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Validation of Polarization angles Based Resonance Modes

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ABSTRACT
The symmetry, tilt and elongation degrees are figures of merit which can be used to describe the radar target shape once incorporated with the target resonance modes. Through optimization of the second moments of the quadrature-polarized residues matrix, the angles are determined by the optimum co-null polarization states. The approach is tested and validated against low signal-to-noise ratio and also the late-time onset selection when extracting the mode set. A wire plane model is used and the results show that with ensemble averaging it possible to have robust polarization angle set, even with small number of sample set.

***Keywords**:* Polarization Angles, Stokes vector, Singularity Expansion Method, Feature set

I. INTRODUCTION

Based on the Singularity model [1], the resonance mode terms, namely frequency and residue, could be extracted from the late time portion of the target temporal response by the use of Method Pencil of Function (MPOF)[2]. Only the frequencies are target size dependent but, to a high degree, independent of target aspect to radar and polarization directions. Therefore, in deriving a feature set for the purpose of radar target identification, researchers have used resonance based techniques, for example[3-8] and sometimes incorporated polarization characteristics or contrasting to improve identification performance, for example [9-13]. In [14-17], the author explored the concept of applying polarization characteristics to broad resonance modes to achieve better discrimination among targets of similar geometries and electrical dimensions, and throughout demonstrated the following:

In[18], it was demonstrated that a polarization angle set can reflect symmetries, tilt and elongation degrees in the target once incorporated with the target resonance modes. Importantly, the polarization angle set is more meaningful presentation of the target attributes, i.e. directly reflecting its shape characteristics. For a single resonance, the associated angle set is determined from a quadrature-polarized residue matrix related to quadrature polarization directions, namely two co-polarized and reciprocal cross-polarized directions. The residues in a single polarization matrix should all be associated with the same resonance mode to reflect the true polarization characteristic of this resonance. Therefore, proper extraction is necessary so not to omit or misalign a resonance along any polarization direction in this matrix. Unfortunately, omitting or misaligning a resonance can occur if the residue-to-noise ratio is low, or even due to the MPOF extraction sensitivity to selection of the SEM parameters, such as the onset of the late time or the modal order of the resonances, i.e. number of resonances in the model.

This paper present a study on the effect of noise and onset selection on the polarization angle set. The purpose is to validate the robustness of the angle set even with noise presence and improper onset selection of late time. This paper is outlined as follows: Section II presents a formulation to derive the polarization angles. Section III presents the results which include description of the simulation procedures and the validation process of the proposed feature set. Section IV reaches conclusions and indicates directions for further work.

II. FORMULATION

For a quadrature polarization directions, the backscattered response set y in any orthogonal linear basis, e.g. (h,v), forms a R^{2x2} matrix, and according to SEM model will be expressed as a series of resonance modes as follows

$$\mathbf{y} = \sum_{n=1}^{M} \mathbf{C}_n e^{-(\sigma_n + j\omega_n)t} \quad (1)$$

Such that

$$C=\begin{bmatrix} c_{hh} & c_{hv} \\ c_{vh} & c_{vv} \end{bmatrix} \quad (2)$$

Here $t>T_L$, and T_L denotes the late time onset after which the incident wave has totally passed the target. The mode terms σ, ω and c denote the: damping factor, resonant frequency and complex residue. The modal order M gives the number of modes presumably excited.

The subscripts denote the transmitter and receiver polarization directions, where *hh* and *vv* denote the co-polarized scattering directions or channels, while *hv* and *vh* denote the cross-polarized scattering channels (reciprocal for monostatic case). Since the polarization information is embedded in the mode residues, the time dependence term can be omitted.

The associated received power in the co-pol channel is given by the antenna Stokes vector and the scattering coefficient second moments (Kronecker product of the C matrix and its conjugate) as follows in (3).

Subject to: $g_o=(g_1^2+ g_2^2+g_3^2)^{1/2}$ for fully polarized wave. ^{T} denotes the transpose. The g_o denotes the wave intensity or total instantaneous power, g_1 gives the portion of the wave that is horizontally or vertically polarized, g_2 gives the portion of the wave that is linearly oriented at $\pm 45^o$ and g_3 gives the portion of the wave that is left or right circularly polarized, respectively [16]. In the case of a partially polarized wave due to clutter or noise, ensemble-time averaging of Stokes vector is used.

For the one antenna case (monostatic case), optimization involves properly choosing the antenna polarization states such that power developed at the receiving antenna terminals is maximum, minimum, or null for a given resonance mode. The power optimization will be carried out for the co-pol only, since all the target physical attributes can be inferred from the co-pol CPS. Without loss of generalization, the received power in (3) can be maximized and minimized by applying the Lagrangian multiplier method to the antenna Stokes vector with the constraint that the transmit power is normalized to unity. The constraint condition Φ written in terms of the Stokes sub-variables is then defined as

$$\Phi(g_1,g_2,g_3) = \sqrt{g_1^2 + g_2^2 + g_3^2} - 1 = 0 \qquad (4)$$

The variations of the antenna Stokes variables (g_1,g_2,g_3) will lead to maximizing or minimizing the received power at the reception terminals, where the optimum co-pol powers can be found by simultaneously solving for the first partial derivatives of (3) subject to the constraint condition in (4).

This procedure results in three simultaneous partial derivative equations as follows:

$$\frac{\partial P_c}{\partial g_m} - \mu \frac{\partial \Phi}{\partial g_m} = 0, \quad m = 1,2,3. \qquad (5)$$

Here μ is the Lagrangian multiplier and gives the rate of change of the power quantity being optimized as a function of the constraint variables. Solving (5) produces two pairs of co-pol CPS. These are the orthogonal (antipodal) co-pol max pair (cm_1,cm_2) and the co-pol null pair (cn_1,cn_2).

The polarization angles can be determined from the Stokes vectors of null pair (cn_1,cn_2).Firstly, the elongation degree is determined by taking the dot product of the null vectors ($|g_{cn1}\bullet g_{cn2}|$). A value of one represent a totally long and thin shaped target, e.g. wire, and a value of zero represent a totally round shaped target, e.g. sphere. Secondly, by taking the element-by-element sum of the two co-null Stokes vectors, i.e. [g(cn1).+g(cn2)], the symmetry degree is determined by taking the ½arcsin(g_3) of the sum vector, such that 0^o represent a symmetrical target and $\pm 45^o$ represent a totally asymmetrical target. Finally, the tilt degree is determined by taking the ½arctan (g_2/g_1) of the sum vector.

III. RESULTS & SIMULATION

In general, the simulated backscattered frequency-domain data were generated by method of moments algorithm (MoM) using FEKO [19]. Filtered by a Gaussian window to create the effect of a Gaussian shaped impulse, the frequency return is transformed to the time-domain by Fourier Transform; and then corrupted by additive white Gaussian noise (AWGN) with the assumption that the power of a signal is 0 dBW. Since additive, the noise power added to the signal will increase with specular return as the specular return is relatively higher in power compared with the late portion, i.e. oscillatory return. Finally, the resonance modes are extracted by applying the MPOF to the FFT time signal, and then the polarization angles are determined. Here, a variance figure-of-merit (VAF) measures how much the reconstructed signal resembles the original one when reconstructed from the extracted resonance modes.

$$P_c=[g_o\ g_1\ g_2\ g_3]^T.\begin{pmatrix}1&0&0&1\\1&0&0&-1\\0&1&1&0\\0&j&-j&0\end{pmatrix}.(|[C]\otimes[C]^*|).\begin{pmatrix}1&0&0&1\\1&0&0&-1\\0&1&1&0\\0&j&-j&0\end{pmatrix}^{-1}.[g_o\ g_1\ g_2\ g_3] \qquad (3)$$

A. Simulations

For this, a model wire plane consisting of four geometries is used as shown in Fig.1, with the simulation parameters depicted in Table I. The geometries are namely: nose, wings, mid and tail stabilizers. The angle θ_w defines the wings inclination angle degree, while θ_t defines the tails inclination angle degree from the target longitudinal axis. In this case, a model with inclination set $(\theta_w,\theta_t)=(45^o,45^o)$ is used. Changing the angles θ_w and θ_t has no effect on the geometries dimensions (i.e. the set of resonant frequencies is fixed) but leads to different shapes (i.e. different set of residues), and subsequently, different polarization angle set. The incidence is set normal to maximize the negative effect of specular return on the extraction performance.

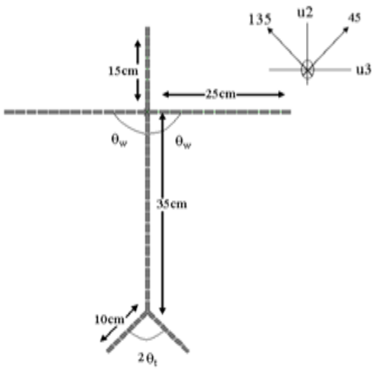
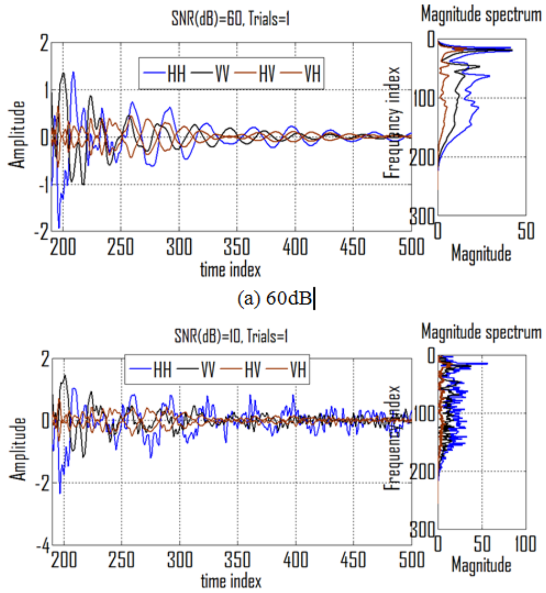


Fig.1. Dimensions (in cm) of the generalized aircraft model. The angles θ_w and θ_t give the model different shapes, but do not change the model dimensions.

TABLE I.FEKO SIMULATION VALUES

Parameter	*Value*
start Frequency	*1.9 MHz*
stop Frequency	*1 GHz*
# frequency Points	*256*
excitation source voltage	*1V*
incidence direction	*Normal*

Fig.2 shows the early-plus-late-time FFT temporal for arbitrary time onset at the 190th time index, and with the spectral response as inset. Since less sensitive to specular reflections, and subsequently, less sensitive to late-time onset the VH and HV late-time returns are less affected by the additive noise. This suggests that the higher ordered residues in the co-pol channel, compared to the cross-pol channel, are more susceptible to this additive noise and onset selection, as will be seen later. In general, there will be some degree of frequency drifting in the residues along the quadrature polarization channels.



(b) 10dB

Fig.2. The temporal with onset=190.Inset (a): the spectral response.

B. Extraction Performance with early time

To evaluate the performance of the residue extraction in presence of additive noise and for different time onset, Fig 3 presents three set of tests for a different *SNR* levels and ensemble average, i.e. trials. The first set is for 60dB, the second one is for 10dB with no averaging, and the final set is for 10dB with averaging of 10 trials. In addition, there are slight and uncorrelated shifts in the frequency of the extracted modes from channel to channel. Shifts in the third and the fourth residues are more noticeable and this is due the weak return. In the contrary, the first and second demonstrate more stability with low *SNR*. This suggests that a good practice is to allow a guard or margin of time from the early time when extracting the quadrature-polarized group of residues. Fig 4 depicts the performance with no specular and 31 time-index truncated from the late-time portion compared with tests depicted in Fig 3.

Table II shows the polarization angle results based on four set of test along the four resonances of interest. In general, even with noise perturbation, the physical attributes of the polarization angles suggest that the geometries are all symmetrical about the longitudinal axis since their associated ellipticity angle is negligible. Also they are tilted by 18-29% of quarter, i.e. vicinity of 20^o counter clock-wise from the polarization basis directions except. The elongation degree displays dihedral attribute associated with the 2-4th ordered, this is due to the significant of the skewed wings on the total time response. In all, the elongation merit is distinctively less affected by lower *SNR*.

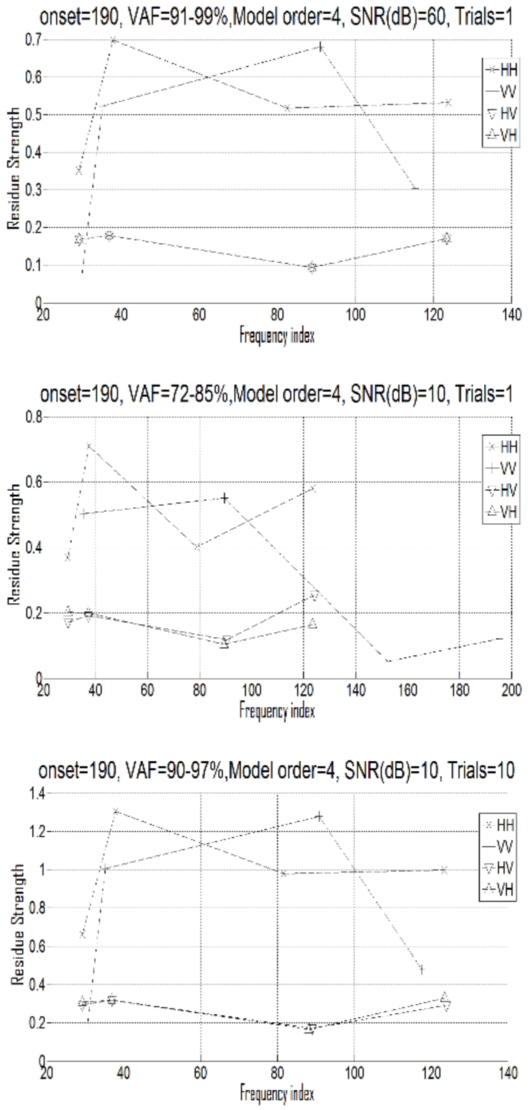


Fig 3.The quadrature-polarized residue pattern with some early time portion included.

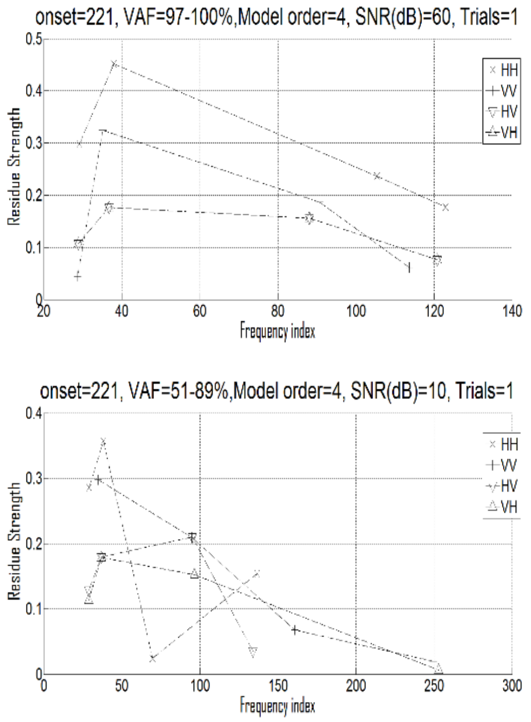


Fig 4.The quadrature-polarized residue pattern with the early time excluded.

TABLE II. POLARIZATION ANGELS VS. SNR AND #TRIALS.

SNR	#Samples(Trials)	Onset index	Frequency(Index)	Symmetry(0-45°)	Tilt (0-90°)	Elongation (0-45°)
60dB	*1*	*190*	*29*	*-2.1*	*24.6*	*14.4*
			37	*4.1*	*16.9*	*40.4*
			89	*3.3*	*21.8*	*39.6*
			123	*5.5*	*27.0*	*31.3*
60dB	*1*	*220*	*29*	*-3.9*	*19.8*	*7.2*
			37	*-7.4*	*13.4*	*40.4*
			88	*-33.0*	*8.3*	*39.1*
			121	*-3.0*	*20.1*	*30.7*
10dB	*1*	*190*	*30*	*10.5*	*33.4*	*33.2*
			37	*21.3*	*29.7*	*35.2*
			89	*-2.9*	*15.1*	*18.0*
			123	*1.0*	*19.6*	*22.1*
10dB	*10*	*190*	*29*	*-3.12*	*25.9*	*17.4*
			37	*3.80*	*19.1*	*40.6*
			89	*2.56*	*25.5*	*39.8*
			123	*4.69*	*25.7*	*30.4*

IV. CONCLUSIONS

The residue pattern of the cross-polarized is less affected by the additive noise due the lack of specular contribution in its response. Noticeably, the higher ordered residues are weaker and therefore more susceptible to noise. For high *SNR*, the over truncation of the late time portion has no effect on the lower resonances and gives higher VAF; on the contrary, the VAF degrades for low *SNR* as most of the signal power is truncated. Finally, the resonance-based polarization angles are robust with low ensemble average, and distinctively the elongation degree demonstrated more resilience to noise and late time truncation.

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