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USING POLARIZATION DISCRIMINANTS FOR TARGET CLASSIFICATION AND IDENTIFICATION

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ABSTRACT

The exploitation of target polarization behavior to improve radar performance is a subject of increasing interest. This typically requires the use of polarimetric radars which are capable of measuring the full target scattering matrix in real time. Information thus obtained can be processed to be optimally exploited to enhance target classification and identification by radar. Different techniques have been proposed for such an objective, which are briefly examined in this paper. Their inherent capabilities are highlighted while potential developments in this field of applications are discussed.

INTRODUCTION

Polarization, together with usual amplitude, time, frequency and bearing descriptors of radar signals, completes the information which can be obtained on target returns in monostatic radars.
The exploitation of the echo polarization state is currently a subject of interest /1/, due to theoretical and technological advances, as well as to the development of new radar applications. This typically requires the use of polarimetric radars which are capable of measuring the full target scattering matrix in real time. Polarimetric information has also been considered to enhance target classification and identification capabilities by radar /2/. Alternative polarization descriptors have been proposed as target discriminants. Among these the independent scattering matrix elements, as well as other equivalent sets of parameters more related to physical, geometrical or particular properties of target have been considered. The Mueller's matrix parameters, their statistical averages and the parameters of Huynen's target decomposition are also considered meaningful polarization-based discriminants.
However target behavior is strongly depending on the electrical

behavior, shape and exposure of target, as well as on transmission frequency. Ambiguity problems can arise expecially when the range of frequency and target exposure is limiteoly explored. These problems are more evident with low resolution radars.

In this paper polarization-based techniques proposed as a means to enhance target classification and identification radar capabilities are examined. To this purpose different polarization based discriminants are preliminary defined and their inherent capabilities are highlighted.

Potential developments in this field of applications are then discussed.

POLARIZATION-BASED TARGET DISCRIMINANTS

When excited by a monochromatic wave the polarization behavior of a target is fully described by its 2x2 complex-valued scattering matrix S, which relates the polarization vector $\underline{h}_T \triangleq [h_{TA}, h_{TB}]'$ of the incident wave with the polarization vector $\underline{h}_S \triangleq [h_{SA}, h_{SB}]'$, of the backscattered wave /3/, namely:

$$\underline{h}_S = S\,\underline{h}_T \tag{1}$$

where

$$S = \begin{bmatrix} S_{AA} & S_{AB} \\ S_{BA} & S_{BB} \end{bmatrix} \tag{2}$$

for any specified orthogonal polarization basis A-B used for representing the polarization vectors. If $\underline{h}_R \triangleq [h_{RA}, h_{RB}]'$ represents the polarization of the receiving antenna, the amplitude of the received signal is given by:

$$v = \underline{h}'_R\, S\, \underline{h}_T \tag{3}$$

In a monostatic radar the measurement of S typically requires that the orthogonal polarizations A and B are alternately radiated while two orthogonally polarized channels are simultaneously available on reception.

Since the reciprocity condition is generally met, we have:

$$S_{AB} = S_{BA} \tag{4}$$

Furtnermore the absolute phase of S is usually disregarded because of its dependence on the two-way propagation delay. Consequently, five independent parameters need to define the scattering matrix. These parameters are given by the amplitudes and relative phases of the S elements.

To equivalently represent the scattering matrix, alternative sets of parameters can be adopted, which can sometimes be related to physical and geometrical features of the radar object.
Five independent parameters $(m, \psi, \tau, \nu, \gamma)$, which uniquely and alternatively represent the above scattering matrix, come out while solving the eigenvalue problem arising when looking for the transmit polarization which maximizes or minimizes the backscattered power /4/. The following meaning can be attributed to such parameters:

- m: "target magnitude". This is the maximum amplitude of the received signal and it is an overall measure of target size or radar cross-section.
- ψ: "target orientation angle". This is a measure of the orientation of the target around the line of sight.
- τ: "target helicity angle". This is a measure of target simmetry with respect to right-hand and left-hand circular polarizations.
- ν: "target skip angle". This can be related to the number of bounces of the reflected signal.
- γ: "target polarizability angle". This is a measure of the target's ability to polarize incident unpolarized radiation.

Notice that only m is target size dependent.

Another equivalent set of undipendent target parameters is obtained through the copular nulls (COPOL nulls) /4/: they are two polarization vectors, $\underline{x}_1$ and $\underline{x}_2$, giving rise to a backscattered wave which is polarized orthogonally to the incident wave. The COPOL nulls are generally represented through two couples of indipendent polarization parameters which, together with the parameter m ("target magnitude"), still constitute an alternative set of parametrs uniquely defining the scattering matrix.

The scattering matrix changes with the reference polarization basis. Some parameters are invariant with respect to the polarization basis changement which can be expressed through an appropriate, unitary transformation matrix /5/: such parameters are the determinant, $|S|$, and the Span, $\text{Span}\{S\} \triangleq |S_{AA}|^2+|S_{AB}|^2+|S_{BA}|^2+|S_{BB}|^2$ of the scattering matrix. The invariance property of these parameters makes them attracting for target classification applications, even if they alone do not uniquely define the scattering matrix. These parameters are also insensitive to changes of the target orientation angle around the line of sight.

When the absolute phase of S is disregarded, the target polarization behavior is equivalently described through the Mueller matrix of target. This is a 4x4 real-valued matrix which allows the backscattered power received by the antenna to be expressed as follows /4/:

$$P \triangleq |\bar{V}^2| = \underline{g}_R' \, M \, \underline{g}_T \qquad (5)$$

where $\underline{g}_T$ and $\underline{g}_R$ are the Stokes vectors which describe the antenna polarization in transmission and reception respectively. Due to simmetry conditions only nine parameters fully describe M. These parameters can singly be related to specific polarization properties of target, connected with its physical and geometrical features /4/. Only five of these parameters are indipendent.

When the radar object behavior is time-varying, the observed backscattered wave is partially polarized. In this case, at least for quasi-monochromatic waves, the scattering matrix $S \triangleq S(t)$ still can express the time-varying behavior of the object, through the relationship (1). However, in this situation a statistical approach is also appropriate. This can be operated by expressing the average received power as follows:

$$\bar{P}_R = \underline{g}_R \quad R \, \underline{g}_T \qquad (6)$$

where $R \triangleq \langle M(t) \rangle$ is the average Mueller matrix and $\underline{g}_T$ and $\underline{g}_R$ are defined as in (5). The elements of R are time-averaged elements of M(t), evaluated during the target observation time. The matrix R is still described by nine, but generally indeoendent parameters. These parameters are distinctive features of the statistical target behavior during the related observation time.

According to the Huynen's theorem, the scattering matrix of a time-varying object can be decomposed as follows /4/:

$$S(t) = a_o(t) \, S_o + S_N(t) \qquad (7)$$

where $a_0(t)$ is a complex scalar quantity, S_0 is the scattering matrix of a fixed target and $S_N(t)$ is the scattering matrix of the so-called N-target. The two parts are mutually uncorrelated, thus leading to the following corresponding average Mueller matrix:

$$R = M_0 + R_N \tag{8}$$

Five independent parameters define M_0, while four independent parameters are sufficient for defining R_N. Totally they constitute an alternative independent set of nine parameters which still uniquely define R. This decomposition fits into the intuitive concept of representing a time-varying target by mean stationary target (effective), defined by S_0, with fluctuations given by the scalar $a_0(t)$, plus a residual part (noise), defined by $S_N(t)$ or R_N, which indicates how that time-varying target varies from its mean stationary representation. This concept makes the parameters derived from the Huynen's target decomposition physically sound for target representation. Based on a vector-formulation of the scattering matrix and the definition of the related coherency matrix, another equivalent, but more general, target representation has also recently been proposed by Huynen /6/. While allowing a direct application of the target decomposition theorem, this target representation provides an equivalent set of target parameters which can more easily be derived from the scattering matrix measurements.

Various measurements methods can be applied in order to obtain the above defined parameters. Both coherent measurements of the scattering matrix elements and/or power measurements at different polarizations are purposely needed /7/, /2/, /8/. The direct measurement of the scattering elements is usually preferred, because this requires few different measurements while being compatible with Doppler signal processing. Nevertheless, since the absolute phase is not accounted for polarization analysis, an incoherent radar could alternatively be used. The direct measurement of the scattering matrix requires fast switching of two orthogonal polarizations in transmission while receiving the backscattered field through two orthogonally polarized channels.

EXPLOITING POLARIZATION-BASED DISCRIMINANTS FOR TARGET CLASSIFICATION

As shown before alternative sets of five independent parameters can be used to represent a "fixed target", while fully exploiting the polarization information which is inherent in the target e.m. backscattering phenomenon. For any specified antenna-polarization basis these parameters depend on the electrical properties, shape and exposure of the real target as well as on the transmission frequency. In a monostatic, monofrequency radar additional information can be collected once these parameters are measured as a function of time while target exposure is changing due to target motion. In this case statistical averages of the measurements can alternatively be carried out within slots of the target .obsvervation time, in order to correspondingly extract the set of nine parameters describing the Mueller's matrix or its Huynen's decomposition.
Target features, fully exploiting polarimetric behaviour of targets, can thus be extracted during the change of target exposure, through a deterministic or a statistical approach, in order to enhance radar capabilities of target classification. These capabilities are related to the typical scattering properties of the targets of interest, which we now discuss briefly.

Target identification could be approached as an inverse scattering problem, in order to attempt reconstruction of the object's exact shape from its radar returns. This generally requires an unlimited range of frequencies and target exposures /9/ while polarization target descriptors are also to be considered /10/.
In practice such a range is usually unlimited and ambiguities can arise in the target identification process.
This consideration applies also when the target backscattering is only exploited at the high-frequency region, we are concerned with for the present analysis. This region corresponds to wavelengths much smaller than the target size. Microwave and millimeter wave frequencies, used in most radars, belong to this region.

High-frequency backscattering from complex targets is essentially a local phenomenon. In fact, both mathematical analysis and measurements show that the backscattered wave can be regarded as a sum of a finite number of contributions arising from corresponding scattering centers.
The related backscattered wave in most cases depends on the shape and

conducting properties of a small surface around the backscattering center. In fact, backscattering contributions can arise, for example from specular-reflection points, and diffraction points associated with discontinuities and changes in curvature (or in spatial derivatives of such curvatures) of the body. The position of the backscattering centers is sensitive to target exposure, especially in the case of specular reflections. In general targets possess an asymmetrical shape and a partially conducting surface, therefore depolarization can accur. In particular it occurs whenever the local curvature changes. In this respect, different polarization properties are possessed by the various backscattering centers /11/.
This behavior determines different effects on the target polarization descriptors according to whether a low-resolution or high-resolution radar is employed.

In a low resolution radar many unresolved backscattered centers interact in generating the target return. Furthermore the contributions of thease centers, and particularly their relative phase, are quite sensitive to target exposure. Therefore both amplitude, phase and polarization discriminants can rapidly change with target exposure when target is complex. This behavior can frequently determine ambiguities in the above described deterministic approach for classification of complex targets, based on tracing polarization discriminants during target observation time. This problem has been highlighted through target numerical modelling when using COPOL tracing /12/. Analogous problems can arise when using a different, but equivalent set of polarization discriminants. Obviously, ambiguities increase when a reduced set of polarization discriminants is used. Furthermore, due to measurement difficulties polarization discriminats do not usually account for the absolute phase of the scattering matrix. This is suspected to introduce significant ambiguities in polarization signatures /13/.
The statistical approach previously described, based on the time averaged parameters of the Mueller matrix or its decomposition through the Huynen's theorem, although reduces the dimension of the target feature set made available during observation time, it presents the following advantages /14/

- higher robustness to small changes of the target exposure caused by target motion perturbations;
- higher robustness to background noise or clutter;
- reduced complexity in classification.

However, no results are commonly available on this type of target classification procedure.

Although widespread applicability of polarization based target classification and identification appears doubtful when using low resolution radars, in particular cases this type of application could result as being profitable, expecially when some of the following conditions are met:

- the considered targets are few and quite simply shaped;
- target size is small;
- some a priori information on target exposure is available;
- target is distributed, but composed by uniformly shaped and densely distributed small particles.

Due to the latter condition polarimetric classification of hydrometeors has indeed shown its profitability /15/. When the above conditions occur, a reduced set of polarization-based discriminants can be considered. In this case, since the extracted target features are generally antenna polarization basis depending, the use of invariant parameters, such as the span and the determinant of the scattering matrix, is advisable.

Polarization ambiguities can be reduced with high resolution radars, when interfering scattering centers are sufficiently spatially resolved. In this case polarization based discriminants of their backscattering contributions, together with their spatial distributions, can provide distinctive and meaningful target features for target classification and identification. This means that polarization information can usefully be exploited when radar resolution is enhanced towards a vectorial target imaging capability. This can partially be achieved with pulse compression techniques which increase down-range (along range) target resolution /16/. In some applications, mainly with short range applications, active spot scanning techniques can also be used to increase angular resolution /17/,/18/.

Exploiting polarization information in high resolution radars increases system complexity. This also occurs in data processing, because the dimension of the target feature set is increased. Proper reduction of the feature set is an open problem. In this connection, it is expected that high correlation between target images extracted for different target exposure can be helpful.

In general optimal exploitation of polarization for target classification is to be associated with broadband excitation of target. This can simply be operated through pulse-compression techniques or multifrequency target measurements /19/, /20/. It is envisaged that polarimetric radar capability can reduce the range of frequency and target exposure to be explored to reach the radar performance required in target classification. However theoretical and experimental background in this promising subject is still insufficient.

CONCLUSIONS AND PERSPECTIVES

Polarization-based discriminants do not appear to have patential widespread applicability for target classification in low-resolution radars. More promising is the field of high resolution radar or broadband target excitation, but this field still requires theoretical advances and further experimental knowledge. Short range and tracking radars appear more suitable for these polarimetric applications. Some possibilities also exist for remote sensing through polarimetric SAR /21/.

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