Compact polarimetry SAR for natural surface characterization: an attractive compromise

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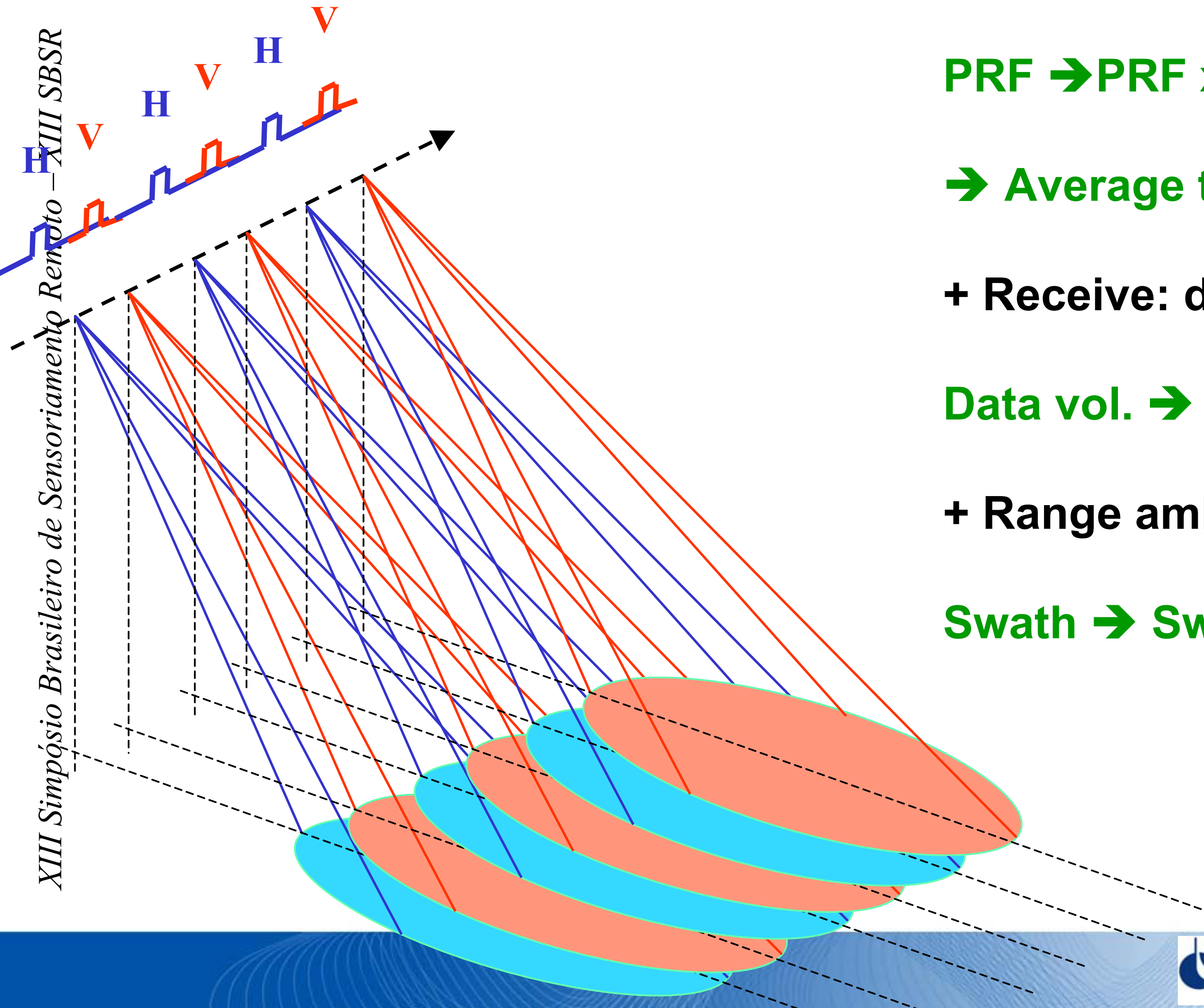
Outline of the presentation

- Introduction to Compact Polarimetry
- System consideration
- PolSAR analysis
- PolInSAR analysis
- Atmospheric effect
- Recommendations from PolINSAR 2007
- Conclusions

Full polarimetry: the burden of the chronogram



Transmit : dual versus single

PRF ➔PRF x 2

➔ Average transmit power X 2

+ Receive: dual versus single

Data vol. ➔ Data vol. x 2

+ Range ambiguity condition :

Swath ➔ Swath / 2

Example with ALOS system

Mode	Swath	Resolution	Incidence angle
HH	70km	10m	39°
HH/HV or VV/VH	70km	20m	39°
Quad-pol	30km	30m	24°

Compact Polarimetry: optimisation

- Compact polarimetry
  - 1 polarization on transmit
  - 2 polarizations on receive (with phase coherence)
- ALOS example:
  - H on transmit, H and V on receive
  - V on transmit, H and V on receive
- What is the best polarization on transmit?
- What are the best polarizations on receive?

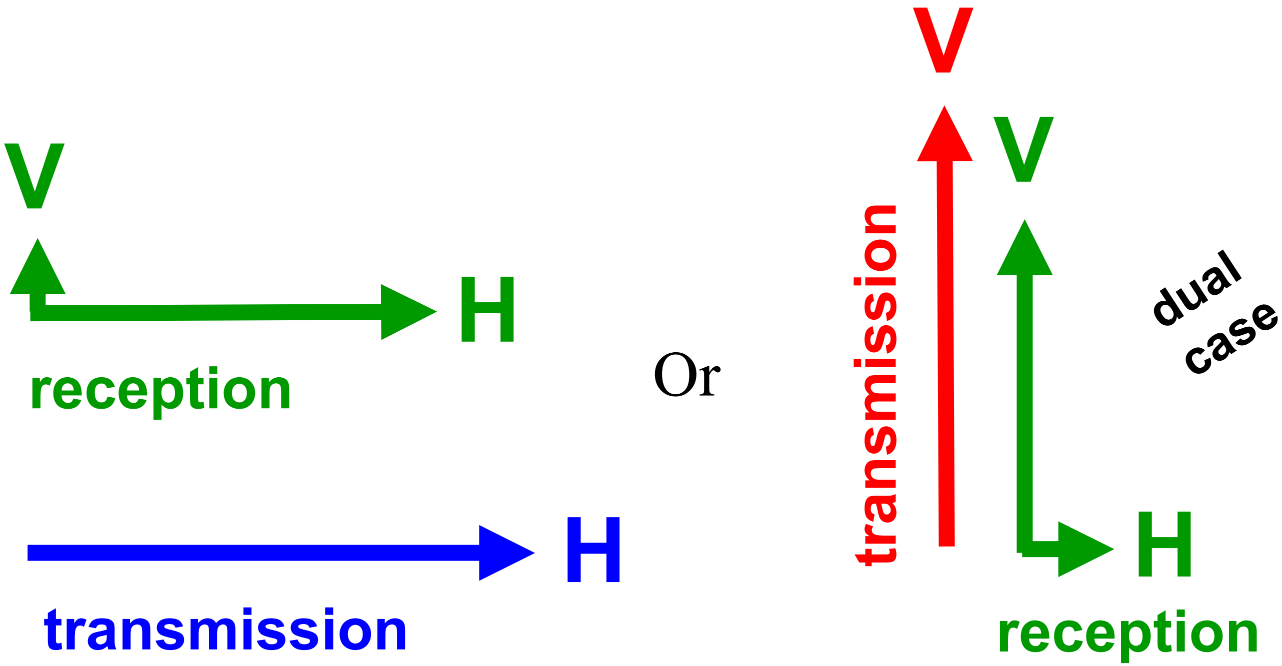
Background publications

- *J.C. Souyris, S. Mingot, "Polarimetry based on one transmitting and two receiving polarizations : the p/4 mode", Proceedings IGARSS'02, Toronto, Canada, July 2002*
- *Concept presentation @ POLINSAR'2003*
- *J.C. Souyris, P. Imbo, R. Fjortoft, S. Mingot, J.S. Lee, "Compact polarimetry based on symmetry properties of geophysical media : the p/4 mode", IEEE Transactions on Geoscience and Remote Sensing, vol. 43, n°3, Mars 2005, pp. 634-646.*
- *N. Stacy, M. Preiss, "Compact polarimetric analysis of X band SAR data", in. Proc. EUSAR'06, Dresden, Germany, May 2006*
- *Keith Raney, "Hybrid polarimetric SAR Architecture", Proceedings IGARSS'06 , July 2006*
- *Keith Raney, "Dual-Polarized SAR and Stokes Parameters," IEEE Geoscience and Remote Sensing Letters, vol. 3, pp. 317-319, 2006.*
- *POLINSAR2007*
  - *Souyris, Raney, Ainswoth, Lardeux, Dubois-Fernandez …*

The revenge of deserted symmetry

Current approach in dual-pol

ALOS, ENVISAT



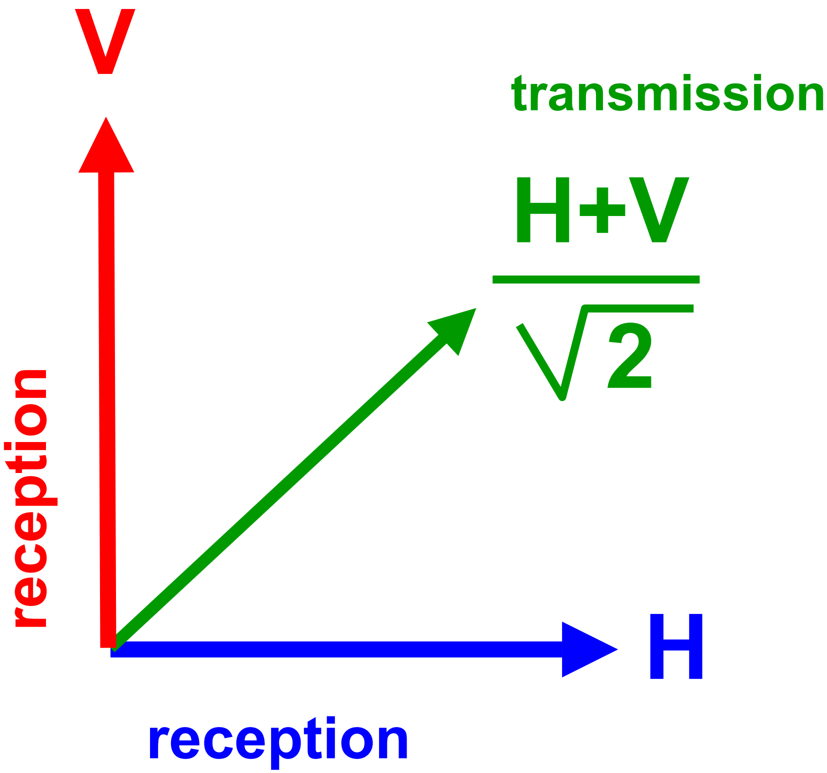
Reception of two « unbalanced signals » on Co- and X- channels

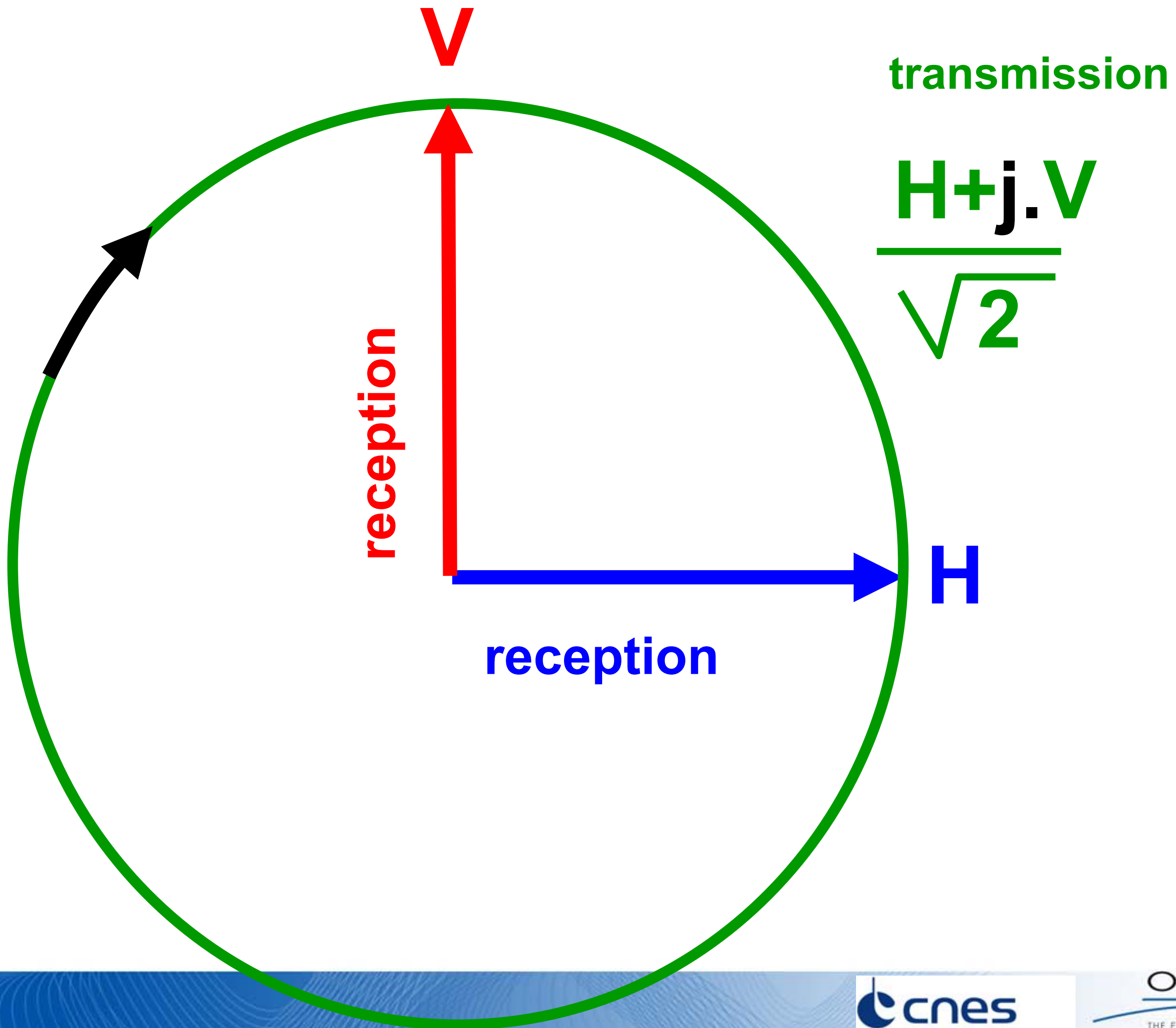
Why is it a poor choice for natural targets?

- Acquisition of HH and HV
- Co-pol and cross-pol are not correlated
  - Reflection symmetry hypothesis

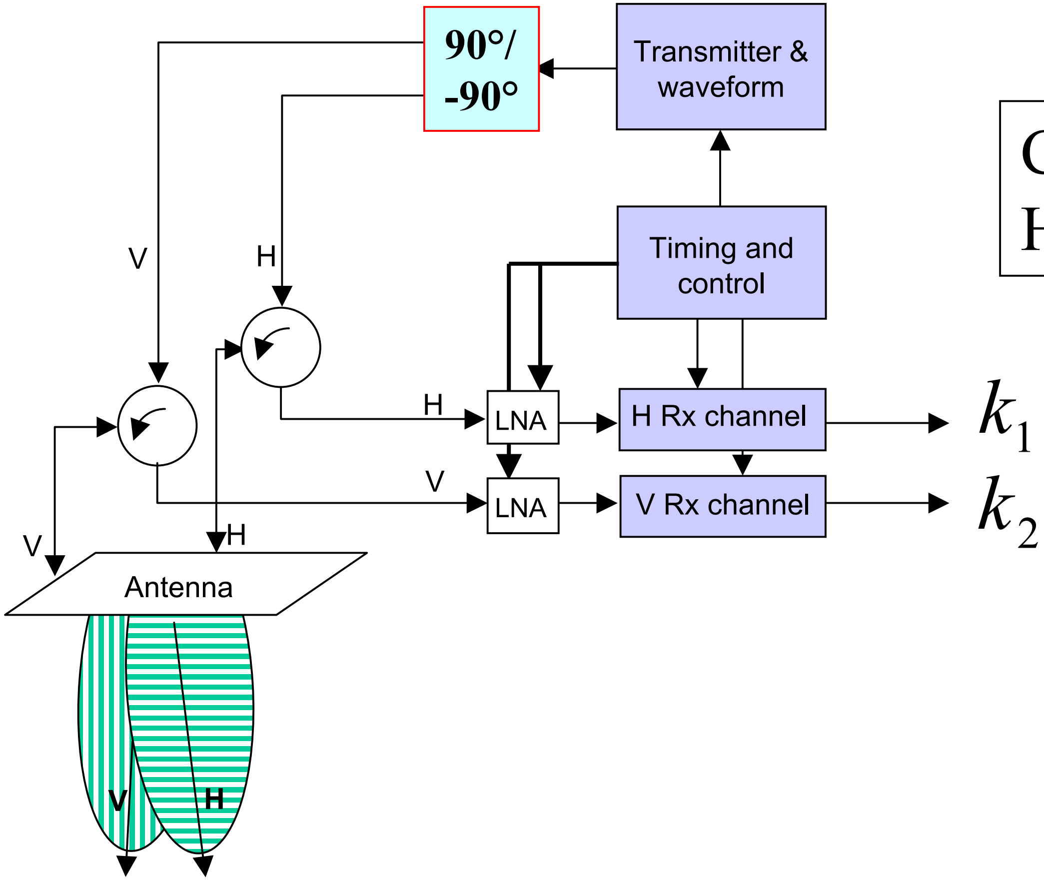
$$\langle s_{HH} \cdot s_{HV}^* \rangle \approx \langle s_{VV} \cdot s_{HV}^* \rangle \approx 0$$

- Phase information is useless
- Phase and correlation between HH and VV : important parameters


V
transmission
$\frac{H+V}{\sqrt{2}}$
reception
H
reception


V
transmission
H+j.V
√2
reception
H
reception

Compact polarimetry architecture



Circular transmit:	90°
H+V transmit:	0°

Three modes for evaluation

Target Vector: $\vec{k} = \begin{bmatrix} k_1 \\ k_2 \end{bmatrix}$

Name	Mode	Transmit	Receive 1	Receive 2
PC1	45°	45°	H	V
PC2	Circular	RC	RC	LC
PC3	Hybrid	RC	H	V

PC1 → $\begin{bmatrix} HH + HV \\ HV + VV \end{bmatrix}$

PC2 → $\begin{bmatrix} HH + 2jHV - VV \\ HH + VV \end{bmatrix}$

PC3 → $\begin{bmatrix} HH \pm jHV \\ HV \pm jVV \end{bmatrix}$

Equivalence of PC2 et PC3

$$\vec{k}_{PC2} = \begin{bmatrix} HH + 2jHV - VV \\ HH + VV \end{bmatrix} \qquad \vec{k}_{PC3} = \begin{bmatrix} HH + jHV \\ HV + jVV \end{bmatrix}$$

$$\vec{k}_{PC2} = \begin{pmatrix} 1 & j \\ 1 & -j \end{pmatrix} \vec{k}_{PC3}$$

We will consider only PC3 from now on.

PolSAR Analysis

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POLSAR analysis with CP data?

- Learn to use it as is:
  - K Raney and the new Stokes parameters
  - S Cloude and the “dual-pol” entropy alpha parameters
- Reconstruct a pseudo full polar information
  - JC Souyris
  - T Ainsworth
  - C Lardeux

Raney's approach: Stokes parameters

- **Stokes parameters are necessary and sufficient to fully characterize the received EM field**
- ***Stokes parameters require relative phase***
- **Transmit circular polarization**

*NB: **NOT quad-pol**; backscattered field only, not the scattering matrix*

Key to the design

	Hybrid Polarity	Conventional
S_1	$= < \|E_H\|^2 + \|E_V\|^2 >$	$< \|E_L\|^2 + \|E_R\|^2 >$
S_2	$= < \|E_H\|^2 - \|E_V\|^2 >$	$2\,\mathrm{Re} < E_L E_R^* >$
S_3	$= 2\,\mathrm{Re} < E_H E_V^* >$	$2\,\mathrm{Im} < E_L E_R^* >$
S_4	$= -2\,\mathrm{Im} < E_H E_V^* >$	$- < \|E_L\|^2 - \|E_R\|^2 >$

Stokes "child" parameters (selected)

Degree of polarization

$$m = (S_2^2 + S_3^2 + S_4^2)^{½} / S_1$$

Fundamental; 1:1 mapping *wrt* Entropy *E*
$E \sim (1 - m^2)^{\gamma}$, $\gamma \sim 0.74$

Degree of linear polarization

$$m_L = (S_2^2 + S_3^2)^{½} / S_1$$

Indicator of volume *vs.* subsurface scattering if $m_L > 0$ (if CP transmission)

Circular polarization ratio

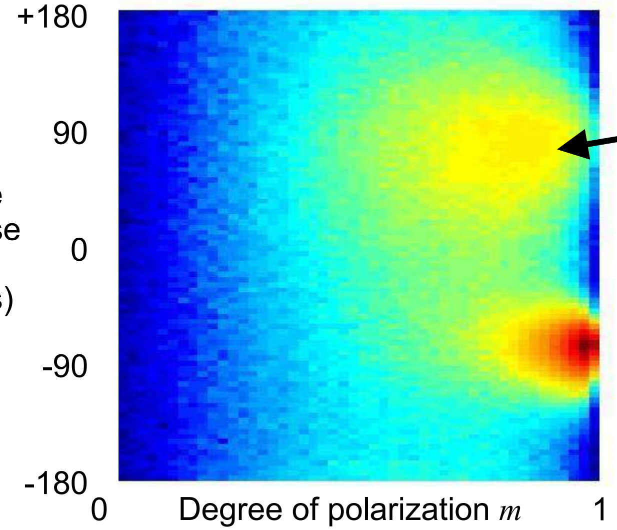
$$\boldsymbol{\mu}_C = (S_1 - S_4) / (S_1 + S_4)$$

Indicator of scattering associated with planetary ice deposits or dihedrals: $\boldsymbol{\mu}_C > \sim 0.4$

Relative phase $\delta = \arctan(S_4 / S_3)$

Sensitive indicator of "double bounce" backscattering

RH-Pol bacscatter Decomposition in m- *δ space*



Expected opposite-sense phase signal in response to circularly polarized transmissions, indicating single-bounce (specular) or triple-bounce backscatter

Phase signal of same-sense circularly-polarized return in response to circularly polarized transmissions, which indicates double bounce (dihedral) or coherent backscatter effect (volumetric water ice)

Stokes-parameter based transformation from hybrid-polarity SAR image data to m-δ feature space

Polarimetric SAR data, Courtesy, JPL

Souyris' approach: "Pseudo" covariance matrix

$$\begin{bmatrix} \langle k_1 k_1^* \rangle & \langle k_2 k_1^* \rangle \\ \langle k_1 k_2^* \rangle & \langle k_2 k_2^* \rangle \end{bmatrix} \Rightarrow \begin{bmatrix} \langle S_{HH} S_{HH}^* \rangle & \langle S_{HH} S_{HV}^* \rangle & \langle S_{HH} S_{VV}^* \rangle \\ \langle S_{HV} S_{HH}^* \rangle & \langle S_{HV} S_{HV}^* \rangle & \langle S_{HV} S_{VV}^* \rangle \\ \langle S_{VV} S_{HH}^* \rangle & \langle S_{VV} S_{HV}^* \rangle & \langle S_{VV} S_{VV}^* \rangle \end{bmatrix}$$

4 measures

9 unknowns

Reconstruction of the covariance matrix

H1: Reflection symmetry

$$\left\langle s_{HH} \cdot s_{HV}^{*} \right\rangle \approx \left\langle s_{VV} \cdot s_{HV}^{*} \right\rangle \approx 0$$

$$\begin{bmatrix} \langle k_1 k_1^* \rangle & \langle k_2 k_1^* \rangle \\ \langle k_1 k_2^* \rangle & \langle k_2 k_2^* \rangle \end{bmatrix} \Rightarrow \begin{bmatrix} \langle S_{HH} S_{HH}^* \rangle & 0 & \langle S_{HH} S_{VV}^* \rangle \\ 0 & \langle S_{HV} S_{HV}^* \rangle & 0 \\ \langle S_{VV} S_{HH}^* \rangle & 0 & \langle S_{VV} S_{VV}^* \rangle \end{bmatrix}$$

4 measures

5 unknowns

Reconstruction of the covariance matrix

H2: HV linked to the randomness

$$\frac{4\left\langle s_{HV}\cdot s_{HV}^{*}\right\rangle}{\left\langle s_{HH}\cdot s_{HH}^{*}\right\rangle+\left\langle s_{VV}\cdot s_{VV}^{*}\right\rangle}=(1-\frac{\left\langle s_{HH}\cdot s_{VV}^{*}\right\rangle}{\sqrt{\left\langle s_{HH}\cdot s_{HH}^{*}\right\rangle\left\langle s_{VV}\cdot s_{VV}^{*}\right\rangle}})$$

$$\begin{bmatrix}\left\langle k_1k_1^*\right\rangle & \left\langle k_2k_1^*\right\rangle \\ \left\langle k_1k_2^*\right\rangle & \left\langle k_2k_2^*\right\rangle\end{bmatrix} \longrightarrow \begin{bmatrix}\left\langle S_{HH}S_{HH}^*\right\rangle & 0 & \left\langle S_{HH}S_{VV}^*\right\rangle \\ 0 & \left\langle S_{HV}S_{HV}^*\right\rangle & 0 \\ \left\langle S_{VV}S_{HH}^*\right\rangle & 0 & \left\langle S_{VV}S_{VV}^*\right\rangle\end{bmatrix}$$

4 measures

5 unknowns + 1 equation

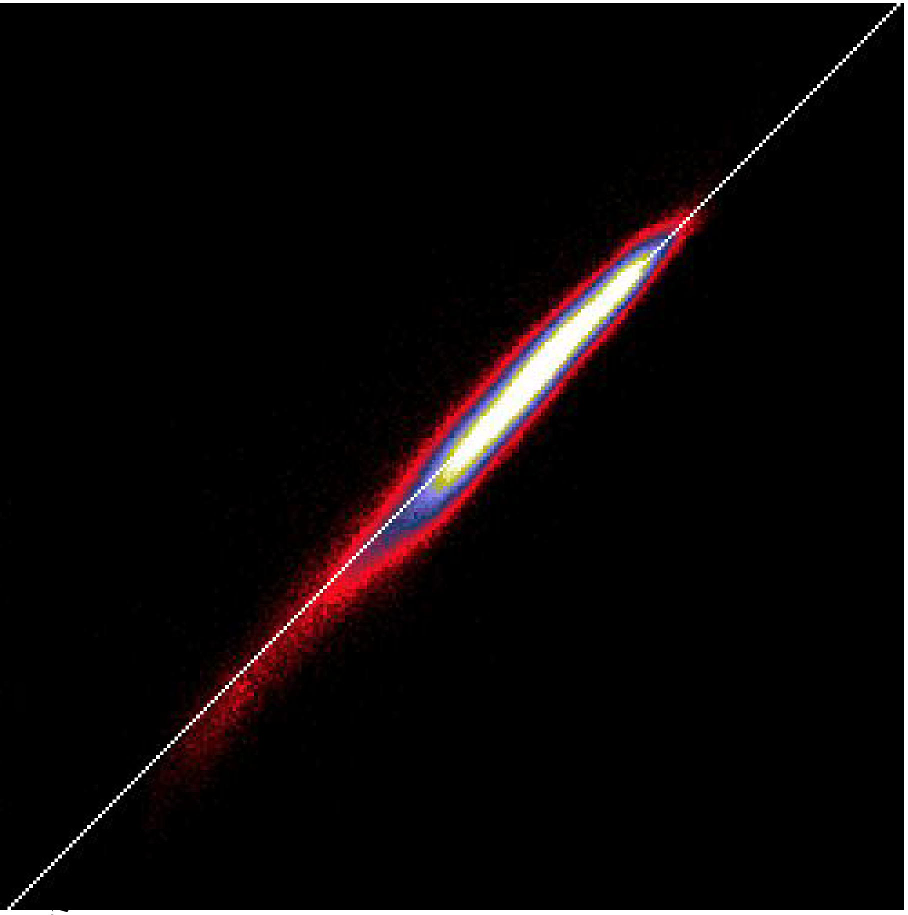
Reconstruction of the covariance matrix

- Examples with X, L and P bands
- Modes PC1 and PC3

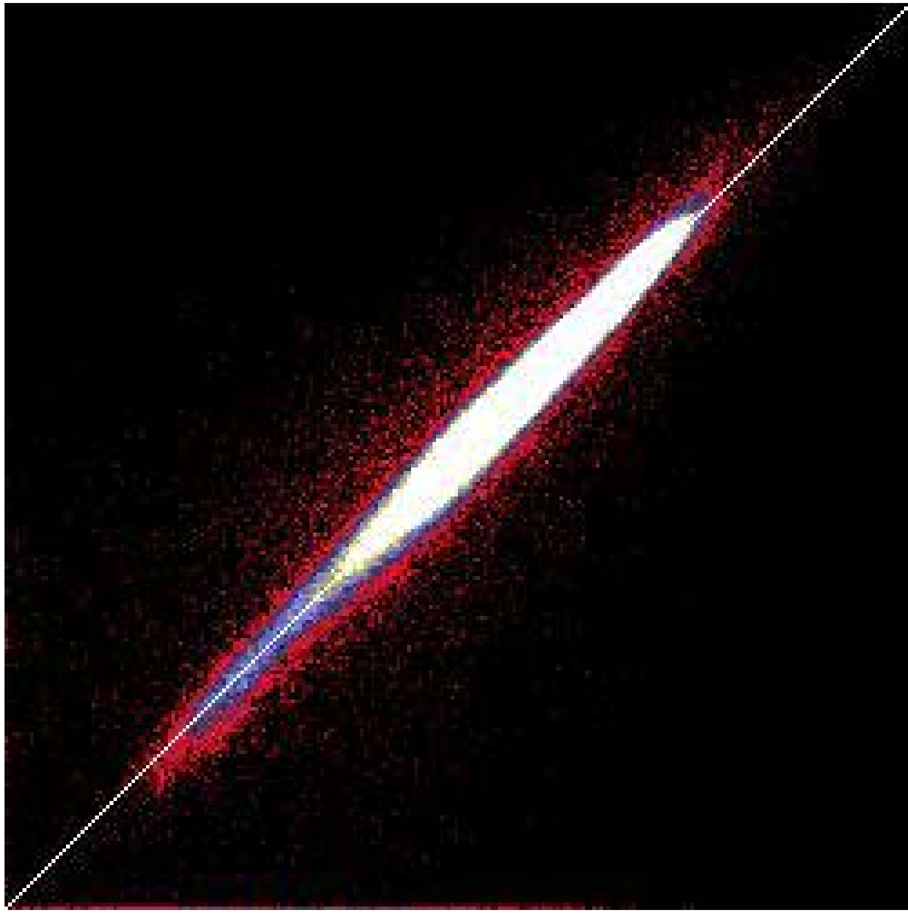
Name	Mode	Transmit	Receive 1	Receive 2
PC1	45°	45°	H	V
PC2	Circular	RC	RC	LC
PC3	Hybrid	RC	H	V

P Band over Nezer Forest

P-Band: Reconstruction of the HH term



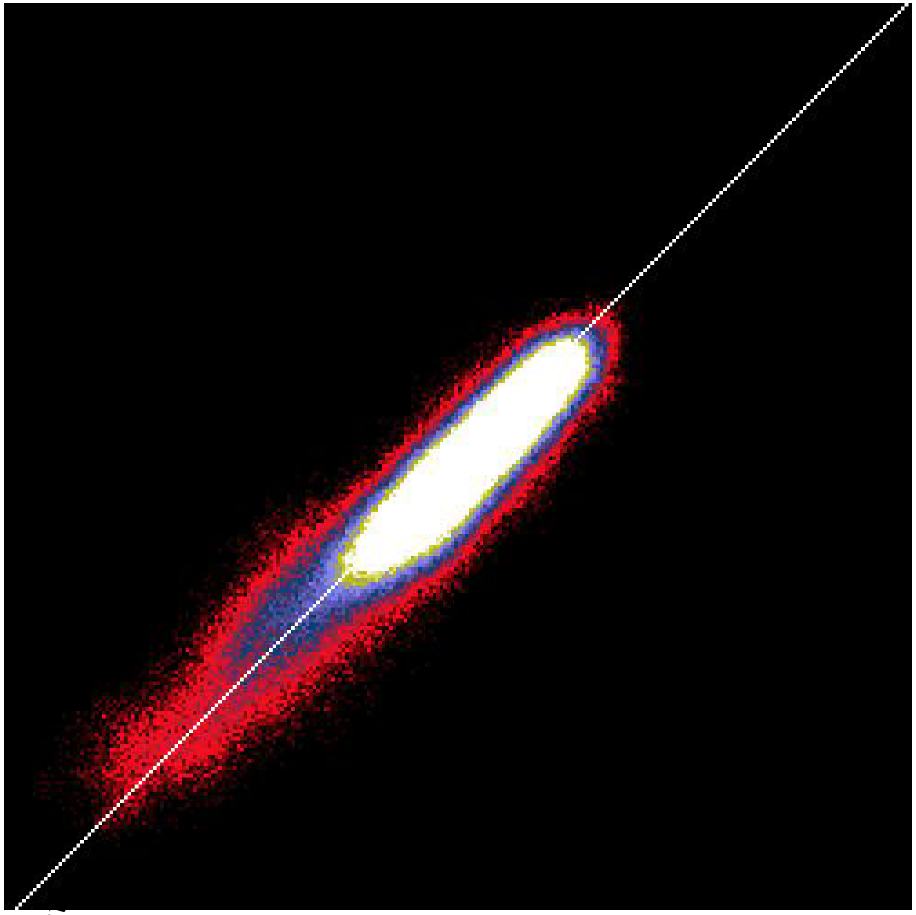
Mode π/4



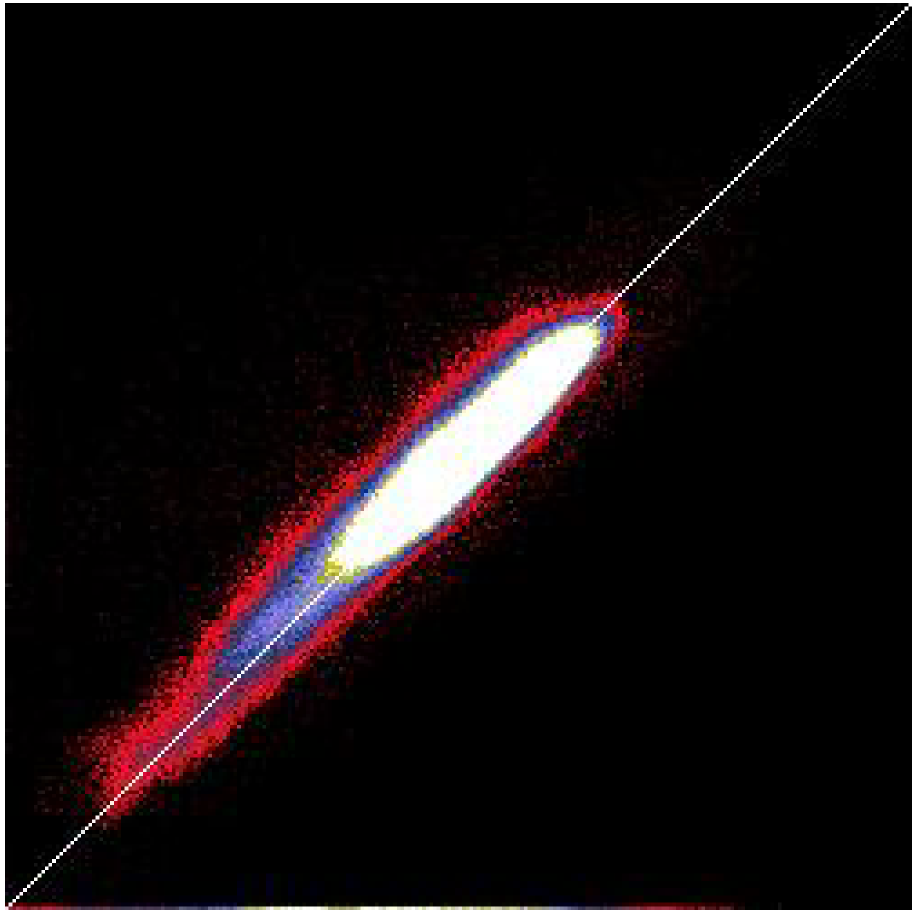
Mode hybrid

Window 7x7, 5 iterations, scale =[-20dB,+20dB]

P-Band: Reconstruction of the Hv



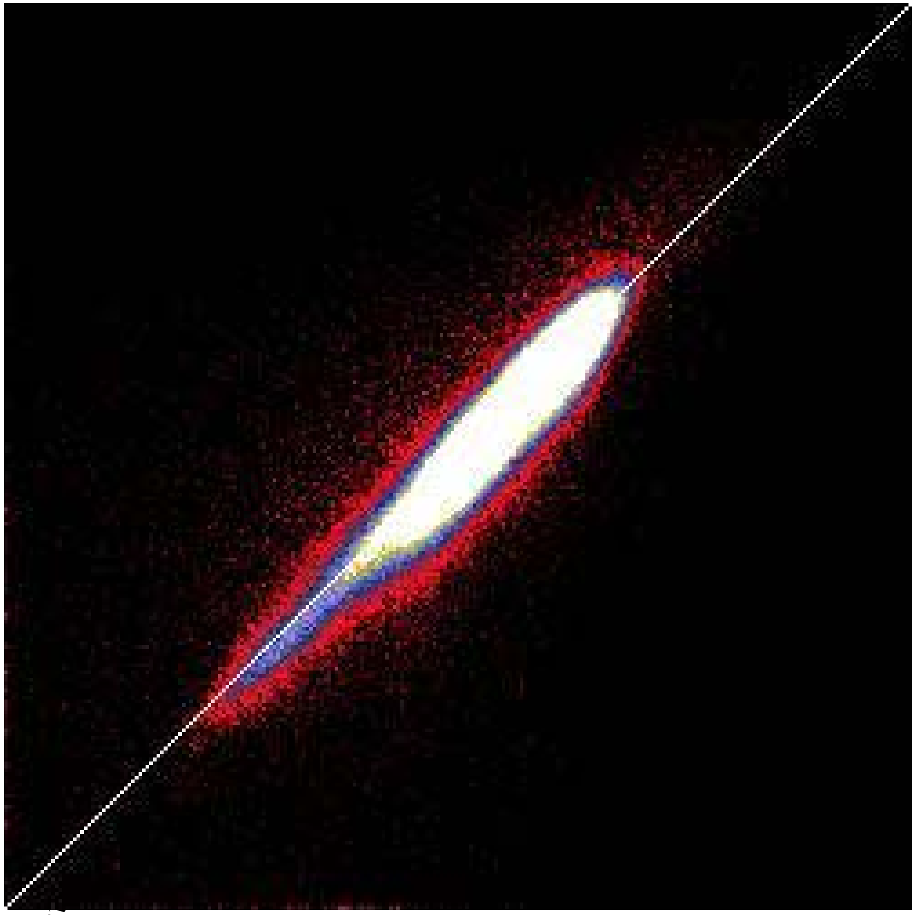
Mode π/4



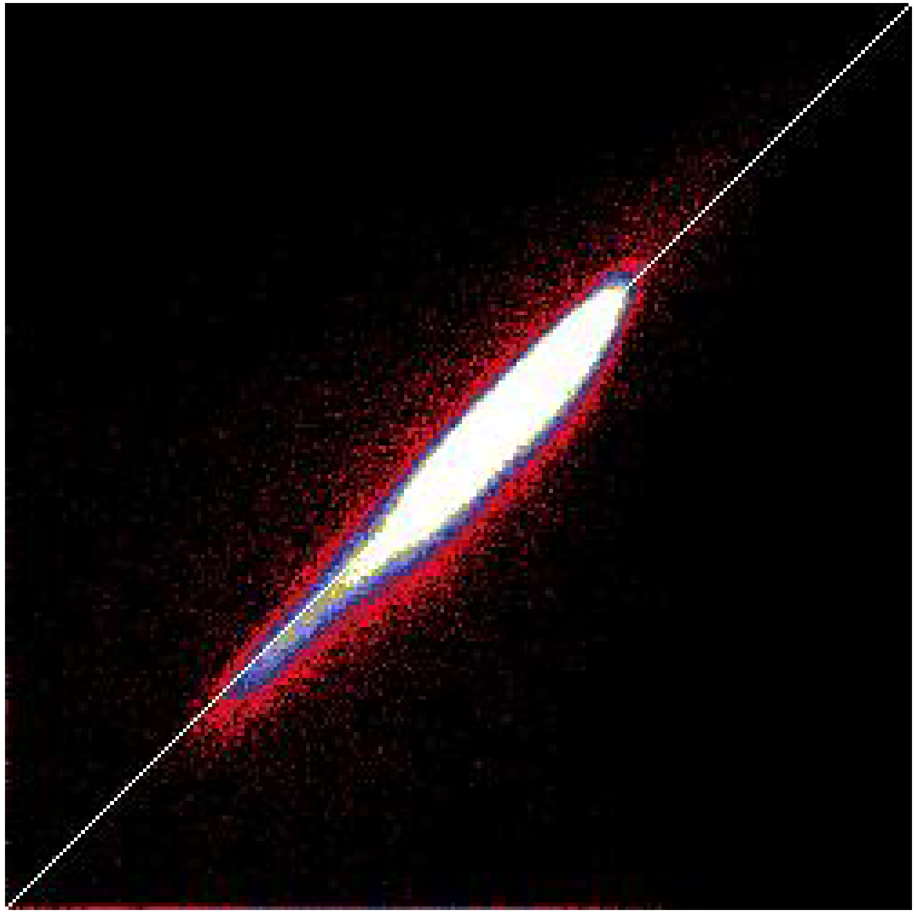
Mode hybrid

Window 7x7, 5 iterations, scale =[-20dB,+20dB]

P-Band: Reconstruction of the VV



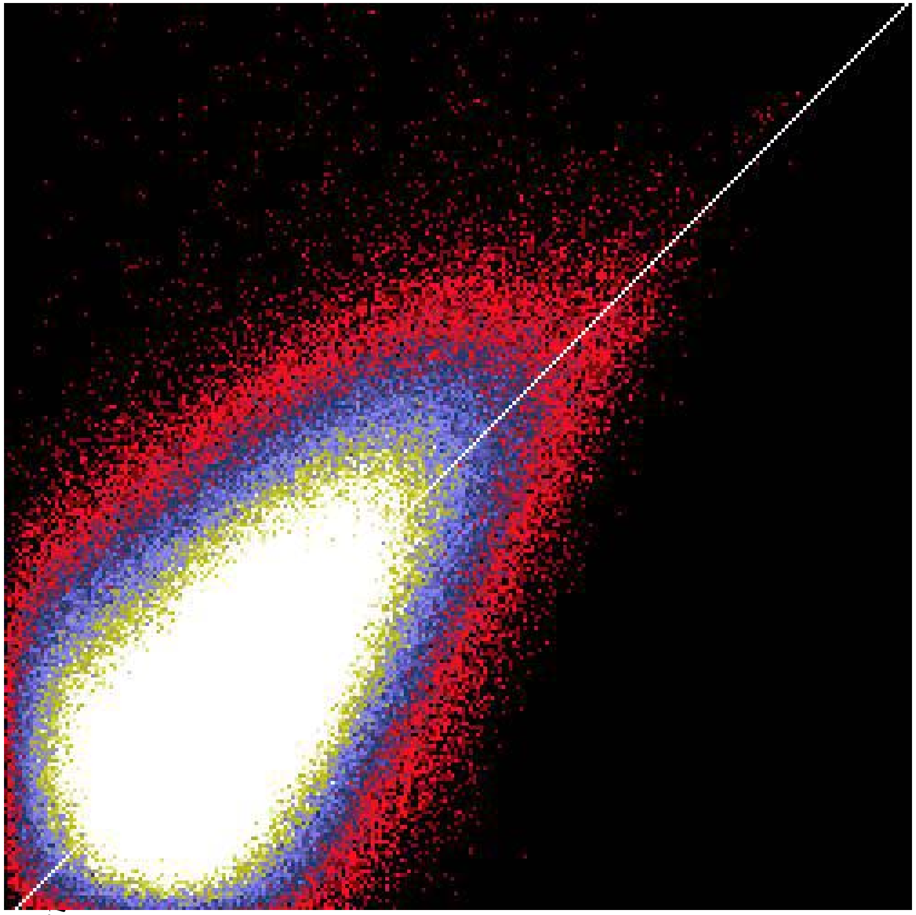
Mode π/4



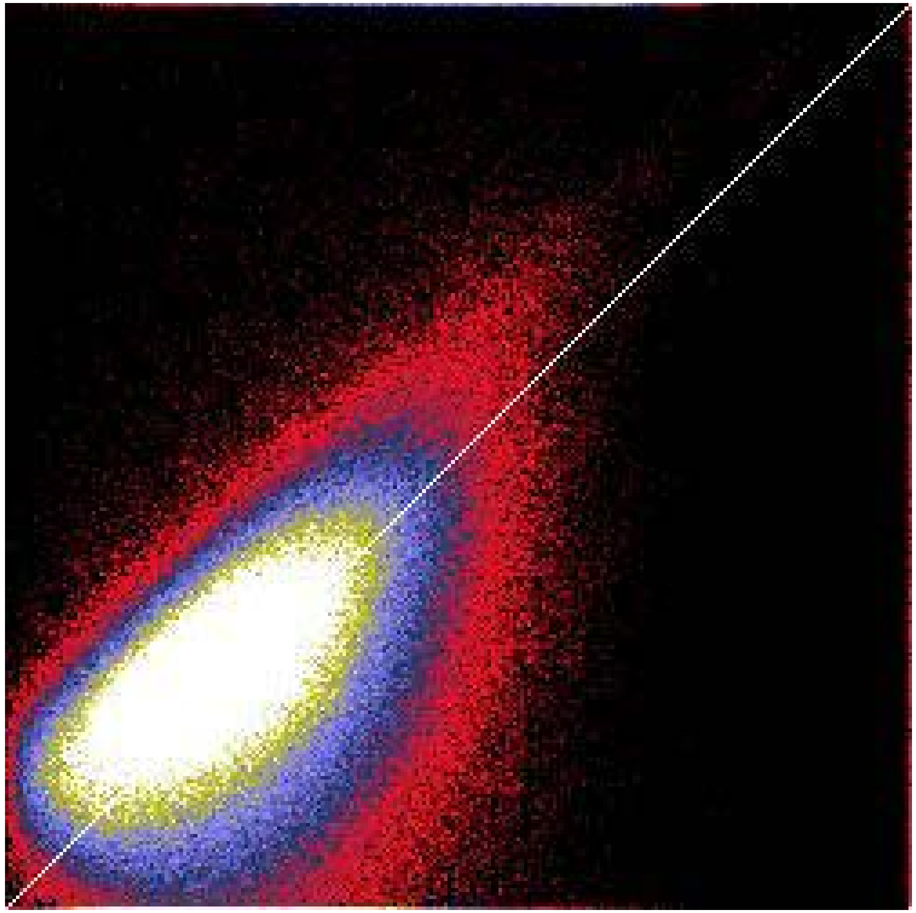
Mode hybrid

Window 7x7, 5 iterations, scale =[-20dB,+20dB]

P-Band: Reconstruction Hh-Vv coherence



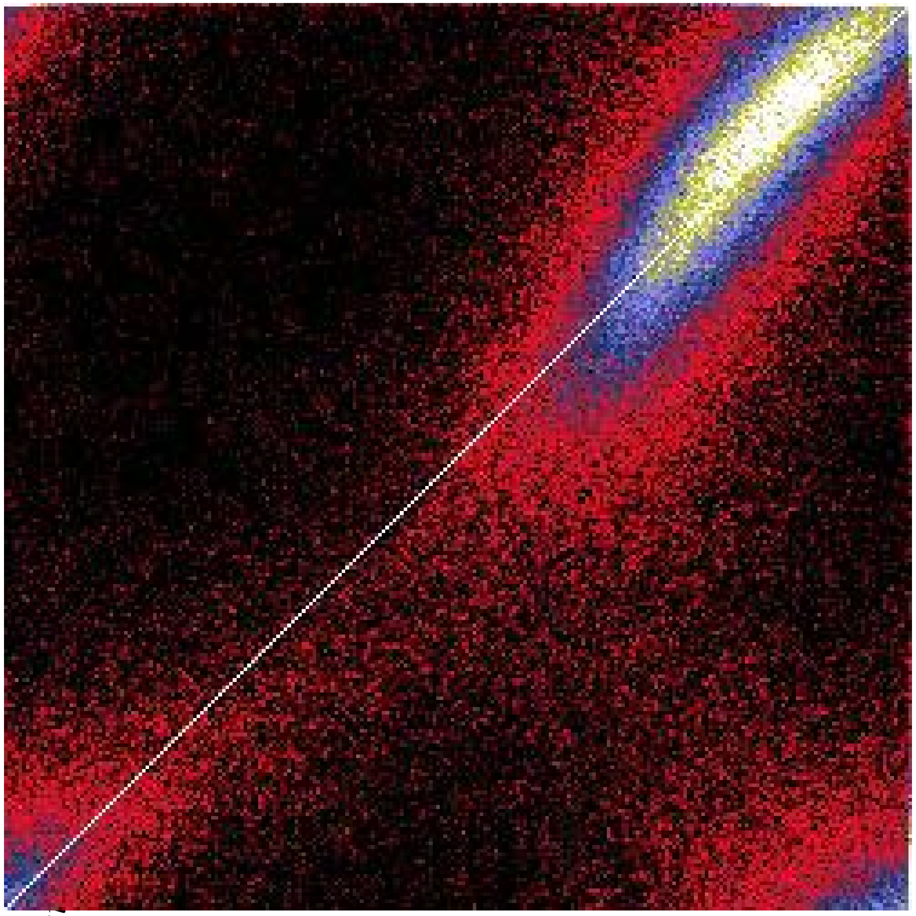
Mode π/4



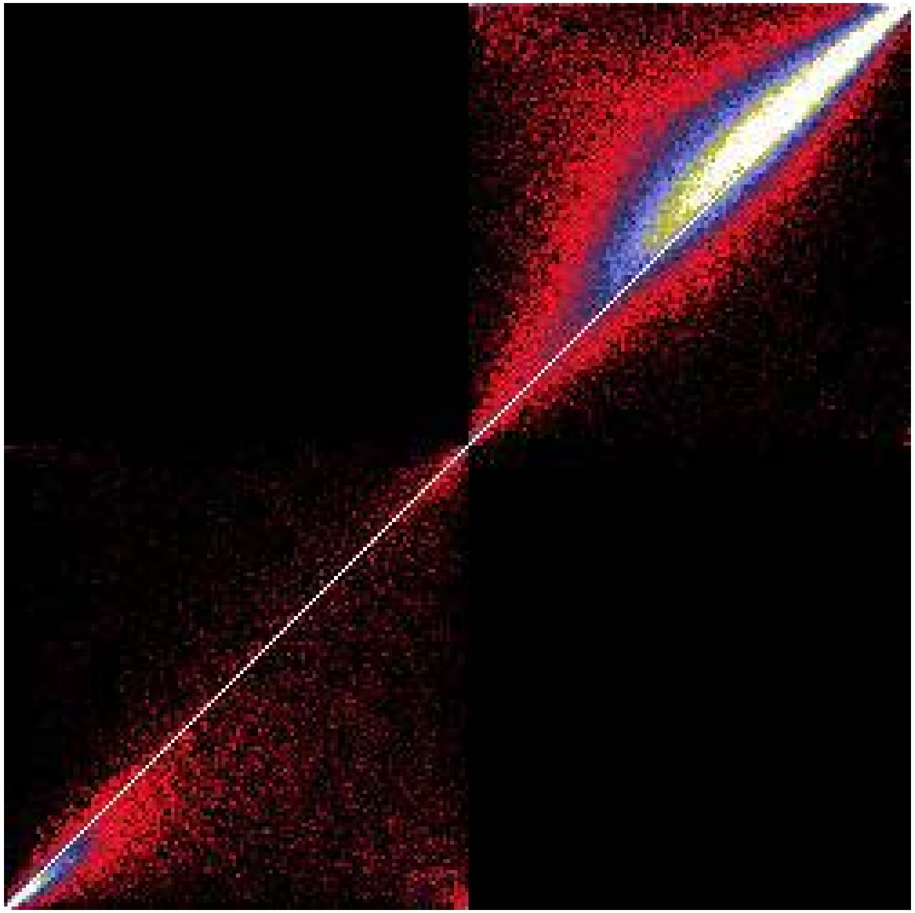
Mode hybrid

Window 7x7, 5 iterations, scale =[0,1]

P-Band: Reconstruction Hh-Vv phase



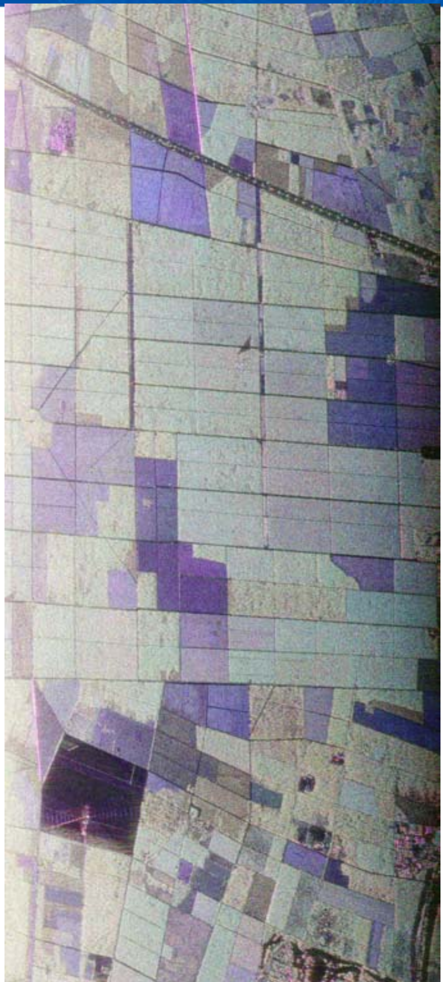
Mode π/4



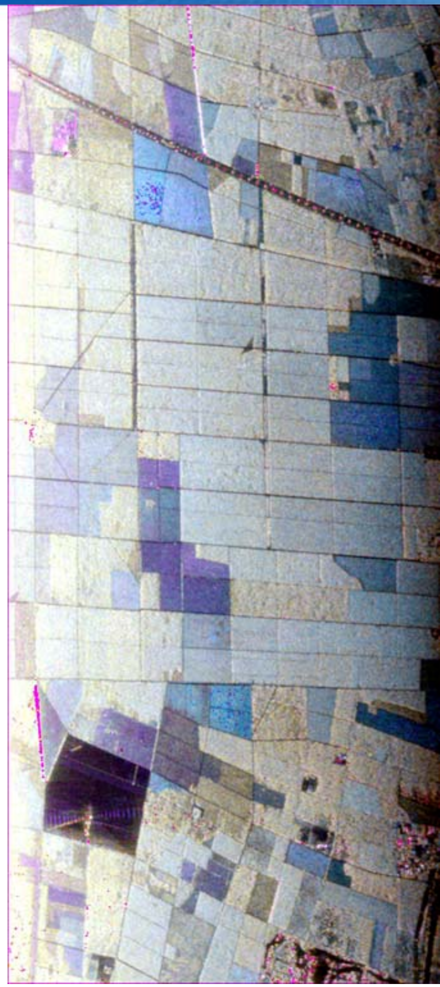
Mode hybrid

Window 7x7, 5 iterations, scale =[0,360°]

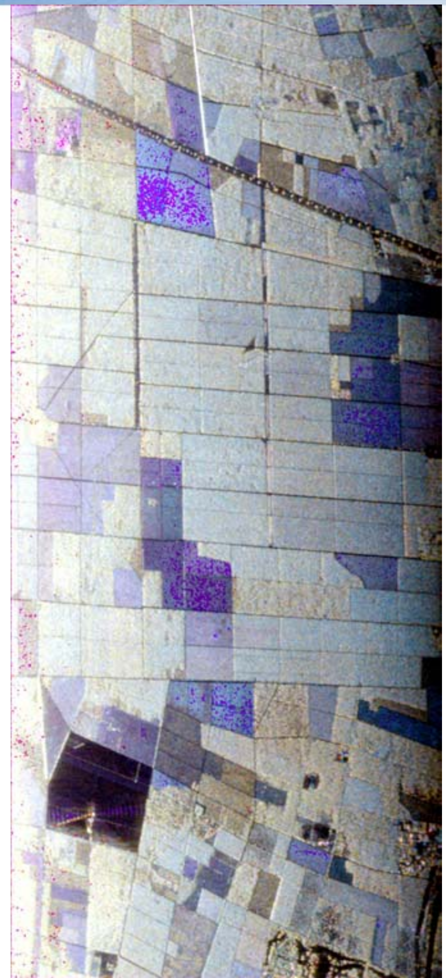
P-Band: False color representation



Full polar



π /4

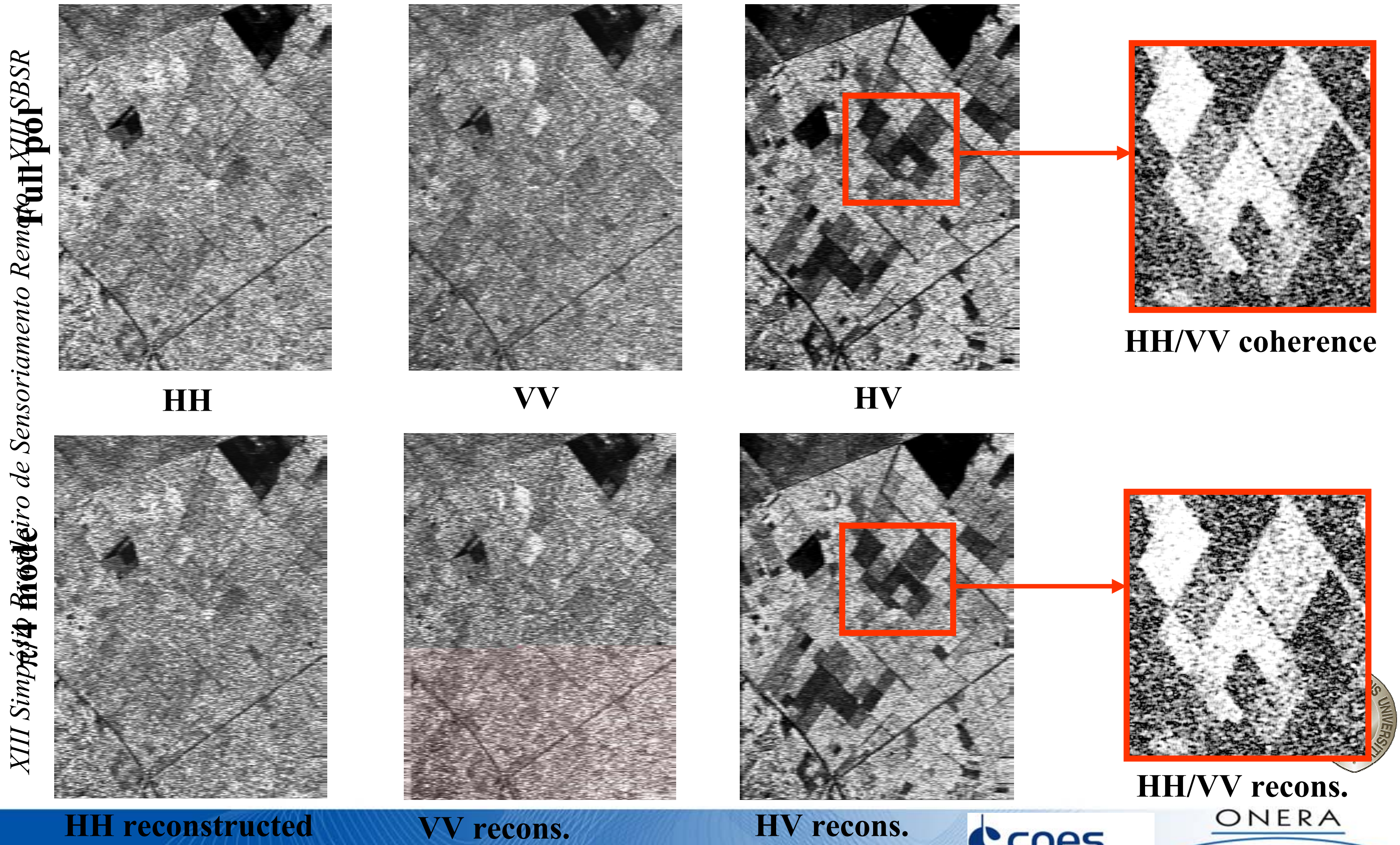


Hybrid

R: HH, G=HV, B=VV

L Band: Reconstruction performance

L band



X-Band: False color representation

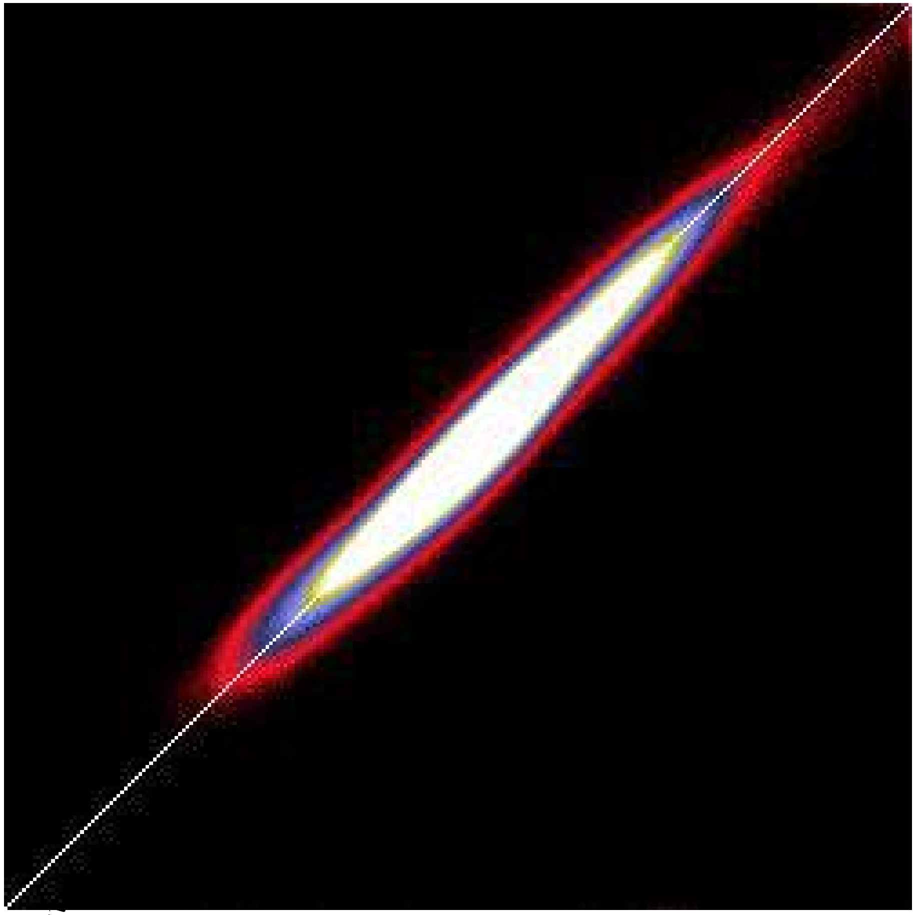
Full polar

$\pi/4$

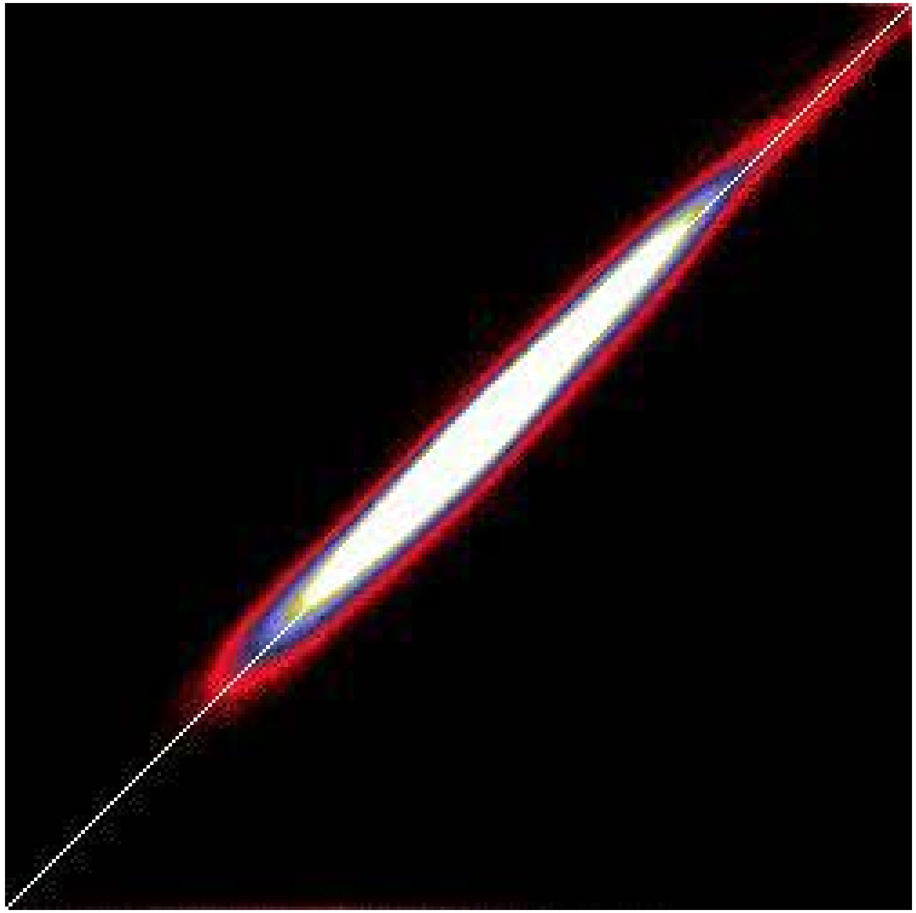
Hybrid

R: HH, G=HV, B=VV

X Band: Reconstruction HH



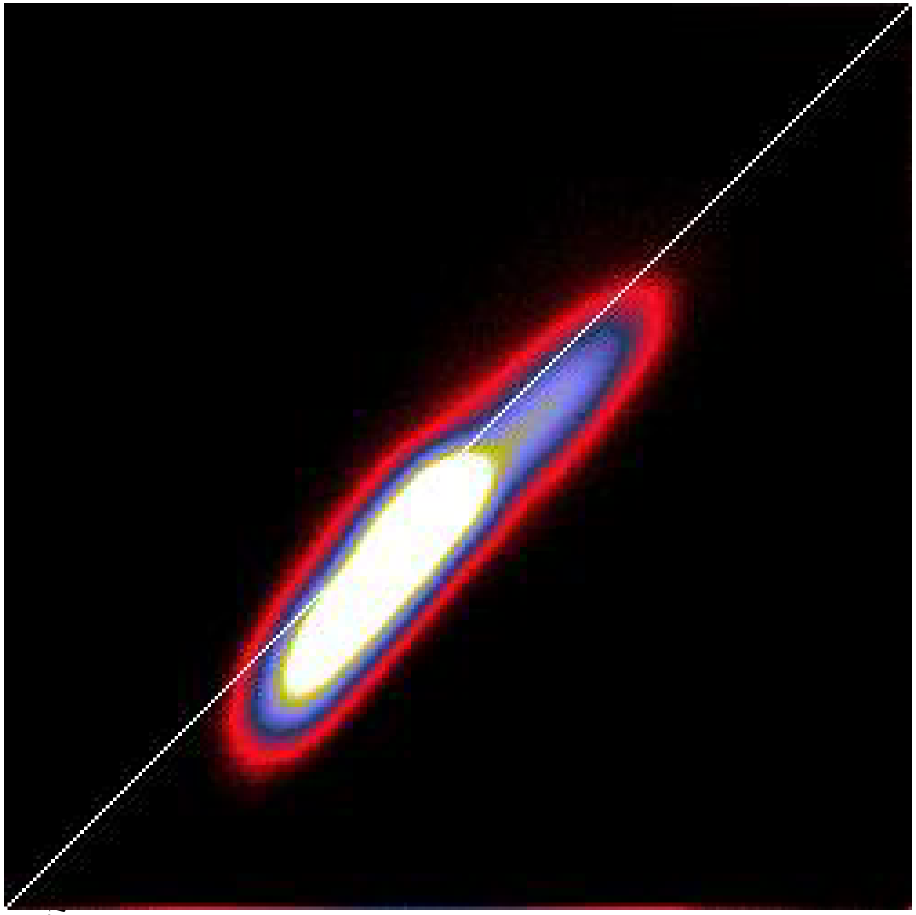
Mode π/4



Mode hybrid

Window 7x7, 5 iterations, scale =[-40dB,0dB]

X Band: Reconstruction Hv

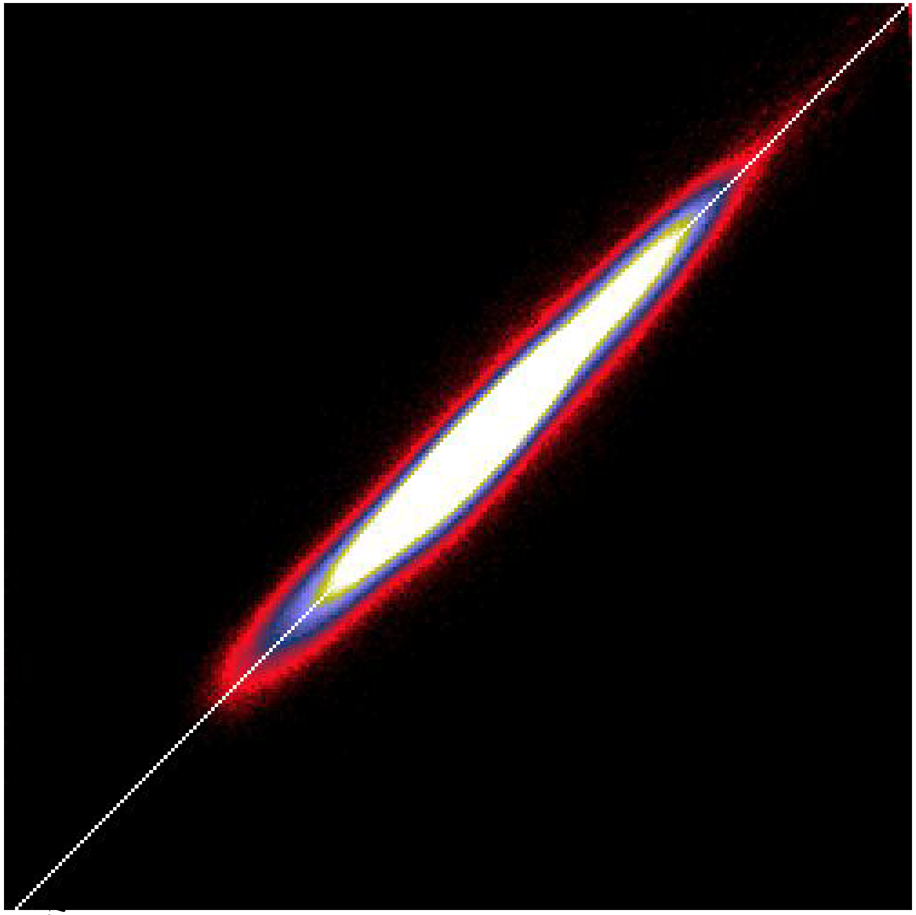


Mode π/4

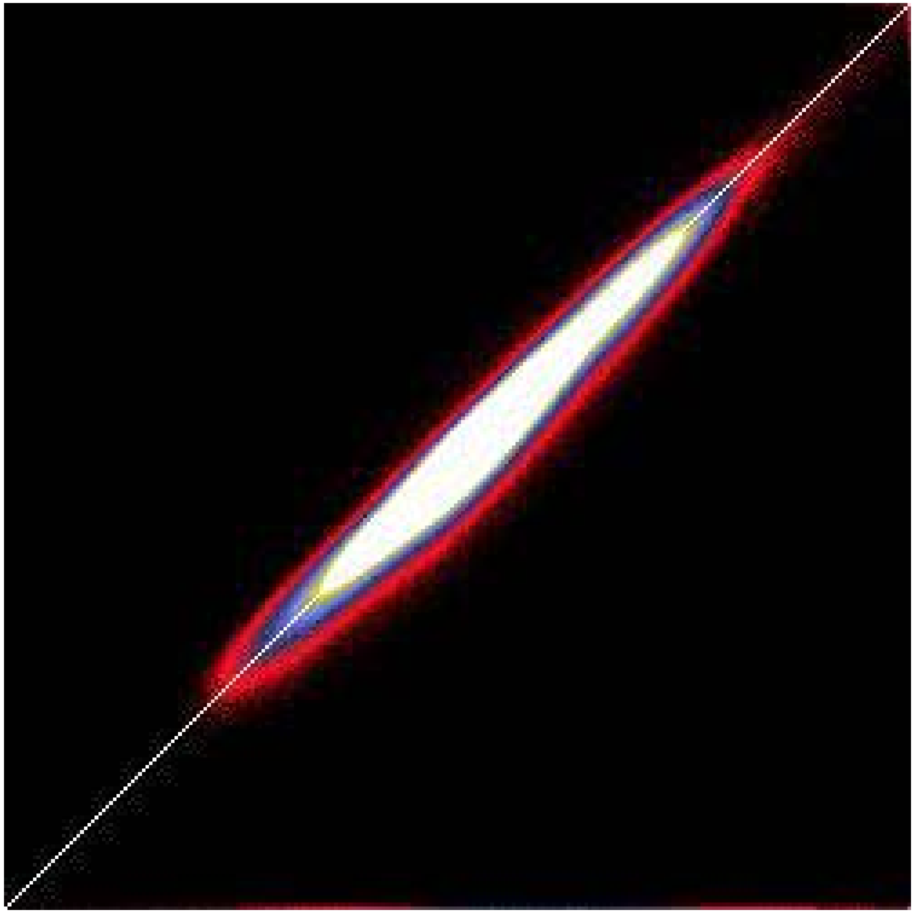
Mode hybrid

Window 7x7, 5 iterations, scale =[-40dB,0dB]

X Band: Reconstruction Vv



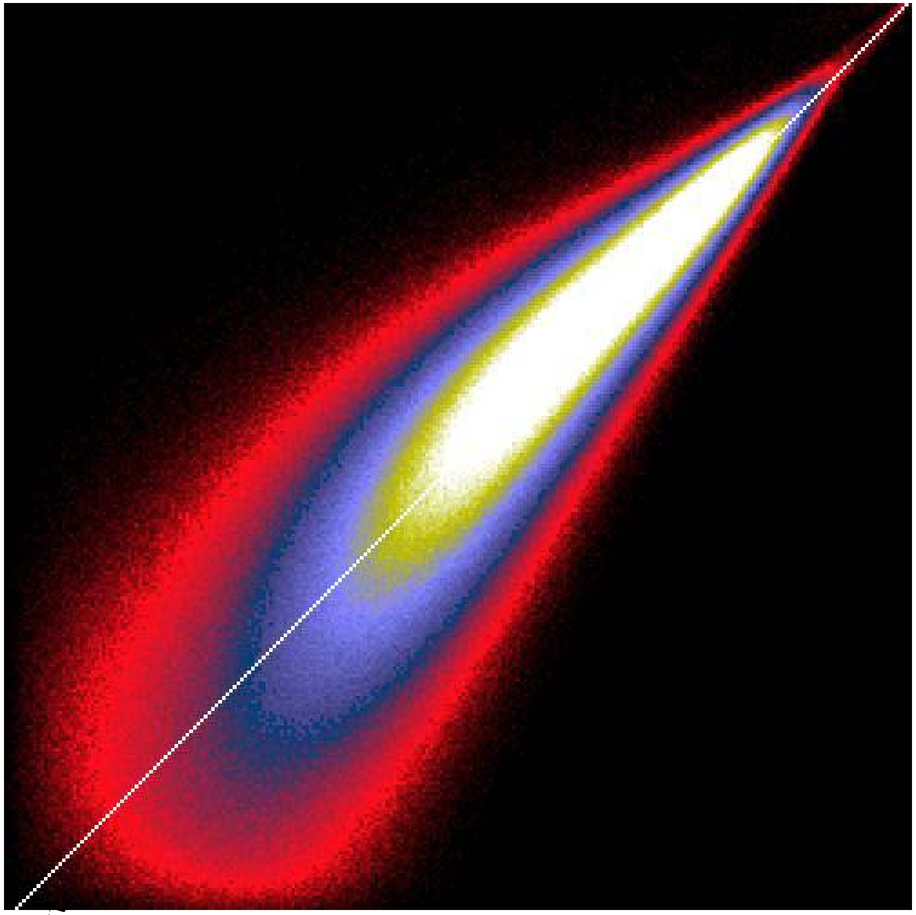
Mode π/4



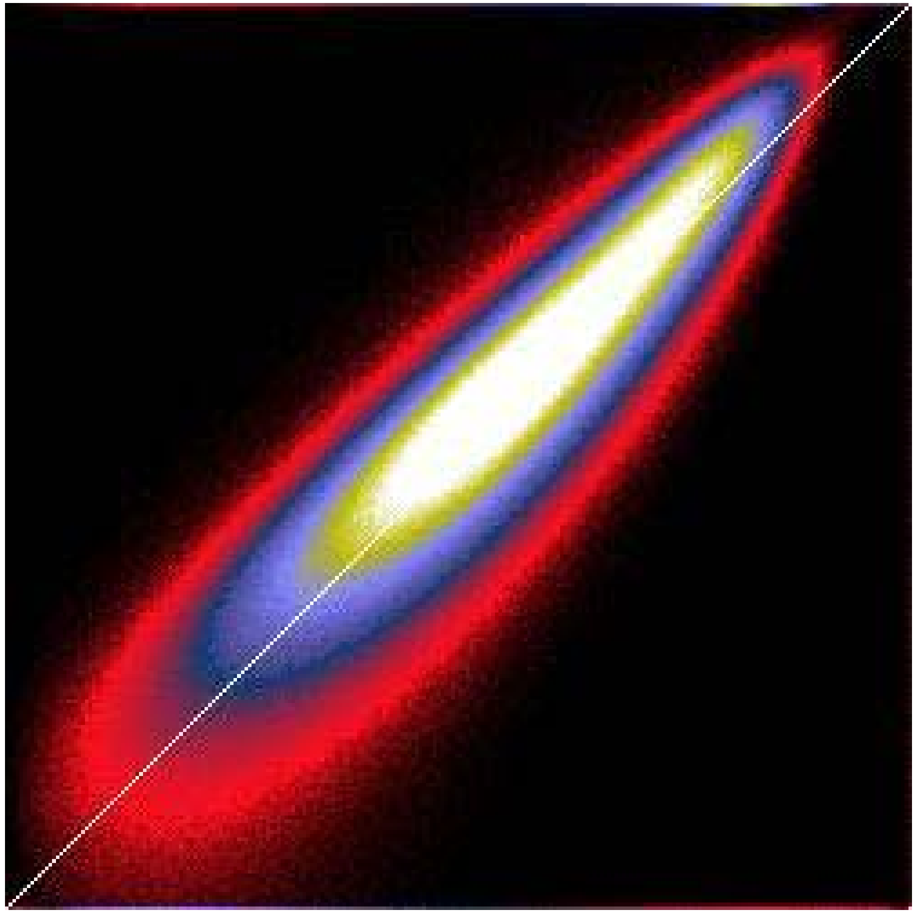
Mode hybrid

Window 7x7, 5 iterations, scale =[-40dB,0dB]

X-Band: Reconstruction Hh-Vv coherence



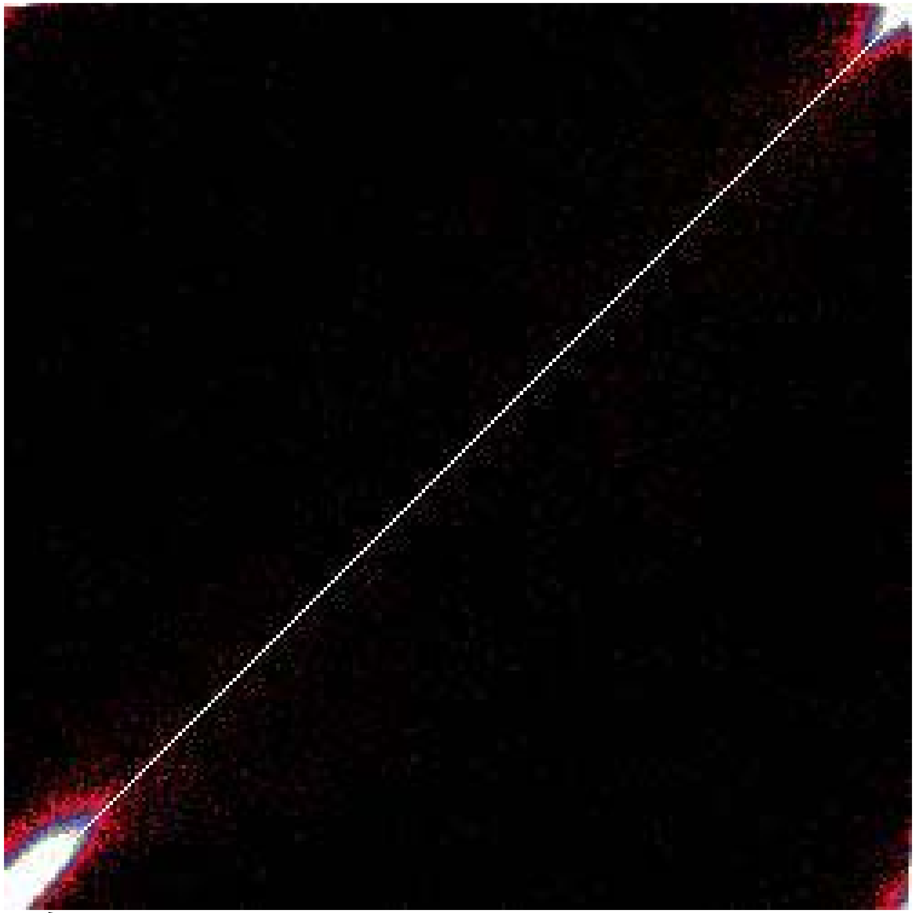
Mode $\pi/4$

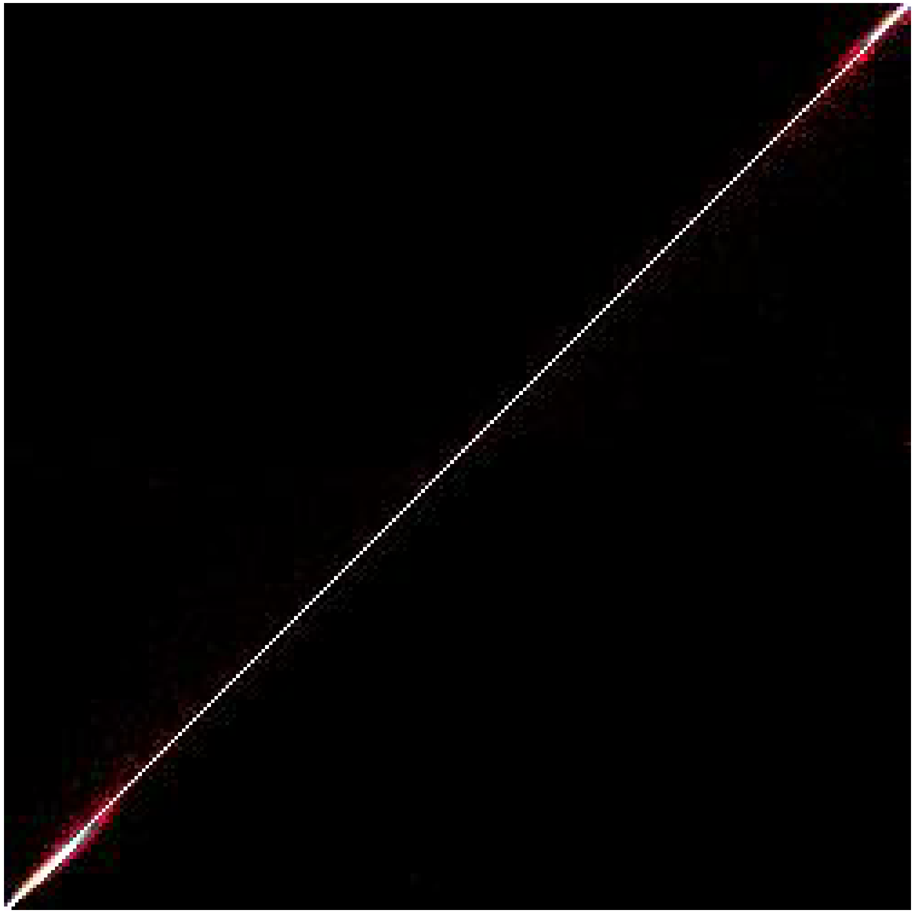


Mode hybrid

Window 7x7, 5 iterations, scale =[0,1]

X Band: Reconstruction Hh-Vv phase





Mode π/4

Mode hybrid

Window 7x7, 5 iterations, scale =[0,360°]

Compact PolInSAR analysis

RVOG model

P-Band specificity

Inversion results from Compact Polarimetry

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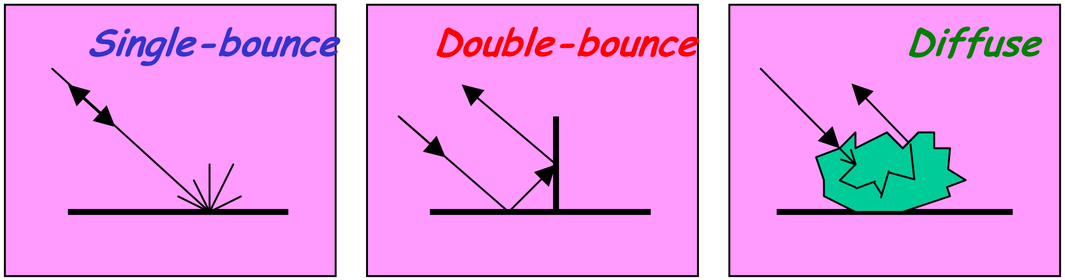
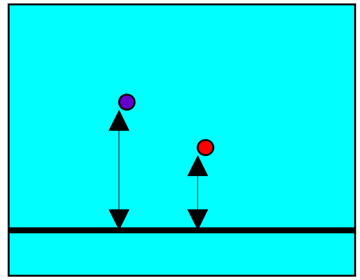
PolInSar data for biomass

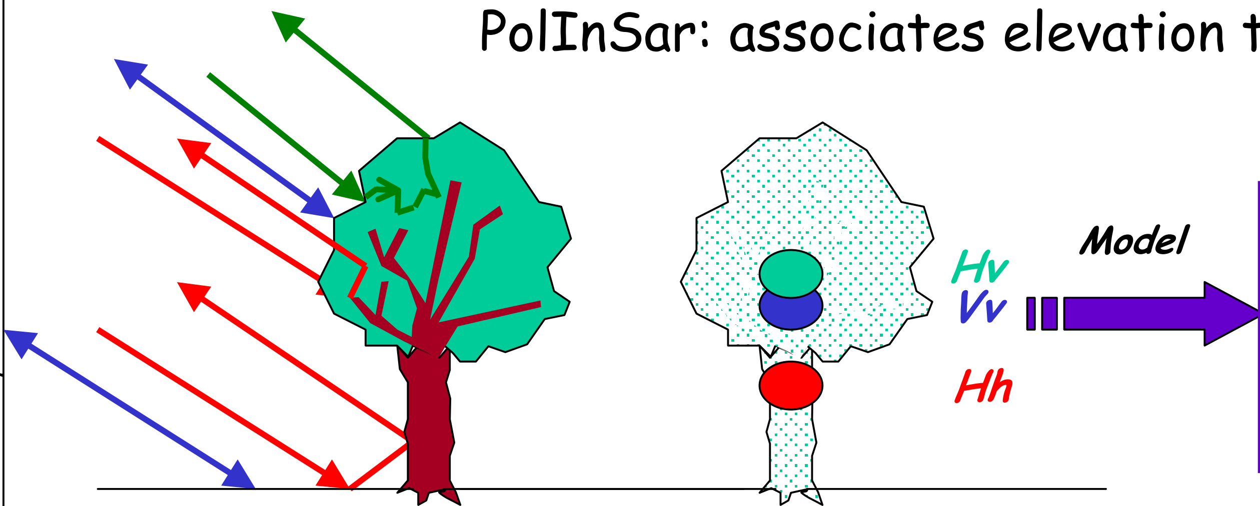
Polarimetry: identifies the scattering type



Interferometry: elevation



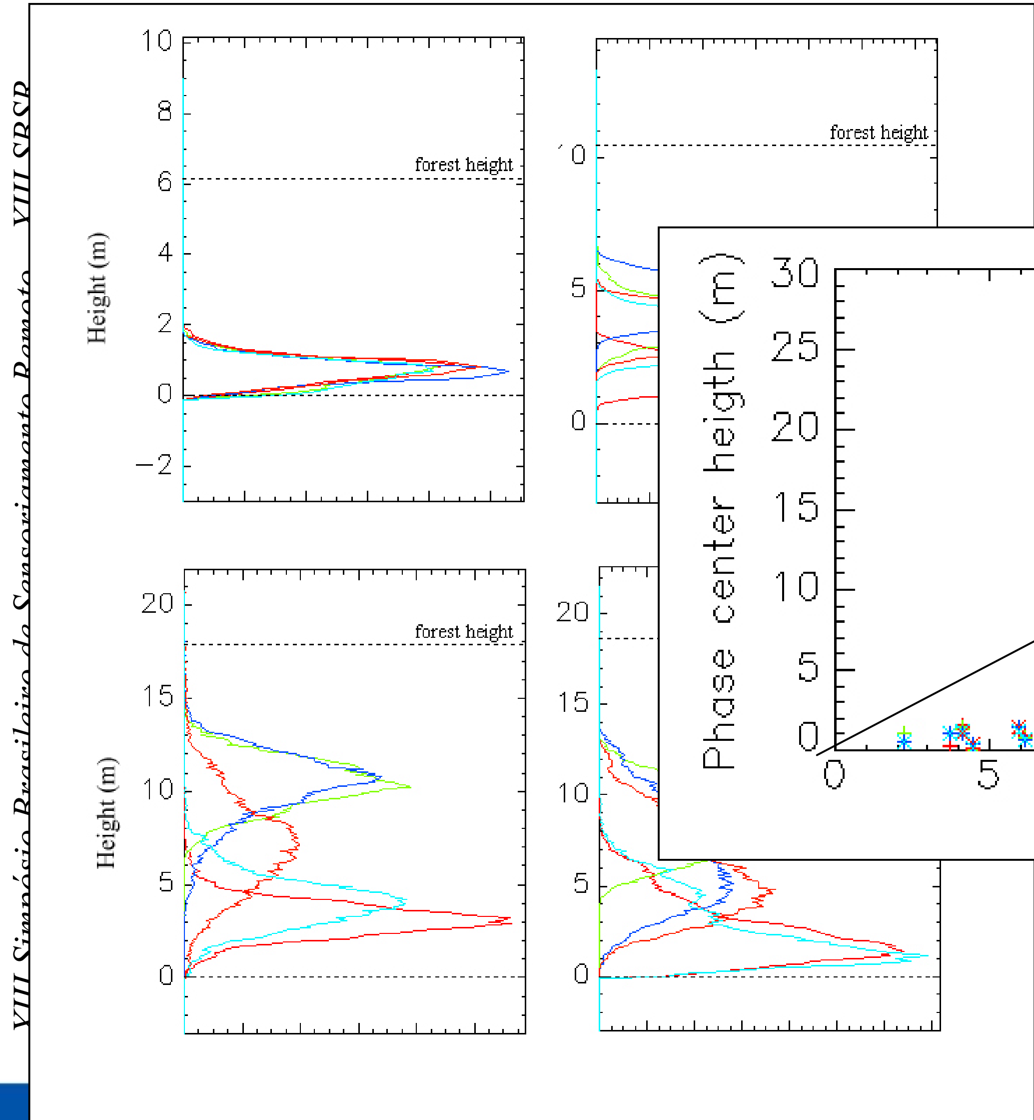
PolInSar: associates elevation to scattering type

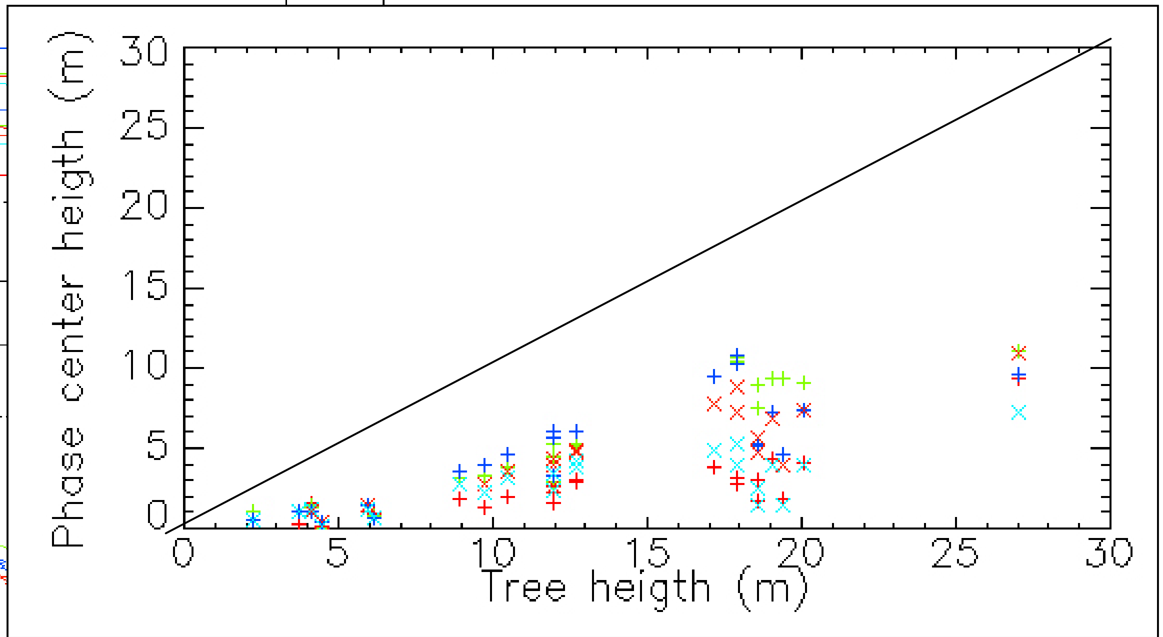


Biophysical parameters

- *tree height*
- *tree biomass*
- *attenuation*
- *…*

PolInSar analysis

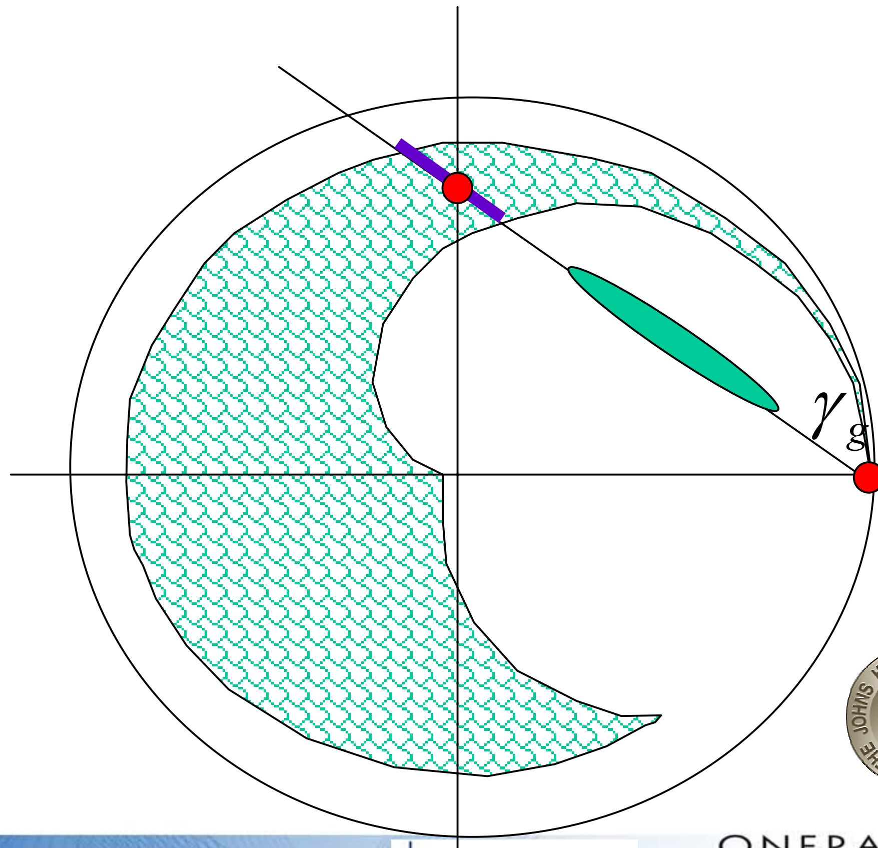




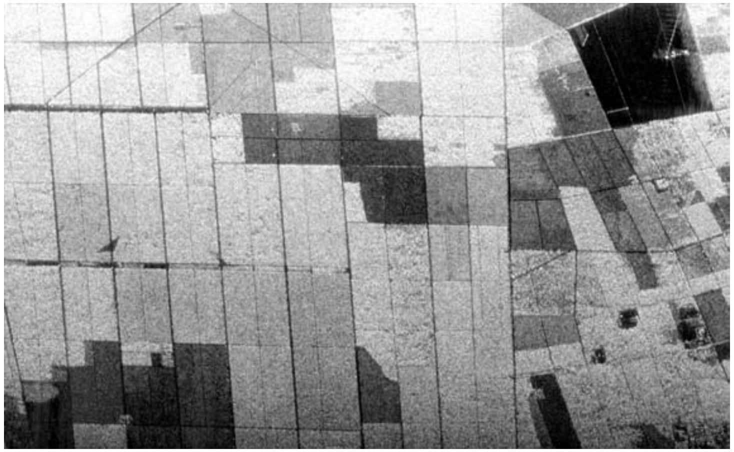
HH, HV, VV, HH+VV, HH-VV

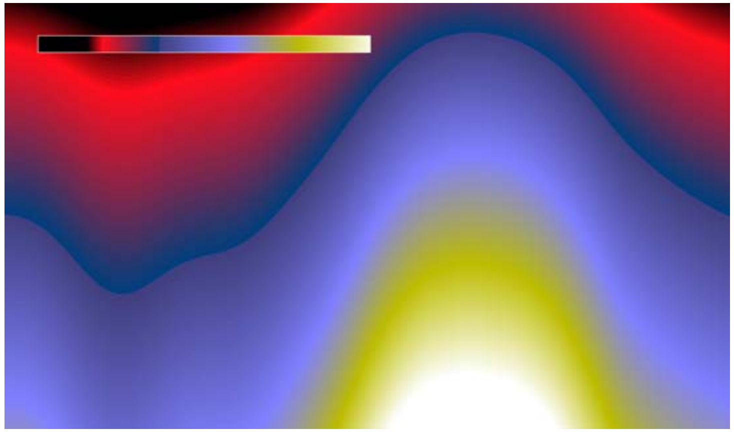
Inversion PolInSAR

- Standard Inversion RVoG
- Adapted to P-Band
  - Known extinction
  - Range of extinction
  - Time-frequency

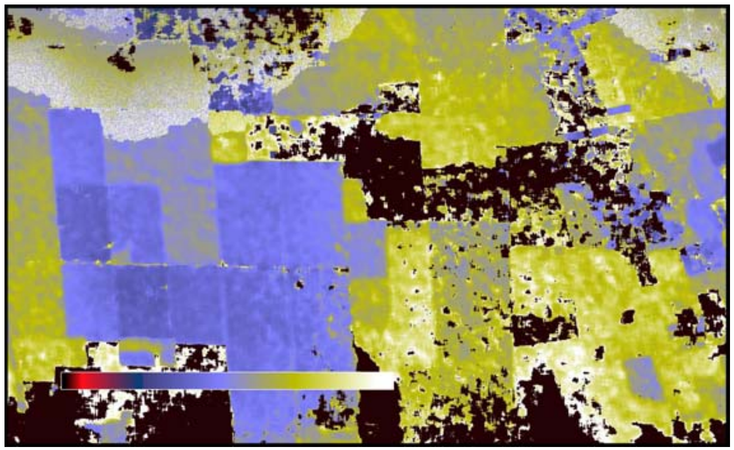


PolInSAR results at P band

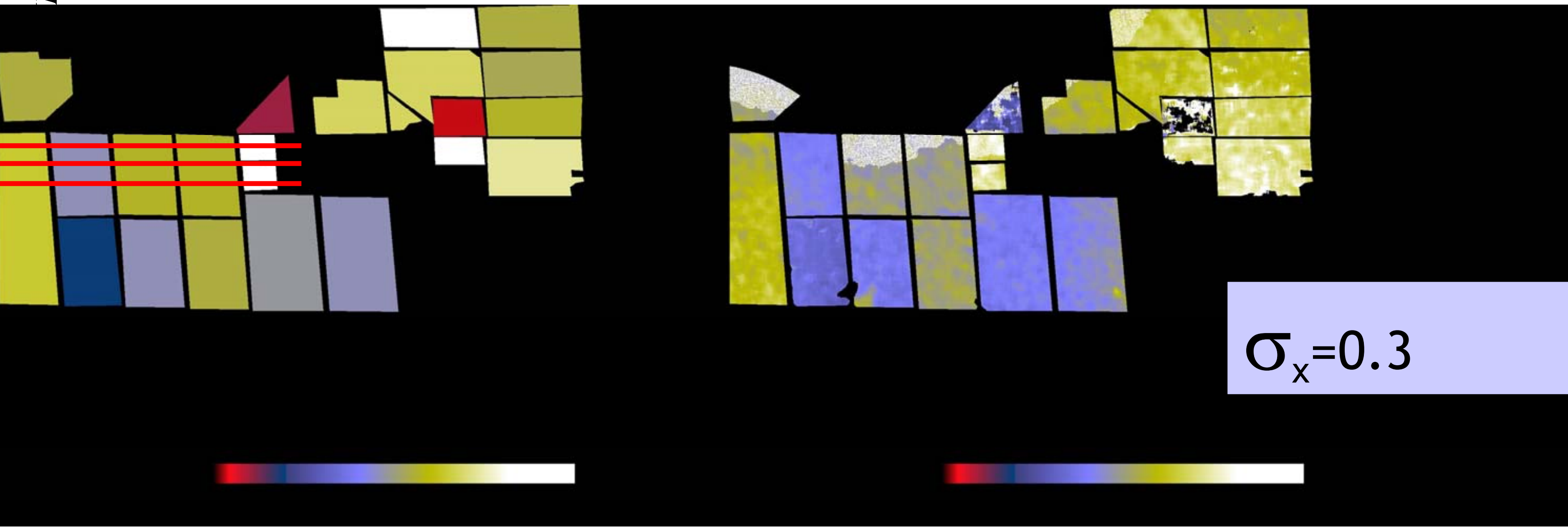




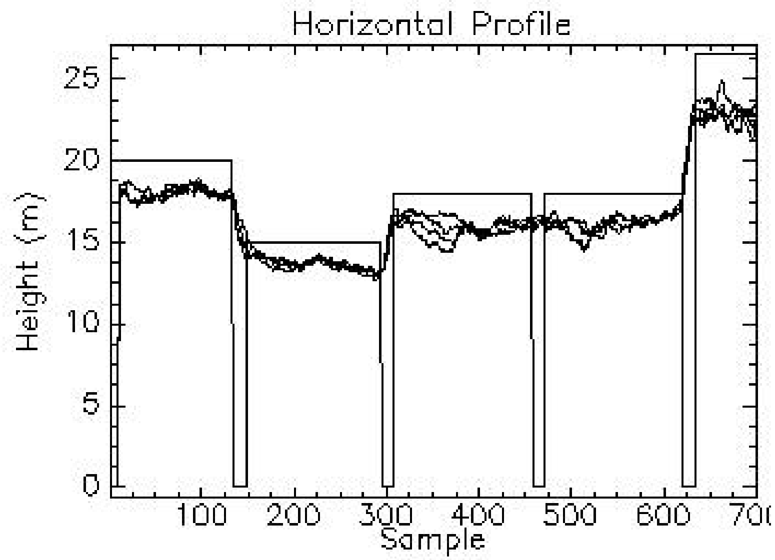
σ_x=0.3 dB/m

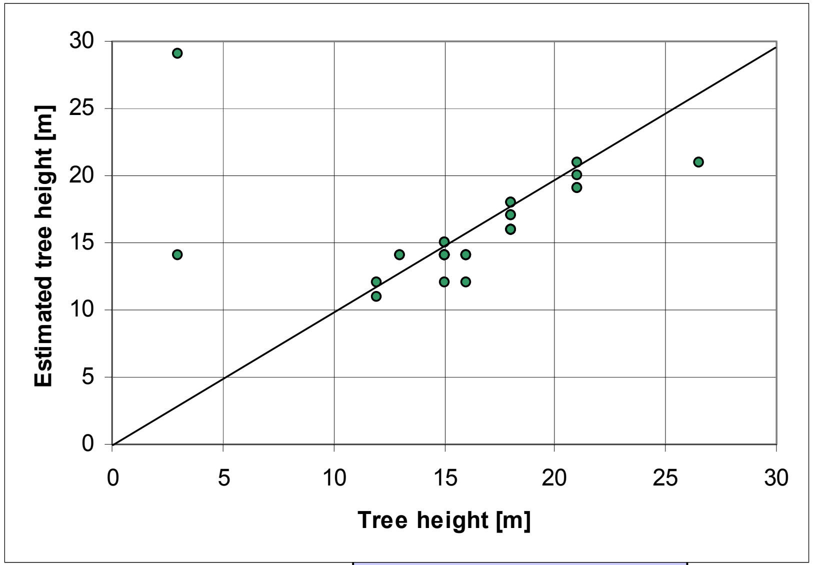


PolInSAR results at P band



PolInSAR results at P band

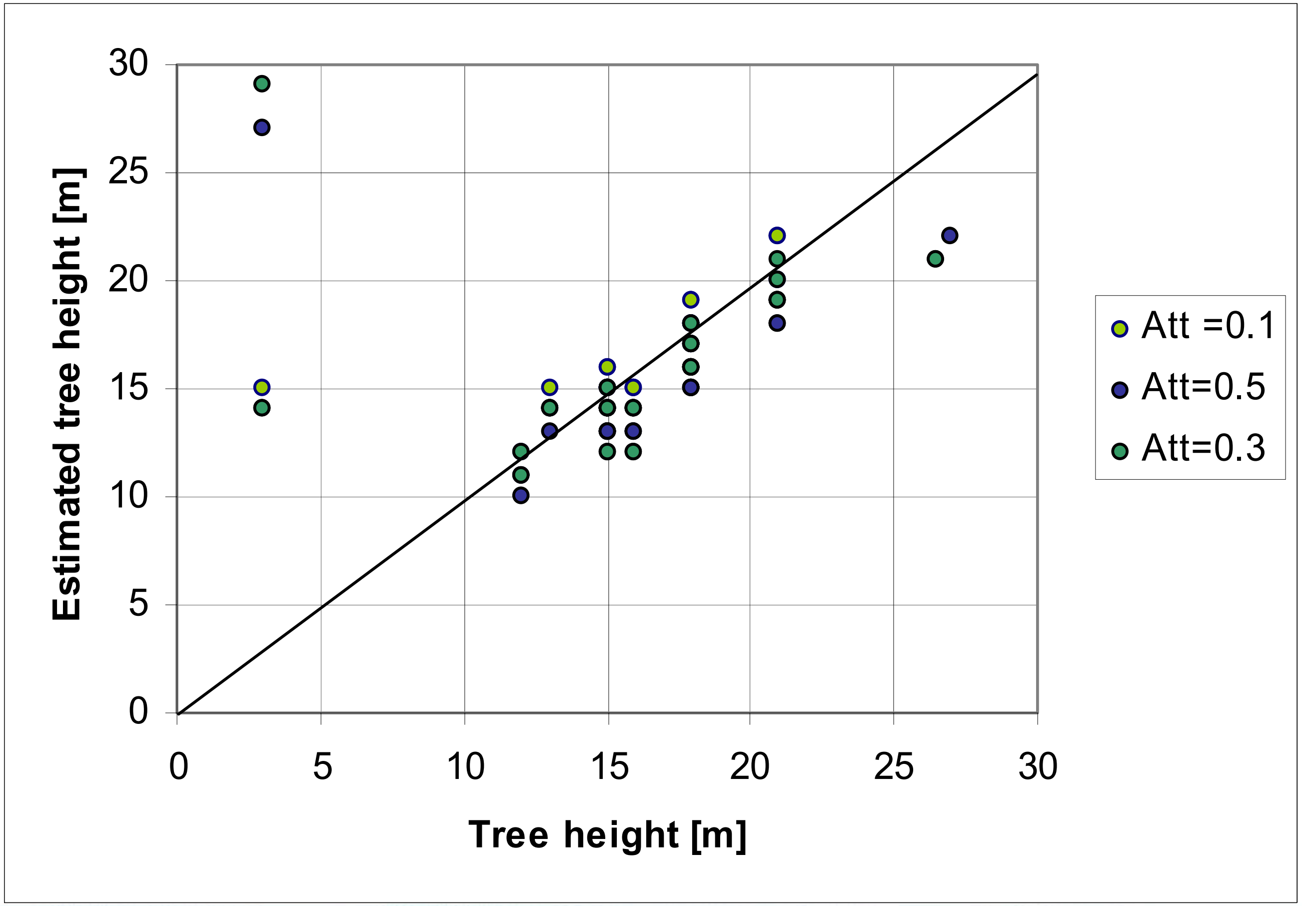




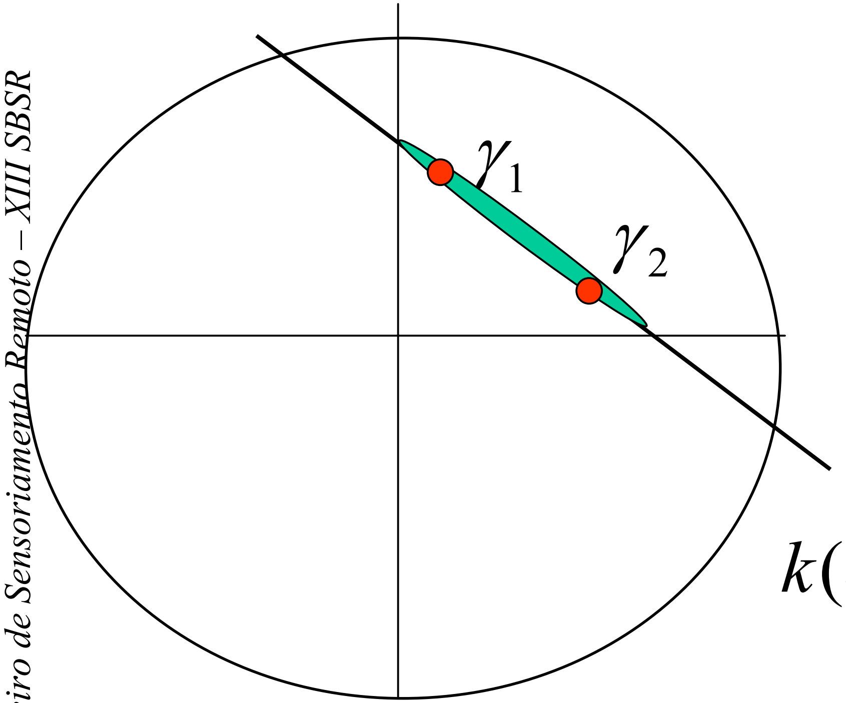
σ_x=0.3dB/m

RMS error = 1.2m

PolInSAR inversion at P band



Compact PolInSar

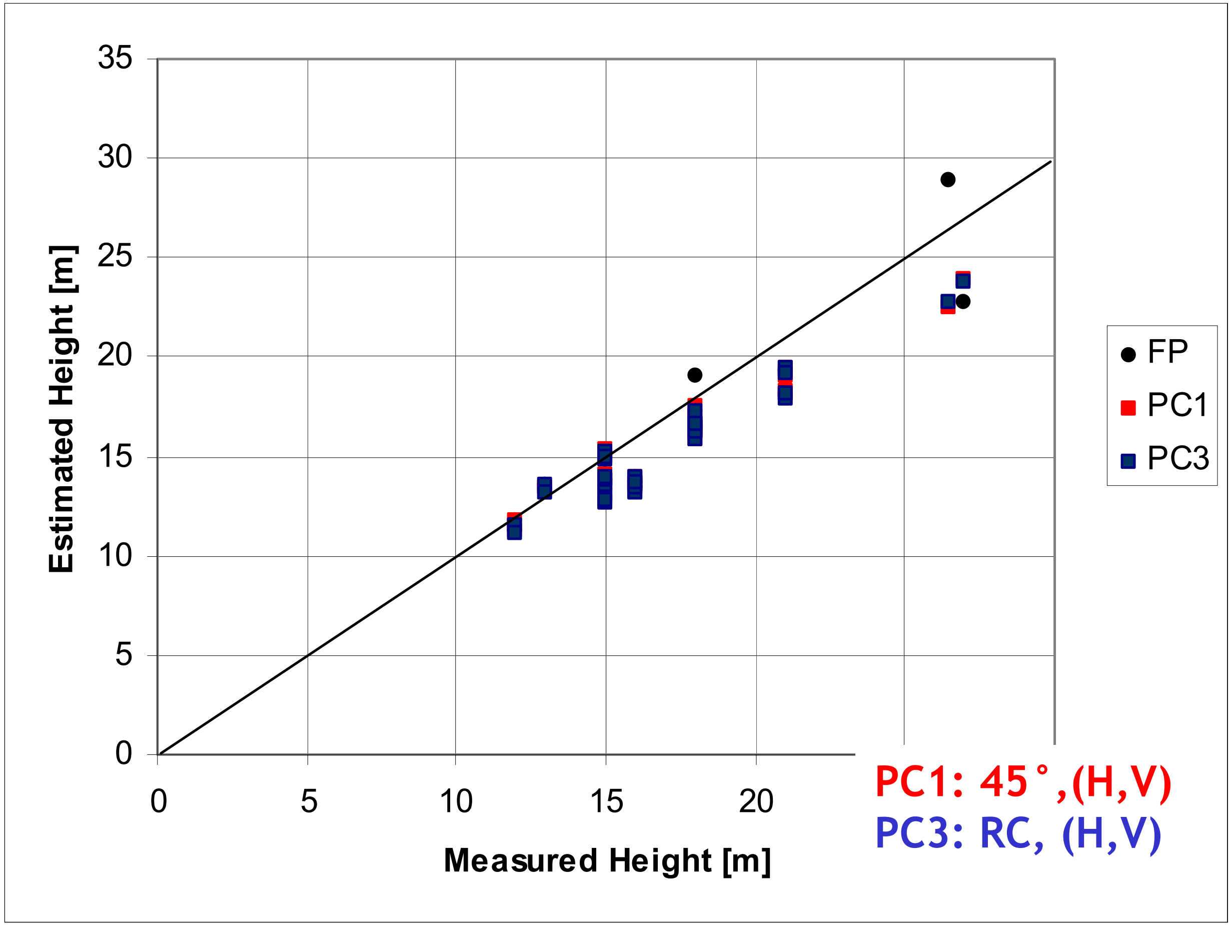


$$\begin{bmatrix} k_1 \\ k_2 \end{bmatrix}_M \quad \begin{bmatrix} k_1 \\ k_2 \end{bmatrix}_S \rightarrow \gamma_1 \quad \gamma_2$$

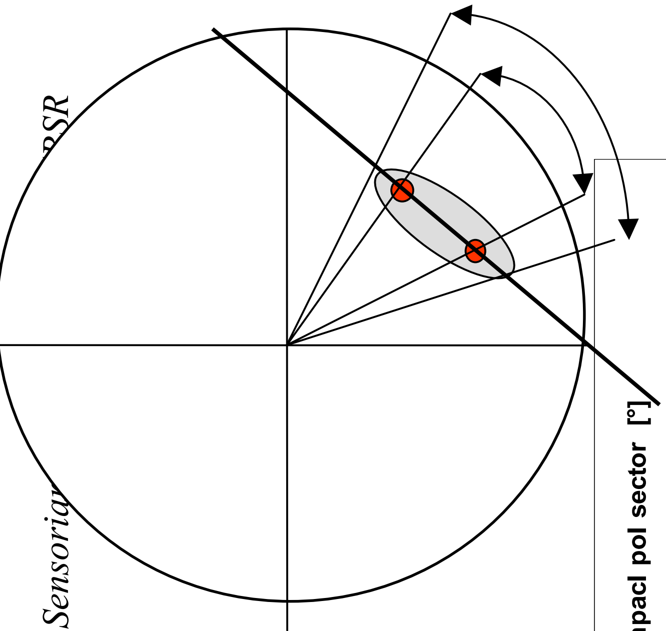
$$k(\psi, \chi) = \cos\psi . k_1 + \sin\psi . k_2 e^{j\chi}$$

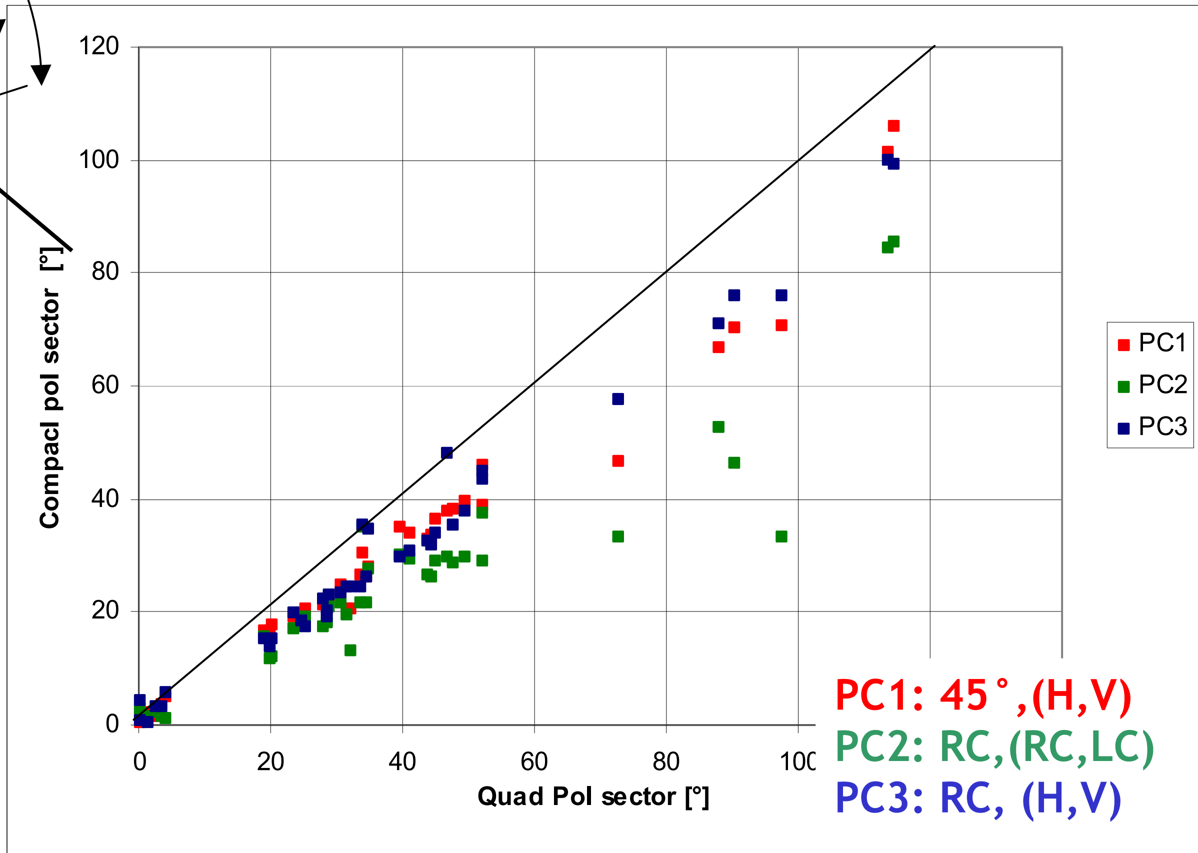
For all $\psi, \chi,$ compute $\gamma_{\psi\chi}$ → Inversion as before

Compact polinsar inversion



Compact PolInSar inversion





PC1: 45°,(H,V)
PC2: RC,(RC,LC)
PC3: RC, (H,V)

Compact Polarimetry and atmospheric effects

Introduction

Mode selection

PolSAR

PoLinSAR

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Ionospheric Effects

- Faraday rotation

$$M = \begin{pmatrix} \cos\Omega & \sin\Omega \\ -\sin\Omega & \cos\Omega \end{pmatrix} \begin{pmatrix} S_{HH} & S_{HV} \\ S_{HV} & S_{VV} \end{pmatrix} \begin{pmatrix} \cos\Omega & \sin\Omega \\ -\sin\Omega & \cos\Omega \end{pmatrix}$$

- Dispersivity
- Scintillation
  - What is the spatial scale of the TEC variation?

Ionospheric Correction on Full Polar data

$$M_{RR} = S_{RR} \qquad M_{LR} = e^{2j\Omega} S_{LR}$$

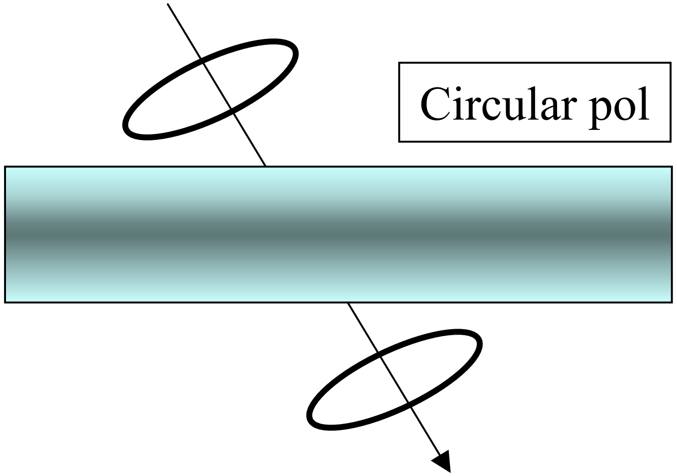
$$M_{LL} = S_{LL} \qquad M_{RL} = e^{-2j\Omega} S_{RL}$$

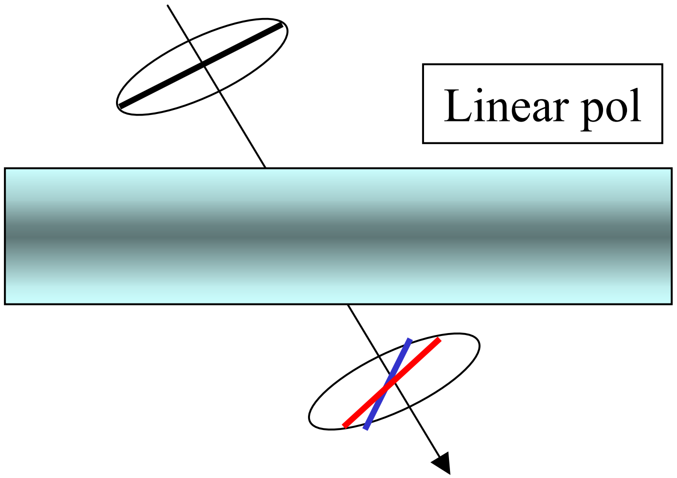
On any targets *

$$Arg(\langle M_{LR} M^{*}_{RL} \rangle) = 4\Omega$$

* Bickel and Bates, Proc IRE, 1965….

Transmitting a circular polarized wave, a logical choice





Transmitting a circularly polarized wave guaranties that the scattering element always sees the same incident wave. This is not the case with any other polarizations.

The scattered field is traveling back to the radar and is rotated. On reception, two orthogonal polarization provides the full reception of the scattered field.

Selecting the compact polarimetry modes…

- Full polarimetry is four dimensional
  - 2 orientation and 2 ellipticity angles
- Compact polarimetry provides access to a sub-space of the full polar observation space
  - 2 dimensional : one orientation and one ellipticity angles

- **The observed sub-space varies with ionosphere, except when transmitting circular**

- **This invariance is essential to provide consistent information…**

- **From now on, PC3**
  - **(Circular on transmit, H and V on receive)**

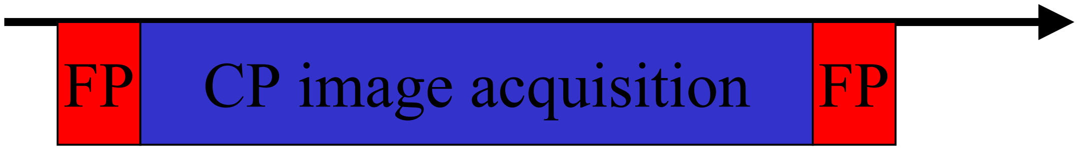
Ionospheric Correction & Compact Polarimetry

- New concept and on-going work
- Two different problems
  - PolSAR analysis
  - PolInSAR analysis
- Promising preliminary results in both cases
  - Evolving rapidly
  - To be completed

PolSAR and ionophere: possible approaches

- Estimation of Ω before and after acquisition
  - A few “full polar” bursts to estimate Ω
  - Acquisition CP and corrections.
  - Spatial variability of ionosphere?

$$Arg(\langle M_{LR} M_{RL}^{*} \rangle) = 4\Omega$$



- Estimation of Ω on particular targets
  - Single bounce surfaces :

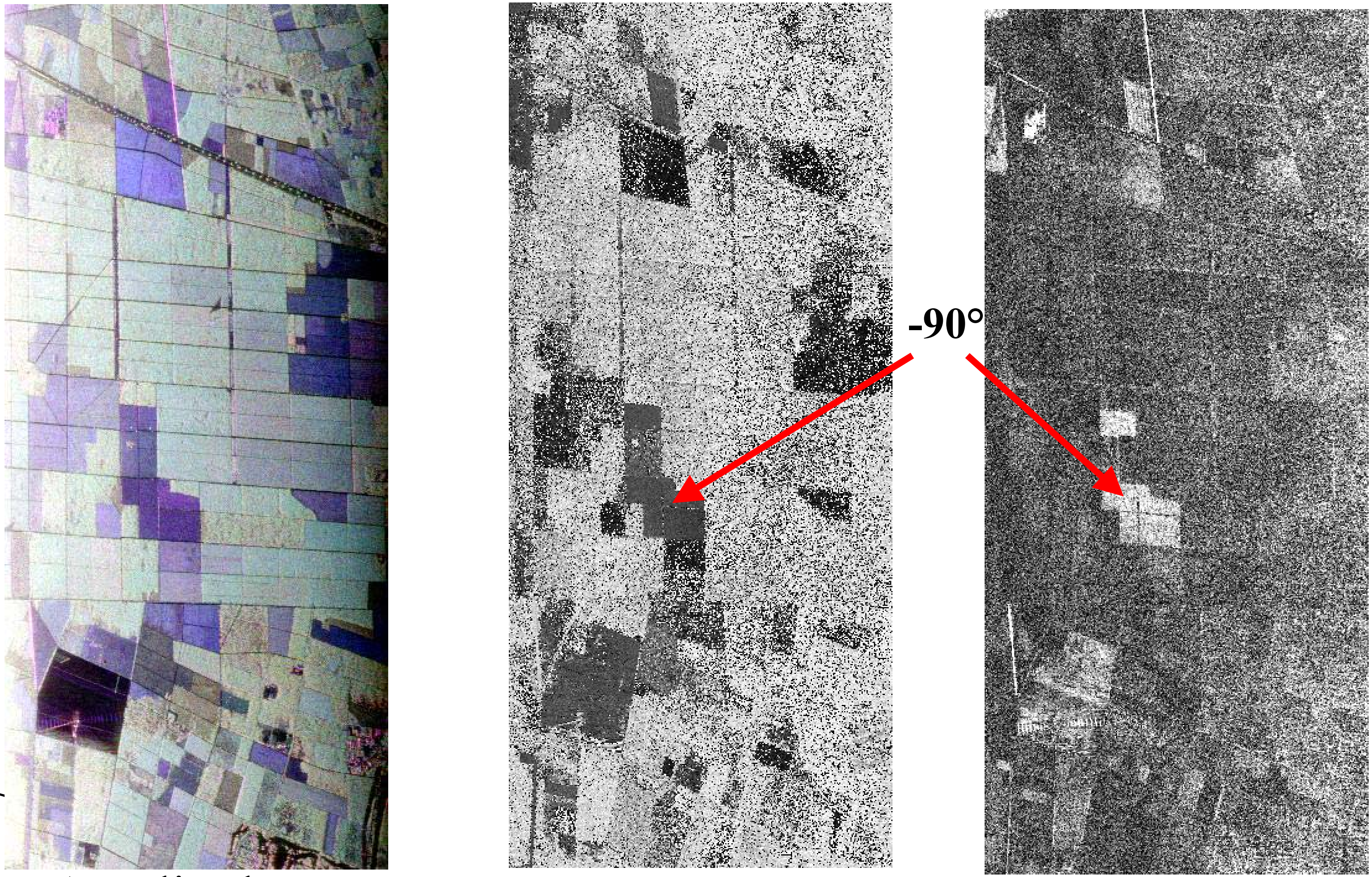
$$\mathrm{Im}(\langle S_{LL} S_{LR}^{*} \rangle) = 180° or 0°$$

$$\mathrm{Im}(\langle S_{LH} S_{LV}^{*} \rangle) = -90°$$

  - Estimation:

$$2\Omega = Arg(\langle M_{LL} M_{LR}^{*} \rangle) \angle 180°$$

Compact PolSAR and ionosphere



Amplitude Phase LH LV Coherence LH LV

PolSAR and ionosphere

- Arg(LH LV*)= -90° on bare surface (high coherence)
  - varies with ionosphere

- Arg(LL LC*)=180° on bare surface (high coherence)
  - shifts by 2 Ω with ionosphere

- Potential techniques to estimate the ionosphere on compact polarimetry acquisition. How accurately? Investigation still going on…

- Once the ionosphere is estimated, it is possible to invert it (in the circular transmit case)

Faraday rotation and compact PolInSar

Mode PC3

$$\vec{k}_{ref} \longrightarrow \boxed{\Omega_1} \longrightarrow \vec{k}^{\,ref}_{\Omega_1}$$

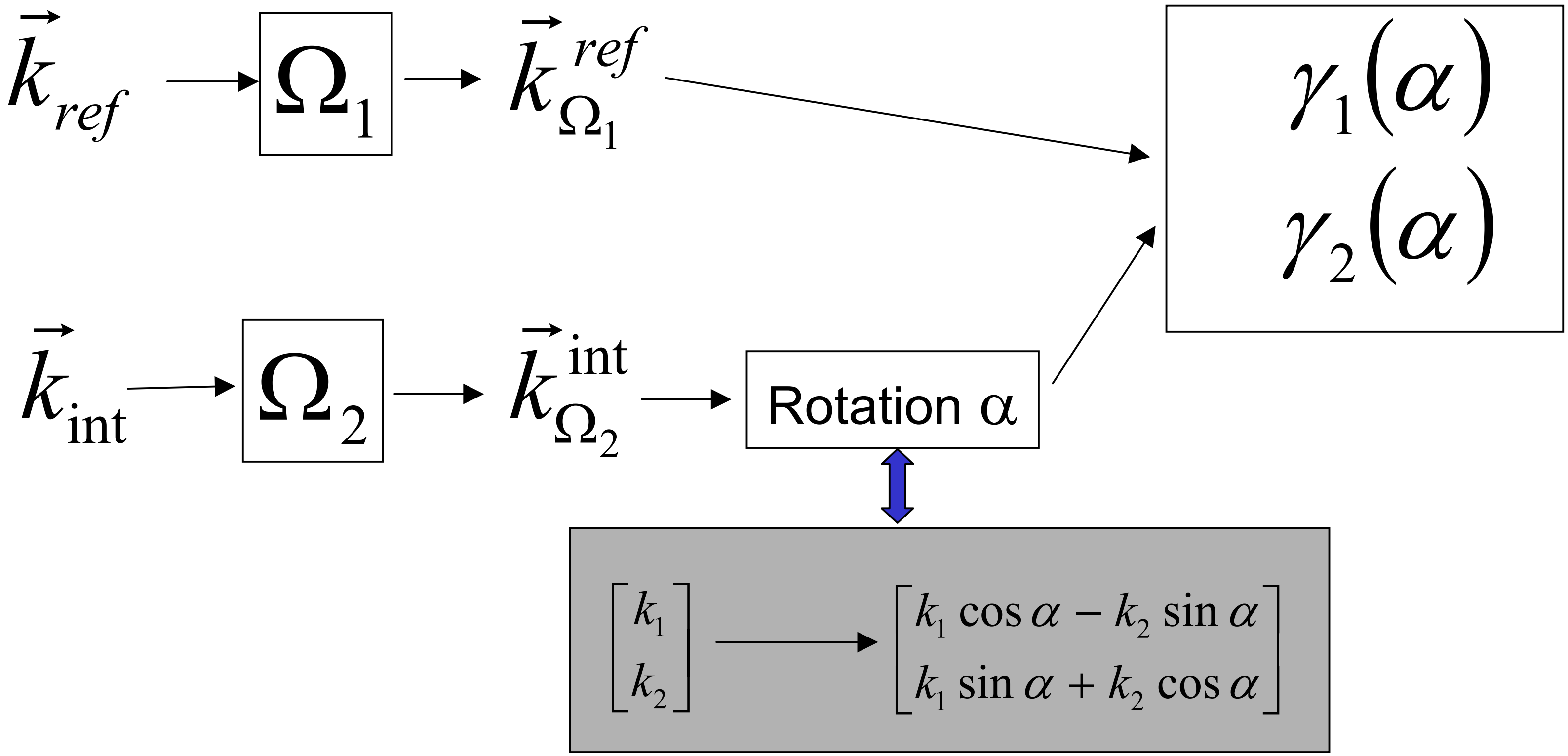
Different angles → loss of coherence

$$\vec{k}_{\text{int}} \longrightarrow \boxed{\Omega_2} \longrightarrow \vec{k}^{\,\text{int}}_{\Omega_2}$$

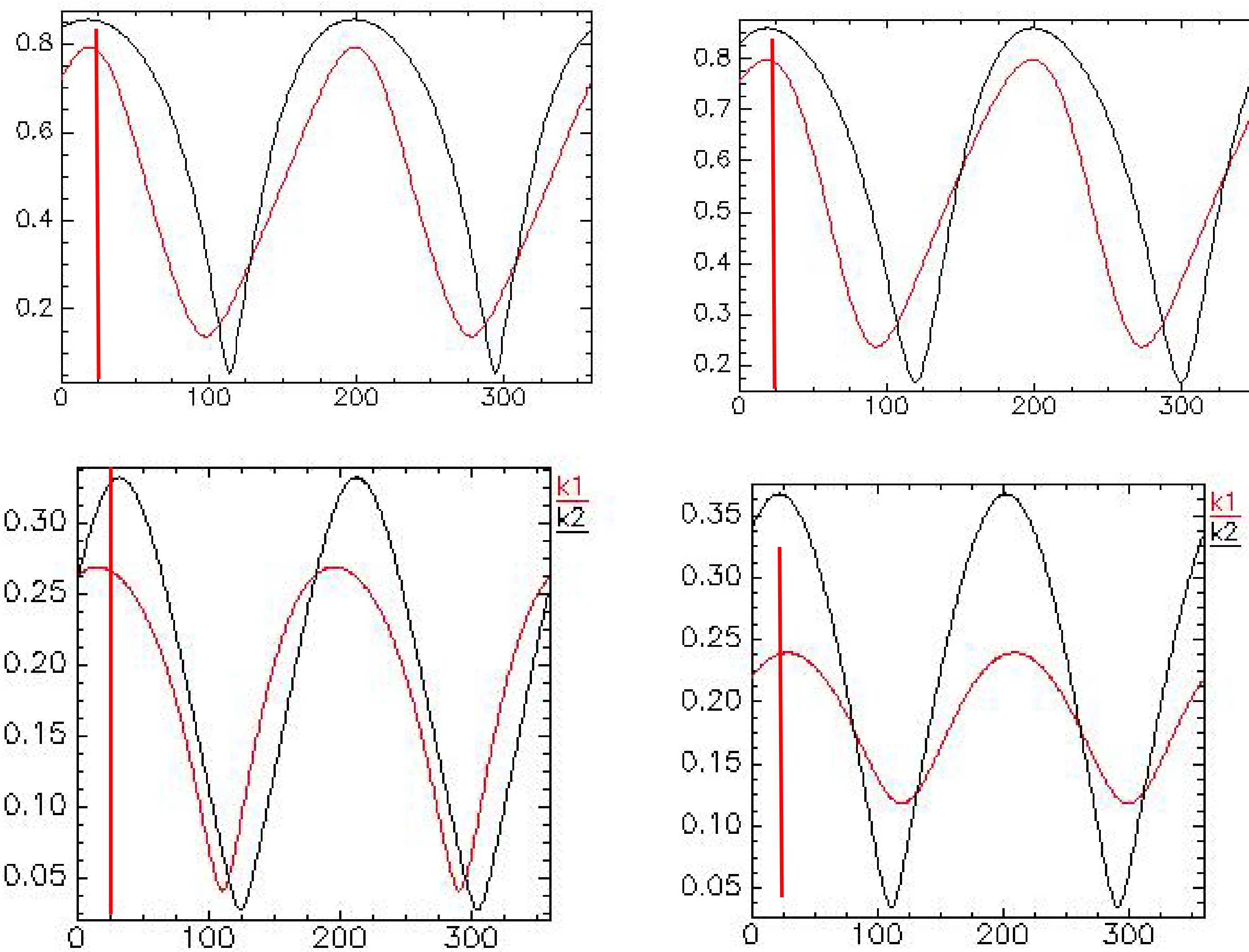
$$\begin{bmatrix} HH \pm jHV \\ HV \pm jVV \end{bmatrix} \longrightarrow \begin{bmatrix} HH(\cos^2\Omega + j\sin\Omega\cos\Omega) + jHV + VV(-\sin^2\Omega + j\sin\Omega\cos\Omega) \\ -HH(j\sin^2\Omega + \sin\Omega\cos\Omega) + HV + VV(j\cos^2\Omega - \sin\Omega\cos\Omega) \end{bmatrix}$$

But we are in the same observation sub-space

Faraday rotation and compact PolInSar



Compact PolInSAR: Estimation of Faraday (1/2)



$\gamma_1(\alpha)$

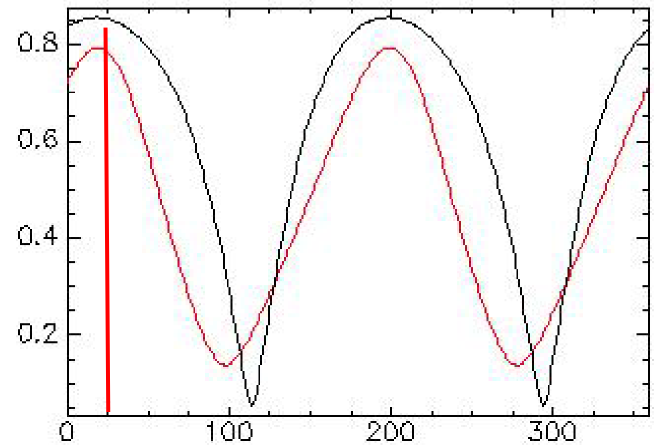
$\gamma_1(\alpha)$

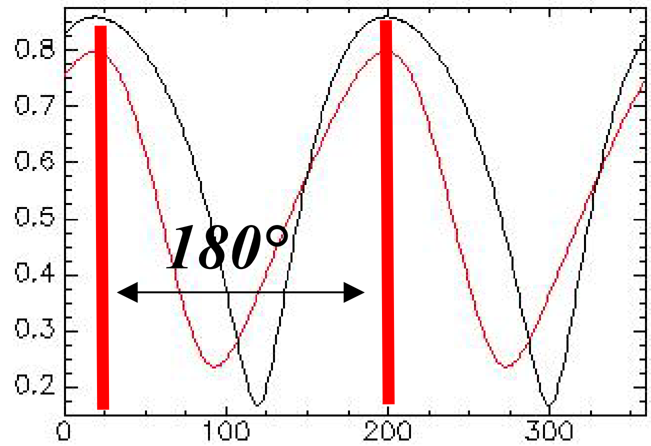
$\Omega_1 = 0°$

$\Omega_2 = 20°$

Different areas: ionospheric differences of 20°

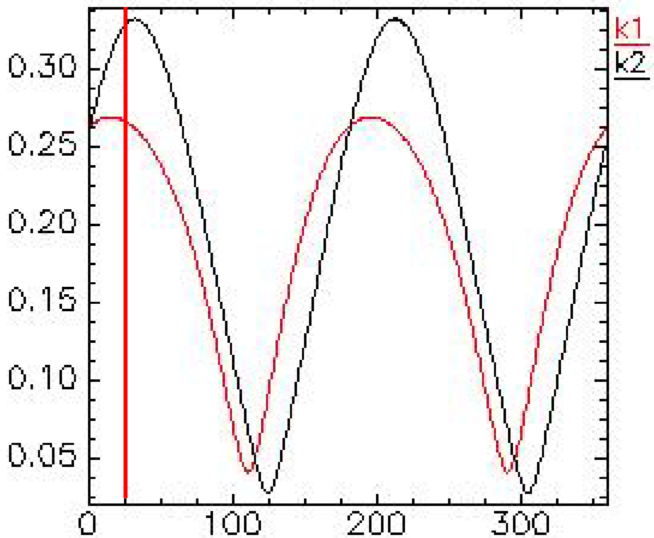
Compact PolInSAR: Estimation of Faraday (2/2)

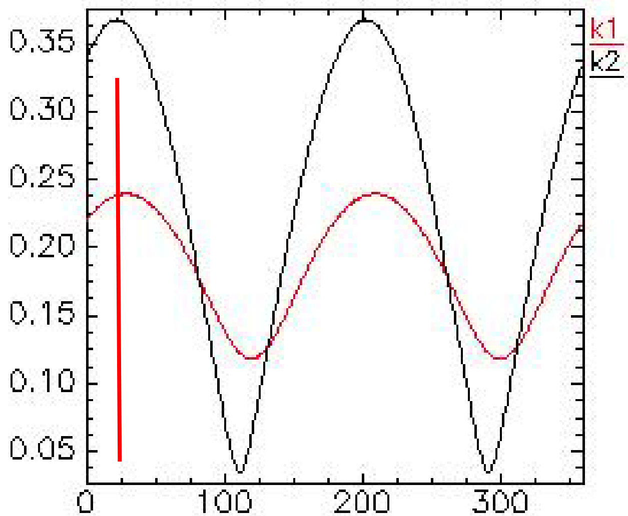




$\gamma_1(\alpha)$

$\gamma_1(\alpha)$





$$\Omega_1 = 0°$$
$$\Omega_2 = 20°$$

Different areas: ionospheric differences of 20°

Compact PolInSAR

- Two solutions (±1) provide the same inversion
  - The line is just rotated by 180°
- Given two acquisitions acquired with a different ionophere in mode PC3 (CH,CV), we can correct for the differential ionospheric angle to within a few degrees
- How robust is the inversion to a few degree differential ionosphere?

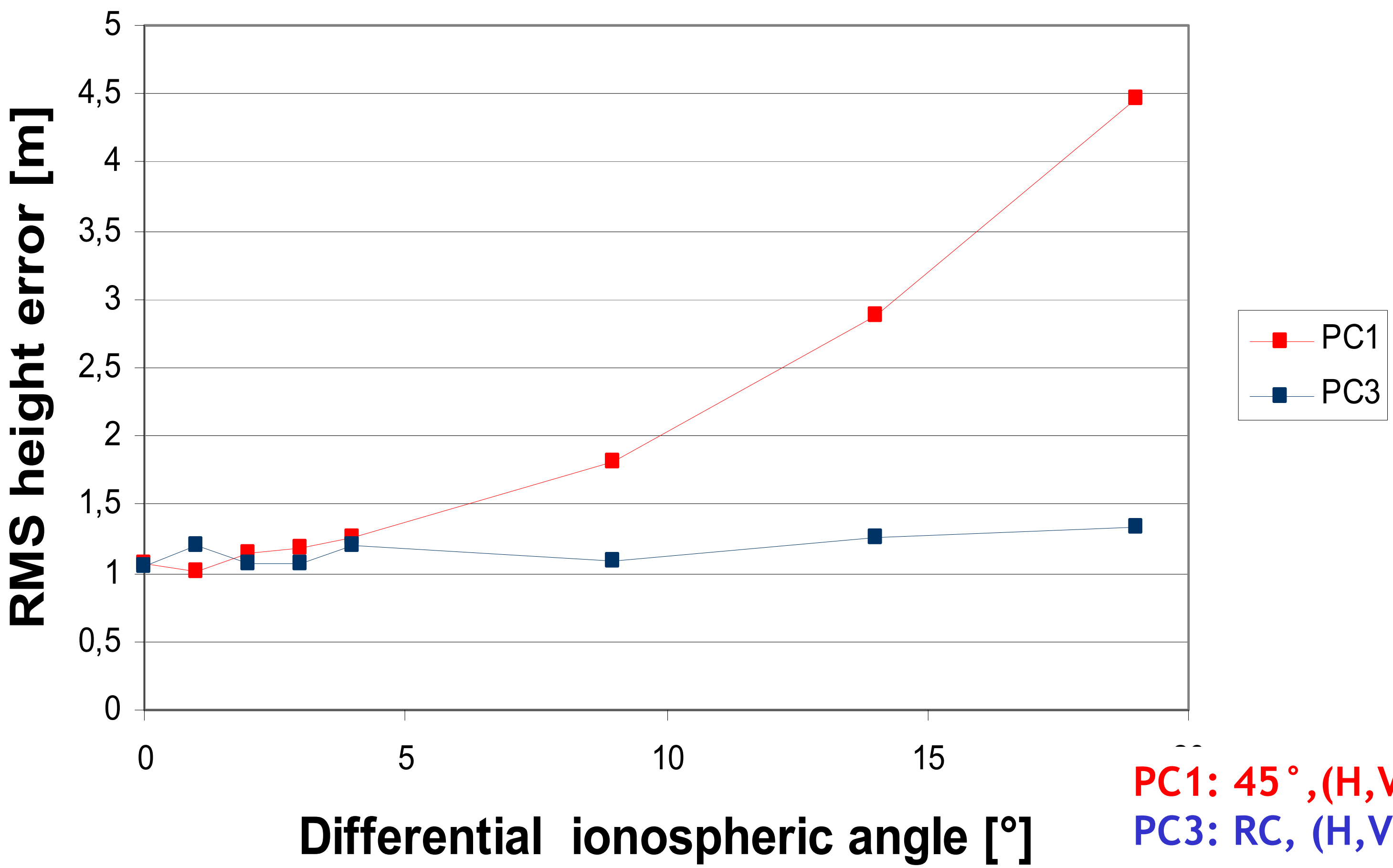
Robustness of inversion

$$\vec{k}_{ref} \longrightarrow \Omega_1 \longrightarrow \vec{k}_{\Omega ref}$$

$$\vec{k}_{\text{int}} \longrightarrow \Omega_2 \longrightarrow \vec{k}_{\Omega \text{int}}$$

$$\begin{array}{|c|} \hline \gamma_1(\Omega_1, \Omega_2) \\ \gamma_2(\Omega_1, \Omega_2) \\ \hline \end{array} \longrightarrow h$$

Different ionosphere on both acquisitions



PC1: 45°,(H,V)
PC3: RC, (H,V)

Different ionosphere on both acquisitions

Compact PolInSAR inversion

- Estimate the differential Faraday angle by maximizing the coherences over several areas.
- Correct one acquisition with this estimation
- Compute a large set of coherence by varying the orientation and ellipticity on the receive antenna
- Compute the line
- Select the ground point
- Intersection of the line with the curve of the volume only coherence associated with a given attenuation

Compact polarimetry

What do we know?

What else do we need to know?

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Conclusions from on-going work (1/2)…

- Complementary to full polarimetry
  - Compatible system design
  - Provides better coverage
  - Should be considered as another mode of operation, like dual-pol mode for ALOS
- PolSAR analysis
  - Specific compact polarimetric analysis possible (Raney, Cloude)
  - Reconstruction of the full polar covariance matrix for natural targets
  - Reconstruction possible for urban targets (Ainsworth)
  - **Information at pixel level is not preserved**
- Compact PolInSAR
  - Very good performance for RVOG inversion at P Band
  - Analysis to be extended to other datasets, different trees, mixed forest, significant slopes…

Conclusions from on-going work (2/2)…

- Circular transmit provides invariance of the observation space with respect of ionosphere

- PolSAR and ionosphere
  - Potential schemes for correction for PolSAR data…promising but to be investigated further

- PolInSAR and ionosphere
  - PolInSAR ionospheric correction has been demonstrated in a test case. Small improvements to the inversion are necessary.

Recommendations for POLINSAR2007 (1/2)

Compact polarimetry session chaired by Freeman and Souyris

- The effect of terrain slope on CP signals must be carefully assessed
- Faraday effects : it seems that some CP options (circular pol. transmission) would tolerate Faraday rotation to up to 10-15°. Issue of 1st concern as P band is a good candidate for CP
- Comparison between CP and FP must include both POLSAR & POL-INSAR aspects
- Antenna trade-offs must be investigated
- Technologically speaking, the design of a quad-pol mode and of a CP mode are compatible : CP can be easily integrated on FP architectures

Recommendations for POLINSAR2007 (2/2)

- Applications

  - Earth observation : “working point” should be identified in the framework of biomass – vegetation applications (P band) – assumptions for FP reconstruction usually verified

  - Ice applications : geophysical parameters not known precisely. Relations with POL-INSAR parameters to be established first

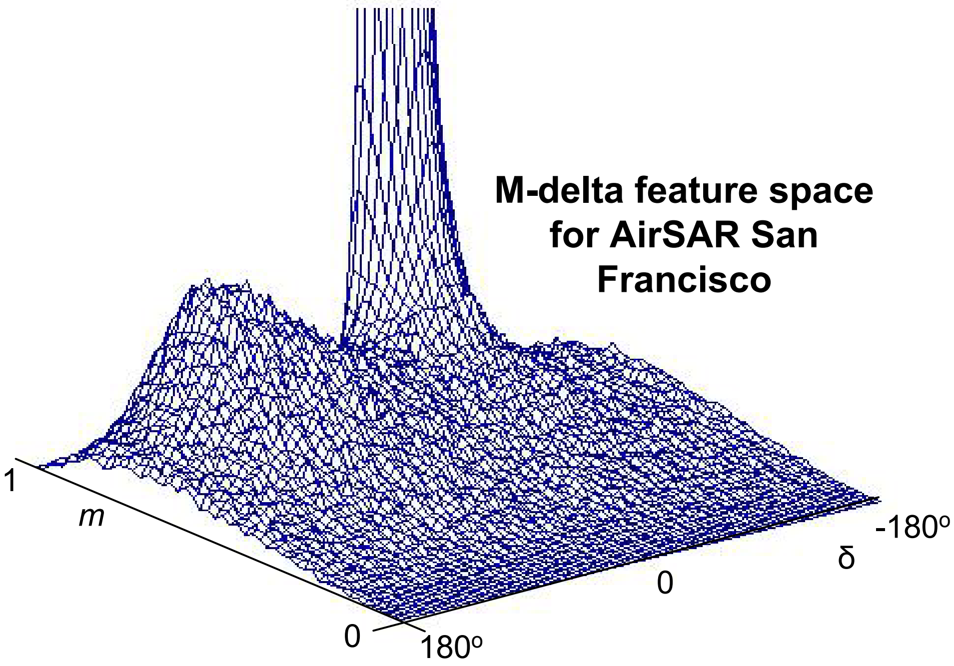
  - Surface-Subsurface scattering @ large incidence angles appear to be compliant with CP : need more investigation

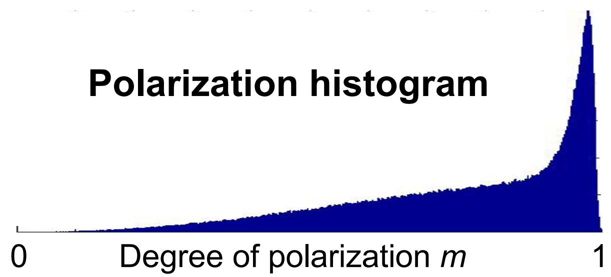
More specifically…

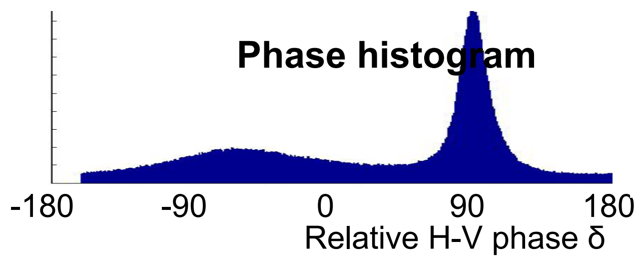
- Calibration scheme
  - Influence of the accuracy of the dephasing device
  - Importance of the accurate balancing of the H and V on transmit
  - More specific work needed… System design, internal calibration…
- PolSAR analysis
  - Evaluation has to be done for each specific application for a representative range of conditions
- PolInSAR analysis
  - Evaluation has to be done for a representative range of conditions
  - Plain interferometry is compromised by ionosphere.
- Better knowledge of ionosphere
  - To be taken into account in the studies
  - Are the models accurate in the ionospheric effect description?
  - Sequencing some modes to get to the ionosphere…
  - More on the spatial variability

Degree-of-polarization / phase feature space

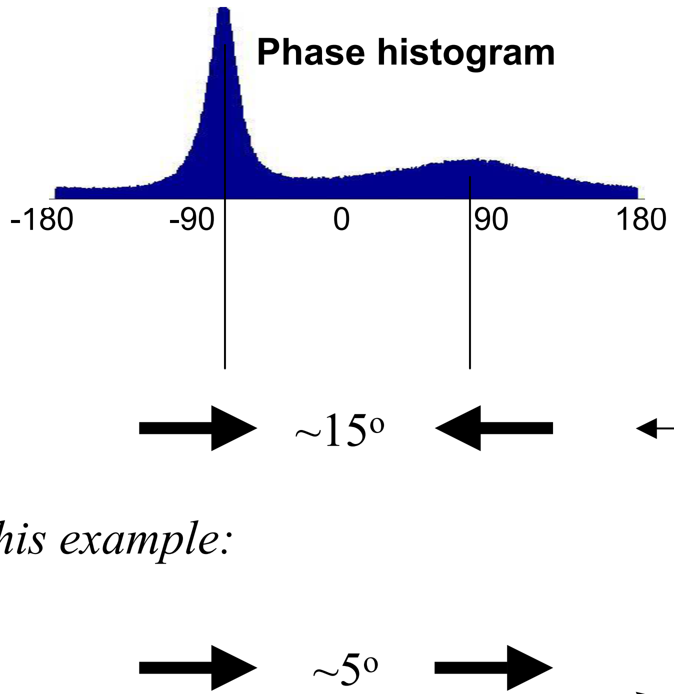
Essentially a two-dimensional histogram of relative phase and degree of polarization







Phase Calibration



This example:

- Transmit H/V phase

  Appears as equal shifts of the "90-degree" peaks toward (or away from) zero

- Receive H/V phase

  Appears as a linear shift of both peaks toward larger (or smaller) relative phase