QUANTIZATION OF POLARIZATION STATES THROUGH SCATTERING MECHANISMS

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ABSTRACT

In this paper, we introduce a new technique that relates the split of polarization states through various scattering mechanisms. We use the finite-difference time domain (FDTD) method in our computations since, by its nature, FDTD can model an ultrawideband source and can separate the various scattering mechanisms by exploiting causality. The key idea is that, once a non-monochromatic wave is incident upon a scattering object, the various spectral components will be differently depolarized upon scattering depending upon the shape and material composition of the object. In the case studied here, all of the impinging spectral components are co-polarized (whereas arbitrary polarization distributions are permitted more generally). Fundamentally, we are exploring a concept similar to the split or quantization of energy states in quantum mechanics. We first introduce the concept of the quantization of polarization states, and then we explain the formulation of the “State Space Matrix” in relationship to the polarization gaps. Once the technique is introduced, we demonstrate its potential applications to realistic problems such as materials detection.

INTRODUCTION

We have seen the exploitation of polarization in various fields and applications such as target detection or in communication systems. In literature [1]...[10], polarimetry is extensively implemented for target detection where in some of these references, polarization theory is described very thoroughly developing mathematical models and the basic theoretical foundation. Most of these methods are based on scattering matrices off various surfaces and simple metallic structures such as dihedrals etc; the exact solutions are based on high frequency methods [11], [12] [13]. At lower frequencies, where the wavelength and the size of the scatterer are comparable, numerical methods play a major role in analyzing polarimetric scattering since high frequency methods can not be used in those applications. Lately, polarimetry was extended in material detection [14],[15],[16]; for instance in [14], there is a significant effort to implement holographic imaging, but it only describes shapes hidden under clothes, still though, it fails to distinguish materials. In our case, we have chosen the FDTD (finite difference time domain) method [17],[18], since it handles complex scatters in terms of shapes and materials and it also gives us time space dilation capabilities in which case we are able to isolate various scattering mechanisms. The FDTD method was extensively used by others in which cases they have included validations as well [19], [20]. Initially we began with the concept of composite antenna pattern [21], by using the FDTD method and combining with [22]. Furthermore the FDTD [21] was used to develop algorithms for detecting materials in the near field as well [23]. As an extension of [19] or [21] (far field) we pursued and developed [24] and [25] where such applications will impact target signatures in multi spectra polarimetry. In this paper we extensively use the XFDTD package from REMCOM [21] which we have validated in [25] where a detailed accuracy analysis was done and the simulation results were compared with measured data from [12]. For that purpose, we’ll not repeat the accuracy/measurements analysis in this paper. In [24] we have introduced and formulated the concept for quantization state space matrix but, we did not go through specific applications or implementation. In this paper we implement the concept of multispectra polarimetry, in which case we generate plane waves [21] incident on various scatterers at various frequencies. The quantization (or split)
of polarization states is a result of the interaction of an incident wideband electromagnetic wave on various scatterers. The split or the gap of the polarization states depends on the nature of the scatterer, the incident frequencies and the angle of incidence. We introduce and implement for the first time the concept of the quantization matrix [24], revealing the unique properties of scatterers or even materials. This research leads to multi spectral polarimetry which links the measurement of quantization of polarization states associated through various scattering mechanisms and materials. This is a similar and very close concept related to the quantization of energy states in quantum mechanics. The measurement of the split of polarization states or the polarization gap helps to obtain unique signatures in characterizing materials or types of scatterers etc. Various types of scatterers are less sensitive to depolarization phenomena compared to others. For instance a flat metallic surface versus a wedge is less sensitive to depolarization at different frequencies. It should also be mentioned at this point that the higher the number of frequencies, the larger the quantization matrix and therefore the larger the resolution or the accuracy of detection. The Poincare sphere formulation and analysis in relationship to the antenna field components were taken from [7]. Finally we form the quantization state space matrix associated with the various frequencies and the split of polarization states and map the polarization states on the Poincare sphere. The combination of the various trajectories among the polarization states gives a unique signature for each scatterer. We further prove the validity and the correctness of the quantization matrix [21] by using different applications. More specifically, we show that the wedge or a rough surface is more sensitive to polarization decomposition compared to a flat scattering surface, by showing their corresponding state space matrices. Furthermore we extend our analysis on material detection for realistic problems, such as explosives detection around the human body.

2. DESCRIPTION OF OUR APPROACH

We illuminate a target with a plane wave at a certain angle of incidence and polarization by using the FDTD [21], as shown in Fig. 1a. Then, we generate the equivalent 3-D bistatic RCS (RADAR cross section) pattern, for that particular case. The equivalent 3-D antenna pattern for Fig 1a is shown in Fig. 1b below. The scatterer in Fig. 1a is illuminated by a plane (far field) which was initiated by a Tx antenna (source) of vertical polarization; this is initial Tx antenna is considered as our referenced polarization. This new RCS pattern, is treated as radiating antenna. In the far field, we receive the re-radiated field and compare the new polarization to the reference polarization, which is the probe Rx antenna or Tx antenna. In a monostatic scenario the Tx and Rx could be the same as the reference antenna. Usually the Rx antenna has the same polarization as the Tx for reference purposes. It should be mentioned at this point, that the reflected field at the receiving point is in the form as shown in equation 1a and 1b assuming that both polarizations are available.

\[ E_\theta = a + jb \]  
(1a)
\[ E_\phi = a' + jb' \]  
(1b)

Once the field components are available from 1a and 1b, then the rest of the parameters required for further polarimetric analysis are obtained from [7].
In most of our applications in the next sections the probe Rx antenna is a dipole, with vertical polarization. Basically that approach serves both monostatic and bistatic scenarios. In our case we chose the bistatic case which is a more general representation.

### 3. POLARIZATION STATE SPACE DEFINITION

In [24], the concept was clearly presented with potential applications, but no specific results were given, where in this paper we clarify and prove the concept with applications. It is understood that Electromagnetic waves at different frequencies are depolarized at different levels. For clarity we’ll assume the initial incident waves have the same polarizations. In general though, the incident polarizations don’t have to be the same. We define as polarization state space, the polarization space separating (corresponding trajectory) at least two polarization states on the Poincare sphere, as shown in Fig. 2 below.

The interaction of the incident wave with the scatterer causes the polarization gap which is the difference of the incident Polarization state compared to the reflected wave final polarization state. The polarization gap in Fig. 2.0 is due to the initial polarization state jump from the initial state to the final one. Definitely that depolarizing gap is related to the target material type, shape and incident frequency. The case of Fig. 5 corresponds to a single frequency. In the next section we extend our approach to three frequencies. The number of frequencies is arbitrary, but also good enough to demonstrate the state space concept in a more general manner.
3.1 Polarization State Space Matrix for 3 Frequencies

In this section we expand the single frequency polarization state gap concept to three different incident frequencies polarization state space concept. As it was indicated earlier for simplicity we assume that all incident frequencies have the same polarization state, located at \( f_{sp} \) position in Fig. 3.0. It is expected that the 3 different frequencies will interact with the scatterer differently. How much differently, that depends on the type of the scatterer, angle of incidence/observation and also the frequency gap between the incident waves.

We define the Polarization State Space Matrix shown in Fig. 3.0, \( m_1 \), as a Matrix that represents the Polarization gaps or polarization matching factor among the various polarization states. As it was indicated, upon reflection, the initial states (for the three frequencies) depolarize ending up at new locations \( f_1 \), \( f_2 \) and \( f_3 \) as shown in Fig. 3.0; the initial states \( f_{sp} \) correspond to the same point, which implies that all the frequencies are initially co-polarized which is a specific case and easier to clarify. According to Fig. 3.0, the polarization gaps can be defined as:

\[
f_{sp}-f_1 = f_{11}, \quad f_{sp}-f_2 = f_{22}, \quad f_{sp}-f_3 = f_{33}
\]

correspond to the diagonal elements of the Polarization State Space Matrix (\( m_1 \)). Going further, we do have \( f_{23} \) ie the polarization state space from state \( f_2 \) to state \( f_3 \), Fig. 3.0; that fills the state space matrix element \( f_{23} \). Similarly for the polarization state space points between the states \( f_2 \) and \( f_1 \) we have the state space matrix element \( f_{21} \). In a similar way, we fill the rest of the state space matrix elements by taking the reciprocal paths, such as \( f_{12}, f_{32} \) etc. It should be noticed that these paths or state space matrix elements may not be reciprocal; for example, for anisotropic media or anisotropic scatterers, the matrix elements do not exhibit reciprocity. It should also be emphasized that the number of frequencies determines the size of the state space matrix; but it also improves the resolution capabilities or discrimination capabilities.

4. RESULTS FOR THE VARIOUS SCATTERING MECHANISM

Our approach was discussed in section 2.0. The next steps will include results indicating the quantization of polarization states; in the last section an effort is made to show a more practical application of this concept.
4.1 Flat metallic surface

The frequencies selected are $f_1=2.4\text{GHz}$ and $f_2=9.4\text{GHz}$ for the scattering problems;

![3-D RCS pattern at $f=2.4\text{GHz}$](image1)

![3-D RCS pattern at $f=9.4\text{GHz}$](image2)

Figures 4a and 4b represent RCS patterns generated from an incident plane wave at vertical polarization. The angle of incidence and observation are shown in Fig. 4a. The same parameters were used for the results of Fig. 4b. The only difference is the incident frequency which is 9.4 GHz for Fig. 4b. As it was expected the radiation pattern in Fig. 4b is more coherent compared to the radiation pattern in Fig. 4a since the frequency is higher.

![Polarization states showing the coherency of polarization at](image3)

Fig. 5. Polarization states showing the coherency of polarization at

The polarization mapping in Fig. 5 above shows the polarization states corresponding to the two frequencies from Figs. 4a and 4b respectively. According to Fig. 5, the polarization states are collocated for both frequencies.

4.2 Reflection off a Rough surface

In Fig. 6.0 we have the same scattering parameters as in Fig. 5.0. The structure in Fig. 6.0 is metallic, but more roughness was added due to the insertion of the metallic cross bars.
The corresponding 3-D patterns of Fig. 6 are shown in Figs. 7a and for both frequencies. It should be noticed that at 2.4GHz the reflected signal seems to be more coherent compared to 9.4GHz, in which case the dimensions of the rectangular grid are closer to the higher frequency wavelength.

The equivalent polarization split of Fig. 7a and b, is shown in Fig. 8 below. The polarization state gaps and their corresponding trajectories are clearly shown below.

Fig. 8. Illustrating the quantization of polarization states of a realistic scatterer shown in Fig. 9.0
In Fig. 8 above, we show the split of the polarization states as it was predicted in section 3.0. First we have the initial states at fsp (f1,f2) co-polarized. Then, we do have a degree of depolarization at 2.4GHz as shown from point fsp to f1. At 9.4GHz we have the polarization gap from fsp to f2 as shown in Fig. 8. The equivalent quantization matrix for Fig. 8 is given by matrix m1.

\[
\begin{bmatrix}
  f_{11} & f_{12} \\
  f_{21} & f_{22}
\end{bmatrix}
= \begin{bmatrix}
  f_{sp} & f_{1} \\
  f_{2} & f_{sp}
\end{bmatrix}
\]

At this point we are just showing evidence for the split of polarization states. The implications and the further analysis of the quantization state space matrix will be discussed next, where we’ll present more practical examples.

### 4.3 Wedge Scattering

We have chosen a rectangular metallic box rotated at 45 degrees in such a way that the wedge is exposed to the incident plane wave, as shown below in Fig. 9. The frequencies used were 2GHz, 9GHz and 15 GHz.

![Incident vertical plane wave: (θ = 65°, φ = 215°)](image)

![Receiving angle at (θ = 90°, φ = 270°)](image)

Fig. 9 Geometry of the scatterer: (20x20x20) cm

Basically we created RCS patterns for each of the above frequencies as shown in figures 4.17 below,

![RCS patterns generated for the various frequencies shown above](image)

(a) f=2GHz  
(b)f=9GHz  
(c)=15GHz

Fig. 10. RCS patterns generated for the various frequencies shown above

The radiation patterns in Fig. 10 represent the various frequencies at the angle of incidence shown in Fig. 9. It is obvious that the patterns tend to be more coherent as we increase the frequency. The various frequencies represent different current distributions which create different radiation patterns.
Receiving the signal from the angle of incidence described in Fig. 9 we generated the polarization state space shown in Fig. 11. In this case the fsp state represents the vertical polarization of the incident plane wave at the wedge in Fig. 9. The single lines represent the diagonal polarization gaps as was described in section 3.1. The $m_{3,3}$ below is formed based on the polarization states given in Fig. 11.

5. SUMMARY AND CONCLUSIONS

In this paper, we introduced a new concept initiated from [24]. In section 2, we described our approach. In section 3 we introduced the concept quantization of the polarization state space and described the formulation of the state space matrix.

In sections 4.1 and 4.2 we demonstrated the polarization state space, i.e. the split of polarization states , with specific scattering examples. For instance in section 4.1 we demonstrated that the polarization is coherent and the reflected field represents a realistic scenario since the scattering surface of Fig. 4a and 4b is a smooth surface; there was not any quantization of polarization states as it was expected. On the other hand in Fig. 6 and Fig. 7 there was separation of the polarization states between the two frequencies. Finally, in section 4.3, we introduced 3 frequencies, in which case we have shown the split of polarization states in agreement to section 3.1. The $m_{3,3}$ polarization state space matrix represents a practical implementation in that represents a realistic scattering problem.

The conclusion is that we were able to associate a theoretical concept with realistic scattering scenarios. In fact we presented another degree of freedom where we associate the polarization states space in realistic
scattering phenomena applicable not just in material detection as it was presented in [24], but also applicable to various scattering problems for target detection purposes e.t.c.

6. REFERENCES

[21] XFDTD, REMCOM Inc.315 S. Allen St., Suite 222, State Collage, PA 16801