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Polarimetric Intensity Parameterization of radar and other remote sensing sources for advanced exploitation and data fusion

Theory

Ramin Sabry and Paris W. Vachon

Defence R&D Canada – Ottawa
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Abstract

Exploitation of the backscattered field polarization over the wide electromagnetic spectrum, from visible to microwave frequencies, provides an approach to advanced target recognition. It is analytically proven that the current, established framework for full coherent characterization of the scattered field maximizes the extracted target information. It is also shown that such a methodology, which is theoretically similar to the concept of "partial or compact polarimetry", yields comparable results to full or quadrature-polarized systems by incorporating judicious assumptions and assuming/implementing optimal transmitted or illumination field polarizations. On this basis, common characteristic features, interworking and fusion of different polarimetric sensor products in different regions of spectrum, e.g., radar/SAR and Electro-Optical, are investigated and formulated within a robust framework based on full coherent characterization of the scattered field.

Résumé

L'exploitation de la polarisation de champ rétrodiffusée sur une vaste plage du spectre électromagnétique allant de la région visible jusqu'aux fréquences micro-ondes donne une approche de la reconnaissance évoluée des objectifs. On a démontré analytiquement que le cadre établi actuel de caractérisation cohérente intégrale du champ diffusé permet d'extraire un maximum d'informations sur l'objectif. Cette démarche montre aussi qu'une telle méthode qui est théoriquement similaire au concept de la polarimétrie partielle dite compacte donne des résultats comparables aux systèmes à polarimétrie complète ou en quadrature en intégrant de judicieuses hypothèses et en présumant ou mettant en œuvre la polarisation optimale des champs transmis ou leur illumination. En se basant sur ce qui précède, on étudie les caractéristiques communes, l'interfonctionnement et la fusion de divers produits de capteurs polarimétriques dans diverses régions du spectre, p. ex. le radar classique ou le radar à synthèse d'ouverture et des capteurs électro-optiques, et on formule des hypothèses pertinentes dans un cadre robuste basé sur la caractérisation cohérente intégrale du champ diffusé.

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Executive summary

Polarimetric Intensity Parameterization of radar and other remote sensing sources for advanced exploitation and data fusion: Theory

R. Sabry, P.W. Vachon; DRDC Ottawa TM 2008-217; Defence R&D Canada – Ottawa; October 2008.

Introduction: Backscattered Electromagnetic (EM) waveform polarimetry provides additional information for target recognition compared to conventional single channel remote sensing sources. The objective here is to examine the interworking and fusion of EM polarimetric return quantities and measurables associated with certain classes of targets in different regions of EM spectrum. One prominent example is the combination of radar/SAR polarimetry with EM polarimetric sensors in the electro-optical domain.

Results: Preliminary study, formulations and simulations indicate the potential for advanced applications. Simulated results are obtained in the radar/SAR domain. A general analytic framework, valid for different regions of the EM spectrum, is established. Core conceptual similarity to "Compact Polarimetry" that is new, fast growing and proven potent for advanced radar data exploitations, also indicates the significance of the proposed approach. Considering the general property of the scattered EM wave being polychromatic and partially polarized, the analytic polarimetric EM signal is characterized by virtue of the Stokes vector and related parameters.

Significance: The general backscattered polarimetric wave in different regions of the EM spectrum is polychromatic and partially polarized. Also, it has been proven that the measurement potential of polarimetric SAR in response to a random backscatterer is maximized only if the data products are the 4-vector Stokes parameters. Thus, using the developed framework based on the comprehensive Stokes parameters and products provides a means for robust sensor data fusion. The latter offers significant advancement in data exploitation and target recognition due to the following: target scattering characteristics (i.e., identity) are better established over a wider range of the EM spectrum; and polarimetric return characteristics for certain target classes of interest are consistent throughout various regions of the EM spectrum (e.g., polarization selectivity for manmade objects). Hence, proper fusion of EM polarimetric returns in different bands can, in principle, enhance the contrast of such objects/targets compared to those with low or without the addressed polarization selectivity (e.g., clutter). The described EM polarimetric nature (polarization selectivity) manifested in different regions of the spectrum can be effectively exploited for classification purposes.

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Sommaire

Polarimetric Intensity Parameterization of radar and other remote sensing sources for advanced exploitation and data fusion: Theory

R. Sabry, P.W. Vachon; DRDC Ottawa TM 2008-217; R & D pour la défense Canada – Ottawa; Octobre 2008.

Introduction : La polarimétrie des formes d'ondes électromagnétiques rétrodiffusées fournit davantage de données pour la reconnaissance des objectifs que les capteurs de télédétection monovoie classiques. Nous voulons examiner ici l'interfonctionnement et la fusion des grandeurs et variables associées aux échos électromagnétiques et polarimétriques de certaines catégories d'objectifs dans diverses régions du spectre électromagnétique. Un exemple éminent en cette matière est la combinaison de la polarimétrie du radar classique et/ou du radar à synthèse d'ouverture et des capteurs électromagnétiques polarimétriques dans le domaine de l'électro-optique.

Résultats: Des études, formulations et simulations préliminaires montrent qu'il existe un potentiel d'applications évoluées. On obtient des résultats simulés dans le domaine du radar classique et/ou du radar à synthèse d'ouverture. Un cadre analytique général valide pour diverses régions du spectre électromagnétique est défini. Il existe une similarité conceptuelle fondamentale avec la « polarimétrie compacte », autrement dit un potentiel d'innovation éprouvé et croissant rapidement pour des exploitations évoluées des données radar, ce qui démontre aussi la portée de la démarche envisagée. Eu égard aux propriétés générales de l'onde électromagnétique rétrodiffusée, laquelle est à la fois polychromatique et partiellement polarisée, le signal polarimétrique électromagnétique analysé est caractérisé en vertu du théorème de Stokes et des paramètres connexes.

Portée: L'onde polarimétrique rétrodiffusée générale est polychromatique et partiellement polarisée. On a aussi démontré que le potentiel de mesure du radar à synthèse d'ouverture répondant à une rétrodiffusion aléatoire est porté à son maximum uniquement si les données correspondent aux paramètres quadrivectoriels du théorème de Stokes. Donc, l'utilisation du cadre mis au point fondé sur les paramètres et les produits intégraux du théorème de Stokes donne un moyen de réaliser une solide fusion des données de capteurs. Cette fusion présente un avancement important en matière d'exploitation des données et de reconnaissance des objectifs, grâce aux éléments suivants : les caractéristiques de diffusion de l'objectif (c.-à-d. son identité) sont mieux définies sur une plage plus vaste du spectre électromagnétique; les caractéristiques polarimétriques des échos de certaines catégories d'objectifs qui nous intéressent sont uniformes dans diverses régions du spectre électromagnétique (p. ex. la sélectivité de polarisation pour les objets artificiels). Conséquemment, une fusion adéquate des échos électromagnétiques polarimétriques dans diverses bandes peut, en principe, améliorer le contraste de tels objets et/ou objectifs, par rapport à ceux où l'on a peu ou pas tenu compte de la sélectivité de polarisation (c.-à-d. du fouillis radar). La nature électromagnétique et polarimétrique (de l'écho) décrite plus haut (sélectivité de polarisation) qui se manifeste dans diverses régions du spectre peut effectivement être exploitée à des fins de classification.

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Table of contents

List of figures

1 Introduction

Polarization characteristics of the electromagnetic (EM) waveform scattered as a result of interaction with different objects and/or targets provides significant insight into the nature of those targets, hence, providing valuable additional information for target recognition compared to conventional remote sensing sources. This is supported by the well-established physics of EM fields and waves [1]-[5]. Accordingly, EM polarimetry, from visible to microwave frequencies, provides an enhanced capability for advanced target recognition in remote sensing applications.

The goal here is to examine the interworking and fusion of EM polarimetric observables and measurables associated with certain classes of targets in different regions of the EM spectrum. One prominent example is the combination of radar/SAR polarimetry with EM polarimetric sensors in higher frequency bands, e.g., the visible or optical region. Characteristic advantages of such fusion or hybrid approach can be expressed as follows:

- First and foremost, in theory, target identity established through scattering characteristics will be more uniquely defined in a wider range of the EM spectrum even if the spectrum expansion is incoherent (i.e., incoherent bandwidths). Such spectral diversity provides a more comprehensive nature of scattering and the target.

- Polarimetric backscatter characteristics for a certain target class (or classes) of interest are consistent throughout various regions of the EM spectrum (e.g., polarization selectivity for manmade objects). Therefore, proper fusion of EM polarimetric returns in different bands can, in principle, enhance the contrast of such objects/targets compared to those with low or without the addressed polarization selectivity (e.g., clutter).

- The described EM polarimetric nature (polarization selectivity) manifested in different regions of the spectrum can be effectively exploited for calibration purposes. For instance, specification of the target polarization plane (e.g., the polarization orientation angle) may be extracted thus exploiting data from the sensor in one domain for exploitation and calibration in the other domain. Such interworking is applicable and effective for any polarization-related property associated with target physics that is consistent throughout the EM spectrum (or essentially within the operating bands of interest).

The described fusion of polarimetric data from SAR and other sensors from a different region of the EM spectrum, e.g., electro-optics (EO), should be performed within a robust framework based on careful modeling of the EM wave scattering and characteristic observables. As will be described, considering the general property of the scattered EM wave being polychromatic and partially polarized, the analytic polarimetric EM signal can be best-characterized by virtue of the Stokes vector and parameters. The scattering phenomenon can also be formulated within the same framework using Mueller, coherency or variance matrices [1],[6]-[8].

2 Electromagnetic (EM) scattering

The identity of objects/targets interacting with the Electromagnetic (EM) field in remote sensing is characterized by virtue of the EM scattering concept. The EM field scattering operator is analogous to the conventional target reflectivity function but provides a broader and more comprehensive picture of scattering. In particular, it contains information on the scattered field polarization that is valuable for target characterization. Accordingly, the polarimetric scattering operator is a Dyadic or Tensor by nature.

In any region of the EM spectrum, target scattering can be formulated as:

$$\mathbf{F}_s(\mathbf{x},\omega) = \overleftrightarrow{\mathbf{S}}(\mathbf{x},\omega).\mathbf{F}_i(\mathbf{x},\omega) \quad (1)$$

where $\overleftrightarrow{\mathbf{S}}(\mathbf{x},\omega)$ denotes the scattering operator in the space and time-frequency domain, and $\mathbf{F}_i(\mathbf{x},\omega)$, $\mathbf{F}_s(\mathbf{x},\omega)$ represent incident and scattered fields, respectively. For typical applications, these vector field components represent the electric field, i.e., $\mathbf{E}_i(\mathbf{x},\omega)$ and $\mathbf{E}_s(\mathbf{x},\omega)$. In (1), "." denotes the dot or inner product.

As is evident from (1), the identity of a scatterer at position $\mathbf{x}$ is completely and uniquely defined (theoretically) over the whole spectrum. Thus, waveform diversity (for both incident and scattered fields) is required to establish the complete scatterer identity. That is, target recognition will be enhanced through spectrum diversity.

One should note that in the present formalism, the excitation (i.e., incident field) and receive (i.e., scattered field) points may be in different space locations such as those for bistatic radars. Also, the incident field source of scattering may be not controlled or coherent.

The general formalism of (1), although simple in conceptual representation, is very involved for practical target recognition applications. The coherent scattering target operator or matrix that contains comprehensive scatterer information may be difficult to relate to target characteristics for practical applications. This is due to many factors such as the noted incomplete spectral content, random effects, partial or non coherence (with respect to the source excitation/incident field) associated with the scattered field or wave. Considering the above, the scattered field or wave analysis becomes a viable choice for scatterer characterization. This EM field analysis approach that is essentially based on scattering vector analysis (rather than the scattering operator or matrix) is similar to the emerging "compact polarimetry" methodology [9]-[13] that exploits scattering system response to an incomplete set of input EM field components. Although, the unique scattering transfer function is ill-defined mathematically, certain assumptions may be made (e.g., symmetry) to construct the scattering matrix [12].

To extract the most information about the target from its random backscatter response with unknown orientation relative to the known polarity of the radar illumination (i.e., the typical practical scenario), the backscattering measurement potential of SAR should be maximized. The latter is maximized if and only if the data products are the 4 Stokes parameters (or their logical equivalent) [10]. This is in agreement with the statement made earlier based on classical EM physics that the analytic polarimetric EM signal (polychromatic and partially polarized) is best characterized by virtue of the Stokes vector and parameters. The above statement is valid for a polarimetric EM signal throughout the whole spectrum, from the microwave to visible range.

It follows from the above discussion that, for any (or regardless of) illumination or scattering source, the scattered field (and hence target) characterization is optimized by using the 4-vector Stokes parameters. Hereby, a robust platform with a well-defined set of observables is established for interworking between EM polarimetric sensors operating at different regions or bands of the EM spectrum, e.g., SAR and optical polarimetry.

In this work, the wide-spectrum scattered EM field (partially/completely polarized or coherent) is formulated in a unified manner, and in terms of components/products of significance for scattering analysis. Since these EM observables are characterizing field and scattering in different regions of the spectrum, fusion of various sensors utilizing EM remote sensing for advanced exploitation is envisioned.

3 Electromagnetic (EM) field formulation and observables

3.1 EM wave analytic description

A general *polychromatic* EM wave propagating in the direction $\mathbf{r}$ can be analytically represented by:

$$\vec{\mathcal{E}}(\mathbf{r},t)=\mathbf{E}(\mathbf{r},t)\exp\left(j(\omega t-k_0 L(\mathbf{r},t))\right) \tag{2}$$

where $\mathbf{E}(\mathbf{r},t)$ is the complex vector field phasor, $k_0=\dfrac{2\pi}{\lambda}=\dfrac{\omega}{c}$ and c are the vacuum wavenumber and speed of light with λ being the wavelength, and $\mathbf{r}=(x,y,z)$ denotes the position vector. Providing that the waveform bandwidth is small compared to the center frequency, a *quasi-monochromatic* model can be adopted as:

$$\vec{\mathcal{E}}(\mathbf{r},t)=\mathbf{E}(t)\exp\left(j(\omega t-\phi(t))\right) \tag{3}$$

In the spectral domain, the *polychromatic* EM signal (2) can be represented as:

$$\begin{aligned}\tilde{\vec{\mathcal{E}}}(\mathbf{r},\omega)&=\tilde{\mathbf{E}}(\mathbf{r},\omega)\exp\left(-j(k_0\tilde{L}(\mathbf{r},\omega))\right)\\&=\tilde{\mathbf{E}}(\mathbf{r},\omega)\exp\left(-j(k(\mathbf{r},\omega))\right)\end{aligned} \tag{4}$$

In (2) and (4), $L(\mathbf{r},t)$ and $\tilde{L}(\mathbf{r},\omega)$ represent the time and spectral domain *eikonal* functions, respectively. The *eikonal* function, which is commonly used in ray theory, characterizes the ray directions and the wave fronts. The time invariant (or implicit time variant) complex vector EM field/wave in the $\mathbf{EH}$ plane (i.e., perpendicular to the direction of wave propagation or in direction of the Poynting vector) may be expressed as:

$$\mathbf{E}(\mathbf{r}) = E_x(\mathbf{r})\,\mathbf{x} + E_y(\mathbf{r})\,\mathbf{y} = E_x(\mathbf{r})\,(\mathbf{x} + \rho(\mathbf{r})\,\mathbf{y}) \tag{5}$$

where:

$$\rho(\mathbf{r}) = \frac{E_y(\mathbf{r})}{E_x(\mathbf{r})} \tag{6}$$

is a complex factor representing the polarization ratio. In (5), the direction of wave propagation is assumed to be in the $\mathbf{z}$ direction and introduces no loss of generality. Respectively, $\mathbf{x}, \mathbf{y}$ $(\hat{h}, \hat{v})$ represent the scattering or polarimetric basis vectors. One should note that the alignment of the polarimetric basis vectors $\mathbf{x}, \mathbf{y}$ $(\hat{h}, \hat{v})$ is arbitrary. The $\mathbf{x}$ alignment may be set at any angle α (with respect to the universal horizontal plane) and the $\mathbf{y}$ alignment can be found by a 90-degree right-hand rotation around the line of sight (LOS), i.e., $\alpha + 90$. It is, however, imperative to be consistent throughout the entire formulation, in particular, when considering different sensors.

The field complex vector in (5) is general. It can be partially or completely polarized, or completely depolarized. The Stokes vector or parameters are a set of suitable products that can comprehensively describe the polarization state and nature of EM radiation for such general waveforms. The Stokes vector associated with a partially-polarized EM wave (5) is given by [1],[8],[14]:

$$\mathbf{S} = \begin{bmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{bmatrix} = \begin{bmatrix} \left\langle |E_x|^2 \right\rangle + \left\langle |E_y|^2 \right\rangle \\ \left\langle |E_x|^2 \right\rangle - \left\langle |E_y|^2 \right\rangle \\ \left\langle E_x^* E_y + E_x E_y^* \right\rangle \\ j\left\langle E_x^* E_y - E_x E_y^* \right\rangle \end{bmatrix} \tag{7}$$

where $\langle \ldots \rangle$ represents temporal or local spatial averaging. The first vector component S_0 in (7) represents the total power density of the partially-polarized field. The remaining vector components S_1, S_2, S_3 model the polarized component of the EM field, i.e., for an unpolarized EM wave:

$$S_1 = S_2 = S_3 = 0 \tag{8}$$

Decomposing the partially polarized EM wave into completely polarized and completely depolarized field components using (5), gives:

$$\mathbf{E}^P(\mathbf{r}) = E^P{}_x(\mathbf{r})(\mathbf{x} + \rho_P(\mathbf{r})\mathbf{y}) \tag{9}$$

$$\mathbf{E}^U(\mathbf{r}) = E^U{}_x(\mathbf{r})(\mathbf{x} + \rho_U(\mathbf{r})\mathbf{y}) \tag{10}$$

so,

$$\mathbf{E}^{Total}(\mathbf{r}) = \mathbf{E}^P(\mathbf{r}) + \mathbf{E}^U(\mathbf{r}) \tag{11}$$

One obtains for the associated Stokes components:

$$S_1^U = S_2^U = S_3^U = 0 \tag{12}$$

and

$$S_0^U = 2\left\langle \left| E_x^U \right|^2 \right\rangle \qquad \left(\left| \rho_U(\mathbf{r}) \right| = 1 \right) \tag{13}$$

Also,

$$S_0^{Total} = S_0^{U} + \sqrt{\left(S_1^{P}\right)^2 + \left(S_2^{P}\right)^2 + \left(S_3^{P}\right)^2} \tag{14}$$

Alternatively,

$$\mathbf{S}^{Total} = \begin{bmatrix} S_0^{Total} \\ S_1^{Total} \\ S_2^{Total} \\ S_3^{Total} \end{bmatrix} = \begin{bmatrix} 2\left\langle \left|E_x^{U}\right|^2 \right\rangle + \left\langle \left|E_x^{P}\right|^2 \left(1+\left|\rho_P\right|^2\right)\right\rangle \\ \left\langle \left|E_x^{P}\right|^2 \left(1-\left|\rho_P\right|^2\right)\right\rangle \\ 2\left\langle \left|E_x^{P}\right|^2 \operatorname{Re}\left(\rho_P\right)\right\rangle \\ 2\left\langle \left|E_x^{P}\right|^2 \operatorname{Im}\left(\rho_P\right)\right\rangle \end{bmatrix} = \begin{bmatrix} 2\left\langle \left|E_x^{U}\right|^2 \right\rangle \\ 0 \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} \left\langle \left|E_x^{P}\right|^2 \left(1+\left|\rho_P\right|^2\right)\right\rangle \\ \left\langle \left|E_x^{P}\right|^2 \left(1-\left|\rho_P\right|^2\right)\right\rangle \\ 2\left\langle \left|E_x^{P}\right|^2 \operatorname{Re}\left(\rho_P\right)\right\rangle \\ 2\left\langle \left|E_x^{P}\right|^2 \operatorname{Im}\left(\rho_P\right)\right\rangle \end{bmatrix}$$

$$= \begin{bmatrix} 2\left\langle \left|E_x^{U}\right|^2 \right\rangle \\ 0 \\ 0 \\ 0 \end{bmatrix} + \left|E_x^{P}\right|^2 \begin{bmatrix} \left(1+\left|\rho_P\right|^2\right) \\ \left(1-\left|\rho_P\right|^2\right) \\ 2\operatorname{Re}\left(\rho_P\right) \\ 2\operatorname{Im}\left(\rho_P\right) \end{bmatrix} \tag{15}$$

One may also parameterize the Stokes vector in terms of the EM wave polarization ellipse as:

$$\mathbf{S}=\begin{bmatrix}S_0\\S_1\\S_2\\S_3\end{bmatrix}=I_\alpha\begin{bmatrix}1\\m\cos(2\chi)\cos(2\psi)\\m\cos(2\chi)\sin(2\psi)\\m\sin(2\chi)\end{bmatrix} \tag{16}$$

where I_α denotes the total power of the partially-polarized wave (aligned at angle α as described previously) , and m is the degree of polarization given by (using (12)-(14)):

$$m=\frac{S_0^{\;Total}-S_0^{\;U}}{S_0^{\;Total}}=\frac{\sqrt{(S_1)^2+(S_2)^2+(S_3)^2}}{S_0} \tag{17}$$

In (16), χ and ψ are the characteristic parameters describing the EM wave polarization ellipse, i.e., the *ellipticity* and *rotation angles*. As seen from (12)-(14) and (16)-(17), the characteristic parameters χ and ψ describe the polarized portion of the EM wave. As such, the wave polarization and hence the Stokes vector can be mapped on to a 3-dimensional manifold with space angles (χ,ψ). The completely-polarized waves will be located on a sphere of radius I_α (i.e., the *Poincaré* sphere), while the and partially polarized waves lie inside the sphere.

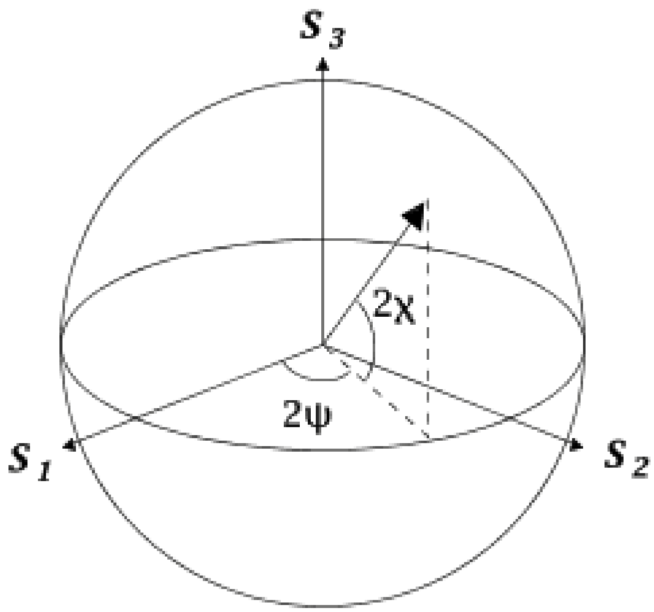

Figure 1. Poincaré Sphere, Stokes Vectors Representation

It is useful to have the analytic representation of some Stokes vector related parameters and products for a partially polarized EM waveform.

The degree of linear polarization is:

$$m_L = \frac{\sqrt{(S_1)^2 + (S_2)^2}}{S_0} = m\cos(2\chi) \tag{18}$$

The circular polarization ratio is:

$$\begin{aligned}\rho_C &= \frac{S_0 - S_3}{S_0 + S_3} = \frac{1 - m_L \tan(2\chi)}{1 + m_L \tan(2\chi)} \\ &= \frac{1 - \sqrt{m^2 - m_L{}^2}}{1 + \sqrt{m^2 - m_L{}^2}}\end{aligned} \tag{19}$$

The polarization ratio phase is:

$$\delta = \arctan\left(\frac{S_3}{S_2}\right) \tag{20}$$

The polarization ratio magnitude angle is:

$$2\alpha_\rho = \arccos\left(\frac{S_1}{m\,S_0}\right) \qquad \left(\tan(\alpha_\rho) = |\rho|\right) \tag{21}$$

And:

$$2\chi = \arctan\left(\frac{S_3}{\sqrt{(S_1)^2 + (S_2)^2}}\right) = \arctan\left(\frac{S_3}{m_L\,S_0}\right) \tag{22}$$

$$2\psi = \arctan\left(\frac{S_2}{S_1}\right) \tag{23}$$

3.2 Stokes vector transformation

As addressed, one important application of the Stokes EM field representation is to study and characterize scattering phenomena as a result of target interaction with the EM wave. Therefore, analytic transformation of the Stokes vector associated with an EM waveform transform under certain operations (e.g., a scattering operator, or a basis transformation) is invaluable. As will be more evident later, the Stokes vector and parameter transformations play an important role in unifying and fusing scattered EM wave (partially polarized) characterization in different spectrum bands and regimes.

For an EM polychromatic wave undergoing a transformation:

$$\mathbf{E}_s(\mathbf{r}) = \overleftrightarrow{T}(\mathbf{r}) \odot \mathbf{E}_i(\mathbf{r}) \tag{24}$$

where $\overleftrightarrow{T}$ represents the operator (e.g., Dyadic) and the symbol "$\odot$" denotes the generalized dot product operator. One can derive the Stokes vector transformation operator (using straightforward operator algebra) as:

$$\vec{\mathbf{G}}(\mathbf{r}) = U_l \left(\overleftrightarrow{T}^a(\mathbf{r}) \overleftrightarrow{T}(\mathbf{r}) \right) U_r \tag{25}$$

where U_l, U_r are the operators defining the transformation from field coherency to Stokes vector, and $\overleftrightarrow{T}^a(\mathbf{r})$ is the adjoint operator to $\overleftrightarrow{T}(\mathbf{r})$. In a more familiar matrix format:

$$\overline{\overline{G}}(\mathbf{r})_{(4\times4)} = U_{l(4\times4)} \left(\overline{\overline{T_{2\times2}}}^*(\mathbf{r}) \otimes \overline{\overline{T_{2\times2}}} \right)_{(4\times4)} U_{r(4\times4)} \tag{26}$$

In (26), the symbol $\otimes$ denotes the *Kronecker* matrix product and:

$$U_r = A_s^{-1} = \begin{bmatrix} 1 & 0 & 0 & 1 \\ 1 & 0 & 0 & 1 \\ 0 & 1 & 1 & 0 \\ 0 & j & -j & 0 \end{bmatrix}^{-1} \tag{27}$$

$$U_l = \begin{bmatrix} 1 & 0 & 0 & 1 \\ 1 & 0 & 0 & 1 \\ 0 & 1 & 1 & 0 \\ 0 & j & -j & 0 \end{bmatrix} \qquad (\textit{for general transfromation})$$

(28)

$$U_l = \begin{bmatrix} 1 & 0 & 0 & 1 \\ 1 & 0 & 0 & 1 \\ 0 & 1 & 1 & 0 \\ 0 & -j & j & 0 \end{bmatrix} \qquad (\textit{for backscattering reception})$$

(29)

Using (25)-(29), the Stokes matrix transform becomes:

$$\mathbf{S}_s(\mathbf{r}) = \overline{\overline{G}}(\mathbf{r}) \odot \mathbf{S}_i(\mathbf{r}) \tag{30}$$

Upon transformation of the input Stokes vector, various alignments of the scattered field Stokes vector can be extracted and analyzed. Projection of the Stokes vector into a certain direction or alignment is not straightforward due to the cross coupling of the field components (i.e., cross terms in power). However, through definition of cross Stokes vectors and Stokes basis vectors (developed and to be reported), projected Stokes and power terms for an arbitrary alignment can be determined.

3.3 Examples

Consider the well-known example of a trihedral corner reflector. The scattering matrix is defined by:

$$\overline{\overline{S}} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \tag{31}$$

According to (26), the Stokes vector transformation matrix is:

$$\overline{\overline{G}}=\begin{bmatrix}1 & 0 & 0 & 0\\ 0 & 1 & 0 & 0\\ 0 & 0 & 1 & 0\\ 0 & 0 & 0 & -1\end{bmatrix} \tag{32}$$

For a general input polarization, the Stokes vector is parameterized by (see (16)):

$$\mathbf{S}_i=\begin{bmatrix}1\\ \cos(2\chi_i)\cos(2\psi_i)\\ \cos(2\chi_i)\sin(2\psi_i)\\ \sin(2\chi_i)\end{bmatrix} \tag{33}$$

and the scattered Stokes vector is readily found as:

$$\mathbf{S}_s=\begin{bmatrix}1\\ \cos(2\chi_s)\cos(2\psi_s)\\ \cos(2\chi_s)\sin(2\psi_s)\\ \sin(2\chi_s)\end{bmatrix}=\begin{bmatrix}1\\ \cos(2\chi_i)\cos(2\psi_i)\\ \cos(2\chi_i)\sin(2\psi_i)\\ -\sin(2\chi_i)\end{bmatrix} \tag{34}$$

Projecting this output vector into the 2 co-pol and cross-pol directions (using the procedure addressed above), one obtains:

$$r_{co-pol}=\frac{1+\cos(4\chi)}{2} \tag{35}$$

and

$$r_{cross-pol} = \frac{1-\cos(4\chi)}{2} \tag{36}$$

The incident field index "*i*" has been dropped in (35) and (36). Figures 2 and 3 depict the co-pol and cross-pol response to a general polarization characterized by ellipticity and rotation angles (χ, ψ). This behaviour of the scattered wave from the trihedral scatterer can be compared to its scattering characteristics in another domain such as EO (by using the described EM analytic framework) for advanced exploitation.

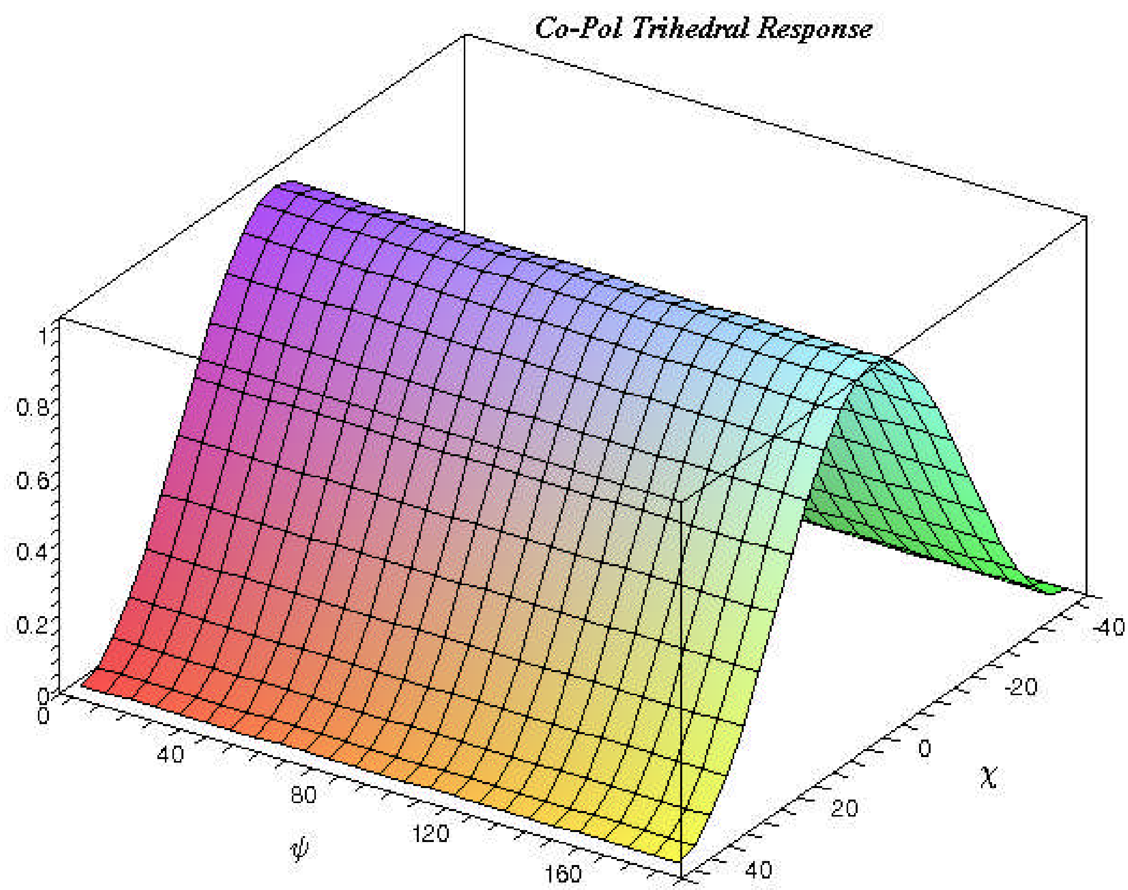

Figure 2. Co-Pol Reflection ratio

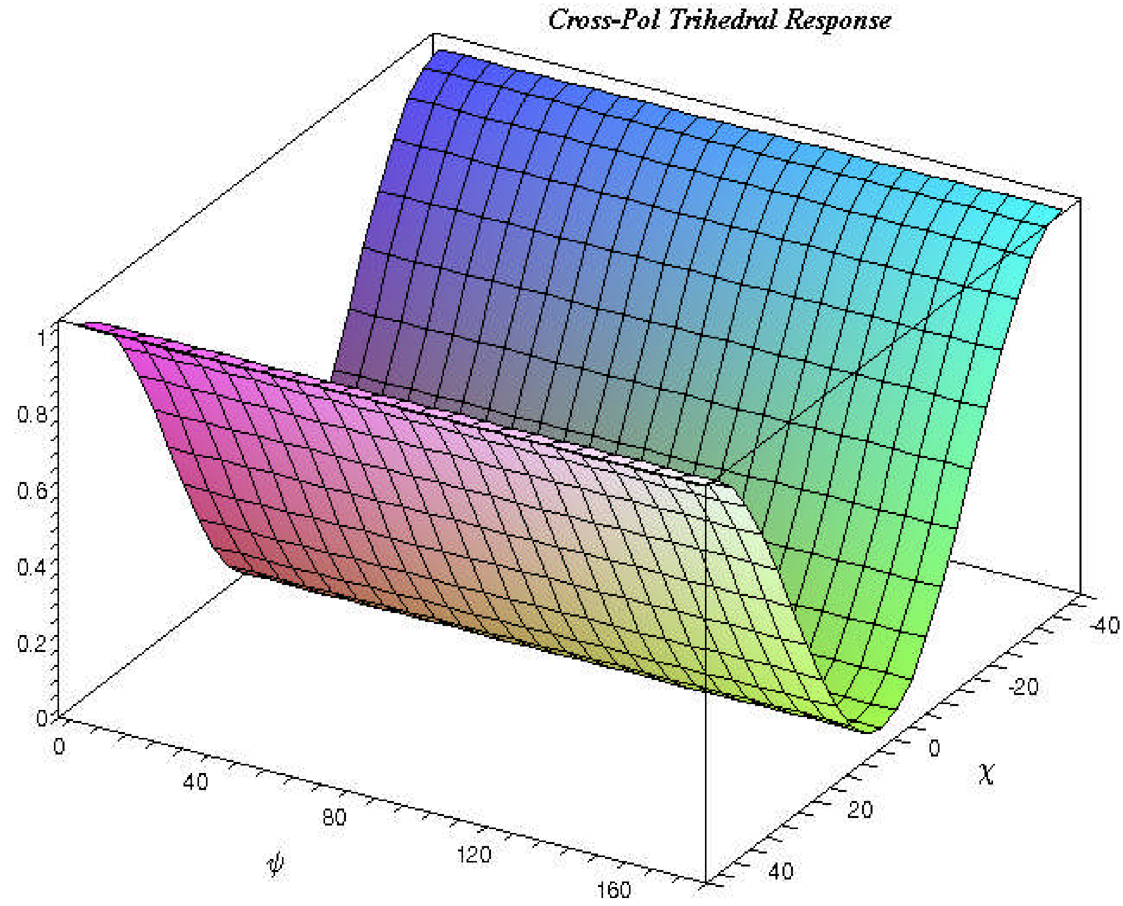

Figure 3. Cross-Pol Reflection ratio

4 Compact Polarimetry Concept

The identity of a target interacting with the EM field and/or wave is established via formulation of scattering and by virtue of a scattering operator or matrix. Although as theoretically discussed earlier, performance of such fully-polarized radar system (i.e., quadrature-polarized) is unique and has no substitute in providing complete target backscattering information, it comes with an attendant cost, e.g., lower radar swath coverage, higher antenna transmitter power requirements. As a result, the concept of "partial polarimetry" or "compact polarimetry" has emerged in recent years and several papers on the subject have been published [10]-[12], [15]-[16]. The main objective of this line of research is to achieve certain appealing characteristics of a fully-polarized system without actual realization of a quadrature-polarized system. Partial or dual polarimetry is essentially a step up from a single channel system towards the fully polarimetric system that is an effective strategy when the polarimetric system resources are limited or not available. It is also compatible as an optional mode for a fully polarimetric radar system [9].

As addressed, the backscattering measurements using polarimetric sensors operating at any wavelength or frequency are optimized and the extracted information maximized using Stokes or equivalent to Stokes parameters. It has been demonstrated that partial or compact polarimetry can emulate many aspects of the full or quadrature-polarized system output products and information [12],[16], e.g., scattering or coherency matrix, by incorporating certain *a priori* information such as reflection and rotation symmetry. Nonetheless, Stokes vector parameterization and analysis represent the identifying nature and characteristics of compact or dual-pol polarimetry.

In a compact polarimetry scenario or dual polarization radar/SAR system, a single polarization EM signal is transmitted (illumination) and the backscattered EM signal is coherently received in two orthogonal polarizations. The choice of the transmit signal is arbitrary, i.e., any polarization, as well as the choice for two orthogonal receive basis polarizations that construct a complete 2-dimensional space to characterize the scattered (in general, partially polarized) EM signal.

Judicious selection of these polarization sets for transmission and reception can optimize the system architecture and satisfy the operational requirements for applications of interest. Any assumed orthogonal polarization set at the receiving end, maximizes the backscattering information through constitution of a complete vector space. However, choice of polarization basis at reception can affect and optimize a radar's design with respect to reliability, architecture, mass and power considerations. The nature of the application and targets of interest determines the optimal transmitted polarization. For instance, applications manifesting rotational invariance imply a requirement for transmitted circular polarization (CT). Circular polarization transmit and linear (i.e., h and v) polarization receive mode (CTLR) has been found to be the optimum architecture for lunar or planetary exploration and a good alternative to linear polarization for Earth-observing SAR systems [9]. One of the initial compact polarimetric modes referred to as the $\frac{\pi}{4}$ mode [11], [17], utilizes a transmitted field polarized at 45° and linear polarization receive orthogonal set (e.g., h, v). The $\frac{\pi}{4}$ mode is successful in decomposition analysis involving scenes with scatterers predominantly oriented in horizontal and vertical directions. Both of these mixed-polarity modes, CTLR and $\frac{\pi}{4}$, enjoy extensive meteorological radar heritage [18]-[19]. Also, end-to-end circular polarimetry, i.e., Circular polarization transmit and Circular polarization receive mode (i.e., dual circular polarimetric (DCP)) has an extensive heritage in radar astronomy [20]-[23].

The scattering vectors associated with the described modes CTLR, DCP, and $\frac{\pi}{4}$ can be expressed in terms of the standard quad-pol scattering matrix components as following:

$$\mathbf{k}_{CTLR} = \frac{1}{\sqrt{2}} \begin{bmatrix} S_{hh} + jS_{hv} \\ jS_{vv} + S_{vh} \end{bmatrix} \tag{37}$$

$$\mathbf{k}_{DCP} = \begin{bmatrix} S_{RR} \\ S_{RL} \end{bmatrix} \tag{38}$$

where "R" and "L" denote right and left circular polarizations, and:

$$\mathbf{k}_{\frac{\pi}{4}} = \frac{1}{\sqrt{2}} \begin{bmatrix} S_{hh} + S_{hv} \\ S_{vv} + S_{vh} \end{bmatrix} \tag{39}$$

The described compact polarimetry fundamentals are similar to the theoretical foundation that the present mutisensor interworking and fusion proposal is based on. In brief, the core methodology is to enhance the extracted backscattering information by: 1) modeling and full characterization of the scattered EM field using two coherent orthogonal polarizations, chosen based on the system design and architecture requirements; and 2) designing a compact polarimetry mode for intended applications based on respective requirements and constraints. <u>In the current report, the described methodology and/or analytic tool is intended to formulate and enhance the common information in the polarimetric backscattered field from different sensors (e.g., radar/SAR and electro-optical) for advanced interworking and fusion.</u>

5 EM field intensity products and observables

It can be shown that the Stokes vector associated with a scattered EM wave (16) is constructed by measuring the field intensity at 4 polarizations or alignments $I_\alpha, I_\beta, I_\gamma, I_\sigma$. The alignment angles $\alpha, \beta, \gamma, \sigma$ may conventionally be set at $0^\circ, 45^\circ, 90^\circ, 135^\circ$ for ease of computations. The choice of these 4 angles is arbitrary but may involve more complicated computations.

One can show that under any polarization rotation, the first Stokes parameter S_0 is invariant and equal to sum of intensities of 2 orthogonal alignments:

$$S_0 = I_\theta + I_{\theta+90} \qquad (for \;\; all \;\; \theta) \tag{40}$$

Thus:

$$S_0 = \frac{1}{2}\left(I_\alpha + I_{\alpha+90} + I_\beta + I_{\beta+90}\right) \tag{41}$$

or in the special case:

$$S_0 = \frac{1}{2}\left(I_0 + I_{45} + I_{90} + I_{135}\right) \tag{42}$$

Other Stokes parameters can be derived using a similar approach. More specifically:

$$S_1 = I_0 - I_{90} \tag{43}$$

$$S_2 = I_{45} - I_{135} \tag{44}$$

and:

$$S_3 = \frac{1}{2}\begin{bmatrix}\left(m^2-4\right)\left(I_0^2+I_{45}^2+I_{90}^2+I_{135}^2\right)+2\left(m^2+4\right)\left(I_0\,I_{90}+I_{45}\,I_{135}\right)\\ +2\,m^2\left(I_0\,I_{45}+I_0\,I_{135}+I_{45}\,I_{90}+I_{90}\,I_{135}\right)\end{bmatrix}^{\frac{1}{2}} \tag{45}$$

where m is the degree of polarization. In order to provide a complete picture of the scattered EM field, i.e., Stokes 4-parameters, the degree of polarization m in (45) must be evaluated. This parameter may be estimated using a number of techniques such as entropy-based extraction [17], or measurement of the polarization ratio angle (21).

The described Stokes vector, parameters and related quantities constitute a unified frame of observables for the scattered wave (fully or partially polarized) analysis throughout a wide EM spectrum. As such, it can be used to formulate the interworking and fusion of SAR and EO polarimetry for advanced target exploitation.

As an example, for the observed scattered field intensity that can be compared and fused for enhanced exploitation, consider the incident EM field with a general polarization described by (33). As derived, the scattered field by a trihedral corner backscatterer received at the receive antenna is given by (34).

From (40)-(44), one can write:

$$I_0 = \frac{S_0 + S_1}{2} \tag{46}$$

$$I_{90} = \frac{S_0 - S_1}{2} \tag{47}$$

$$I_{45} = \frac{S_0 + S_2}{2} \tag{48}$$

$$I_{135} = \frac{S_0 - S_2}{2} \tag{49}$$

Using (34), one obtains:

$$I_0 = \frac{1 + \cos(2\chi)\cos(2\psi)}{2} \tag{50}$$

$$I_{90} = \frac{1 - \cos(2\chi)\cos(2\psi)}{2} \tag{51}$$

$$I_{45} = \frac{1 + \cos(2\chi)\sin(2\psi)}{2} \tag{52}$$

$$I_{135} = \frac{1 - \cos(2\chi)\sin(2\psi)}{2} \tag{53}$$

Simulations depicted in Figures 4-7 show the above scattered field intensity variations in terms of the input EM field polarization variations or choice of transmitted polarization, i.e., the ellipticity and rotation angles χ, ψ .

The results provide a tool to compare or combine polarimetric SAR scattering products with other EM polarimetric sensor (e.g., EO) products based on a robust and accurate theoretical foundation. The significance of these results are better appreciated when considering that standard EO polarimetric products are typically expressed in terms of 4 field-intensity outputs (i.e., $I_0, I_{45}, I_{90}, I_{135}$) of polarization filters associated with the described 4-angles. Hence, the means for effective fusion is provided.

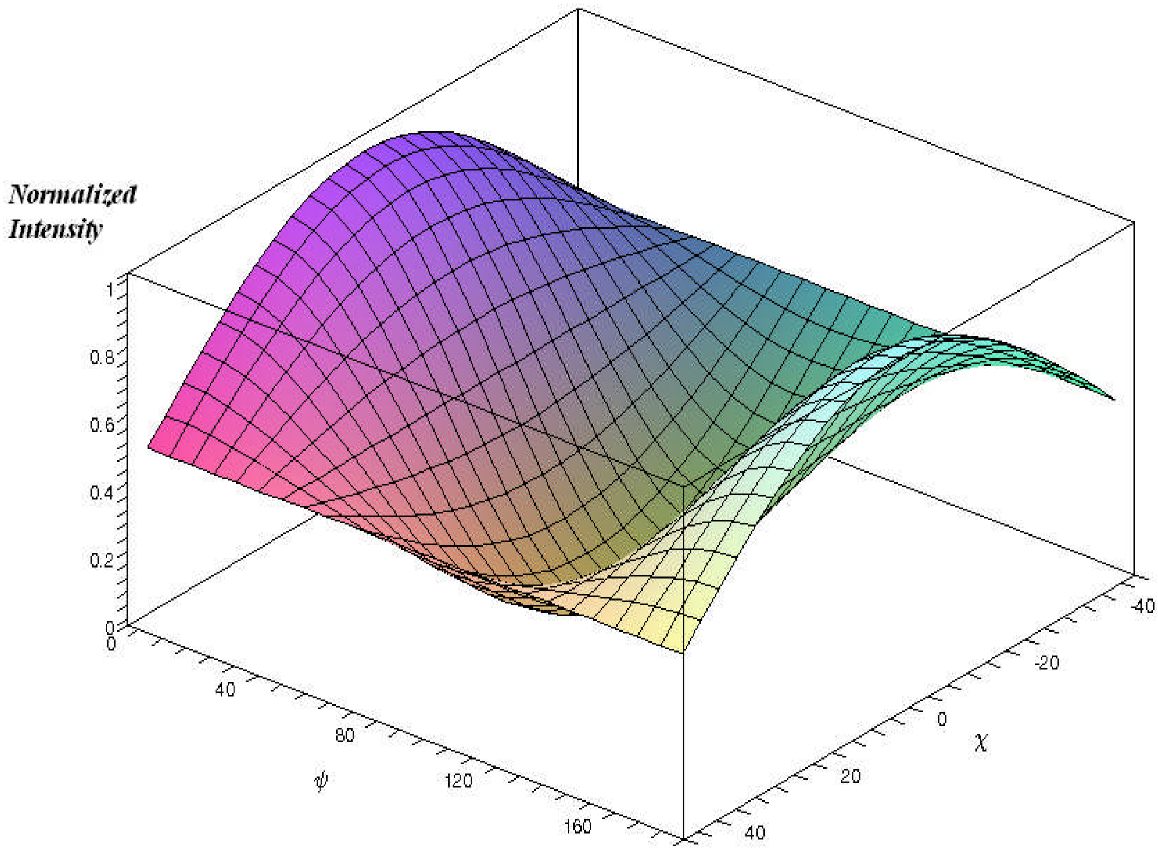

Figure 4. Trihedral Corner Reflector Scattered Field Intensity I_0 *(General Illumination Polarization* χ, ψ *).*

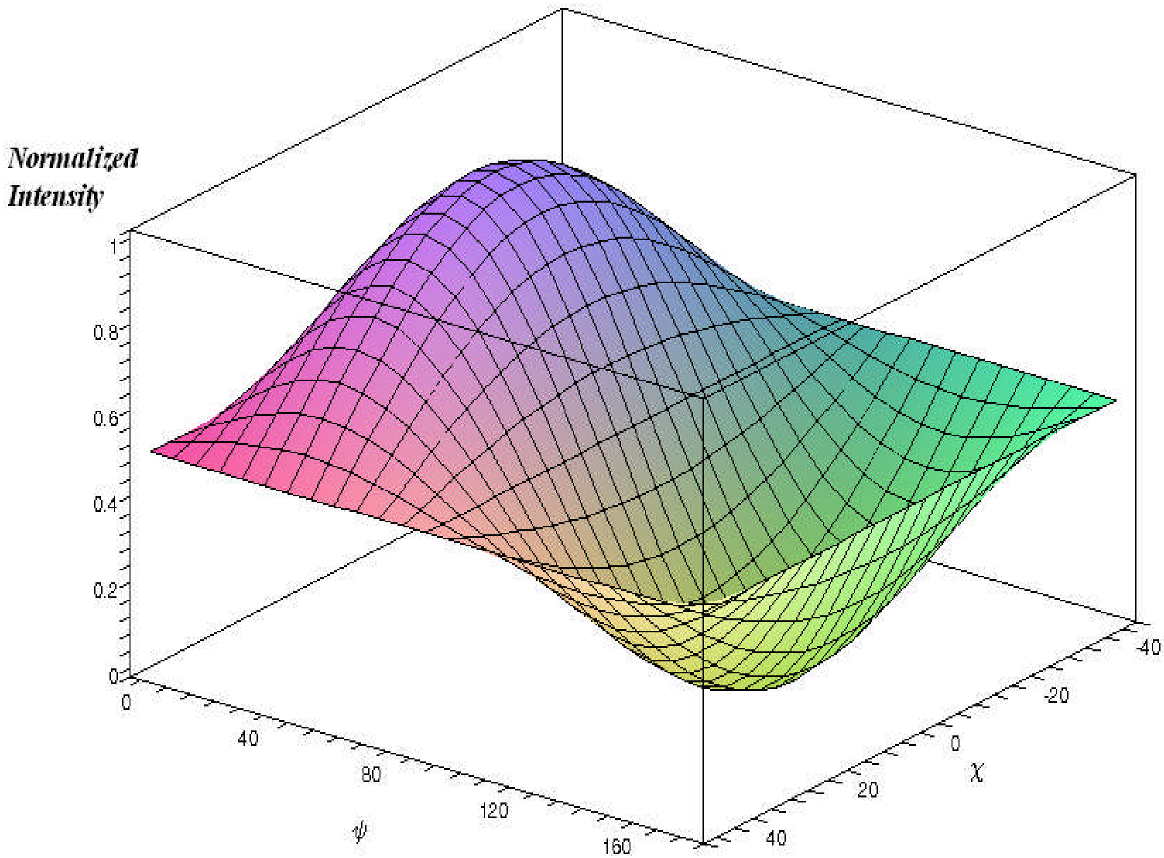

Figure 5. Trihedral Corner Reflector Scattered Field Intensity I_{45} (General Illumination Polarization χ, ψ).

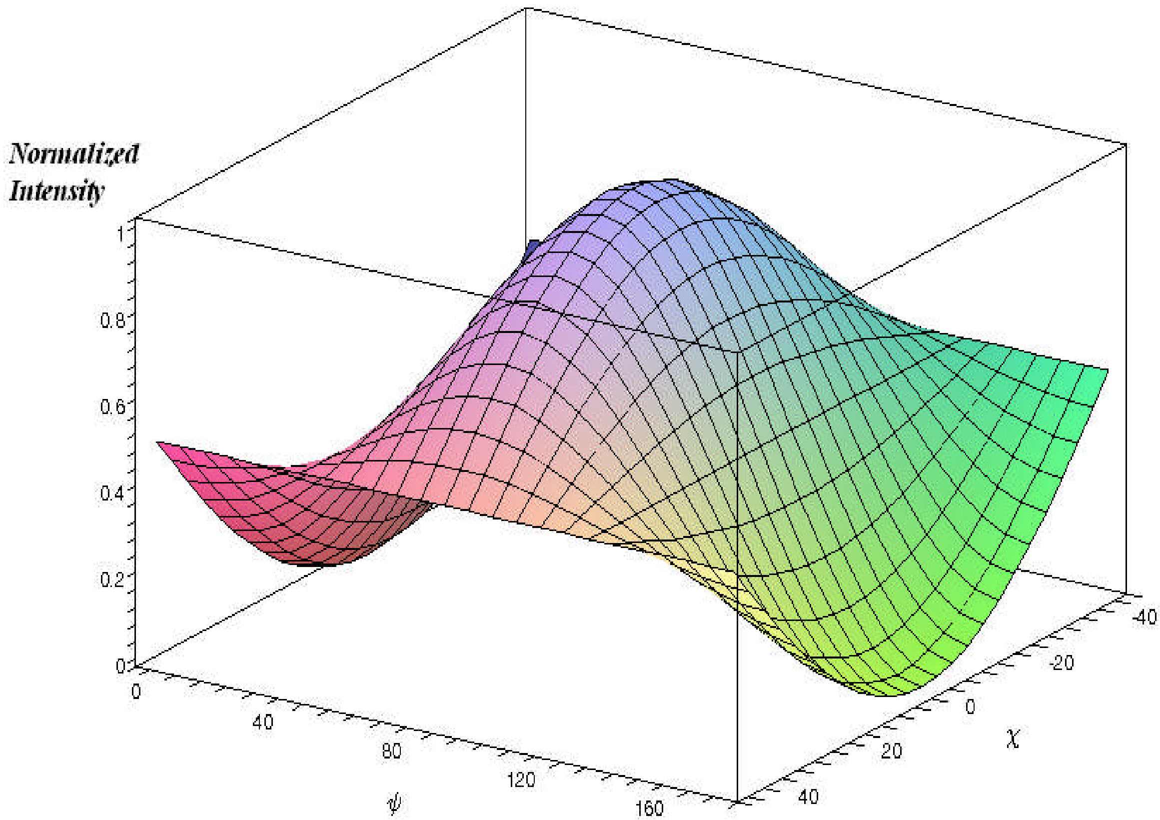

Figure 6. Trihedral Corner Reflector Scattered Field Intensity I_{90} *(General Illumination Polarization* χ, ψ *).*

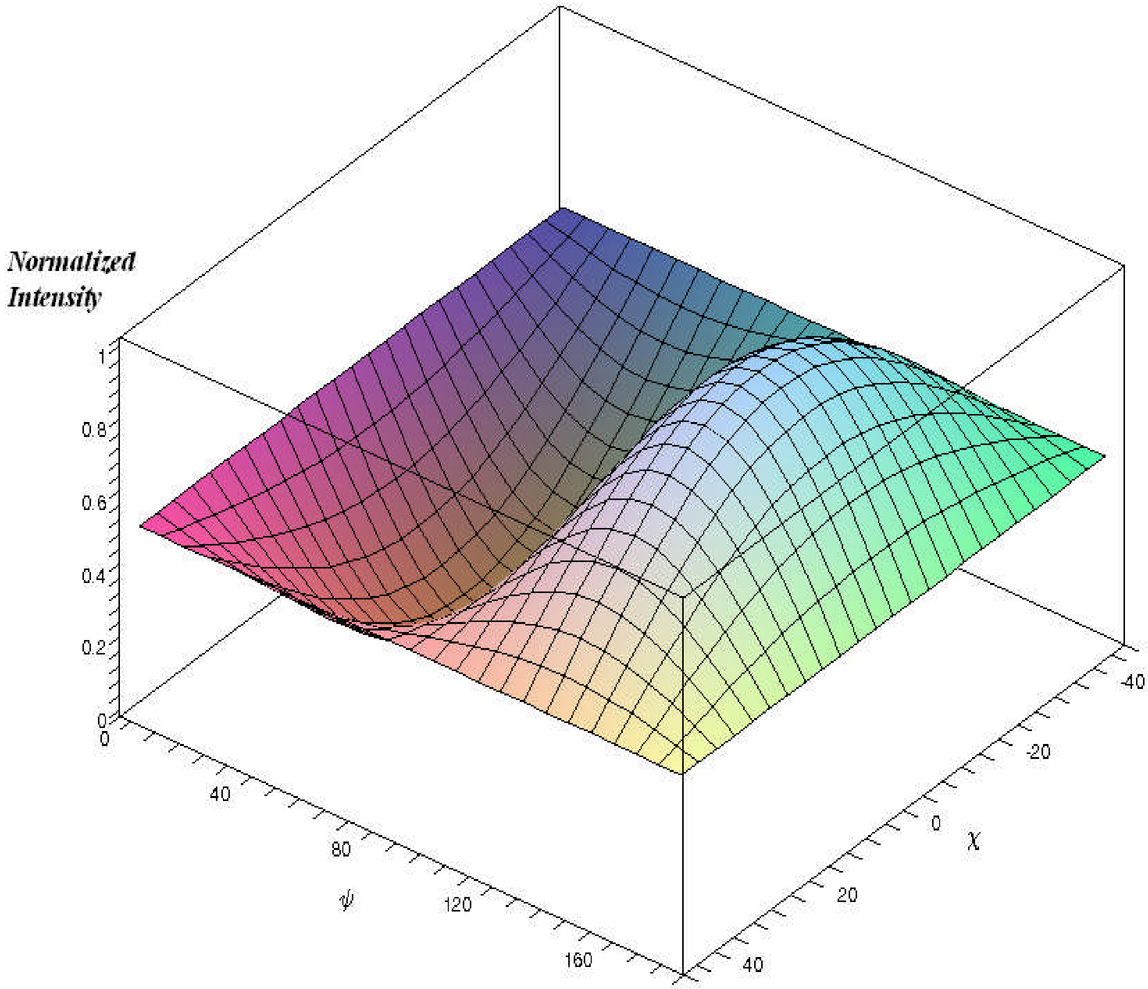

Figure 7. Trihedral Corner Reflector Scattered Field Intensity I_{135} *(General Illumination Polarization* χ, ψ *).*

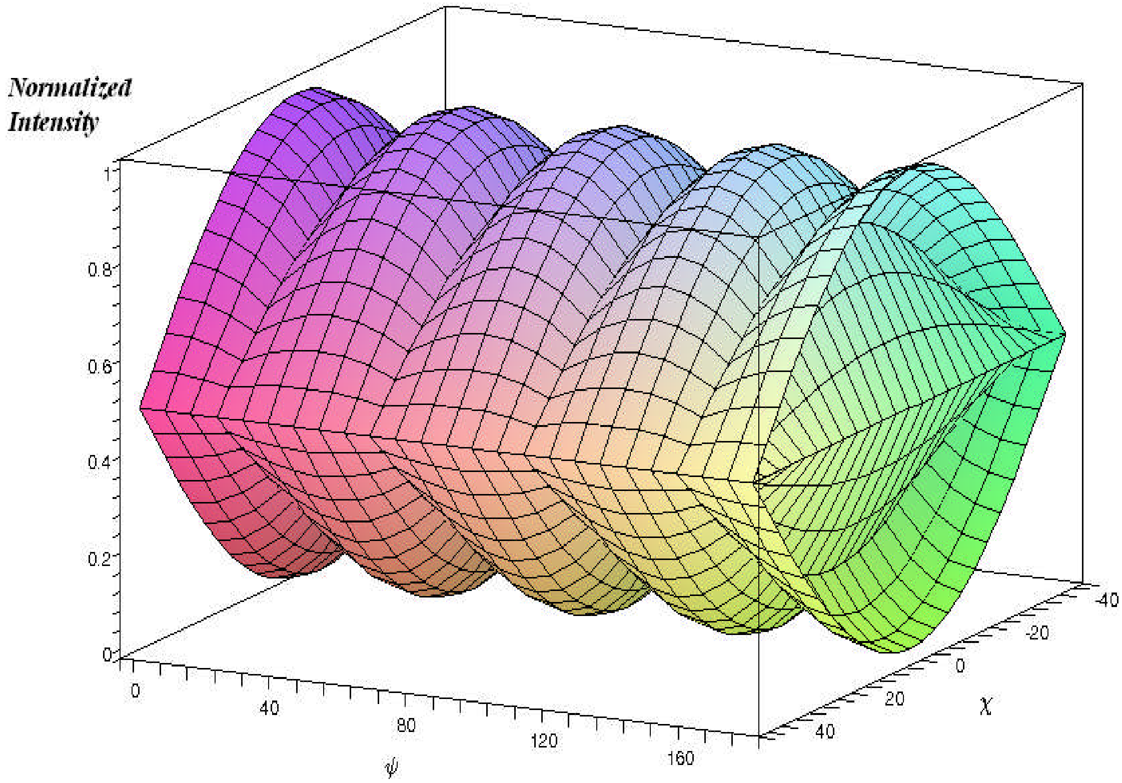

Figure 8. Trihedral Corner Reflector Scattered Field Total Intensity in 4 Manifolds, i.e., $I_0, I_{45}, I_{90}, I_{135}$ (General Illumination Polarization χ, ψ).

6 Conclusions and future direction

Polarimetric characteristics of the EM waveform provide valuable additional information for target recognition compared to conventional remote sensing techniques. The objective here has been to examine the fusion of EM polarimetric quantities and measurables associated with certain classes of targets in different regions of the EM spectrum. One prominent example is the combination of radar/SAR polarimetry with EM polarimetric sensors in the electro-optical domain.

The described EM polarimetry fusion within different bands must be carried out within a robust theoretical framework based on the physics of partially polarized EM waves scattered at different operating wavelengths. Using this framework, sensor fusion can yield a significant advancement in target recognition due to the following: target scattering characteristics (i.e., identity) are better-established in a wider range of the EM spectrum, even if this spectrum expansion is incoherent (i.e., incoherent bandwidths); polarimetric backscatter characteristics for certain target classes of interest are consistent throughout various regions of the EM spectrum (e.g., polarization selectivity for manmade objects). Fusion of EM polarimetric returns in different bands can, in principle, enhance the contrast of such objects/targets compared to those with low or without the addressed polarization selectivity (e.g., clutter). The described EM polarimetric nature (i.e., polarization selectivity) manifested in different regions of the spectrum can be effectively exploited for modification and calibration purposes.

As addressed, the analytic framework should be based on a careful study and modeling of the EM wave scattering and respective characteristic observables in different regions of the spectrum. Considering the general property of the scattered EM wave being polychromatic and partially polarized, the analytic polarimetric EM signal can be characterized by the virtue of the Stokes vector and parameters. These parameters and related products can be used as an effective means for sensor data combination and fusion.

The proven potent and fast growing field of partial or compact polarimetry is established based on fundamentals similar to the theoretical foundation that the present mutisensor interworking and fusion proposal is based on. The core methodology is to enhance the extracted backscattering information by:

I. modeling and full characterization of the scattered EM field using two coherent orthogonal polarizations, chosen based on the system design and architecture requirements;

II. designing compact polarimetry modes, or essentially transmit or illumination optimization for intended applications based on respective requirements and constraints.

One should note, however, to maximize the extracted common information for sensor fusion, full intensity or Stokes parameters (4-vector) description is required (as addressed in Section 5).

Here, the described methodology and/or analytic tool is used to formulate and maximize common information in the polarimetric backscattered field from different sensors (e.g., radar/SAR and optical) for advanced fusion.

To provide a means for advanced exploitation and recognition through an optimal combination of sensor data (e.g., SAR and EO), the following directions are proposed:

1. Secure polarimetric data for a certain target class (or classes) of interest using radar and EO sensors;

2. Formulate/format the data in terms of analytic EM wave vectors (Stokes vectors and parameters); and

3. Investigate scattered EM wave polarization characteristics related to the physics of the target that are consistent in all (or both) EM regions for enhanced fusion calibration and exploitation in one domain using the data and target characteristics from the other domain.

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DRDC	Defence Research & Development Canada
DRDKIM	Director Research and Development Knowledge and Information Management
R&D	Research & Development

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Exploitation of the backscattered field polarization over the wide electromagnetic spectrum, from visible to microwave frequencies, provides an approach to advanced target recognition. It is analytically proven that the current, established framework for full coherent characterization of the scattered field maximizes the extracted target information. It is also shown that such a methodology, which is theoretically similar to the concept of "partial or compact polarimetry", yields comparable results to full or quadrature-polarized systems by incorporating judicious assumptions and assuming/implementing optimal transmitted or illumination field polarizations. On this basis, common characteristic features, interworking and fusion of different polarimetric sensor products in different regions of spectrum, e.g., radar/SAR and Electro-Optical, are investigated and formulated within a robust framework based on full coherent characterization of the scattered field.

L'exploitation de la polarisation de champ rétrodiffusée sur une vaste plage du spectre électromagnétique allant de la région visible jusqu'aux fréquences micro-ondes donne une approche de la reconnaissance évoluée des objectifs. On a démontré analytiquement que le cadre établi actuel de caractérisation cohérente intégrale du champ diffusé permet d'extraire un maximum d'informations sur l'objectif. Cette démarche montre aussi qu'une telle méthode qui est théoriquement similaire au concept de la polarimétrie partielle dite compacte donne des résultats comparables aux systèmes à polarimétrie complète ou en quadrature en intégrant de judicieuses hypothèses et en présumant ou mettant en œuvre la polarisation optimale des champs transmis ou leur illumination. En se basant sur ce qui précède, on étudie les caractéristiques communes, l'interfonctionnement et la fusion de divers produits de capteurs polarimétriques dans diverses régions du spectre, p. ex. le radar classique ou le radar à synthèse d'ouverture et des capteurs électro-optiques, et on formule des hypothèses pertinentes dans un cadre robuste basé sur la caractérisation cohérente intégrale du champ diffusé.

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