Advances of Techniques for Utilizing Polarimetric Features of Radar Targets

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ABSTRACT

The scattering properties of a radar target can only be fully characterized by measuring a scattering matrix in which the elements represent the combinations of transmit and receive polarization states. The amount of information gathered by a traditional single polarization radar may therefore be even very limited, for example when the single polarization response is near zero while the cross polarized return is at a maximum. By polarimetric processing, different scatterers, i.e., scattering mechanisms, can be completely and coherently separated, even if they are located within the same resolution cell of the radar image. This is particularly important in relation to non-cooperative target identification and recognition. Nevertheless, the practical utilization of polarization for optimizing information content has not gained more widespread interest until very recently. This is mainly due to a lack of proper technology in the past, but also due to negative conclusions drawn from early experiments with polarimetric radar. At the moment, significant efforts are put into the development of techniques for efficiently and conveniently handling polarimetric data. Such techniques differ considerably from techniques known from traditional single polarization target imaging, since one has to deal with a matrix for each resolution cell instead of just a single scalar. In this paper, some of the advances and advantages of polarimetric radar techniques will be reviewed and presented in an application-oriented perspective, emphasizing the potential of utilizing the information contained in the polarization transforming properties of radar targets.

INTRODUCTION

The vectorial nature of the electromagnetic fields, on which any radar system is based, implies that the full amount of potentially available information can only be exploited by employing polarimetric radar systems, i.e., systems capable of measuring all four combinations of two orthogonal polarizations. For simplicity and cost-effectiveness, however, traditional operational radar systems have been single-polarization systems employing one and the same polarization on both transmission and reception. Such systems have obviously served many needs satisfactorily, but for modern high resolution applications, such as target classification, identification and recognition, the properties and capabilities of polarimetric systems cannot be ignored without a severe loss of useful target information. This was realized rather early in civilian remote sensing applications using high-resolution SAR (Synthetic Aperture Radar) systems, and single-polarization systems would simply not be able to produce the classification results that are delivered by modern polarimetric SAR systems.

In the military community, however, the issue of polarimetric radar has been surrounded by skeptics and opposition, largely based on claims that the money could be spent more efficiently on other performance parameters, like range resolution. One reason for this, of course, is the obvious fact that the polarimetric techniques could not readily be implemented as upgrades to existing radars. Nevertheless, with the technological developments that have taken place in recent years, the implementation of full polarimetric

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capability should no longer be considered as an unrealistic sophistication that the military does not need. On the contrary, the additional information provided by such systems could be crucial for satisfactorily solving the complex tasks required in today's battlefields. Therefore, a relevant question is rather: Can the military of the future afford to continue ignoring the additional information that can be accessed by polarimetric radar systems only? In the following, the basic properties and characteristics of polarimetric radar data will be reviewed in an application-oriented perspective.

POLARIMETRIC PROCESSING TECHNIQUES

The first systematic studies of the utilization of the polarization of radar waves were carried out by Kennaugh in the early 1950's. During these studies, the eigenvalue problem associated with the 2x2 scattering matrix was considered, and it was later treated in great detail by Huynen, who rigorously formulated the existence of maximum and minimum (null) polarizations. He pointed out how these can be made to form the so-called Huynen-fork on the Poincaré sphere, and he presented an elegant mathematical formulation of how the scattering matrix can be represented by a set of five independent real parameters, the so-called Huynen-Euler parameters. In these early days of radar polarimetry, the handling and analysis of the multi-channel data posed quite a challenge, and original geometrical representations and interpretations were developed alongside with the underlying mathematical formulations. Undoubtedly, this contributed to scaring away many a radar engineer from considering any practical utilization of such techniques.

With the advent of the digital computer, polarimetric data can be visualized and handled without mastering the complex mathematics and the associated geometrical constructions. Once the algorithms are implemented, the digestion is taken care of by the computer, and the results are presented in easily interpretable graphical outputs. General classification algorithms may take virtually any raw data and convert the information contents to useful end-results. Nevertheless, the compact forms from the early days should not be forgotten, and could in fact contribute to making the processing more efficient. A good example of this is the aforementioned Huynen-Euler parameters, and this is where we shall take the outset for a review of the fundamental properties of polarimetric radar data.

NULL-POLARIZATIONS AND HUYNEN-EULER PARAMETERS

The complex-valued scattering matrix with the four combinations of transmit and receive polarization (horizontal and vertical in the most common, linear polarization basis), containing a total of six independent parameters,

$$[S] = \begin{bmatrix} HH & HV \\ VH & VV \end{bmatrix},$$

can be transformed to a diagonal form (with no cross-polarization terms) and represented by another six real parameters in the following form,

$$[S] = m \begin{bmatrix} e^{j2(v+\zeta)} & 0 \\ 0 & \tan^2 \gamma e^{-j2(v-\zeta)} \end{bmatrix},$$

which is the scattering matrix that would be measured by transmitting and receiving the associated optimum polarization (in general elliptical).

The following interpretations are commonly assigned to the individual parameters:

m (m≥0), the maximum polarization, i.e., the maximum attainable response from the target, which would be obtained if the optimum polarization were used by the radar.

. (-180E<.#180E), the absolute phase of the scattering matrix.

< (-45E<<#45E), the skip angle, related to the number of times a return signal has been reflected within the target; if the return signal is predominantly due to scattering mechanisms with an odd number of reflections (or bounces), < will be close to zero; for this reason, < has also been referred to as the degree of double bounce, but it should be noted that targets can have <=45E even when only a minor part of the reflected signal is due to even-bounce scattering.

((0E#(#45E), the characteristic angle, also denoted the polarizability angle (Holm), the latter referring to the fact that targets with (=45E do not repolarize the incident wave while targets with (=0E completely determine the polarization of the returned wave.

The last two of the six parameters characterize the associated optimum polarization:

P (-90E<P#90E), the orientation angle of the target, determining the orientation angle of the optimum polarization for the target.

ϑ_m (-45E#ϑ_m#45E), the helicity angle, which represents the ellipticity of the optimum polarization for the target.

The advantage of these parameters is that they are invariant descriptors and therefore can be determined independently of the polarization basis (e.g., linear or circular) that was used to measure the raw data of the scattering matrix – provided that the data have been properly calibrated.

POLARIMETRIC DECOMPOSITION

To illustrate the significance of such a characterization, let us consider the measured radar response from a dihedral (also referred to as a diplane in the following), which is an important type of scatterer in practical applications. It is characterized by the following scattering matrix,

$$[S]_{dihedral(\theta)} = \begin{bmatrix} HH & HV \\ VH & VV \end{bmatrix} = m \begin{bmatrix} \cos 2\theta & \sin 2\theta \\ \sin 2\theta & -\cos 2\theta \end{bmatrix}$$

The true strength (radar cross section) of such a scatterer is given by *m*, but evidently, the RCS value which is measured by a traditional radar system (e.g., HH-polarized) will depend heavily on the actual orientation angle of the scatterer. In contrast, a polarimetric radar will be able to tell the true strength, and in addition, the orientation angle, θ, can be determined.

From this simple example, it is clear how a polarimetric radar can provide useful target information, which could never be extracted by a non-polarimetric radar, and which could be of decisive importance for correct classification of complex targets.

Another unique advantage of a polarimetric radar system is the ability to distinguish between different *types* of scatterers, notably between even- and odd-bounce scattering contributions. To illustrate this, let us consider the combined scattering from a sphere and a dihedral located within the same resolution cell.

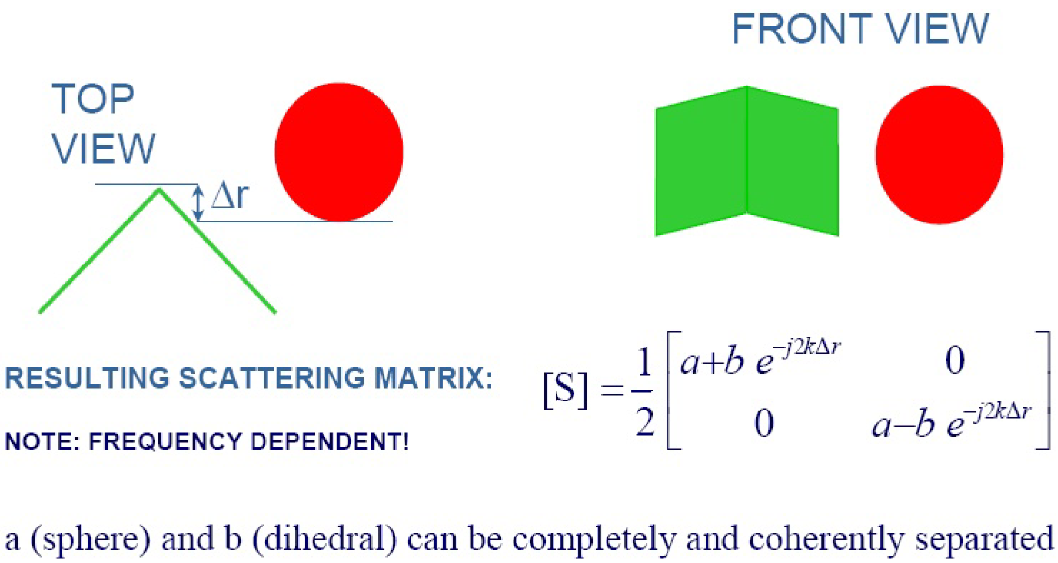

Fig. 1: Combined scattering from odd-bounce reflector and even-bounce reflector. Sum and difference of the diagonal elements of the scattering matrix separate sphere and diplane contributions completely, whereby interference between these two scattering mechanisms is eliminated.

The individual unity scattering matrices are given by,

$$[S]_{sphere} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

$$[S]_{diplane(\theta)} = \begin{bmatrix} \cos 2\theta & \sin 2\theta \\ \sin 2\theta & -\cos 2\theta \end{bmatrix}$$

while the combined scattering from a sphere of strength a and a diplane of strength b can be expressed as follows, provided that the phase centers are at the same range (Δr = 0 in Fig. 1),

$$[S]_{sph+dipl(\theta)} = \begin{bmatrix} HH & HV \\ VH & VV \end{bmatrix} = a\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} + b\begin{bmatrix} \cos 2\theta & \sin 2\theta \\ \sin 2\theta & -\cos 2\theta \end{bmatrix}$$

By the simple operation $HH + VV$, the sphere contribution can be completely and coherently separated from the corner reflector contribution. This means that the interference between the two contributions, which is unavoidable in the single polarization case, can be eliminated, so that the true intensity of the scattering centres can be determined. For high-resolution ISAR imaging, where the required motion compensation is usually based on a single, dominating scattering contribution, this is of great significance, because a more stable phase history can be obtained if interference between scattering constituents can be avoided or reduced.

PAULI SPIN MATRIX DECOMPOSITION

More generally, the above decomposition is expressed by the Pauli decomposition, based on the Pauli spin matrices, as follows,

$$[S] = k_1[S]_{sphere} + k_2[S]_{diplane(0°)} + k_3[S]_{diplane(45°)}$$

where the coefficients are given by,

$$\underline{k} = \begin{bmatrix} k_1 & k_2 & k_3 \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} S_{HH} + S_{VV} & S_{HH} - S_{VV} & 2S_{HV} \end{bmatrix}^T .$$

This is a so-called coherent decomposition, in which the elements are complex values, i.e., they have an absolute phase term associated with them and have to be added as complex (voltage related) quantities, unlike the incoherent formulations which operate on real (power related) quantities. The three involved component matrices (sphere, 0° rotated diplane, and 45° rotated diplane) form an orthogonal set which is often used as the outset for further incoherent, statistical processing in terms of covariance and coherency matrices. However, in this review of the more fundamental properties of polarimetric radar data, we leave these approaches out of consideration.

The coefficients of the Pauli decomposition (k_1, k_2, k_3) can be used as features for automatic classification algorithms as an alternative to the direct use of the *HH, HV, VV* elements. Likewise, the magnitudes of the elements are frequently used to generate RGB images from high-resolution SAR/ISAR data. The Pauli components have a closer relation to the underlying physical scattering mechanisms than the raw elements of the scattering matrix, and hence are more suited for interpretation of the data. However, the components still depend on the measurement basis, i.e., the orientation of the scatterer relative to the radar. Moreover, the fact that two of the components effectively represent double-bounce scattering renders the interpretation somehow ambiguous.

SPHERE, DIPLANE, HELIX DECOMPOSITION

In an attempt to remedy these deficiencies, the sphere, diplane, helix decomposition was developed, based on the observation that any given symmetric scattering matrix can be represented in terms of the elementary scattering matrices for a sphere, a dihedral (diplane), and a helix,

$$[S] = e^{j\varphi}\{e^{j\varphi_s} k_s [S]_{sphere} + k_d [S]_{diplane(\theta)} + k_h [S]_{helix(\theta)}\}$$

$$[S]_{sphere} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

$$[S]_{diplane(\theta)} = \begin{bmatrix} \cos 2\theta & \sin 2\theta \\ \sin 2\theta & -\cos 2\theta \end{bmatrix}$$

$$[S]_{helix(\theta)} = \frac{1}{2} e^{\mp j2\theta} \begin{bmatrix} 1 & \pm j \\ \pm j & -1 \end{bmatrix}$$

In terms of the elements of the scattering matrix in a circular polarization basis, the parameters of this decomposition are given as follows,

$$k_s = |S_{RL}|;\quad k_d^+ = |S_{LL}|;\quad k_d^- = |S_{RR}|$$

$$k_h^+ = |S_{RR}| - |S_{LL}|;\quad k_h^- = |S_{LL}| - |S_{RR}|$$

$$\varphi = \tfrac{1}{2}(\varphi_{RR} + \varphi_{LL} - \pi)$$

$$\theta = \tfrac{1}{4}(\varphi_{RR} - \varphi_{LL} + \pi)$$

$$\varphi_s = \varphi_{RL} - \tfrac{1}{2}(\varphi_{RR} + \varphi_{LL})$$

The transformation from the linear polarization basis to the circular polarization basis is simply given by these formulas,

$$S_{RR} = j\,S_{HV} + \tfrac{1}{2}(S_{HH} - S_{VV})$$
$$S_{LL} = j\,S_{HV} - \tfrac{1}{2}(S_{HH} - S_{VV})$$
$$S_{RL} = \tfrac{j}{2}(S_{HH} + S_{VV})$$

The advantage of this orientation invariant representation is that a pure even-bounce scatterer always shows up in just one component. On the other hand, if two or more even-bounce scatterers are present within the same resolution cell, this may result in both diplane and helix components in the polarimetric decomposition. Mathematically, this is because the diplane and helix matrices are not orthogonal. In practical applications, the helix component may be considered as a measure of the purity of the diplane component, which may be of importance for determining suited dominant scatterers for motion compensation in high-resolution SAR/ISAR imaging.

APPLICATION EXAMPLES

An illustrative comparison of the Pauli and the SDH representations is shown in Fig. 2 and Fig. 3. These figures show part of a scene with Copenhagen Airport at L-band and a resolution of 1.5 m. Note how double bounce reflections stay green in the SDH representation, while they fall in the red and green channel of the Pauli representation, depending on the incidental orientation angle.

In Table 1, an extract of some classification experiments is shown, based on data from the German E-SAR system operated by the German Aerospace Centre (DLR). The classification performance of three different feature sets has been compared for a scene at the Oberpfaffenhofen test site [8]. The training areas were classified into the following categories: water, houses, roads, trees, grass, field 1 and field 2. The overall accuracy is summarized in Table 1 for two different algorithms: maximum likelihood and minimum distance. A detailed discussion of the results may be found in [8] and [9], and is not within the scope of the present paper. However, some main observations are in order. The SDH set of parameters clearly results in the best classification performance, while the Pauli coefficients, rather surprisingly, do not result in a better performance than using the raw scattering matrix elements. It should be noted, however, that not all the available information in the scattering matrix (5 relevant independent parameters per pixel) has been used in the above sets of parameters. In fact, only the magnitudes of the complex coefficients have been used. The results therefore seem to indicate that the SDH decomposition is an efficient way of confining as much information as possible in only three parameters, which is of importance in relation to efficiency of automatic algorithms. The classification performance if only one of the polarimetric channels, e.g. HH alone, had been used, was not included in these tests.

Despite the fact that the above classification results were obtained for classification of extended ground targets using SAR data, similar results should be expected for classification of air targets using 2D ISAR data as well as 1D HRR data.

CONCLUSIONS

The basic properties and capabilities of polarimetric radar were reviewed in an application oriented perspective. It was demonstrated how target characteristic features, which cannot be determined from traditional single-polarization data, can be easily extracted from fully polarimetric radar data. Such information could be of decisive importance for successful radar target identification and classification, but also other applications, such as weather radar, greatly benefit from the extra information provided by a fully polarimetric capability.

"Any radar should be polarimetric." – *Dr. Richard Huynen*

Fig. 2: Part of Copenhagen Airport. L-band, SDH: red=sphere, green=diplane, blue=helix.

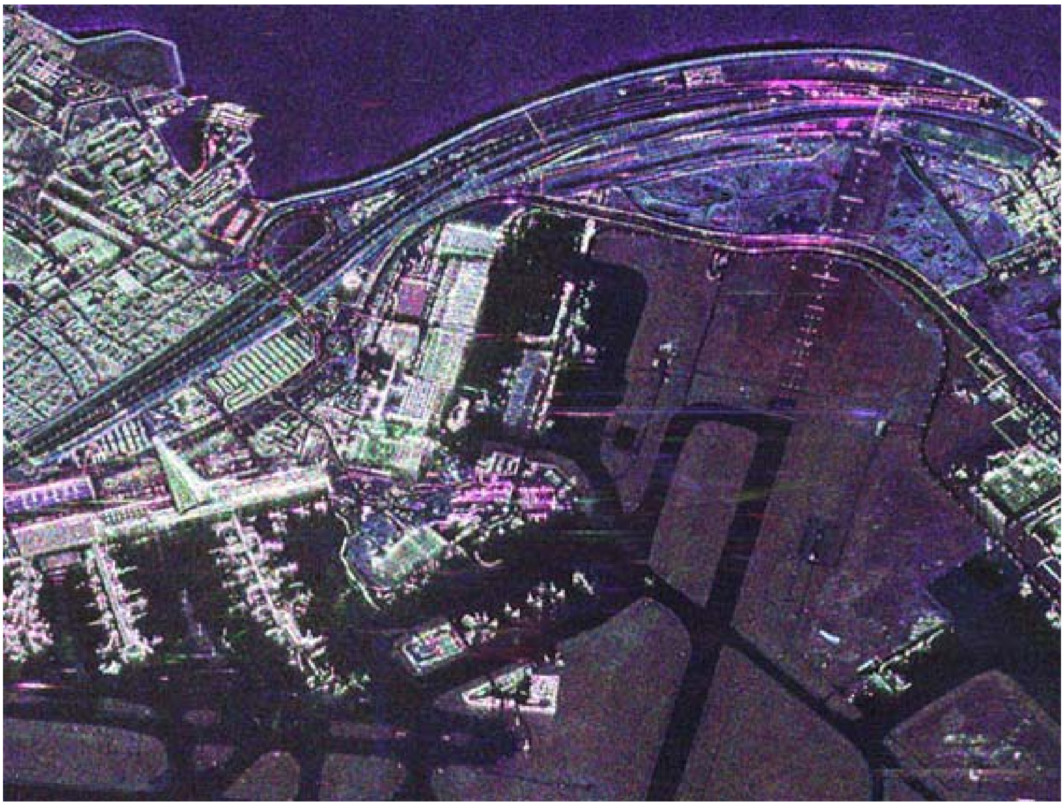

Fig. 3: Part of Copenhagen Airport. L-band, Pauli: red=HH-VV, green=HV+VH, blue=HH+VV.

Table 1: Accuracy estimates of classification tests (15x15-pixel averaging window)

Classification algorithm **Polarization parameters**	Maximum likelihood Ov. Acc. (%)	Minimum distance Ov. Acc. (%)
HH, HV, VV magnitudes	57.03	50.96
Characteristic null-polarisations	66.24	64.41
Pauli coefficients	57.61	52.27
SDH coefficients	87.37	77.04

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