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COMPARISON OF OPTIMIZATION PROCEDURES FOR RADAR SCATTERING MATRICES

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1. INTRODUCTION

Basic principles of radar polarimetry are introduced and various optimization procedures for the propagation (scattering) range operator equation and the received power are presented and compared. It is assumed that the radar is a complete coherent dual orthogonal (A,B) transmit/receive antenna system of high channel isolation and antenna side-lobe reduction, where in the case of wave interaction with a discrete stationary point target the propagation (scattering) matrix is given by the 2x2 coherent Jones (Sinclair) matrix $[S(A,B)]$, the 2x2 complex Graves power $[G(AB)]$, the 3x3 or 4x4 complex covariance matrix $[\Sigma(A,B)]$, and/or the 4x4 real Mueller (Kennaugh) power density matrix $[M]$ for the symmetric (monostatic reciprocal: $S_{AB} = S_{BA}$) or the asymmetric (general bistatic, monostatic non-reciprocal: $S_{AB} \neq S_{BA}$) cases, respectively. Four distinctly separate optimization procedures are here introduced for the symmetric case, demonstrating that for the coherent (deterministic) scattering scenario the solutions obtained from optimizing the pertinent power density expressions associated with either $[S(A,B)]$,$[G(AB)]$,$[\Sigma(A,B)]$ and/or $[M]$ are identical, and so approximately also for the partially polarized case, whereas for the partially coherent case more elaborate optimization procedures for the 3x3 covariance and/or 4x4 Mueller matrices need to be employed utilizing special properties of Lie group SU(n = 2,3,4) expansions, i.e., the 2x2 Pauli spin $[\sigma_i, i = 0,1, 2,3]$, the 3x3 Hausdorff (Gell-Mann)$[\sigma_i, i = 1,2,\cdots 8]$ and the 4x4 Dirac $[\Theta_i, i = 0,1,2,\cdots 15]$ matrices.

It is shown that there exist in total five unique pairs of characteristic polarization states for the symmetric coherent scattering matrix $[S(A,B)]$ of which two pairs, corresponding to the cross-polarization (x-pol) null and co-polarization (co-pol) maxima, are identical; whereas the x-pol max and x-pol saddle point pairs are distinct. These three pairs of orthogonal characteristic polarization states are also mutually at right angles to one another on the polarization sphere. The fifth pair, the (in general) non-orthogonal co-pol null pair, lies in the plane spanned by the co-pol max, or equivalently the x-pol null, and the x-pol max pairs which determine the 'target characteristic plane (circle) of Kennaugh' and the angle between the co-polar nulls is bisected by the line joining the two co-pol maxs; and together with the orthogonal x-pol saddlepoint pair, being at right angles to this plane, they re-establish Huynen's 'polarization fork' concept. The distinctly different optimization approaches are compared by one illustrative example in which, besides the 'polarization forks', also the co-pol and x-pol power density plots and the relative co/cross-polarization phase (polarimetric correlation coefficient) plots are presented.

Based on this complete description of isolated and distributed scatterers, polarimetric target classification, target-versus-clutter discrimination, and optimal contrast enhancement algorithms are derived and shown to be of great utility in the proper interpretation of POL-RAD/SAR microwave signatures in terrestrial and planetary remote sensing.

2. OVERVIEW

The basic principle of radar polarimetry is based on the concept of characteristic polarization states first introduced by Kennaugh [1], who demonstrated that there exist radar polarization states for which the radar receives minimum /maximum power. This min/max polarization state theory was extended primarily by Huynen[2], who introduced the "polarization fork" concept, and more recently by us [3-10] and at DLR-Oberpfaffenhofen [11]. With the advent of dual polarization coherent radar [12] and Pol-SAR [13] systems, radar polarimetry has become a subject of recurring and globally intensifying interest in recent years [14-16]. Inspite of extensive studies of this theory, a final rigorous and complete formulation still is warranted [4]. Different approaches were introduced for determining these characteristic polarization states by using the voltage equation eigenvalue problem of the scattering matrix [1,2], the basis transformation techniques [3,6,7], the three-stage procedure for the complex Graves power matrix [3,5], the Mueller matrix approach for the "degenerate coherent Stokes vector case" [8,9],.and more recently, the polarimetric co-variance matrix optimization procedure [10,11]. All of these methods are compared and it is shown how each of them contributes partially towards a complete understanding of coherent scattering matrix properties. More approaches still may be required to completely resolve all unanswered questions even for the coherent case, for example, such as those recently presented in [16] for applications to radar meteorology; and a more rigorous group-theoretic approach of optimizing the Sinclair, covariance, and Mueller matrices expanded in terms of Lie (SU(2), SU(3),SU(4/2)) groups associated with the Pauli spin matrices as pursued vigorously by Cloude [16]. Whereas, a unique optimization method for the general partially coherent case still does not exist, considerable progress was made in determining an optimization approach for the partially polarized case [4,8,10, 16] for which it is assumed that the wave incident on a stochastic scatterer is completely polarized. Also, it is shown in [10] that there exist 'physical realizability' conditions to which the elements of the 4x4 Mueller matrices are subjected in order to identify erroneous measurement results such as of scattered waves with degree of polarization greater than unity [16]. These and similar 'physical realizability' conditions apply, in general, also in the partially polarized case requiring a four-dimensional polarization sphere treatment together with a SU(4/2) group-theoretic treatment especially for the general asymmetric matrix cases, which will be considered in another forthcoming paper [10]. Finally, optimal contrast enhancement algorithms are introduced [10,17] and applied to optimal image feature extraction in POL-RAD/SAR image interpretation [18,19].

3. INTERRELATION OF SCATTERING MATRICES

a) 2x2 coherent (complex) **Sinclair matrix** $[S(AB)]$, $\vec{E}_s(AB) = [S(AB)]\vec{E}_i(AB)$, $[S(AB)] = \begin{bmatrix} S_{AA} & S_{AB} \\ S_{BA} & S_{BB} \end{bmatrix}$ with $\vec{E}(AB)$ denoting electric field vector;

b) 2x2 hermitian (complex) **Graves matrix** $[G(AB)]$, $[G(AB)] = [S(AB)]^{+}[S(AB)]$ with $\{\ \}^{+}$ denoting hermitian conjugate;

c) 3x3 hermitian (complex) **Covariance matrix** $[\Sigma(AB)]$ $[\Sigma(AB)] = \vec{\Omega}(AB)\vec{\Omega}(AB)^{+}$, $\vec{\Omega}(AB = BA)^{T} = (S_{AA}\ \ \sqrt{2}S_{BB}\ \ S_{BB})$ with $\{\ \}^{T}$ denoting transpose of covariance feature vector $\vec{\Omega}(AB = BA)$, satisfying $||\vec{\Omega}||^2 = \mathrm{Span}[S(AB)] = |S_{AA}|^2 + 2|S_{AB}|^2 + |S_{BB}|^2$;

d) 4x4 real **Mueller power density matrix [M]**, $\vec{g}_s = [M]\vec{g}_i$ with $[M] = [A(AB)]([S(AB)]\otimes[S(AB)]^{*})[A(AB)]^{-1}$ where $[A(AB)]$ denotes the 4x4 Kronecker expansion matrix with $\otimes$ denoting tensorial matrix multiplication, and $\vec{g}_{s,i}$ representing the scattered (s) and incident (i) Stokes vectors.

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