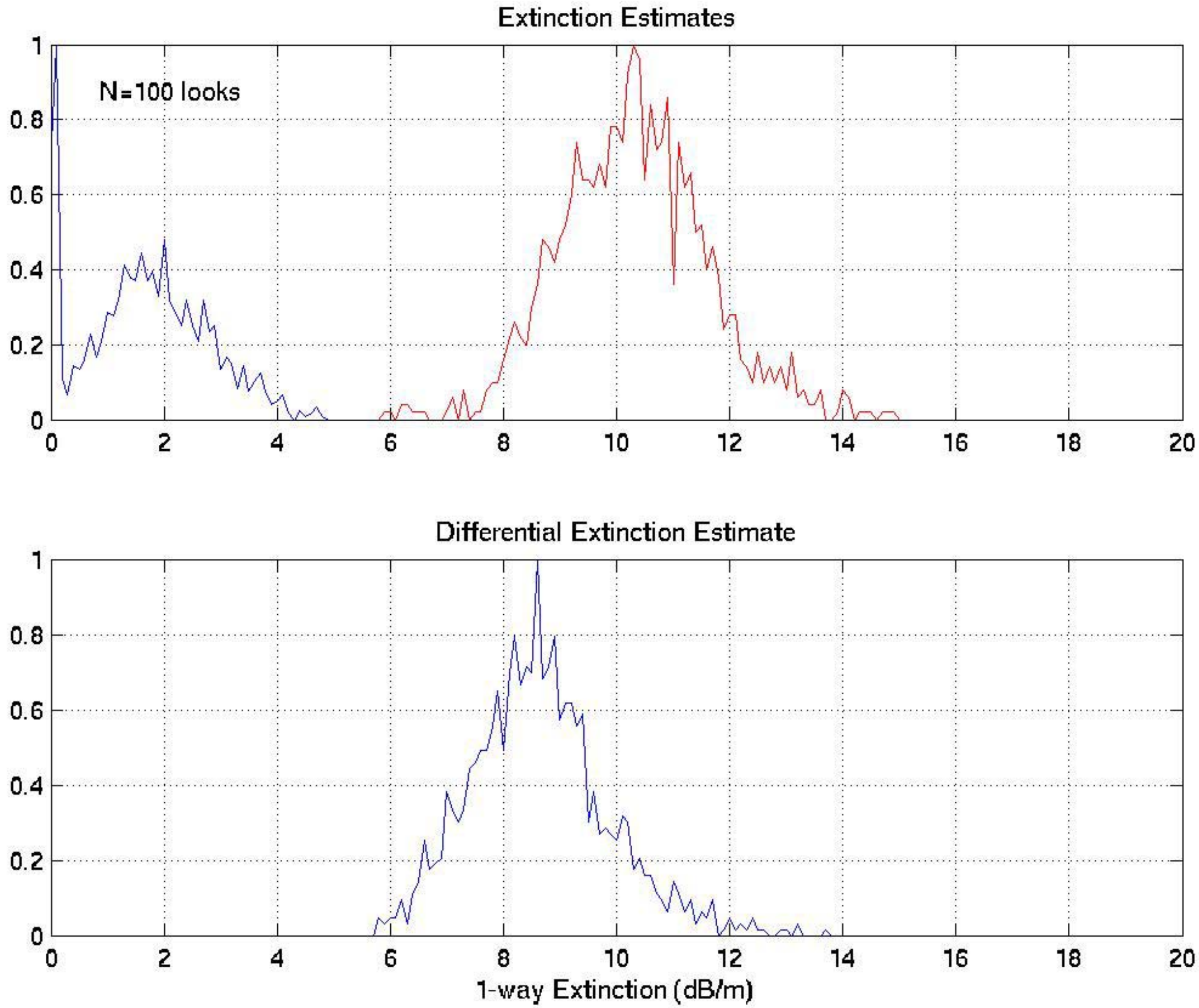


2 coherent models analysed:
Dr Pierre Borderies, ONERA, France
Dr Mark Williams, DSTO, Australia



DSTO Simulated GB-POLInSAR scene
(C-Band analysis
to be presented @ IGARSS 2005)

Ovog Inversion
C-Band Wheat (PolInSAR Simulator)



Conclusions

- POLSAR phase is most useful in low entropy situations, where it can be used for improved ship detection, oil slick monitoring, littoral zone remote sensing

- Vegetation cover of land surfaces raises entropy…
reduces the impact of quantitative parameter estimation using polarimetry alone…
One solution is to employ radar interferometry …user 'control' of vegetation entropy

- But single channel interferometry is underdetermined for vegetation cover
…multi-parameter interferometry is an important research topic
.. GB-SAR systems can help design 'best' parameter set…

- One example is polarimetric SAR interferometry ..POLInSAR
which is well suited to planned space-borne satellites (ALOS-PALSAR/Terrasar-L)
(single wavelength, single baseline…)
… but suffers from problems with temporal decorrelation in repeat pass systems
…well suited to single pass interferometer designs of the future…tandem/cartwheel etc.

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Analysis of Polarimetric Interferometric SAR data

ESA ESRIN Contract 17893/03/I-LG

PolarimetricInterferometric Mission and Application Study