Radar Target Identification Using a Combined Early-Time/Late-Time E-Pulse Technique

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***Abstract*—The E-pulse technique has been applied in the past to both the early- and the late-time components of a transient radar response. While the late-time E-pulse technique uses aspect-independent waveforms, the early-time E-pulse technique requires a separate waveform for each target aspect angle and thus significantly more storage and processing time. This paper discusses a combination of the two techniques that employs the early-time technique to remove ambiguities generated from application of the late-time method. By narrowing the possible range of aspect angles of the potential targets, the early-time technique can be employed more efficiently.**

***Index Terms*—Inverse problems, radar target recognition.**

I. Introduction

It has been repeatedly demonstrated [1]–[10] that radar-target identification is possible using the late-time portion of the transient response of a radar target and the E-pulse technique. Recently [11], prompted by the observation of Hurst [12] and Altes [13], the authors have applied the same method to the early-time portion of the target response. Either technique can be used independently to identify a target or the two techniques may be combined into a single method.

A serious disadvantage to using the late-time technique is that when the target resonant response is available, it is often far below the early-time portion in signal strength (though not necessarily in total energy). When the signal-to-noise ratio (SNR) is low, identification using the late-time technique often leads to ambiguous results due to overlapping natural resonance content in the band of interest. However, the late-time technique has the tremendous advantage of employing aspect-independent waveforms—only one waveform for each target is stored and processed with the unknown target response. In contrast, the early-time technique (which is based upon target scattering centers) results in less ambiguity. This comes, however, at the cost of significantly higher processing time since a separate waveform must be used for each probable target aspect angle. Thus, the early-time technique should only be used to bolster the information obtained using late-time information, unless none is available.

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In those situations where both early- and late-time target information is available, the following combined technique can be used to accelerate the identification process. First, the unknown target response is processed using each of the late-time E-pulses from the target data base. If there is little or no ambiguity, the decision process can be completed at this step. If, however, several good candidate targets are produced, the early-time technique is employed to remove the ambiguity and complete the decision process. Since the number of potential targets has been whittled down, application of the early-time technique is more efficient. However, an additional step can be used to reduce the early-time processing overhead further. If, in addition to the late-time E-pulses, information about the aspect dependence of the late-time response of each target is stored, the range of aspect angles over which the early-time technique must be applied can be narrowed. This can be done efficiently by storing the amplitudes and phases of the target natural modes, reconstructing the late-time response and finding the range of angles over which the response best fits the unknown target data.

This paper outlines an automated early-time frequency-domain E-pulse method and its integration with existing automated late-time E-pulse methods [6] to produce a "combined E-pulse method" for target discrimination. The effectiveness of the combined scheme is verified using the measured responses of B-52, B-58, and F-14 aircraft models.

II. Discrimination Scheme

A. Summaries of Late-Time and Early-Time E-Pulse Techniques

When a short-duration pulse interacts with a radar target, it produces a time-domain scattered field waveform consisting of the effects of two distinct phenomena. As the interrogating pulse passes across the target, specular reflections are returned from localized scattering centers, producing an impulse-like early-time component along with the partial resonances of target substructures. It also establishes the target global resonances after the interrogating pulse has passed the target completely.

In the early 1970's, Baum [14] proposed a model of the late-time transient response and devised a means to calculate the relevant parameters from the geometry of the scatterer. According to his model, the time-domain backscattered field response can be written as a sum of the natural resonance modes of the target as

$$r(t) = \sum_{n=-N}^{N} A_n e^{s_n t} \qquad t > T_L \tag{1}$$

where $s_n = \sigma_n + j\omega_n$ is the aspect-independent complex resonant frequency of the nth target mode occurring in complex-conjugate pairs (i.e., $s_{-n} = s_n^*$), A_n is the aspect-dependent complex amplitude of the nth mode, N is the number of modes excited by the incident pulse, and T_L designates the beginning of the late-time period. For the usual case of backscattering measurements, this time is given by

$$T_L = T_b + 2T_{tr} + T_p \tag{2}$$

where T_b is the time when incident wave strikes the leading edge of the target, T_{tr} is the maximum one-way transient time along the line of sight, and T_p is the pulse width used in measurement system. Equation (1) can also be written in an alternative form as

$$r(t) = \sum_{n=1}^{N} a_n e^{\sigma_n^t} \cos(\omega_n t + \phi_n). \tag{3}$$

The aspect-independent nature of the natural resonance frequencies has prompted the development of several target discrimination schemes, including the K-pulse and late-time E-pulse techniques. Although these techniques use aspect-independent waveforms, they ignore the early-time component of the transient response, which often has a higher signal strength.

Altes [13] has proposed a simple model for the early-time response

$$r_E(t) \approx \sum_{m=1}^{M} p(t) * h_m(t - T_m) \qquad t < T_L \tag{4}$$

where $p(t)$ is the incident pulse and $h_m(t)$ is the localized impulse response originating at the mth scattering center at time T_m. In the frequency domain, this response becomes

$$R_E(\omega) = \mathcal{F}[r_E(t)] \approx \sum_{m=1}^{M} P(\omega) H_m(\omega)\, e^{-j\omega T_m} \tag{5}$$

where $H_m(\omega)$ is the transfer function of mth scattering center and $P(\omega)$ is the spectrum of $p(t)$. Hurst and Mittra [12] suggest that the transfer function can be approximated as an exponential function of frequency. Assuming that $P(\omega)$ is a slowly varying function then R_E can be rewritten as

$$R_E(\omega) \approx \sum_{m=1}^{M} B_m\, e^{\tau_m \omega} \tag{6}$$

where $\tau_m = \alpha_m - jT_m$ are called "complex times" and are associated with the scattering center-impulse responses. Note that M is the number of exponential terms which is related to the number of scattering centers. However, M is not the exact scattering center number since the measurement system is bandlimited and more than one exponential term may be needed to represent one scattering center. The exact value of M is not critical and is determined by the desired accuracy of the waveform reconstruction in the extraction technique used [13]. The physics of the scattering process (reflection or diffraction) determines the complexity and amplitude of each scattering center contribution in (6). See [21] for a thorough description of the modeling of scattering centers using exponential functions. Also, see [15] for a related technique which uses Prony's method in the analysis of target scattering centers.

There exists an obvious duality between the temporal late-time response (1) and the spectral early-time response (6). This duality allows the direct application of the late-time E-pulse technique to spectral early-time data.

In summary, both the temporal late-time response and the spectral early-time response can be expressed in a general exponential form

$$f(x) = \sum_{k=1}^{K} c_k\, e^{Q_k x} \qquad X_L < x < X_F \tag{7}$$

where c_k and Q_k are complex constants, X_L, X_F are the domain of the signal measurement, and x represents time in the case of a late-time response or frequency in the case of an early-time response. An E-pulse $e(x)$ is a real waveform with finite duration X_E, which, when convolved with $f(x)$, eliminates a preselected component of the exponential series. In particular, the entire series can be eliminated resulting in

$$c(x) = e(x) * f(x) = \int_0^{X_E} f(x') e(x - x')\, dx' \equiv 0$$
$$X_L + X_E < x < X_F. \tag{8}$$

The conditions for obtaining an extinction pulse are presented in the context of resonance cancellation as

$$E(s = Q_k) = E(s = Q_k^*) = 0 \tag{9}$$

where $E(s)$ is the Laplace transform of $e(x)$. The E-pulse mode-extraction technique can be used to find $e(t)$ [16]–[18], Q_k can then be found from (9) and c_k is extracted using the least squares method.

B. Quantification of Radar Target Discrimination Using Early-Time E-Pulse Technique

The E-pulses for the spectral early-time response can be synthesized in a manner similar to that used for the late-time responses [16]–[18] except that the spectrum of the early-time response is used instead of the late-time temporal response. Also, the quantification of discrimination for the early-time automated scheme is very similar to that for a late-time scheme [6]. There are, however, some subtle differences between the late-time methods and the early-time methods that require some discussion.

For quantification, a definition similar to the late-time E-pulse discrimination number (LEDN) is used for the early-time E-pulse discrimination number (EEDN)

$$\text{EEDN} = \frac{\displaystyle\int_{\omega_{lo}}^{\omega_{hi}} |e(\omega) * r(\omega)|\, d\omega}{\displaystyle\int_0^{\omega_{ep}} e(\omega)^2\, d\omega} \tag{10}$$

where $e(\omega)$ is the early-time frequency domain E-pulse response, $r(\omega)$ is the spectrum of the early-time target response, ω_{lo} and ω_{hi} are the lower and upper frequency limits of the measurement system, and ω_{ep} is the frequency duration of $e(\omega)$. The early-time E-pulse discrimination ratio (EEDR) is identical to that used for late-time [6]

$$\text{EEDR(dB)} = 10.0 \log_{10}\left\{\frac{\text{(EEDN)}}{\min\text{(EEDN)}}\right\}. \tag{11}$$

The early-time E-pulse method is based on the spectrum of the early-time response. Thus, care must be exercised when defining a reference in the transient response to avoid shifting the complex frequencies of the exponential sinusoidal waveforms that make up the early-time spectrum. This is especially true when using the measured transient data required for early-time E-pulse synthesis for realistic targets (e.g., aircraft, missiles).

This sensitivity to the $t = 0$ reference arises when frequency domain E-pulses for the early-time response are constructed and subsequently used to process an independently measured response whose $t = 0$ reference point has shifted by an amount τ from the response used to synthesize the E-pulse. It is found that the effectiveness of the early-time frequency domain E-pulse is reduced.

To circumvent this problem, a reference feature for each early-time response is needed. This is allowable for early-time discrimination since the aspect angle of the target (discussed in the following section) is assumed to be known. A simple reference is the maximal point in the early-time response. Unfortunately, this is not sufficient since there are usually some slight shifts associated with each measurement due to equipment variations or slight changes in aspect angle. To overcome this difficulty, the discrimination process is repeated for slightly different values of τ. The value of τ corresponding to the minimal EEDN for one of the E-pulses can then be used. The correct target is identified with the E-pulse corresponding to an EEDR value of zero; the EEDR values of the other targets are greater than zero.

C. Determination of Aspect Angle

The aspect angle of the target identified using the late-time scheme is determined by minimizing the squared difference between the measured late-time response and the response of the candidate target reconstructed using the modal amplitudes and phases extracted from laboratory data and saved in a data base. The aspect angle which minimizes the squared-error difference is taken to be the angle of the target. Note that there is also a scaling factor to be determined since the overall amplitude of the measured response will be different from that measured in the lab. This scaling factor can be computed by least squares at each point in the search for the aspect angle.

The reconstructed waveform for the lth target at the jth aspect angle can be written as

$$r_{l,j} = \sum_{n=1}^{N} a_{l,j,n}\, e^{\sigma_{l,n} t} \cos(\omega_{l,n} t + \phi_{l,j,n}) \tag{12}$$

where $a_{l,j,n}$, the amplitude of the nth mode of target l at aspect j and $\phi_{l,j,n}$ (the phase angle) are stored in a data base, as are the aspect-independent natural frequencies $\sigma_{l,n} + j\omega_{l,n}$. The squared-error difference between this reconstructed waveform and the measured data is defined as

$$\epsilon_{l,j} = \sum_{i=1}^{M_p} [m(t_i) - K_{l,j} r_{l,j}(t_i)]^2 \tag{13}$$

where t_i is the time at sample point i, M_p is the number of points in the late-time response and $K_{l,j}$ is the scaling factor. $K_{l,j}$ is determined by minimizing $\epsilon_{l,j}$ as

$$K_{l,j} = \frac{\displaystyle\sum_{i=1}^{M_p} [m(t_i) r_{l,j}(t_i)]}{\displaystyle\sum_{i=1}^{M_p} r_{l,j}^2(t_i)}. \tag{14}$$

Since different candidate targets may have different late-time periods, a normalized error quantity—the squared-error per point (SEPP)—is needed. This is defined as

$$\text{SEPP}_{l,j} = \frac{1}{M_p} \frac{\displaystyle\sum_{i=1}^{M_p} [m(t_i) - K_{l,j}(t_i) r_{l,j}(t_i)]^2}{\displaystyle\sum_{i=1}^{M_p} m^2(t_i)} \tag{15}$$

where the denominator is the energy in the late-time response. A measure of the quality of the smallest error is given by the "squared-error ratio" (SER), defined as

$$\text{SER}_{l,j}\,\text{(dB)} = 10.0 \log_{10}\left\{\frac{\text{SEPP}_{l,j}}{\min\text{(SEPP)}}\right\}. \tag{16}$$

Thus, the aspect angle and target producing 0-dB SER is the most probable candidate.

III. Demonstration of the Combined E-Pulse Technique

Two sets of antennas covering adjacent frequency bands have been used to increase the bandwidth and allow for both strong early and late-time signals to be measured for a single aircraft at various angles of incidence. A data splicing routine was developed in an effort to accomplish this [19]. In the case of the B-52, a 1 : 72 scale model was measured over the band 2-18 GHz, while a 1 : 144 scale model was measured over the band 0.4–4.4 GHz. The orientation and location of the antennas

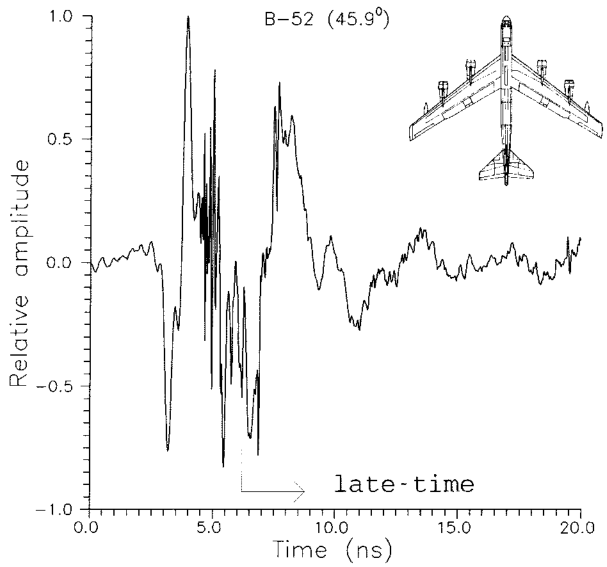

Fig. 1. Spliced transient response of B-52 aircraft model at 45.9° incidence.

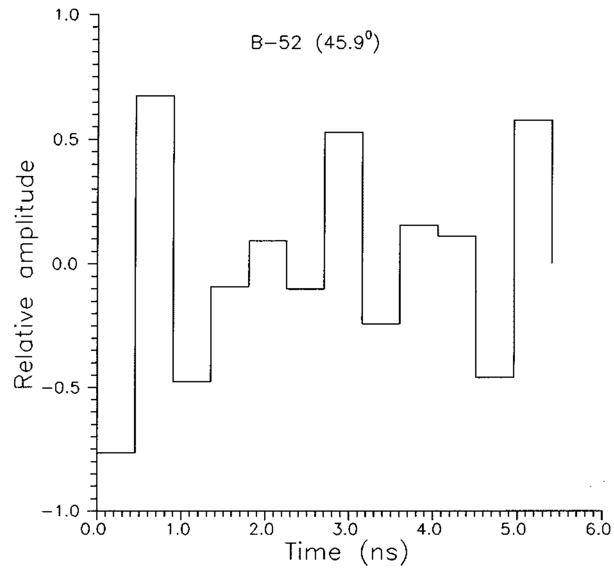

Fig. 2. Late-time E-pulse constructed to cancel late-time B-52 response.

and the targets were maintained throughout the measurements. The amplitudes of the low-band data were scaled by 2.0 and the frequency step size by a factor of 0.5 by the application of the linearity principle to the measured data because of the known scale ratio of two between the model targets. The two data sets were spliced together in the frequency domain at one preselected frequency for all of the measured responses (0–89.1° at an increment of 2.7°). The resulting ultrawide-band frequency data, equivalent to 0.2–18.0 GHz for the larger target, was interpolated down to dc and then Fourier transformed into the time domain by weighting the frequency-domain spectrum with a double Gaussian function, thus retaining the lower frequency information.

Fig. 1 shows the scattered time domain response of a B-52 target at aspect angle of 45.9° from nose on obtained from the spliced frequency data (0–18 GHz) with the polarization in the plane of wings. Note the occurrence of a strong late-time oscillatory component appearing after the excitation signal has passed the target (around 6.1 ns), resulting from the low-frequency component of the spliced data. The combined E-pulse technique can be used to perform radar target discrimination since both early-time and late-time responses are strongly present.

As a demonstration of the combined E-pulse technique, 1 : 72 scale B-52, 1 : 48 scale B-58 and 1 : 48 F-14 models have been measured within the band 0–18 GHz and inverse transformed into the time domain, as described above. Each target has been measured from 0–89.1° at a 2.7° increment and late-time E-pulses have been constructed using information from several aspect angles. Fig. 2 shows late-time E-pulse of the B-52 constructed to cancel its late-time response. Fig. 3 shows the convolution of the B-52 response measured at 45.9° with the late-time E-pulses of the B-52, B-58, and F-14. The beginning of the late-time convolutions of the B-52, B-58, and F-14 are 14.2, 14.1, and 13.9 ns, respectively. Using the definition of LEDR, the B-52 has an LEDR of 0 dB while the B-58 and F-14 have an LEDR of 20.5 and 29.8 dB, respectively. In this case, the difference is so large that the B-52 can be easily identified. However, if additional noise is added to simulate an actual measurement in the field, the identification becomes more ambiguous.

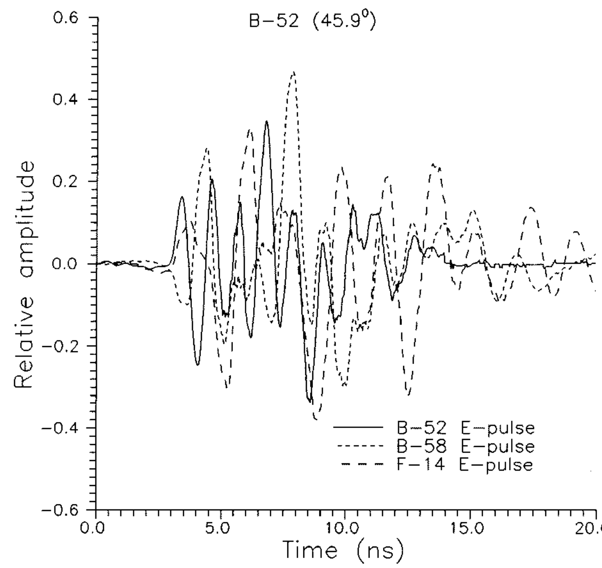

Fig. 3. Convolution of late-time B-52 response measured at 45.9° generated using spliced data with late-time E-pulses of B-52, B-58, and F-14.

To simulate a more realistic scenario, the B-52 response at 45.9° was chosen to be the measured response of an unknown target. The response was scaled by a factor of 10, white Gaussian noise was added using the definition of SNR given in [6], and the reconstructed responses of the three potential targets were best fit to the noisy waveform. The resulting SER is shown in Figs. 4–6. When the B-52 is the anticipated target, the SER is minimized for the correct angle 45.9° regardless of the noise level. However, the rate at which the SER increases as the aspect angle moves away from 45.9° decreases with increasing noise; that is, as the noise gets worse, it is harder to tell with certainty that the aspect angle is 45.9°. When

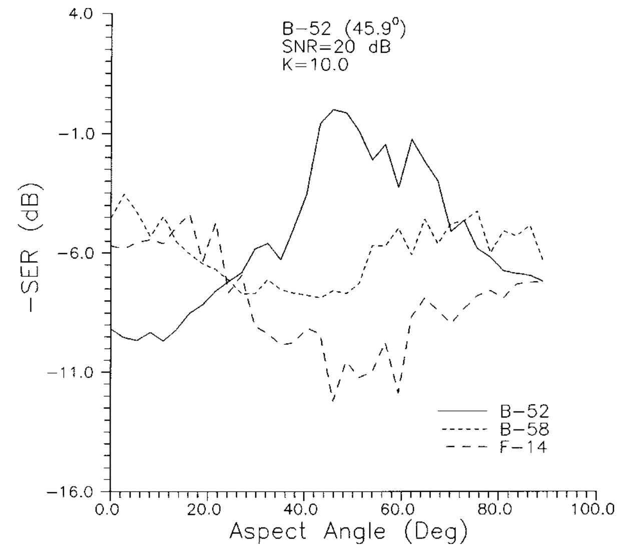

Fig. 4. SER of B-52 response measured at 45.9° aspect angle for different candidate targets, as a function of aspect angle. SNR = 20 dB.

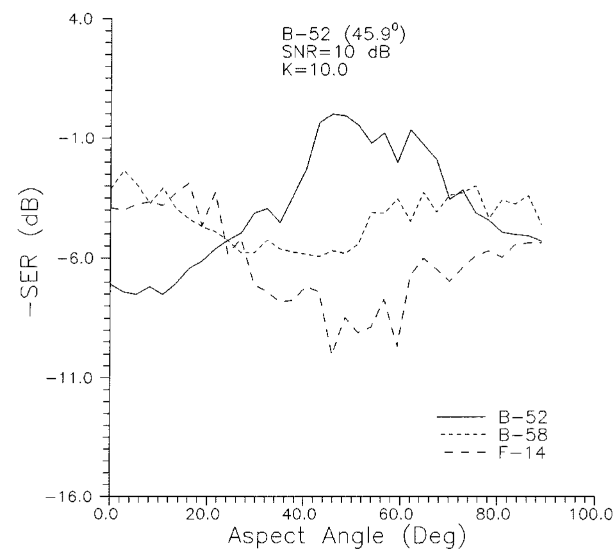

Fig. 5. SER of the noisy B-52 response measured at 45.9° aspect angle for different candidate targets, as a function of aspect angle. SNR = 10 dB.

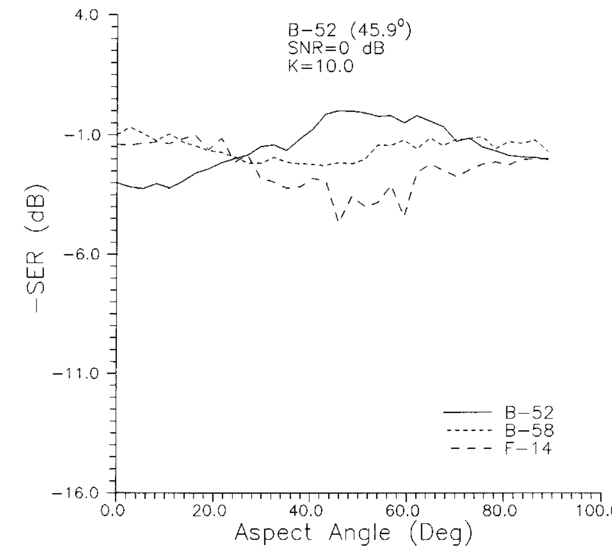

Fig. 6. SER of the noisy B-52 response measured at 45.9° aspect angle for different candidate targets, as a function of aspect angle. SNR = 0 dB.

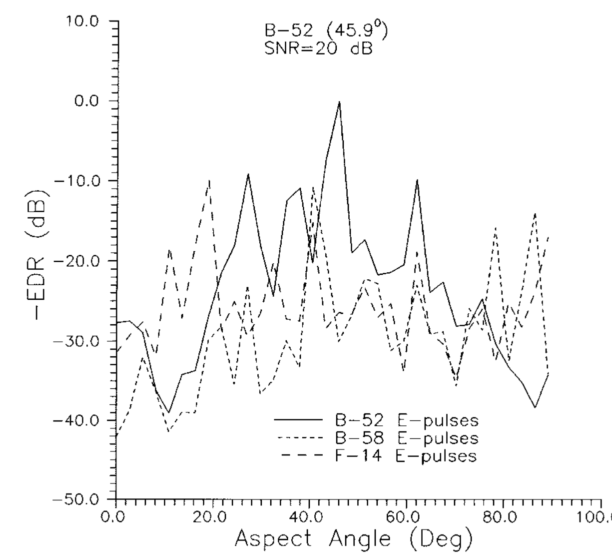

Fig. 7. Early-time discrimination of B-52 measured at 45.9° aspect angle for different candidate targets as a function of aspect angle. SNR = 20 dB.

the B-58 and F-14 are the anticipated targets and the SNR is low, certain aspect angles near 0° produce nearly as good a best fit as the B-52 near 45.9°. Thus, it is difficult to tell if the target is a B-52 at 45.9° or an F-14 or B-58 near 0°.

For low values of SNR, the B-52 has the largest SER for the approximate range of aspect angles 40–70°. However, it is barely above the B-58 in the range 0–20° and the F-14 in the range 0–25°. Thus, to verify the that the B-52 is the actual target, the early-time E-pulse scheme may be applied within each of these aspect angle ranges.

The beginning time of the measured responses must be determined in a manner similar to that explained in [6] before the early-time E-pulse technique is applied. The difference between the peak time and the beginning time t_{pb} is stored in the target library for all measured aspect angles. The response is shifted by the expected beginning time and the Fourier transform is applied to the early time portion of the response. The real or imaginary parts of the spectral early-time response are then used to synthesize the E-pulses. All the E-pulses are stored in the target library along with information on the two way transit time, effective transmitted pulse width, and t_{pb} for each aspect angle.

Since partial resonances are present in the early-time transient response of the B-52 (shown in Fig. 2), the early-time transient response is not optimally useful for early-time E-pulse discrimination. A purely specular early-time transient response can be obtained by truncating the spectrum to the band 2–18 GHz, weighting with a Gaussian modulated cosine function [20] centered at 10.0 GHz, and then inverse transformed using the FFT.

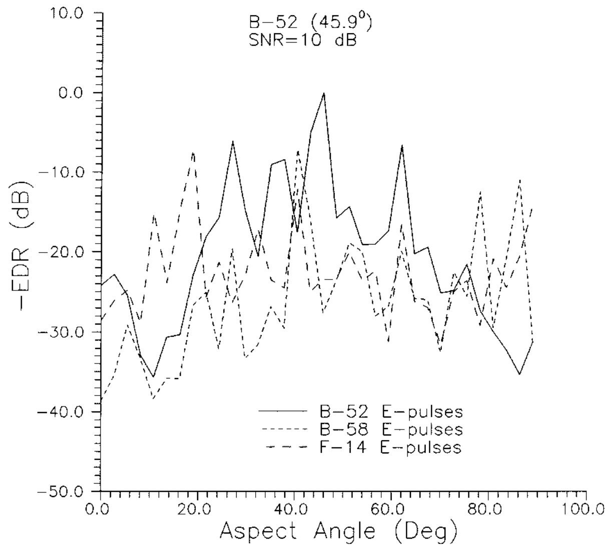

Fig. 8. Early-time discrimination of B-52 measured at 45.9° aspect angle for different candidate targets as a function of aspect angle. SNR = 10 dB.

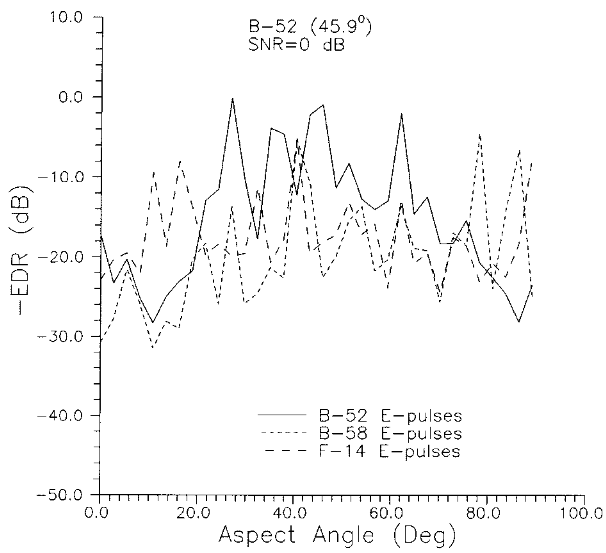

Fig. 9. Early-time discrimination of B-52 measured at 45.9° aspect angle for different candidate targets as a function of aspect angle. SNR = 0 dB.

Early-time E-pulses have been constructed for each target at each measured aspect angle. Convolution of the 49.5° B-52 spectrum with each of the E-pulses produces the plots shown in Figs. 7–9. It can be seen that for all of the noise levels, the B-52 E-pulses produce the maximum EDR, and that EDR occurs near 49.5°. Since the aspect angle range has been narrowed from the use of the late-time data, the E-pulses need only be employed over a small range of the displayed angles and, thus, the proper target is identified with a minimum of processing effort.

IV. Conclusions

A technique has been introduced that combines the late and early-time E-pulse techniques to reduce the early-time processing effort. By narrowing down the number of potential targets, and by determining the most likely range of aspect angles for each target, the early-time E-pulse method can be applied more efficiently. The measured responses of scaled B-52, F-14, and B-58 aircraft have been used to demonstrate the potential of the method. Extending the technique to a larger number of targets, including targets of similar geometry, will be left to future study.

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Prior to entering graduate school, he was employed as an Engineer with the Illinois Institute of Technology Research Institute, Annapolis, MD. While in graduate school, he held various teaching and research assistant positions, including a year with the University of Michigan Radiation Laboratory, Ann Arbor. After graduate school, he continued working at Michigan State University as a Research Fellow. In 1994, he joined the General Motors R&D Center, Warren, MI, as a Staff Fellow. He spent the 1996 academic year as a Visiting Professor of electrical engineering at the University of Idaho, Moscow, ID, and is now working as an Independent Software Developer and Consultant. His research interests include ultrawide-band radar, modeling of vehicular antennas, and the application of genetic algorithms to analog circuits.

Edward J. Rothwell (S'84–M'85–SM'92) was born in Grand Rapids, MI, on September 8, 1957. He received the B.S. degree in electrical engineering from Michigan Technological University, Houghton, in 1979, the M.S. degree in electrical engineering and the Electrical Engineer degree from Stanford University, Stanford, CA, in 1980 and 1982, respectively, and the Ph.D. degree in electrical engineering from Michigan State University, East Lansing, in 1985.

He worked for Raytheon Co., Microwave and Power Tube Division, Waltham, MA, from 1979 to 1982, with a concentration on low-power traveling wave tubes, and for MIT Lincoln Laboratory, Lexington, MA, in 1985. He has been at Michigan State University from 1985 to 1990 as an Assistant Professor of electrical engineering and since 1990 as an Associate Professor.

Dr. Rothwell is a Member of Phi Kappa Phi, Sigma Xi, and Commission B of URSI. He held the Dean's Distinguished Fellowship at Michigan State University, East Lansing. He received the John D. Withrow Award for teaching excellence from the College of Engineering at Michigan State University in 1991 and again in 1996.

Kun-Mu Chen (SM'64–F'76) was born in Taipei, Taiwan, on February 3, 1933. He received the B.S. degree in electrical engineering from National Taiwan University, Taipei, in 1955, and the M.S. and Ph.D. degrees in applied physics from Harvard University, Cambridge, MA, in 1958 and 1960, respectively.

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Dr. Chen is a Fellow of AAAS. He received the Distinguished Faculty Award from Michigan State University in 1976, the Withrow Distinguished Scholar Award from the College of Engineering, Michigan State University, in 1993, and the Outstanding Achievement Award from the Taiwanese American Foundation in 1984.

Dennis P. Nyquist (S'63–M'67–SM'92–F'97) was born in Detroit, MI, on August 18, 1939. He received the B.S.E.E. degree from Lawrence Technological University, Southfield, MI, in 1961, the M.S.E.E. degree from Wayne State University, Detroit, MI, in 1964, and the Ph.D. degree in electrical engineering from Michigan State University, East Lansing, MI, in 1966.

In 1966, he joined the Michigan State University faculty and in 1979 he became a Professor. His current research interests included electromagnetic interactions in integrated electronics, electromagnetic characterization of materials, and transient electromagnetics.

Dr. Nyquist maintains membership in Commission B of URSI, Sigma Xi, Tau Beta Pi, and Phi Kappa Phi. He was the recipient of the Michigan State University Teacher–Scholar Award in 1969 and the Michigan State University Distinguished Faculty Award in 1997. He also received the John D. Withrow Award for Research Excellence from the College of Engineering of Michigan State University in 1996.