Development of Polarimetric Vector Signal and Tensor Image Processing In Wideband Interferometric POL-RAD/SAR Signature Analysis

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Abstract - Based on the complete transmission versus scattering matrix description and the availability of the associated sets of four distinct matrices, vector signal (PMSF) and tensor image (PMIF) signature processing algorithms are introduced for the optimization of useful target versus clutter ratios. The usefulness of implementing the **"Optimal Polarimetric Constant Enhancement Coefficients (OPCEC)"** into the **PMSF/PMIF** formulations is verified. It is shown how these concepts can be applied in the extrawideband *multi-spectral* polarimetric sensing and imaging for **Optical Image Feature Extraction (OPIFE)** in **"Wideband Interferometric Sensing and Imaging Polarimetry (WISIP)"** with applications to wide area surveillance of the terrestrial and planetary covers.

1. Introduction: Definition of Transmission Versus Scattering Matrix Sets

Recently both optical (lidar) and microwave (radar) polarimetry enjoyed the long overdue recognition and technological implementation experts had expected due to the immense improvement it has to offer in imaging resolution and contrast enhancement of low observables embedded in strong dynamically changing background clutter. Whereas, in classical optical polarimetry major emphasis is paid to the transmission versus the reflection properties of electromagnetic vector wave particle interaction, in microwave (radar) polarimetry predominantly the monostatic (backscattering) and bistatic scattering behavior is analyzed [1,2]. Unfortunately, in the literature the appropriate transmission and scattering-type matrices are not always distinguished properly as those ought to be. Succinct comparative analyses of the propagation versus backscatter type matrices will be developed by incorporating the proper coordinate systems, the distinct definitions of various related polarization state descriptors for both the coherent and the partially coherent cases, and by introducing the well-known coherency matrix [J], properly defined for the two distinct transmission $[J_T]$ versus scattering $[J_S]$ modes of operations [3].

For these two distinct vector wave medium interaction cases - in order of complexity - a set of four distinct matrices is introduced in each case including: (i) the 2x2 complex phasor (coherent) Jones transmission [T] versus Sinclair scattering [S] matrices; (ii) the associated 2x2 complex coherent power density transmission matrices $[F] = [T]^t[T]$ versus the Graves $[G] = [S]^t[S]$ complex coherent power scattering matrices (with t denoting the Hermitian conjugate); (iii) the 4x4 real power density Mueller Propagation [M] versus Kennaugh Scattering [K] matrices (of which an optical, but non-identical alternate is the Stokes reflection matrix); and (iv) the 3x3 (symmetric: monostatic reciprocal) or 4x4 (asymmetric: general bistatic and/or non-reciprocal) Polarimetric Covariance Transmission [Υ] versus Scattering [Σ] matrices [4 - 11].

Distinction: Transmission ↔ Scattering

Coherent Phasor Matrices [2x2]

$$[T] \quad \leftrightarrow \quad [S]$$

(similarity) (consimilarity)

Coherent Power Density Matrices [2x2]

$$[F] = [T]^t[T] \quad \leftrightarrow \quad [G] = [S]^t[S]$$

Partially Polarized/Coherent [4x4],[10]

$$[M] = [M_c] + [M_x] \quad \leftrightarrow \quad [K] = [K_c] + [K_x]$$

Covariance Feature Vector/Matrix (symmetric: 3x3, asymmetric: 4x4)

$$[\Upsilon] = [\vec{\Phi}][\vec{\Phi}]^t \quad \leftrightarrow \quad [\Sigma] = [\vec{\Omega}][\vec{\Omega}]^t$$

Transformation Matrices: Great care needs to be taken in defining the correct sets of transformation matrices [V] ↔ [U], [B] ↔ [A], and [Φ] ↔ [Ψ] (and the correct absolute transformation phase and other 'polarimetric phase' relations).

Coherent Case

$$[T'] = [V][T] \quad \leftrightarrow \quad [S'] = [U][S]$$

Power Density Matrices (coherent)

$$[F'] = [W_v][F] \quad \leftrightarrow \quad [G] = [W_u][S]$$

Power Density Matrices (partially coherent)

$$[M'] = [A][M] \quad \leftrightarrow \quad [K'] = [B][K]$$

Covariance Matrices (partially coherent)

$$[\Upsilon'] = [\Phi][\Upsilon] \quad \leftrightarrow \quad [\Sigma'] = [\Psi][\Sigma]$$

Transmission and Scattering Matrix Tryptics: The two separate distinct sets of transmission versus scattering matrices may be related by the transmission matrix trypics [4,5]:

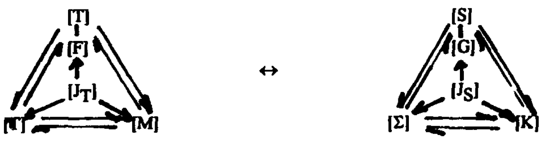
$$\{[T]\Leftarrow([F]) \leftarrow [\Upsilon]\leftarrow([J_T]) \rightarrow [M]\} \quad \leftrightarrow \quad \{[S]\Leftarrow([G]) \leftarrow [\Sigma]\leftarrow([J_S]) \rightarrow [K]\}$$

for which the optimization procedures satisfy the standard similarity versus consimilarity matrix eigenvalue/vector problems, in both the transmission and the scattering cases and allow the expansions of the related matrices in terms of the 2x2 Pauli $[\sigma_i]$, i = 1,2,3, the 3x3 Gell-Mann [δ, i = 1,...,8, and the 4x4 Dirac $[\theta_i]$, i = 1,...,15, anti-Hermitian matrices associated with the SU(2), SU(3) and SU(4) Lorentz (Lie) groups, respectively [4,6].

Cloude's Approach: Based on central importance of the coherency matrix in polarimetry [5].

and its implications. (Huynen's SU(2) group expansion)

Boerner's extension of Cloude's trypics [4,6].



Upon introduction of these two distinct and unique sets of transmission versus scattering matrix tryptics, it is now possible to readdress the matrix optimization and decomposition problems in a systematic way.

2. Matrix Optimization Approach:

(Similarity versus Consimilarity Eigen-value/vector Problems)

Derivation of the Optimal (characteristic) Polarization States: Although considerable progress was made in advancing the Kennaugh target characteristic polarization theory and Huynen's polarization fork concept, no

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fully transparent theory, separating the forward scattering (propagation) from the backscattering (monostatic and bistatic scattering cases) and/or its interactive relations was hitherto developed. Instead, these distinct wave scatterer interaction cases are wildly mixed up in the literature. However, with the recent advances made by Horn and Hong [7,8] in analyzing **'similarity'** versus **'consimilarity'** eigenvalue/vector problems, we are now equipped to resolve the fine points **(pitfalls)** of radar polarimetry once and for all [6,9].

Transformation Invariants

Eigenvalue/Vector Problems (Similarity versus Consimilarity) [7,8]

[T], [F] ↔ [S], [G] Trace{[F]} = Span[T] = Invariant

Trace{[G]} = Span[S] = Invariant

Det [T] = inv. |Det [S]| = inv.

Partially coherent case (covariance)

[Υ] ↔ [Σ] Trace[Υ] = Trace [M] = Span [T] = Inv,

Span[Υ] = invariant

Trace[Σ] = Trace[K] = Span [S] = Inv,

Span[Σ] invariant

[M] ↔ [K] Stochasticity coefficients [3,4,6,9,12]

As a result of these canonical polarimetric matrix invariants, the appropriate **'covariance matrix invariance ratio (cmir)'** may be [3] defined with γ_i representing the non-negative eigenvalues of the covariance matrix [Σ] with $0 \le \gamma_1 \le \gamma_2 \le \gamma_3$ as [3]

$$cmir = \frac{\sqrt{Span[\Sigma]}}{Trace[\Sigma]} = \frac{\sqrt{Span[\Sigma]}}{Span[S]} = \frac{\{\sum_{i=1}^{3} \gamma_i^2\}^{1/2}}{\sum_{i=1}^{3} \gamma_i} = Inv \le 1$$

which plays a significant role specifically as a measure (standard) for speckle reduction [9].

The Extended Polarization Fork

For the monostatic reciprocal case ($S_{AB} = S_{BA}$) it is shown via a corrected con-eigenvalue/vector approach and con-similarity transformation that there exist in total five pairs of characteristic polarization states [11]: The orthogonal cross-polarization null and co-polarization state pairs, being identical and sharing one main circle with the co-polarization null and the orthogonal cross-polarization maximum state pairs, the latter being at right angles (on the polarization sphere) to the cross-polarization null pairs; and another newly identified pair: the orthogonal cross-polarization saddle point extrema which are normal to the plane (main or target characteristic circle) spanned by the other four pairs on the polarization sphere. With this complete and unique con-eigenvalue/vector and con-similarity transformation mathematical description of Huynen's polarization fork concept [4,6,9,], it is now readily possible to resolve the remaining unanswered questions in the polarimetric radar target optimization problem for the coherent case, and also for the partially polarized cases.

Optimal Polarization States:

Comparison of existing Optimization Approaches for Extracting the Characteristics Polarization States (Monostatic and Antimonostatic; Forward Propagation or Transmission Line Case)

Optimization Approach:

- Critical Point (transformation) Method [3,11]

  [T] ↔ [S]

- Lagrangian Multiplier Method (sixth order equations: Balois groups) [10,3,12]

  [Υ] ↔ [Σ]

By introduction of these unique optimization approaches, the uniqueness of the **'Characteristic Polarization State Descriptors [13]** and of the **Extended Polarization Fork Concept'** [14] can be shown [3,4,6] and it is then possible to derive the associated 'OPCEC', PMSF, PMIF, and OPIFE concepts.

3. Development of the 'Optimal Polarimetric Contrast Enhancement Coefficients (OPCEC)'

A unified presentation of **Polarimetric Transmission** versus ***Scattering Optimization*** *formulations is in sight.* It is shown that Kennaugh's and Huynen's [14] original concepts of the optimal polarization states are correct and that a unique **'Polarimetric Radar'** theory now can finally be 'fine tuned' for deriving the pertinent algorithms essential to advancing high resolution electromagnetic sensing and imaging [4,6,9]. Also, the ultimate goal of deriving the unique set of **'Optimal Contrast Enhancement Coefficients: OPCEC,'** required for scatter feature discrimination, is herewith feasible, and now can be strongly advanced [3,9].

Next to determining the eigenvalue and optimization problems for the scattering matrix set [S(AB)], [G(AB)], [Σ(AB)], [K] and the propagation matrix set [T(AB)], [F(AB)], [Υ(AB)], and [M] and its optimal (characteristic) polarization states, representing "a formidable still not completely resolved problem for either symmetric or definitely for the asymmetric cases", equally important, the exact and correct expressions for the enhancement of the optimal contrast between two classes of scatterers or scatterer ensembles must be determined. In general, these two distinct classes of scatterers may be defined as 'T' and 'C' where 'T' defines, for example, the desirable (useful) scatterer **(target: 'T')** and 'C' the undesirable scatterer ensemble (clutter: 'C') against which 'T' is to be discriminated or to be contrasted. The formal development of these **"OPCEC'** expressions associated with a specific matrix description in terms of either [S(AB)], [G(AB)], [Σ(AB)], [K], and/or any combination of such, is in parts still unresolved, yet solutions are in need for introducing more meaningful and polarimetrically unique definitions for the polarimetric co/cross-polar **'signal-to-clutter ratio', 'co/cross-polar detection merit factors,'** etc. In the following, some of these **'OPCEC'** expressions are introduced for the separate cases of 'a priori' knowledge on [S(AB)], [G(AB)], [Σ(AB)], [K], and/or [T(AB)], [F(AB)], [Υ(AB)], [M], where in most cases unique 'OPCEC' expressions for mixed co/cross-polar power density and/or relative phase coefficient problems must be found [3,11].

a)OPCEC for $P_{c/x}(\rho)$ given [S(AB)] for T and C: 'opcec [S]' [3]

$$opcec\{[S]\} = \frac{Pc/x\{[S(AB)T]\}}{Pc/x\{[S(AB)C]\}} = \frac{\vec{h}^T_{A,B}[S(AB)T]\bar{E}_T}{\vec{h}^T_{A,B}[S(AB)C]\bar{E}_T}$$

b)OPCEC for $P_{c/x}(\rho)$ given [G(AB)] for T and C: 'opcec [G]' [3]

$$opcec\{[G]\} = \frac{PC/X/T\{[G(AB)T]\}}{PC/X/T\{[G(AB)C]\}} = \frac{\vec{e}^{+}_{X/C/T}[GC]\bar{E}_T}{\vec{e}^{+}_{X/C/T}[GC]\bar{E}_T}$$

c)OPCEC for $P_{c/x}(\rho)$ and $P_{c\perp}$ given [Σ(AB)]: 'opcec [Σ(P_i)] [3]

From inspection of the definitions of [Σ(AB)] and [Σ($\rho_\perp$)], it is apparent that in general, a distinct combination of optimal contrast enhancement relations between two scatterer classes 'T' and 'C' exists, involving either P_c(T) versus $P_{c\perp}$(C) or P_c(C), P_x(C); P_x(T) versus P_c(C), $P_{c\perp}$(C) or P_x(C); or versus its complex conjugate, etc., and similar expressions can be found for $R_c(\rho)$, $R_x(\rho)$, etc., depending on the specific nature of [Σ(AB)$_T$] and [Σ(AB)$_C$]. Little yet is known and the solutions for optimizing [$\tilde{M}_T$] versus [$\tilde{M}_C$] must first be established [12] in order to interpret the solutions for these cases as is shown in [10].

d) OPCEC for $P_{c/x}$ given [K] or [M] for T and C: 'opcec [M_i]

In general, a partially coherent wave $\vec{g}$ can be decomposed according to [3] into its completely polarized component $\vec{g}_q$ and unpolarized component $\vec{g}_u$, and it is the total polarized energy of the desired scatterer 'T' which is to be optimized by minimizing the respective power contribution of the undesirable scatterers 'C' [3,10]. The solution of this rather complex multiparameter polarimetric optimization problem depends strongly on that for finding a complete set of solutions for the single scatterer solution of [M] and [Σ], and the opcec solutions for [Σ(AB)]. Here one of many possible distinct opcec definitions developed in (Tanaka, Boerner 1992) [15] is introduced, assuming that [M_T] and [M_c] are known and the ratio of the completely polarized components $(g_o^q)T$ is to be optimized versus $(g_o^q)C$ such that

$$opcec\{[M(g_o^q)]\} = \frac{(g_o^q)T}{(g_o^q)C} = \sqrt{\frac{g_{T1}^2 + g_{T2}^2 + g_{T3}^2}{g_{C1}^2 + g_{C2}^2 + g_{C3}^2}} = \sqrt{\frac{\vec{g}_T[\overline{M}_T]^T[\overline{M}_T]\vec{g}_T}{\vec{g}[\overline{M}_C]^T[\overline{M}_C]g_T}}$$

with [M] denoting a ixj subset of [M] where $[\overline{M}]_{ij}$, i=1,2,3,; j=0,1,2,3, etc.

4. Development of the Polarimetric Matched Vector-Signal/Tensor-Image Filters: PMSF/PMIF

Polarization-agile SAR, like **MB/UWB-POL-SAR**, provides coherent magnitude and phase data of the co- and cross- polarized scattering matrix elements on a pixel-by-pixel basis, i.e., every pixel of the image consists of eight unique real parameters. Since various terrains or targets respond to one polarization state more than others, an incident polarization could be chosen to enhance the response of one type of terrain (target) while suppressing, i.e., not using a preferred polarization state, for objects or background within the image region (clutter). Furthermore, the receiver antenna polarization state (post-processor-PMIF) can be tuned such that the incoming scattered wave can either be suppressed or completely received by properly matching the signals during image processing. One method which will accomplish this task is called the **'Polarization Matched Image Filter (PMIF)'**, whereas the **'Polarimetric Matched Signal Filter (PMSF)'** deals with the corresponding problem of agile vector **signal optimization** and is not being further discussed here (see references). The PMIF has the following characteristics [12]:

- it offers the freedom of changing the transmitted or received polarization states in a post-processing mode, assuming that the scattering matrix elements are measured and calibrated correctly, i.e., are pure target-characteristic parameters (invariant) and will not depend on antenna polarization characteristics, propagation path distortions, etc.;
- the PMF can be used as an adjustable tuner (filter) to transmit or receive a desirable polarization which will enhance a specific target feature such as ships or other man-made objects or ocean wave patterns, etc., in a adaptive post-processing mode. Optimal performance of the PMIF is based on the statistical evaluation prior to the imaging/graphics process. The PMIF method reduces human intervention during the decision process which is a first step toward automation; and it also allows for complete polarimetric matching to known desirable scatterer (target) versus undesirable scatterers (clutter), where the scattering matrix can be modeled in advance; thus, rendering the **"Polarimetric Matched (Signal/Image) Filtering"** method feasible.

5. Development of the Optimal Image Feature Extraction (OPIFE) :

Then, as a next step, based on the complete solution to the OPCEC, PMSF/PMIF extraction problems, the most important application of radar polarimetry may be approached which addresses the multi-spectral wideband, interferometric **POL-RAD/POL-SAR/POL-SACT/POL-ISAR** data fusion problems of developing **'Optimal Polarimetric Image Feature Extraction: OPIFE'** Algorithms together with joy-stick manipulated **'Optimal Multi-dimensional Visual Image Display: OMVDIP'** modes for the express purpose of developing **'self-correcting target acquisition operators'** which can be implemented into **'intelligent, automated sensors'**.

6. Development of CATI/LTBL POL-SAR Image Interferometry:

With the recent advent of **high precision electronic navigational tools such** as **DGPS** (Differential Global Positioning System), **PINS** (Precision Inertial Navigation System), **AMCS** (Automatic Motion Compensation System) technology, it is now possible to achieve highly stable motion-compensated airborne and space imagery with passive and active sensors. Therefore, not only will we be able to recover high precision stationary (snapshot coherent) images, but high resolution interferometric imagery can now be realized, i.e., differential small wide area spatial as well as short-to-long duration temporal changes can be recovered. In addition to **'Cross/Along-Track Inflight (CATI)'** interferometry for improving accuracy of altitudal/longitudal-/latitudinal target/surface coordinates, also repeat-track (aircraft)/orbit (spacecraft) Long Temporal Base Line (LTBL) image interferometry can now be achieved with precision time correlation of the order of nano-seconds and image interferometry at millimeter accuracies provided recent advances of spread-spectrum technology is implemented in the **DGPS/PINS/AMCS** systems as being pursued vigorously at NAWCADWAR, Code 5024/NRaD- 30) [16].

Therefore, it has now become possible to determine minute changes in surface/ sub-surface deformation for the purpose of the **DRI** of buried objects (e.g. bunkers, arms caches, minefields) or of tectonically stressed regions during an entire earthquake episode. **In order to observe any surface skewing (rotation), complete polarimetric (scattering matrix) POL-SAR acquisition with simultaneous flight path coordinate alignment (with either horizontal or vertical polarization channel orientation) is required.** Thus, ample opportunities exist in further advancing the **PMIF algorithm** to include full dynamic scene handling capabilities.

7. Conclusions and Recommendations:

A comprehensive overview of **'Wideband Interferometric Sensing and Imaging Polarimetry'** was presented together with a well structured identification of various crucial unresolved problems. Based on these meticulous diligent analyses of radar polarimetry, very clear methods of solution (ANSÄTZE) are provided . First, basic polarimetric radar theory and metrology needs to be perfected and the last hurdles must be removed as proposed. Second step, various vector electromagnetic radar inverse scattering theories of more complicated shapes need be solved in order to further perfect the **PMSF/PMIF** algorithms by simultaneous advancement of the **OPCEC/OPIFE** concepts. In Third step, it is proposed to rapidly develop Spread-Spectrum improved, **DGPS**-supported **CATI-LTBL-MB/UWB-POL-SAR** Image Interferometry, which has become feasible for repeat-orbit shuttle/satellite operations and can be resolved also for airborne repeat-track overflights in the nearer future. Because of the tremendous impact **'WISIP'** has on further perfecting **'Day/Night High Resolution Wide Area Surveillance of the Terrestrial and Planetary Covers'**, more funding support for all R&D teams involved in these timely efforts is requested nationally, internationally, and worldwide.

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