FULLY POLARIMETRIC SAR PARAMETERS AND CORRELATION WITH TARGET-SENSOR ORIENTATION AND BUILDING HEIGHT

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INTRODUCTION

The interaction of the radar signals with ground targets mainly depends on the geometrical shapes (including the size, shape and orientation) and the dielectric properties of the scatterers. In SAR remote sensing of urban areas, since buildings are the major scatterers, the backscattered wave is significantly affected by geometrical properties of the buildings such as the orientation and the height of the buildings. One of the advantages of the fully polarimetric SAR data is their ability to reveal and estimate the orientation of targets. A method to approximate target orientation is to calculate the Beta parameter from the eigenvector decomposition of the coherency matrix. This parameter can be considered as a representation of the target orientation about the radar line of sight. The building height information is obtained by the DEM and ancillary survey data for different parts of Tehran. The height classes are considered as low-rise, mid-rise and high-rise.
Several polarimetric SAR parameters are extracted from fully polarimetric datasets to represent contained information of the scene. These parameters are mainly derived from SAR complex analysis and target decomposition techniques. The goal is to investigate and evaluate the sensitivity of the polarimetric parameters to the orientation and the height of the buildings in the study area. A correlation analysis assesses the sensitivity of polarimetric parameters to the target orientation. Similar analysis evaluates the correlation between the above parameters with the actual building height data.

**METHODOLOGY**

The major steps in this research are: 1) obtaining/computing the orientation of the buildings and the building heights; 2) deriving/calculating the polarimetric parameters from complex analysis and target decomposition techniques; and 3) sensitivity analysis and comparison between individual parameters with the building orientation and height.

**Building Orientation Estimation**

Due to the existence of the vertical walls of the buildings and the ground, double-bounce scattering mechanism is the main mechanism in urban areas. Using the fully polarimetric SAR data, the orientation of the targets about the radar line of sight can be estimated in regions with double-bounce scattering. Calculation of the parameter $\beta$ from eigenvector decomposition is a simple way to estimate the target orientation about radar line of sight. According to the eigenvector decomposition theory, the coherency matrix $[T]$ is expressed as:

$$[T] = [U][\Sigma][U]^{-1}$$  \hspace{1cm} (1)

The matrices $[\Sigma]$ and $[U]$ contain the eigenvalues and eigenvectors of the coherency matrix, respectively.

$$[\Sigma] = \begin{bmatrix} \lambda_1 & 0 & 0 \\ 0 & \lambda_2 & 0 \\ 0 & 0 & \lambda_3 \end{bmatrix}, \text{with } \lambda_1 > \lambda_2 > \lambda_3 > 0$$  \hspace{1cm} (2)

$$[U] = \begin{bmatrix} u_1 & u_2 & u_3 \end{bmatrix} = \begin{bmatrix} \cos \alpha & \sin \alpha & 0 \\ 0 & 0 & 1 \\ \sin \delta \cos \beta_1 & \sin \delta \sin \beta_1 & \cos \delta \\ \cos \gamma \cos \beta_2 & \cos \gamma \sin \beta_2 & -\sin \gamma \\ \cos \gamma \cos \beta_3 & \cos \gamma \sin \beta_3 & -\sin \gamma \end{bmatrix}$$  \hspace{1cm} (3)

Angles $\delta$ and $\gamma$ are phase terms with no straightforward meaning. The angle $\beta$ represents the physical orientation of the scattering object which corresponds to the scattering mechanism described by the angle $\alpha$.

The best estimation of $\beta$ is given by calculating the weighted average of this parameter over the image resolution cell as follows:

$$\bar{\beta} = \mu_1 \beta_1 + \mu_2 \beta_2 + \mu_3 \beta_3$$  \hspace{1cm} (4)

Where

$$\mu_n = \frac{1}{\sum_{\alpha_1=1}^{3} t_{\alpha_1}}$$  \hspace{1cm} (5)
Therefore the parameter $\varphi$ can be considered as the representation of the target orientation of a resolution cell.

**Building Height**

DEM model of Tehran has been created by stereography. This information has been overlaid on VHR optical data and for some regions of interests the information was validated with field survey. The building heights were selected and categorized within three classes namely “low-rise” (1-3 stories), “mid-rise” (4-7 stories), and “high-rise” (above 7 stories).

**Polarimetric SAR Parameters**

Several polarimetric parameters are derived mainly from target decomposition theorems and SAR complex analysis. In this study, the coefficients of some well-known coherent and incoherent decomposition techniques are derived. For computation of the parameters from SAR complex analysis, both linear and circular polarization bases are considered.

**A. Parameter Extraction from SAR Complex Analysis:**

**Backscattering Cross Sections in Linear and Circular Basis:** Considering the monostatic case, the scattering matrix is:

$$S = \begin{bmatrix}
S_{HH} & S_{HV} \\
S_{HV} & S_{VV}
\end{bmatrix}$$  \hspace{1cm} (6)

Where H and V are Horizontal and Vertical polarizations, respectively. The backscattering cross section in HH basis is obtained as:

$$\sigma_{HH} = 10 \log |S_{HH}|^2$$  \hspace{1cm} (7)

Similarly, the backscattering cross section in VV and HV basis can be calculated. Also, using the change-of-basis theory, the scattering matrix in circular basis can be calculated and the backscattering cross section is computed similar to Eq. 7. In circular polarization basis, $R$ stands for the Right circular polarization and $L$ for the Left circular polarization.

**Ratios of the Scattering Matrix Elements in Linear and Circular Basis:** Useful information about targets can be achieved by studying the relative behaviour of the ratios between elements of the scattering matrix (i.e. polarimetric channels). For example the ratio of the HH to the VV element is computed as:

$$R_{HH/VV} = 10 \log \left| \frac{S_{HH}}{S_{VV}} \right|^2$$  \hspace{1cm} (8)

The ratios between HV to HH and also HV to VV are derived in a similar way. Furthermore, the ratios of the elements of the scattering matrix in circular polarization are calculated.

**Polarimetric coherence in Linear and Circular Basis:** The polarimetric coherence is defined by:

$$\rho_{AB,XY} = \sqrt{\frac{\langle S_{AB}^* S_{XY} \rangle}{\langle S_{AB,AB}^* \rangle \langle S_{XY,XY}^* \rangle}}$$  \hspace{1cm} (9)

Where $*$ stands for the complex conjugate and $\langle \cdot \rangle$ denotes an averaging over a group of pixels and the subscripts AB and XY mean the polarization states such as HH, HV and VV in HV
linear polarization basis. Similarly, the polarimetric coherence values in circular polarization basis are derived.

**B. Extracted Parameters from Decomposition Techniques**

**Pauli Decomposition Coefficients:** Based on the Pauli decomposition, the scattering matrix \([S]\) is expressed in the so-called Pauli basis. Considering the reciprocity condition in the monostatic case, the scattering matrix can be decomposed as \([5]\):

\[
[S] = \begin{bmatrix}
S_{HH} & S_{HV} \\
S_{VH} & S_{VV}
\end{bmatrix} = \alpha [S]_a + \beta [S]_b + \gamma [S]_c
\]  

(10)

Where \([S]_a, [S]_b, \text{and} [S]_c\) are the scattering matrices corresponding to the single-bounce, double-bounce, and volume scattering mechanisms. Also, the coefficients \(\alpha, \beta, \text{and} \gamma\) are:

\[
\alpha = \frac{S_{HH} + S_{VV} + S_{HV} + S_{VH}}{2}, \quad \beta = \frac{S_{HH} - S_{VV} + S_{HV} - S_{VH}}{2}, \quad \gamma = \sqrt{2S_{HV}}
\]  

(11)

Specially, the intensities of these coefficients, i.e. \(|\alpha|^2, |\beta|^2, \text{and} |\gamma|^2\), are meaningful because they are related to the scattered power of the correspondent scattering mechanisms.

**Krogager Decomposition Coefficients:** According to the Krogager decomposition, the scattering matrix \([S]\) is decomposed into three components: a sphere, a diplane, and helix. Based on the Krogager decomposition, the measured scattering matrix in circular polarization basis is expressed as \([11]\):

\[
[S] = \begin{bmatrix}
S_{HH} & S_{HV} \\
S_{VH} & S_{VV}
\end{bmatrix} = e^{i\phi} \begin{bmatrix}
0 & 1 \\
-1 & 0
\end{bmatrix} + R_a \begin{bmatrix}
0 & e^{i\phi} \\
e^{-i\phi} & 0
\end{bmatrix} + R_h \begin{bmatrix}
e^{i\phi} & 0 \\
0 & -e^{-i\phi}
\end{bmatrix}
\]  

(12)

Where the coefficients of \(Ks, Kd,\) and \(Kh\) are the weights of the sphere, diplane, and helix components of the scattering matrix. The intensities of the Krogager coefficients, i.e. \(|Ks|^2, |Kd|^2, \text{and} |Kh|^2\), represent the scattered power by the correspondent targets.

**Freeman Decomposition Coefficients:** Based on the Freeman decomposition, the Covariance matrix \([C]\) is described as the combination of the responses of three physical mechanisms namely single-bounce, double-bounce, and volume scattering.

\[
[C] = f_s [C]_s + f_d [C]_d + f_v [C]_v
\]  

(13)

The matrices \([C]_s, [C]_d, \text{and} [C]_v\) are equivalent with the covariance matrices due to single-bounce, double-bounce, and volume scattering, respectively. Also, the coefficients of \(f_s, f_d,\) and \(f_v\) are the expansion coefficients that must be determined. By expanding the Eq. 13, it is possible to measure the power scattered by the correspondent scattering mechanisms:

\[
P_s = f_s (1 + |\alpha|^2), \quad P_d = f_d (1 + |\beta|^2), \quad P_v = f_v |\gamma|^2
\]  

(14)

Where \(Ps, Pd, \text{and} Pv\) are interpreted as the power scattered by single-bounce, double-bounce, and volume scattering, respectively.

**Four-component Yamaguchi Decomposition Coefficients:** Yamaguchi proposed a decomposition technique based on Freeman model which describes the Covariance or Coherency matrix as the combination of four scattering mechanisms:

\[
[C] = f_s [C]_s + f_d [C]_d + f_v [C]_v + f_c [C]_c
\]  

(15)

Where \(fs, fd, fv, \text{and} fc\) are the coefficients that have to be calculated. The matrices \([C]_s, [C]_d, [C]_v, \text{and} [C]_h\) are related to the covariance matrices of single-bounce, double-bounce,
volume, and helix scattering mechanisms. Again, four parameters that show the scattered power by correspondent scattering mechanisms can be obtained:

\[
P_1 = \phi_1 (1 + |\theta|^2), \quad P_2 = \phi_2 (1 + |\alpha|^2), \quad P_3 = \phi_3, \quad P_4 = \phi_4
\]  

Since this model does not take into account the reflection symmetry condition, the fourth component, i.e. the helix scattering, is introduced.

**Eigenvector Decomposition Parameters:** The Eigenvector decomposition, which is also called H/A/\(\alpha\) decomposition, is a famous type of incoherent target decomposition technique. In order to interpret the physical information obtained by this technique, three parameters namely H, A, and \(\alpha\) are extracted. The parameter H is called the entropy which is related to the wave depolarization and shows the degree of randomness of the scattering mechanism.

\[
H = \sum_{i=1}^{3} -P_i \log_2(P_i)
\]  

Where \(P_i\) are obtained from Eq. 5.

The parameter A is called the anisotropy which is interpreted as the relative importance of the second eigenvalue to the third one, i.e. representing the difference between the second and third scattering mechanisms.

\[
A = \frac{\lambda_2 - \lambda_3}{\lambda_2 + \lambda_3}
\]  

The angle \(\alpha\) provides information about the type of the scattering mechanism represented by the eigenvectors. This parameter characterizes the single-bounce, double-bounce, and volume scattering over considered pixels. Considering Eqs. 3 and 5, the weighted average scattering mechanism \(\bar{\alpha}\) is calculated as follows:

\[
\bar{\alpha} = \sum_{i=1}^{3} P_i \hat{\alpha}_i
\]

**Sensitivity Analysis**

The Correlation coefficient is a measure of the strength of linear association between two variables. The Correlation coefficient is calculated as:

\[
\text{Corr}(X,Y) = \frac{\sum X \sum Y - \sum X \sum Y}{\sqrt{[\sum X^2 - (\sum X)^2][\sum Y^2 - (\sum Y)^2]}}
\]

In order to select the polarimetric parameters with respect to the target orientation, and building height, a correlation analysis is performed.

**Implementation and Results**

**Building Orientation Study**

The fully polarimetric ALOS-PALSAR data, acquired on 23 April 2009, over Tehran, sets are used. Tab. 1 lists the main specification of the data. To reduce the speckle noise and also in order to produce square pixels in both range and azimuth directions on the ground, a multilooking process with a 6x1 window size (i.e. 6 pixels in azimuth direction and 1 pixel in
range direction) is applied on the data. Thus, the final image resolution used in the computations is 30m in both directions. Also, a 3x3 window size is adopted for computing all polarimetric parameters. The methodology steps are shown in Fig. 1.

### Table 1. Main specifications of the used data

<table>
<thead>
<tr>
<th>Image Mode</th>
<th>Full Polarimetric</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data Format</td>
<td>Single Look Complex (SLC)</td>
</tr>
<tr>
<td>Center Frequency</td>
<td>1270 MHz</td>
</tr>
<tr>
<td>Wavelength</td>
<td>23.6 cm (L-band)</td>
</tr>
<tr>
<td>Band width</td>
<td>14 MHz</td>
</tr>
<tr>
<td>Transmission Power</td>
<td>2 kW (peak power)</td>
</tr>
<tr>
<td>Look Direction</td>
<td>Right</td>
</tr>
<tr>
<td>Look Angle</td>
<td>21.5 degree</td>
</tr>
<tr>
<td>Swath Width</td>
<td>30 Km</td>
</tr>
<tr>
<td>Range Resolution</td>
<td>30 m</td>
</tr>
<tr>
<td>Azimuth Resolution</td>
<td>5 m</td>
</tr>
</tbody>
</table>

Benefiting from a co-registered optical image of the scene, thirty regions are selected in urban areas. Then, the average values of the polarimetric parameters and angle $\beta$ over these regions are computed. Finally, the correlation analysis is performed to evaluate the sensitivity of the polarimetric parameters to the target orientation. It should be mentioned that regions were selected with different orientation angles. The Pauli image, $\beta$ parameter, and optical image of Tehran are shown in Figs 2, 3, and 4, respectively.

The results of the correlation analysis, between the parameters and the Beta value are shown in Table 2.
Table 2. Correlation coefficients between polarimetric parameters and target orientation

<table>
<thead>
<tr>
<th>Correlation Coefficients</th>
<th>Backscattered Cross Section (Linear and Circular Basis)</th>
<th>Ratios of the Scattering Matrix Elements (Linear and Circular Basis)</th>
<th>Polarimetric Coherence (Linear and Circular Basis)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\sigma_{HH}$</td>
<td>$\sigma_{HV}$</td>
<td>$\sigma_{VV}$</td>
</tr>
<tr>
<td>Correlation Coefficient with $\theta$</td>
<td>$-0.48$</td>
<td>$0.64$</td>
<td>$-0.23$</td>
</tr>
<tr>
<td>Pauli Decomposition Coefficients</td>
<td>$\alpha$</td>
<td>$\beta$</td>
<td>$\gamma$</td>
</tr>
<tr>
<td>Correlation Coefficient with $\theta$</td>
<td>$-0.80$</td>
<td>$-0.56$</td>
<td>$-0.64$</td>
</tr>
</tbody>
</table>

Six of the extracted polarimetric parameters have a high correlation with the target orientation. These parameters are: ratio of the HV to HH channels, polarimetric coherence between RR and LL channels, entropy, anisotropy, single-bounce component of the Freeman decomposition, and volume scattering component of the Yamaguchi decomposition. Among these parameters, the ratio of the HV to HH channels has the maximum correlation coefficient with the target orientation (correlation value = $+0.97$) which means this parameter is almost completely dependent on the target orientation. By increasing the value of target orientation, the value of this parameter is increased. Also, the ratio of the RL to RR channels has the minimum correlation value with the target orientation (correlation value = $-0.08$). It means that this parameter can be considered as an independent parameter to the target orientation and is not affected by the object orientation.

**Building Height Study**

A similar process to the above was completed for the building height study. Using the Digital Building Model (DBM) of Tehran, sixteen regions are selected and the average heights of buildings in these regions are calculated. Also, the average values of the polarimetric parameters over these regions are computed. It should be mentioned that during the selection of the regions, all three low-rise, mid-rise, and high-rise building categories were selected. The correlation analysis is performed to assess the sensitivity of each parameter with respect to the building height. Four polarimetric parameters have a high correlation with building height. These parameters are: polarimetric coherence between HH and VV channels, polarimetric coherence between HV and VV channels, coefficient of the helix scattering of the Krogager decomposition, and ratio of the backscattering intensity of LL to RR. The ratio of RR to LL has the most correlation with the building height.
Table 3. Correlation coefficients between polarimetric parameters and building height

<table>
<thead>
<tr>
<th>Correlation Analysis</th>
<th>Backscattering Cross Section (Linear and Circular Basis)</th>
<th>Ratios of the Scattering Matrix Elements (Linear and Circular Basis)</th>
<th>Polarimetric Coherence (Linear and Circular Basis)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mi</td>
<td>H</td>
<td>R</td>
</tr>
<tr>
<td>Correlation Coefficient</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>mi</td>
<td>H</td>
<td>R</td>
</tr>
<tr>
<td>Polymat Decomposition Coefficients</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Correlation Coefficient</td>
<td>0.018</td>
<td>0.059</td>
<td>0.010</td>
</tr>
<tr>
<td>Krogager Decomposition Coefficients</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Correlation Coefficient</td>
<td>0.008</td>
<td>0.012</td>
<td>0.092</td>
</tr>
</tbody>
</table>

ACKNOWLEDGEMENT

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