# POLARIMETRIC INTERFEROMTRY

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## ABSTRACT

SAR polarimetry makes use of the polarization dependent scattering response of each pixel within the imaged area. The polarimetric response is highly sensitive to the scattering mechanism of a pixel. SAR interferometry is sensitive to the location of a pixel and its scattering geometry. The location of a pixel can be measured by the phase difference between two coherent SAR images using SAR interferometry. The interferometric correlation coefficient depends on the distribution of scattering objects. Even though the correlation coefficient does not uniquely depend on the scattering geometry, an empirical approach may exist to produce useful physical information from the interferometric correlation coefficient. Polarimetric interferometry combines both SAR polarimetry and SAR interferometry. The main purpose of using polarimetric interferometry is to extract scattering medium information that may be difficult to obtain from scalar interferometry. This information can also be used to enhance the interferometric SAR capability. Even though the formulation and initial demonstrations appear to be very promising, potential applications of polarimetric interferometry can only be verified by comparing polarimetric interferometry signatures with ground truth data. In order to accomplish this, the NASA/JPL TOPSAR system was modified to collect polarimetric interferometry data at C-band. In this talk, we discuss important issues related to polarimetric interferometry by using NASA/JPL polarimetric interferometry data.

## INTRODUCTION

Since an electromagnetic wave is polarized, natural objects respond differently if the incident wave polarization varies. In 1852, Stokes described partially polarized light by using the Stokes parameters. In 1946, George Sinclair used a 2 x 2 coherent scattering matrix to illustrate the radar target property as a polarization transformer. In the 1960s and 1970s, many researchers studied various remote sensing applications based on radar polarimetry [1]. The NASA/JPL AIRSAR system is considered to be the first imaging radar polarimeter [2]. By using imaging radar, the polarimetric characteristic can be measured for each pixel to understand the scattering mechanism associated with it. Even though the physical property of a pixel may not be easily recognized by the polarimetric response, the geophysical information associated with the scattering mechanism may be inferred from the polarimetric response.

SAR interferometry has enabled two important science applications: surface change detection and topographic mapping [1]. Interferometric measurements are obtained from subtle phase signatures shown in two SAR images; therefore, two images must be coherent. The correlation between two SAR images depends on various parameters: SNR (Signal to Noise Ratio), the pixel scattering property, the radar imaging geometry, and the temporal change of the imaged area. The temporal decorrelation becomes significant if two images are not obtained simultaneously. In 1974, Graham reported the first airborne interferometric SAR system that generated topographic contours using the hardware interference system [3]. The NASA/JPL AIRSAR system demonstrated the DEM (Digital Elevation Model) production capability in 1986. This across track interferometric mode is popularly known as TOPSAR. Basically, SAR interferometry is sensitive to the location of the imaged area and the scattering geometry. The location can be measured by the phase difference between two coherent SAR images. The location of a pixel is represented by the phase center of the pixel; however, the phase center is not easily estimated from the physical pixel geometry since it is related to the phase center by complicated electromagnetic scattering interactions. The interferometric correlation coefficient also depends on the scattering mechanism. Even though the correlation coefficient does not uniquely depend on the scattering geometry, an empirical approach may exist to produce useful physical information from the interferometric correlation.

S. R. Cloude and K. P. Papathanassiou first published the formulation of polarimetric interferometry that combines both SAR interferometry and SAR polarimetry [4]. The main purpose of using polarimetric interferometry is to extract scattering medium information that may be difficult to obtain from scalar interferometry. This scattering information can also be used to find the optimum polarization for interferometric applications. Even though the formulation and initial demonstrations appear to be very promising, potential applications of polarimetric interferometry can only be verified by comparing polarimetric interferometry signatures with ground truth data.

## SAR POLARIMETRY AND DATA REPRESENTATIONS

In this section, we discuss various coherent scattering vectors to represent polarimetric SAR data. Using the linear polarization basis, the scattering vector $\vec{k}_L$ can be written as

$$\vec{k}_L = \begin{bmatrix} S_{hh} \\ \sqrt{2}S_{hv} \\ S_{vv} \end{bmatrix} \tag{1}$$

where $S_{xy}$ means the scattering response when a transmit electromagnetic wave is y-polarized while the receive antenna is x-polarized. Another coherent scattering vector using the Pauli matrix basis is given by

$$\vec{k}_P = \frac{1}{\sqrt{2}} \begin{bmatrix} S_{hh} + S_{vv} \\ 2S_{hv} \\ S_{vv} - S_{hh} \end{bmatrix} \tag{2}$$

The coherent scattering vector using the circular polarization basis can be expressed as

$$\vec{k}_C = \frac{1}{2} \begin{bmatrix} S_{hh} - S_{vv} + 2iS_{hv} \\ S_{hh} + S_{vv} \\ S_{hh} - S_{vv} - 2iS_{hv} \end{bmatrix} \tag{3}$$

When $\vec{k}_L$ and $\vec{k}_P$ are compared, the power associated with each element provide different information. That is,

$$P_L = \left\langle \vec{k}_L . \vec{k}_L^{+} \right\rangle = \begin{bmatrix} \left\langle S_{hh} S_{hh}^{*} \right\rangle \\ 2\left\langle S_{hv} S_{hv}^{*} \right\rangle \\ \left\langle S_{vv} S_{vv}^{*} \right\rangle \end{bmatrix} \tag{4}$$

However, the coherent scattering vector using the Pauli matrix basis includes the co-polarized phase difference as shown in equation (5).

$$P_P = \left\langle \vec{k}_P . \vec{k}_P^{\,+} \right\rangle = \frac{1}{2} \begin{bmatrix} \left\langle S_{hh} S_{hh}{}^{*} \right\rangle + \left\langle S_{vv} S_{vv}{}^{*} \right\rangle + 2 \left\langle |S_{hh}| |S_{vv}| \cos(\phi_{hh} - \phi_{vv}) \right\rangle \\ 4 \left\langle S_{hv} S_{hv}{}^{*} \right\rangle \\ \left\langle S_{hh} S_{hh}{}^{*} \right\rangle + \left\langle S_{vv} S_{vv}{}^{*} \right\rangle - 2 \left\langle |S_{hh}| |S_{vv}| \cos(\phi_{hh} - \phi_{vv}) \right\rangle \end{bmatrix} \tag{5}$$

Notice that the power is conserved regardless of the polarization representation.

To understand polarimetric parameters that may contain the geophysical information, we examined the correlation table based on the linear polarization component as shown in Table 1.

| | $S^*_{hh}$ | $S^*_{hv}$ | $S^*_{vv}$ |
|---|---|---|---|
| $S_{hh}$ | $\left\langle S_{hh} S^*_{hh} \right\rangle$ | $\dfrac{\left\langle S_{hh} S^*_{hv} \right\rangle}{\sqrt{\left\langle S_{hh} S^*_{hh} \right\rangle \left\langle S_{hv} S^*_{hv} \right\rangle}}$ | $\dfrac{\left\langle S_{hh} S^*_{vv} \right\rangle}{\sqrt{\left\langle S_{hh} S^*_{hh} \right\rangle \left\langle S_{vv} S^*_{vv} \right\rangle}}$ |
| $S_{hv}$ | Complex Conjugate | $\left\langle S_{hv} S^*_{hv} \right\rangle$ | $\dfrac{\left\langle S_{hv} S^*_{vv} \right\rangle}{\sqrt{\left\langle S_{hv} S^*_{hv} \right\rangle \left\langle S_{vv} S^*_{vv} \right\rangle}}$ |
| $S_{vv}$ | Complex Conjugate | Complex Conjugate | $\left\langle S_{vv} S^*_{vv} \right\rangle$ |

Table 1. Polarimetric correlations using linear polarization components. The diagonal terms are real and represent the backscattering cross section. The off-diagonal terms are complex and represent the cross correlation.

From Table 1, nine independent quantities can be observed: three backscattering cross sections and three complex (amplitude and phase) cross correlation coefficients. This cross correlation combination can be accomplished by using various coherent scattering vectors such as one using the Pauli matrix basis. The usefulness of these correlation coefficients can only be evaluated when they are compared with ground truth data.

Another way of representing the polarization scattering response is the use of average covariance matrix eigenvalues. The average covariance matrix $[T]$ for azimuthally symmetric scattering objects can be written as

$$[T] = C \begin{bmatrix} 1 & 0 & \rho \\ 0 & \eta & 0 \\ \rho^* & 0 & \zeta \end{bmatrix} \tag{6}$$

where

$$C = \left\langle S_{hh} S^*_{hh} \right\rangle \tag{7}$$

$$\rho = \frac{\left\langle S_{hh} S^*_{vv} \right\rangle}{C} \tag{8}$$

$$\eta = 2 \frac{\left\langle S_{hv} S^*_{hv} \right\rangle}{C} \tag{9}$$

$$\zeta = \frac{\left\langle S_{vv} S_{vv}^* \right\rangle}{C} \tag{10}$$

Then, the covariance matrix can be decomposed into eigenvalues ( $\lambda$ ) and eigenvectors ( $\kappa$ ) as

$$[T] = \lambda_1 \kappa_1 \cdot \kappa_1^+ + \lambda_2 \kappa_2 \cdot \kappa_2^+ + \lambda_3 \kappa_3 \cdot \kappa_3^+ \tag{11}$$

The strength of eigenvalues can be used for identifying the scattering mechanism associated with each pixel.

As shown in above paragraphs, the coherent scattering vector can be written in various ways. Another representation of the polarimetric response can be accomplished by writing the coherent scattering vector as

$$\vec{k} = \left|\vec{k}\right| \hat{u} \tag{12}$$

where $\left|\vec{k}\right|^2$ is proportional to the scattering power and the unitary complex vector is written as

$$\hat{u} = \begin{bmatrix} \cos\alpha \;\; e^{i\phi_1} \\ \sin\alpha \cos\beta \;\; e^{i\phi_2} \\ \sin\alpha \sin\beta \;\; e^{i\phi_3} \end{bmatrix} \tag{13}$$

Then, $|k|^2$, $\alpha,\ \beta,\ \phi_1 - \phi_2$, and $\phi_2 - \phi_3$ can be used to characterize the polarimetric scattering response.

## SAR INTERFEROMETRY: PHASE CENTER AND INTERFEROMETRIC CORRELATION COEFFICIENT

SAR interferometry uses two data sets obtained from both upper and lower antennas. Interferometric data products are summarized in Table 2.

| | $S_u^*$ | $S_l^*$ |
|---|---|---|
| $S_u$ | $\left\langle S_u S_u^* \right\rangle$ | $\dfrac{\left\langle S_u S_l^* \right\rangle}{\sqrt{\left\langle S_u S_u^* \right\rangle \left\langle S_l S_l^* \right\rangle}}$ |
| $S_l$ | Complex Conjugate | $\left\langle S_l S_l^* \right\rangle$ |

Table 2. Interferometric SAR data products. The diagonal terms are real and represent the backscattering cross section of both upper and lower antennas. The off-diagonal terms are complex and represent the interferometric correlation coefficient.

The interferometric correlation coefficient can be expressed as

$$\gamma = \frac{\left\langle S_u S_l^* \right\rangle}{\sqrt{\left\langle S_u S_u^* \right\rangle \left\langle S_l S_l^* \right\rangle}} = \gamma_s \gamma_n \gamma_t \tag{14}$$

where $(1-\gamma_s)$, $(1-\gamma_n)$ and $(1-\gamma_t)$ represent scattering, thermal noise, and temporal decorrelation, respectively. For TOPSAR, the temporal decorrelation disappears since it collects interferometric SAR data simultaneously. The phase of the correlation coefficient is used for generating DEM with proper phase unwrapping while its amplitude is related to the scattering mechanism.

## POLARIMETRIC INTERFEROMETRY

Polarimetric interferometry combines both SAR polarimetry and SAR interferometry. The polarimetric interferometry system can be implemented by collecting polarimetric data for both upper and lower antennas. Using the linear polarization basis, output data products are summarized in Table 3. Various coherent scattering vector representations can also be used to obtain the cross correlation coefficient that enhances the desired scattering property. Two polarimetric data sets can be collected for both upper and lower antennas. The differences in both polarimetric responses are expected to be minor. The same polarization interferometry data can be used to derive DEMs and the decorrelation amount associated with each polarization. The hybrid polarization interferometry data contains both polarization and interferometry dependent decorrelation.

| | $S_{hh}^{(u)*}$ | $S_{hv}^{(u)*}$ | $S_{vv}^{(u)*}$ | $S_{hh}^{(l)*}$ | $S_{hv}^{(l)*}$ | $S_{vv}^{(l)*}$ |
|---|---|---|---|---|---|---|
| $S_{hh}^{(u)}$ | **Upper Antenna Polarimetry** | | | HH interf. | HPI | HPI |
| $S_{hv}^{(u)}$ | | | | HPI | HV interf. | HPI |
| $S_{vv}^{(u)}$ | | | | HPI | HPI | VV interf. |
| $S_{hh}^{(l)}$ | **Complex conjugate of the upper right matrix** | | | **Lower Antenna Polarimetry** | | |
| $S_{hv}^{(l)}$ | | | | | | |
| $S_{vv}^{(l)}$ | | | | | | |

Table 3. Polarimetric interferometric data product. HPI stands for Hybrid Polarization Interferometry.

It is expected that each pixel can be characterized better by using both SAR polarimetry and SAR interferometry. The phase center and the correlation coefficient of each polarization response may be used to retrieve physical scattering features such as the tree height. The usefulness of these data sets must be evaluated by comparing them with the ground truth data. In order to do this evaluation, the polarimetric interferometry data must be calibrated carefully. The calibration procedure is being developed at JPL.

## CONCLUSIONS

In this paper, we presented various scattering vector representations in terms of SAR polarimetry, SAR interferometry, and polarimetric interferometry. In order to use SAR data for science applications, desired geophysical parameters must be measurable when SAR data are properly enhanced. The relationship between SAR data and geophysical parameters can be obtained by both theoretical and empirical approaches. By using the techniques shown in this paper, Pac Rim SAR data can be properly enhanced to be compared with ground truth data. We hope that various new findings can be made by using these techniques and Pac Rim data.

## REFERENCES

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