Speckle reduction has long been recognized as the main problem of coherent imaging and many processing techniques have been advanced to overcome it. The vast majority of these techniques, however, are of a scalar nature simply because vector/matrix imaging data are so sparse and have become available only very recently. We do have such data, which was taken with the NASA/JPL CV-990 dual-polarization L-band (1.225 GHz) SAR (Synthetic Aperture Radar) system, have been made available to us. We investigate the potential of an exclusively polarimetric image filtering approach, which takes full advantage of the matrix data provided on a pixel-by-pixel basis, and complements the existing scalar contrast optimization and speckle reduction techniques. We wish to stress from the outset that our goal is contrast optimization without the help of incoherent averaging over pixels/look, because of the corresponding loss of spatial or temporal resolution.

1. ESSENTIAL POLARIMETRIC DEFINITIONS

Following [1], we define the origin of the coordinate system at the receiving antenna terminals with the $+\hat{z}$-axis directed toward the target (pixel) as shown in [2, Fig. 1]. Note that in SAR applications the receiver and transmitter are co-located but may be different antennas so that the situation is slightly bistatic [3]. The received $E_R$ and the transmitted $E_T$ waves, together with the antenna height $h$ (polarization of the receiving antenna when used as transmitter [3]), can all be written as plane waves in terms of the complex polarization ratio $\gamma = \tan^{-1}(E_y/E_x)$, and $\phi$ and $\alpha$ are the relative and absolute phases, respectively [3], and related by the 2x2 complex Sinclair scattering matrix [5]

$$E_R = [S]E_T, \quad (1)$$

The voltage at the receiving antenna terminals as a function of transmitter and receiver polarizations is given by

$$V = h^T E_R = h^T[S]E_T, \quad (2)$$

where superscript $T$ denotes the transpose (as opposed to hermitian conjugate
"+", see [2, pp. 1471-1473], [3] for details).

Since a complete scattering matrix $[S(HV)]$ is available for every pixel, one can simulate the response of the image to any transmitted polarization $E_T$ by calculating $E_R$ via (1). Furthermore, the response of the image can also be simulated for an arbitrary receiver polarization $h$ via (2). Both equations must be implemented for each pixel of the entire image. The brightness is then assigned to each pixel according to $P = v^*v = (h^TE_R)^*(h^TE_R)$.

2. THE THREE-STAGE PROCEDURE FOR OPTIMIZING THE GRAVES POWER MATRIX $[G]$

The TSP addresses the following problem (see [2, 3] for more details): For a given pixel (i.e., known scattering matrix), find such transmitting and receiving polarizations, for which the received power is maximal (minimal). Mathematically it translates into: find $E_T$ and $h$ such that $V = h^T[S]E_T$ is optimal for a given $[S]$, subject to the constraints $||h|| = ||E_T|| = 1$.

The TSP accomplishes this in three separate stages [1, 2]:

Stage 1) The energy density in the reflected wave (before it reaches the receiver) is optimized as a function of transmitted polarizations via the following eigenvalue problem associated with the Graves power matrix $[G] = [S]^+[S]$

$$([(G) - \lambda[I])E_T, opt = 0$$

Stage 2) At this stage, the polarization state of the reflected wave is computed using the known $E_T, opt$ via (2).

Stage 3) Finally, the receiver polarization is adjusted to ensure that all of the power contained in $E_R, opt$ (reflected wave) is either absorbed or mismatched completely, depending on the application. The former is accomplished with the choices $h = E^*_R$ or $V = h^TE_R = 0$, respectively.

In terms of imaging applications, one expects a given pixel to look relatively "bright" when $E_T$ corresponds to the largest eigenvalue (maximal energy density) and $h$ is adjusted according to (7a), while the adjustment (7b) ensures that the pixel looks "dark", especially when supplemented with the choice of minimal $E_T, opt$.

3. STATISTICAL ANALYSIS OF OPTIMAL POLARIZATIONS & IMAGE FILTERING APPLICATIONS

Use is made of the JPL POL-SAR image data of the San Francisco Bay area [2], considering three specific test regions: (i) ocean, (ii) man-made structures; and (iii) parks. In order to gain insight into the polarimetric response of various terrain and ocean categories, we have performed Stage 1 of the TSP for each pixel of two chosen segments of ocean and urban areas. Let us consider the ocean vs urban region contrast enhancement as a specific application. In order to minimize the ocean return or to maximize city return, the minimum energy eigenvector is computed for each pixel of the ocean patch and the maximum energy eigenvector is computed for the city patch. The eigenvectors corresponding to $\lambda_{min}$, $\lambda_{max}$ are computed according to (3).

In [2, Figs. 3a-b], we present joint bivariate histograms of the $p$ parameters (log-magnitude and phase) for the two surface categories. Each patch contains 40,000 (200 X 200) pixels so that the counting error is about 0.5%. It is
evident from the histograms that the city and the ocean classes exhibit a very
different polarimetric behaviour. The city and the ocean peaks are well separa-
ted "near linear" polarizations, and the peak of the ocean distribution is much
more pronounced. Thus, if the transmitter is adjusted to the peak of the ocean
distribution $\mathbf{E}_T$ (stage 1 of TSP) and $h$ (Stage 3 of TSP), and
adjust them so that the "majority" (i.e., histogram peak) of the "unwanted"
patch pixels "darken". For instance, if $h$ is adjusted in such a way that the
peak in the ocean distribution $\mathbf{E}_R$ satisfies the null polarization state
$$V_{\text{peak}} = h^\top \mathbf{E}_R, \text{peak} = 0,$$
then it is ensured that the majority of the ocean pixels will appear "black" on the
actual image.

The effectiveness of this strategy depends sensitively on the sharpness of the
relevant histogram peaks. Therefore, other image processing techniques, when
used in conjunction with the polarimetric enhancement, should be directed
towards the increase in peak sharpness of the relevant field distributions
(e.g., N X N block averaging, discretization, and quantization, etc.). Here,
however, we concentrate strictly on polarimetric enhancement methods. The con-
trast improvement, due to the TSP, is shown in [2, Fig. 5] and should be con-
trasted with the image of [2, Fig. 2]. One observes a significant improvement
in city vs. ocean contrast. Note that most of the ocean speckle has been
"filtered out" polarimetrically, without significant effect on the urban area
and other man-made structures. This suggests the following procedure (see [2,
Fig. 7]) for the polarimetric matched filter in coherent imaging:

Step 1) Stage 1 of TSP is performed for every pixel;

Step 2) joint bivariate histograms of $\mathbf{E}_T$ (magnitude and phase of $\rho$) are
constructed for various terrain regions;

Step 3) the transmitted field $\mathbf{E}_T$ is adjusted to either the peak of the minimal
eigenvector pdf of the unwanted region (e.g., ocean clutter) or to the peak of
the maximal eigenvector pdf of the region of interest (e.g., bridge, urban area,
etc.), depending on the relative sharpness of the relevant peaks;

Step 4) the scattered field $\mathbf{E}_R$ is computed for each pixel for the $\mathbf{E}_T$ chosen in
Step 3 via (2) and then the histograms (as in Step 2) are repeated for the $\mathbf{E}_R$
distributions;

Step 5) using the $\mathbf{E}_R$-histograms, $h$ is adjusted via eq. (6b) to either mismatch
the peak of the scattered field pdf of the unwanted region or, with eq. (6a),
to match the peak of the pdf of the region of interest;

Step 6) $P = V^*V$ (received power) is computed for each pixel as $P = (h^\top \mathbf{E}_R)^* (h^\top \mathbf{E}_R)$, and the resulting image is displayed.

4. SUMMARY AND CONCLUDING REMARKS

In order to improve the efficiency of the polarimetric filtering method, one
must combine it with other image processing and statistical communication
theory techniques. In particular, the filter efficiency depends critically on peak sharpness of the histograms and one may employ multi-look incoherent averaging, block discretization, and non-uniform quantization [4] to improve "peakedness." Also, a continuous mapping in 3-color space of the three independent polarizations (say, HH, VV, VH) can be used in combination with the polarimetric matched filter to enhance visual detectability of the polarimetric rough surface scattering dependence without destroying the geometric integrity of the image. Finally, an incoherent polarimetric imaging via the 4x4 real Mueller matrix [1,6] may lead to an even more efficient speckle reduction procedure, in particular, for multi-look and multi-frequency images. All of these approaches are currently under investigation at the UIC-EECS/CL, as summarized in various contributions to the Proceedings of NATO-ARW-DIMRP'88 [4] and especially in [2].

5. REFERENCES


