HIGH-RESOLUTION PARAMETRIC MODELING OF CANONICAL RADAR SCATTERERS WITH APPLICATION TO RADAR TARGET IDENTIFICATION

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ABSTRACT

A new approach to scattering center extraction is developed based on a model derived from the Geometric Theory of Diffraction. This model is better matched to the physical scattering process than competing methods. In addition, the model extracts more information about the scattering centers. An estimation algorithm for the model is developed and shown to have superior performance to the Prony algorithm.

I. INTRODUCTION

This paper is concerned with the problem of estimating the location and characteristics of scattering centers from radar scattering data. The scattering data consists of coherent stepped frequency measurements of the radar cross section of a target at a fixed orientation. Our goal is to process this data in order to obtain the range to the radar of each scattering center, along with some parameters which characterize each scattering center (such as amplitude, polarization properties, etc).

There are two main approaches to scattering center location. The first is to take the inverse Discrete Fourier Transform (IDFT) of the frequency response to obtain a range profile, then to extract scattering centers by some sort of processing on this range profile (such as peak location) [1]. This method is known to be resolution limited, with a range resolution limit of approximately $1/B$ where B is the bandwidth of the data.

A second technique is to model the scattering behavior using a parametric model. The parameters which describe the scattering are then estimated from the data. These parameters directly provide the location and characteristics of the scattering centers. The range resolution of this technique is not limited by $1/B$, but is limited by how well the particular model describes the actual scattering behavior.

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Recently, the Prony model has been used to model radar scattering [2, 3]. This model can provide high range resolution; however, the model does not accurately represent diffraction scattering behavior and this model mismatch limits its performance.

In this paper we develop a parametric model which describes the scattering behavior using a Geometric Theory of Diffraction (GTD) model of scattering. This model is more closely matched to the the physical electromagnetic scattering of the object than is the Prony model. As a result, the GTD-based model can more accurately describe the scattering behavior. This increased modeling accuracy is especially noted for measured data with a large relative bandwidth.

II. THE GTD-BASED MODEL

We assume that the available measurements are the scattering matrices $S(f_k)$ for each frequency step f_k, where

$$f_k = f_0 + k\delta_f \quad k = 0 \ldots N-1 \tag{1}$$

Each element of S corresponds to a particular transmit/receive polarization pair.

For high frequencies, the scattering from the target can be decomposed into a finite sum of scattering terms, corresponding to real or virtual scattering centers. A GTD model of this scattering is of the form

$$S(\omega_k) = \sum_{i=1}^{m} \bar{K}_i e^{j2r_i\omega_k/c}(j\omega_k)^{t_i} \tag{2}$$

where m is the model order and $\{\bar{K}_i, r_i, t_i\}_{i=1}^{m}$ are the parameters of the model. Each r_i gives the range of the scattering center, and each $\bar{K}_i$ is a complex-valued amplitude matrix which characterizes the amplitude and polarization properties of the scattering center (see also [4]). The elements of $\bar{K}_i$ correspond to the combinations of transmitted and received polarization. For a single transmit/receive polarization, $\bar{K}_i$ is a complex scalar. The t_i parameter is found from GTD-based physical scattering considerations; $t_i = -1$ corresponds to tip (corner) diffraction, $t_i = -\frac{1}{2}$ corresponds to

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(curved) edge diffraction and $t_i = 0, \frac{1}{2}, 1$ correspond to specular scattering from a curved surface, a curved plate and a flat plate (or dihedral or trihedral), respectively [2, 4] . Thus, we use $t_i \in \{-1, -\frac{1}{2}, 0, \frac{1}{2}, 1\}$ in our model.

III. DESCRIPTION OF THE ALGORITHM

The structure of the algorithm was motivated by the observation that the Prony algorithm is capable of estimating the ranges to the various scattering centers, but not the geometry type parameters. Thus, we first use the Prony method to obtain range parameters of the scattering centers; we then estimate types and amplitudes using the range estimates. A description of the algorithm follows.

1. Use a modified Prony algorithm of model order m to estimate range parameters $\{\hat{r}_i\}_{i=1}^m$. For a detailed description of the Prony algorithm see [3, 5].
2. Order $\{\hat{r}_i\}_{i=1}^m$ from smallest to largest.
   For Each $i = 1 \ldots m$:
   (a) Form $\bar{S}(\omega_k) = S(\omega_k)e^{-j2\hat{r}_i\omega_k/c}$ This 'modulated' scattering data has the i^{th} scattering center at range 0.
   (b) Low pass filter $\{\bar{S}(\omega_k)\}_{k=0}^{N-1}$ to isolate the i^{th} scattering center. The output of this filter is
   $$\tilde{S}(\omega_k) = \bar{K}_i(j\omega_k)^{t_i} \quad k = 0 \ldots N-1$$
   Note that we are treating the frequency data $\bar{S}(\omega_k)$ as a discrete time series and convolving with the filter impulse response to produce $\tilde{S}(\omega_k)$.
   In our implementation, we use a linear phase FIR filter constructed by Hanning windowing the impulse response of an ideal lowpass filter whose cutoff range is r_c. We set $r_c = \frac{1}{10}\min|r_i - r_{i-1}|, |r_i - r_{i+1}|$ subject to a minimum of $\frac{2\pi}{N}$. The impulse response $l(k)$ of the filter is $l(k) = l_{ideal}(k)h_{.1N}(k)$ where $h_{.1N}$ is a Hanning window from index 0 to index $.1N$. Thus L is a causal linear phase FIR lowpass filter of order $.1N$.
   (c) Take the elementwise complex natural logarithm of $\{\tilde{S}(\omega_k)\}_{k=0}^{N-1}$. This produces
   $$\text{Ln } \tilde{S}(\omega_k) = \text{Ln } \bar{K}_i + t_i \text{Ln } j\omega_k \quad k = 0 \ldots N-1$$
   The estimates $\hat{t}_i$ are found by solving this equation in the least squares sense and rounding to the closest value $t_i \in \{-1, -\frac{1}{2}, 0, \frac{1}{2}, 1\}$.
3. Given the estimates $\{\hat{r}_i\}_{i=1}^m$ and $\{\hat{t}_i\}_{i=1}^m$, find $\{\hat{K}_i\}_{i=1}^m$ by linear least squares using (2).

Two characteristics of the above algorithm are worth noting. First the range estimates are obtained using a Prony model, and any inaccuracies there propagate through the algorithm. Such inaccuracies are most pronounced for for small amplitude scattering centers with type $t = -1$. Second, the lowpass filter is assumed to be able to isolate each scattering center. For closely spaced scatterers, this assumption becomes more tenuous. However, this step remains fairly robust because of the rounding of t_i to the nearest half integer.

IV. EXPERIMENTAL RESULTS

In this section we describe experimental results obtained with the algorithms discussed above. We compare these results with those from the Prony algorithm and the IDFT methods. The data used in these experiments consists of compact range measurements of a 2×2 ft flat plate inclined at 46° from the horizontal and rotated 5° from the incoming wavefront, HH polarized. The data were taken at frequencies from 2 GHz to 18 GHz with a 20 MHz step. We perform 10% bandwidth experiments using the 64 points from 10 GHz to 11.28 GHz.

Figure 1 shows the results of applying the GTD-based algorithm to the 10% bandwidth data. The solid line is an IDFT of data synthesized from the model with order $m = 3$, the dashed line is an IDFT of the measured data. The vertical lines indicate the ranges to the scatterers estimated by the algorithm, and the numbers written at the top of the lines are the associated types t. The residual error is 1.9%.

The GTD model gives three scattering centers, each described by its range, type and amplitude. The ranges and types are shown as the three vertical lines, with the type number at the top. For comparison with the IDFT, the solid line is the range profile which is reconstructed from the model parameters using the same bandwidth. Note the very good agreement between the IDFT and the GTD-based range profiles, even though the GTD-based profile is reconstructed from only 9 parameters.

The resolution of the GTD-based model is theoretically unlimited, as depicted by the vertical lines in Figure 1. Alternatively, the GTD-based model can be used to extrapolate the frequency domain scattering data and an IDFT can be applied to the extrapolated data. The result of such an extrapolation procedure is shown in

Figure 2. This Figure can be thought of as just another representation of the same nine model parameters found above.

Note from Figures 1 and 2 that the location of the leading corners is well estimated by the GTD-based procedure (notice also that the type of the scatterer is correct as -1); the range error in the much weaker rear corners is larger. The response at 4.2 m is a creeping wave. Notice that each scatterer is described by a little more than 3 numbers (2 for the complex amplitude, one for the range and 3 bits for the type parameter). Therefore, we have achieved a data reduction factor of more than ten relative to the IDFT.

Figure 3 shows a 3^{rd} order Prony model applied to the same data. The vertical lines again indicate the estimated scatterer locations; the type information is not available from the Prony model. The residual error is 2.2% in this case. Thus, for the same model order, the GTD-based model (Figure 1) provides a 15% better fit to the data as well as more information than does the Prony model.

Figure 4 shows a 7^{th} order GTD-based model applied to the full bandwidth data. The residual error is about 8.7%; this number is larger than for the 10% bandwidth experiment because the range errors become more critical with the larger bandwidth. All four corners are estimated at the correct geometry and except for the rearmost corner, the range errors are quite small. The data compression achieved is approximately a factor 75.

Figure 5 shows a 9^{th} order Prony model applied to the full bandwidth data. The residual error is about 14%; this about 60% worse than the GTD-based model. A 7^{th} order model did not locate the rearmost corner and had a residual error of 17%. Thus, at these wider bandwidths, the GTD-based model provides a much better fit to the data than does the Prony model.

V. CONCLUSIONS

We have developed a GTD-based model that is more closely based on the physical properties of the scattering process than the methods in current use; this leads to smaller errors between model and data as well as extraction of more geometric information, namely the type of the scatterer. These two improvements, closer fit and more information, make the model suitable for improving the performance of automatic target recognition systems. We have shown that the new model can characterize a target with significantly less data than an IDFT and with a smaller residual error than a Prony model. As a result, this model can provide a decision algorithm with a small feature vector which preserves most of the information present in the original data. This in turn permits reduction in the computational cost of the decision algorithm (relative to an IDFT-based system), or improved reliability (relative to a Prony-based system).

The current algorithm assumes that the scatterers are sufficiently separated. In order to handle realistic targets, this assumption needs to be relaxed. Research into improved algorithms is currently under way.

VI. REFERENCES

[1] D. L. Mensa, *High Resolution Radar Imaging.* Dedham, MA: Artech House, 1981.

[2] M. P. Hurst and R. Mittra, "Scattering center analysis via Prony's method," *IEEE Trans. Antennas and Propagation*, vol. AP-35, pp. 986–988, Aug. 1987.

[3] R. Carrière and R. L. Moses, "High resolution radar target modeling using ARMA models," tech. rep., The Ohio State University, Department of Electrical Engineering, ElectroScience Laboratory, May 1989.

[4] W. Leeper, "Identification of scattering mechanisms from measured impulse response signatures of several conducting objects," Master's thesis, The Ohio State University, 1984.

[5] R. Carrière and R. L. Moses, "High resolution radar target modeling using a modified Prony estimator," Submitted to *IEEE Trans. Antennas and Propagation.*

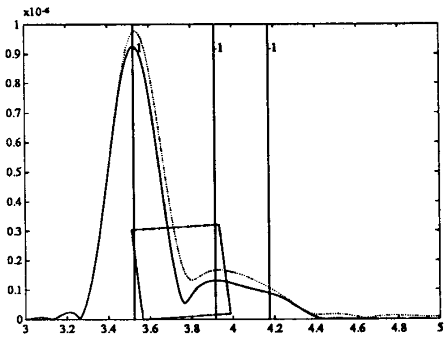

Figure 1: Range profiles for a tilted flat plate. using data from 10–11.28 GHz. Dotted line is IDFT. Vertical lines show ranges and types of scattering centers for a 3rd order GTD-based model. Solid line is range profile reconstructed from GTD-based model for comparison with IDFT.

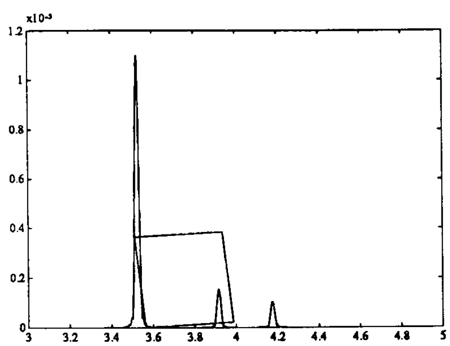

Figure 2: Range profile generated from GTD-based model using data as in Figure 1, but then extrapolated to 4.24–17.04GHz.

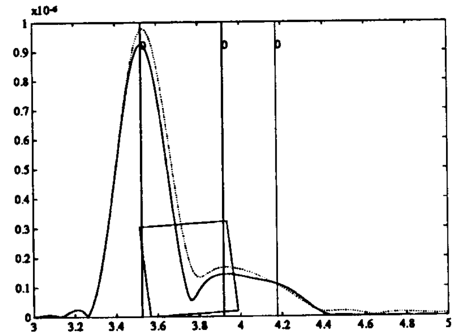

Figure 3: 3rd order Prony model of flat plate data from 10–11.28 GHz; N=64. Curves are are as in Figure 1.

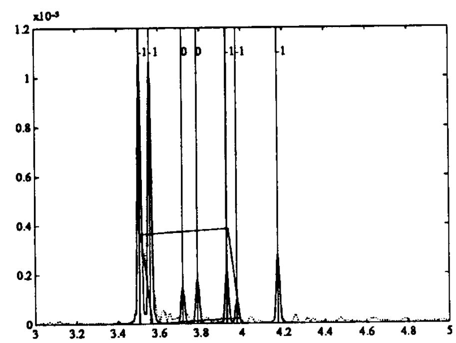

Figure 4: 7th order GTD-based model of flat plate data from 2–18 GHz; N=800. Curves are are as in Figure 1.

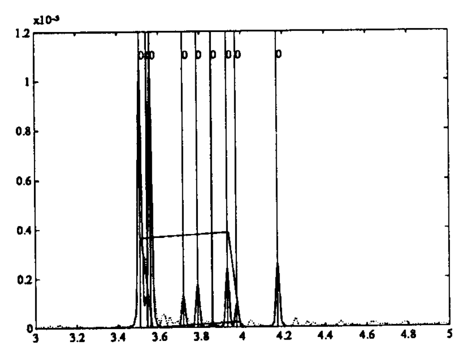

Figure 5: 9th order Prony model of flat plate data from 2–18 GHz; N=800. Curves are are as in Figure 1.