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ADVANCED RADAR DETECTION AND PROCESSING TECHNIQUES FOR LOW ELEC--ETC(U)

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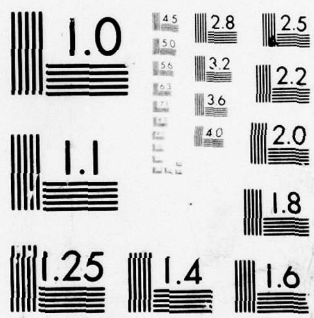
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RADC-TR-79-224
Final Technical Report
September 1979

ROME AIR DEVELOPMENT CENTER

ADVANCED RADAR DETECTION AND PROCESSING TECHNIQUES FOR LOW ELECTROMAGNETIC SCATTERING TARGETS

Teledyne Micronetics

Lee A. Morgan
Steven Weisbrod, Ph.D.

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ROME AIR DEVELOPMENT CENTER
Air Force Systems Command
Griffiss Air Force Base, New York 13441

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Radar cross section measurements were made on Teledyne Micronetics' Radar Range using C-band one nanosecond pulses. The radar target was made up of retrodirective Luneberg lenses variously deployed on a turntable. The number of lenses varied from two to six.

For each deployment of targets, the impulse response was experimentally determined with the help of a sampling scope and the complex conjugate of this

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impulse response was synthesized using power splitters and delay lines. This signal was then transmitted and the RCS enhancement was measured by reducing the level of the transmitted power until the maximum response was equal to a previously established reference level. Subsequently additional power splitters and delay lines were utilized to synthesize matched receiver response and a similar comparison technique was used to measure the increase in the RCS.

The configurations which were tried included equal and unequal spacings and path geometries where the individual reflecting centers were separable and cases where they overlapped.

The observed value of RCS enhancement were compared with the theoretical values and it was demonstrated that the agreement between the two values was in general well within one dB.

PREFACE

This is the Final Report prepared under the Rome Air Development Center Contract No. F30602-78-C-0163. The program was administered by Mr. Daniel Tauroney, RADC/OCTM.

The Project Manager for this effort was Dr. Steven Weisbrod, the Company's Chief Scientist. Other key personnel involved in this program were Mr. Lee A. Morgan, Senior Analyst, Mr. Warren Fey, Director of the Teledyne Micronetics' Radar Range, and Mr. William Hernon, Radar Range Engineer.

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EVALUATION

The contractor was successful in transmitting the targets response function and this maximized the energy in the back-scatter direction. The transmission was changed as a function of aspect angle and resulted in enhancement which was to within a decible of theoretical values.

This will provide better signal to noise ratios for detection and identification of aircraft and missiles. The results are applicable to TPO 2E.

Daniel L. Tauroney

DANIEL L. TAURONEY
Project Engineer

SECTION I

INTRODUCTION

1.1 GENERAL OVERVIEW

This is the Final Technical Report prepared under RADC Contract No. F30602-78-C-0163 to carry out experimental verification of Advanced Radar Detection and Processing Techniques for Low Electromagnetic Scattering (LEMS) Targets.

The theory for enhancement of detection of LEMS targets has been investigated by Purdue University under RADC Contract No. F30602-75-C-0082 and results of that study are described in RADC Report TR-788-89.

Other aspects of this problem have also been studied by Mr. Paul Van Etten of RADC and are described in the RADC Technical Report by Mr. Van Etten entitled Radar Target Cross Section Enhancement by Space-Time Processing (report is dated August 9, 1977).

The theory shows that a considerable enhancement of the radar cross section can be achieved if the transmitted wave is the complex conjugate of the impulse response. Further increase in the RCS can be obtained if similar technique is utilized in processing the received signal.

A number of experimental tests were performed using two to six reflecting centers with equal and unequal spacing and utilizing path geometries where the individual responses were and were not separable. It was demonstrated that theoretical increases in the radar target visibility are achievable and consequently it appears that this approach should lead to a considerable enhancement in the detectability of LEMS targets.

1.2 SUMMARY

Radar cross section measurements were made on Teledyne Micronetics' Radar Range using C-band one nanosecond pulses. The radar target was made up of retrodirective Luneberg lenses variously deployed on a turntable. The number of lenses varied from two to six.

For each deployment of targets, the impulse response was experimentally determined with the help of a sampling scope and complex conjugate of this impulse response was synthesized using power splitters and delay lines. This signal was then transmitted and the RCS enhancement was measured by reducing the level of the transmitted power until the maximum response was equal to a previously established reference level. Subsequently additional power splitters and delay lines were utilized to synthesize matched receiver response and a similar comparison technique was used to measure the increase in the RCS.

The configurations which were tried included equal and unequal spacings and path geometries where the individual reflecting centers were separable and cases where they overlapped.

The observed value of RCS enhancement were compared with the theoretical values and it was demonstrated that the agreement between the two values was in general well within one dB.

Since the potential RCS enhancement for matched receiver or transmitter is equal to the number of reflecting centers (assuming equal magnitudes) and can approach the square of this number for matched receiver and transmitter (matched transceiver) a very substantial enhancement in target detectability is possible especially with complex targets.

The experimental verification of the basic concepts paves way for the next stage of investigation which is aimed at the eventual development of an adaptive system capable of synthesizing in real time the complex conjugate of the impulse response for transmitting and/or matched filler response for receiving.

SECTION II

THEORY

2.1 GENERAL CONSIDERATIONS

The radar return from a complex target which may be represented by a set of simple isolated scatters can be enchanced by properly choosing the radar signal and receiver impulse response.

In order to determine the "best" signal and receiver it is first necessary to define the criteria by which they are to be judged. In this study we have used the maximum signal to noise ratio at the receiver output subject to a constant transmitted energy as the criterion. To make this criterion more precise we define the following quantities:

$e(t) \equiv$ transmitted signal,

$s(t) \equiv$ signal input to receiver,

$r(t) \equiv$ signal output from receiver,

and $n(t) \equiv$ noise output from receiver.

The quantity we wish to maximize is SNR which is given by

$$\mathrm{SNR} = [\mathrm{Max}(r^2)/\int_{-\infty}^{\infty} e^2(t)dt]/\langle n^2\rangle \qquad (1)$$

when $\langle n^2\rangle$ is the expectation of the noise power. We make the usual assumptions that the noise is stationary and independent of the signal. In order to make explicit the role played by the target and receiver we introduce their respective impulse responses h and k. In terms of these impulse responses the following relationships may be established:

$$s(t) = \int_{-\infty}^{\infty} e(\tau)h(t-\tau)d\tau, \qquad (2)$$

and $$r(t) = \int_{-\infty}^{\infty} s(\tau)k(t-\tau)d\tau. \qquad (3)$$

Parts of the remainder of this discussion will be simplified by introducing the spectral representations of each of the above quantities which we will denote by the corresponding upper case symbol. Thus:

$$e(t) = (1/2\pi)\int_{-\infty}^{\infty} E(\omega)\exp(j\omega t)d\omega$$

where $E(\omega)$ is the complex frequency spectrum of the signal $e(t)$. The expected noise power which appears in Equation 1 can be expressed in terms of the input noise spectral density (N^2) and the receiver impulse response as follows*:

$$\langle n^2 \rangle = (1/2\pi)\int_{-\infty}^{\infty} N^2 |K(\omega)|^2 d\omega \tag{4}$$
$$= N^2 \int_{-\infty}^{\infty} |k(\tau)|^2 d\tau$$

where the last form follows from the first by Parseval's Theorem.

It is well known that the maximum signal-to-noise ratio is obtained if the receiver is matched to the signal. In other words, if $k(t) = s(T-t)$ then the signal-to-noise ratio will be maximum at $t=T$ and this will be the largest possible value. Thus:

$$SNR \leq \int_{-\infty}^{\infty} s^2(t)dt / [N^2 \int_{-\infty}^{\infty} e^2(t)dt] \tag{5}$$

with equality holding only if the receiver is a matched receiver. The University of Purdue studies have denoted the right hand side of Equation 5 (without the constant N^2) by the symbol R and have defined the optimum signal as one which maximizes this quantity. In this program we have included cases for which the receiver is not matched (and the results therefore suboptimum in the strict sense) and investigated signals which maximize Equation 1. In particular, it will be shown that the signal which maximizes Equation 1 when the receiver characteristics are fixed is not necessarily the same as that which maximizes Equation 5.

In the remainder of this discussion we will confine ourselves to targets which consist of a number of discrete point scatters. In the case of M scatterers the target impulse response h, is given by

$$h(t) = \sum_{1}^{M} a_m \delta(t-\tau_m) \tag{6}$$

where a_m is the scattering amplitude of the mth scatterer. With this restriction, the signal input to the receiver becomes

$$s(t) = \sum_{1}^{M} a_m e(t-\tau_m). \tag{7}$$

---

* c.f. M. Schwartz, W. Bennett, and S. Stein, "Communication Systems and Techniques", McGraw Hill Book Co., New York, 1916. Chapters 1 and 2.

The reference system to which all other systems will be compared is one which has a single, very short, transmit pulse of unit energy and a receiver that is matched to the transmitted pulse shape (i.e., $k_o(t) = e_o(T-t)$. The reference signal-to-noise ratio is SNR_o and is given by

$$SNR_o = Max(a_m{}^2)/N^2. \tag{8}$$

This utilizes the fact that the pulses are so short that

$$\int_{-\infty}^{\infty} e_o(t-\tau_m)e_o(t-\tau_\ell)dt = \begin{matrix} 0 \\ 1 \end{matrix} \text{ if } \begin{matrix} \ell \neq m \\ \ell = m \end{matrix} \tag{9}$$

We will consider three cases, the "matched receiver", "matched transmitter", and "matched transceiver."

2.2 MATCHED RECEIVER

The matched receiver system is one in which a single short pulse is transmitted and the receiver is designed to maximize Equation 1. In this case, the input to the receiver, s(t), is just an approximation of the target impulse response, h(t), and Equation 1 is maximized by matching the receiver to this signal. The optimum receiver impulse response is therefore given by

$$k(t) = h(T-t).$$

The transmit pulse is that of the reference system and the signal-to-noise ratio therefore becomes

$$SNR = \sum_1^M a_m{}^2/N^2$$

for the matched receiver. The matched receiver gain, defined as the ratio of the SNR for this system to that of the reference system, is denoted by G_R and is given by

$$G_R = \Sigma a_m{}^2/Max(a_m{}^2) \leq M \tag{10}$$

where equality holds only if all of the target scatters have equal amplitudes.

2.3 MATCHED TRANSMITTER

The matched transmitter case is one in which the transmitted signal is chosen to maximize the SNR when the receiver is the reference receiver $(k(t) = k_O(t))$. The signal out of the receiver can be written in general as

$$r(t) = \int_{-\infty}^{\infty} k(t-\tau)\left[\int_{-\infty}^{\infty} e(u)h(\tau-u)du\right]d\tau \qquad (11)$$

$$= \int_{-\infty}^{\infty} e(u)\left[\int_{-\infty}^{\infty} h(\tau-u)k(t-\tau)d\tau\right]du$$

$$= \int_{-\infty}^{\infty} e(u)f(t-u)du$$

where $f(t) = \int_{-\infty}^{\infty} h(\tau)k(t-\tau)d\tau.$ (12)

In the matched transmitter case both the target and receiver impulse responses are fixed so that the total energy in f(t) is a constant. With these factors in mind then we can express the SNR as

$$\mathrm{SNR} = A\ \mathrm{Max}\ \{(e*f)^2\}/\left[\int_{-\infty}^{\infty} e^2(t)\ dt \int_{-\infty}^{\infty} f^2(t)dt\right] \qquad (13)$$

where the constant, A, is given by

$$A = \int_{-\infty}^{\infty} f^2(t)dt/\left[N^2 \int_{-\infty}^{\infty} k_o{}^2(t)dt\right].$$

The signal which maximizes Equation 12 is the time inverse of the function f. Thus, for the matched transmitter case the optimum signal is given by

$$e(t) = f(T-t) = \sum_{1}^{M} a_m e_o(t-T_o+\tau_m) \qquad (14)$$

and the gain, G_T, is found to be

$$G_T = \sum_{1}^{M} a_m{}^2/\mathrm{Max}(a_m{}^2) \qquad (15)$$

which is equal to the matched receiver gain.

2.4 MATCHED TRANSCEIVER

The matched transceiver problem is one of determining the optimum transmitted waveform where the receiver is matched. As shown above, when the receiver is matched the SNR is maximized by the same signal that maximizes the ratio of signal energy input to the receiver to signal energy transmitted which is the quantity R used in the Purdue studies.

The quantity which we wish to maximize is

$$R = \int_{-\infty}^{\infty}\left\{\sum_{1}^{M} a_m e(t-\tau_m)\right\}^2 dt/\int_{-\infty}^{\infty} e^2(t)dt \qquad (16)$$

Using the spectral representation of e this can be rewritten as

$$R = \sum_{1}^{M}\sum_{1}^{M} a_\ell a_m \int_{-\infty}^{\infty} |E(\omega)|^2 \cos[\omega(\tau_\ell - \tau_m)]\,d\omega \Big/ \int_{-\infty}^{\infty} |E(\omega)|^2 d\omega \quad (17)$$

A general solution of these equations is not known. If however the signals are limited to those with discrete frequency spectra (which is true of all idealized pulse radar systems) then the problem simplifies somewhat. Assume that the signal has a line spectrum such that

$$\int_{-\infty}^{\infty} |E(\omega)|^2 f(\omega)\,d\omega = \Sigma b_i f(\omega_i) \quad (18)$$

Then the energy ratio, R, becomes

$$R = \sum_{1}^{M} a_\ell \sum_{1}^{M} a_m \Sigma b_i \cos[\omega_i(\tau_\ell - \tau_m)] / \Sigma b_i$$

$$= \Sigma b_i \left|\sum_{1}^{M} a_m \exp(j\omega_i \tau_m)\right|^2 / \Sigma b_i \quad (19)$$

Since the b_i are all positive (they are the energy at the corresponding frequency) it follows that the energy ratio given by Equation 19 is less than or equal to $(\Sigma|a_m|)^2$ with equality holding only if $\omega_i\tau_m$ is a constant modulo 2π for all m. Satisfying this requirement is possible only if the relative delays (i.e., $\tau_m - \tau_1$) are integral multiples of some constant τ_0. Since this implies that the ratios of relative delays will be rational numbers it is not in general possible to satisfy this requirement.

It is conjectured, but has not been proven, that for a given target, the maximum value of R may be approached within an arbitrarily small error with an arbitrarily defined probability less than one if the frequencies f_i are not restricted. To show that this is plausible consider the following argument.

The ratio of R to the maximum possible R is greater than or equal to $1-\varepsilon$ if

$$a_m \cos[\omega_i(\tau_m - \tau_1)] \geq |a_m|(1-\varepsilon)$$

for all m which in turn is true if

$$2f_i(\tau_m - \tau_1) = N_m + \delta_m. \quad (20)$$

where N_m is an even or odd integer depending upon whether a_m

is positive or negative and $|\delta_m| \leq \Delta$ where $\cos(\pi\Delta) = 1-\varepsilon$.

The conjecture is that there exists at least one f_i satisfying Equation 20 and the related conditions. This may be a surprisingly high frequency however. For example, consider four targets with delays 0, $1/\pi$, $1/e$, and $1/\sqrt{2}$. Let $\Delta = 0.1$ ($1-\varepsilon = .95 = -0.44$dB). Then the conjecture is that there exists an f_i such that the three numbers f_i/π, f_i/e, and $f_i/\sqrt{2}$ when rounded to 1 decimal place are integers. The smallest nontrivial f (not zero) clearly is of the order of π. The smallest solution however, is 100.45. Thus, if the spacings were in nanoseconds, one would begin looking for an "optimum" frequency near 3 GHz but would not be certain of finding one below 100 GHz even with the optimum frequency defined as one with a response 0.4 dB below the theoretical maximum.

If the digits of each delay when written in a number system base $1/\Delta$ are random one could compute the probability that the first digit after the "decimal point" is zero for M-1 products formed by multiplying these delays by an arbitrary number f and from this deduce how large f must be before at least one set of products will "round" to zero remainder. We have not performed such calculations, but it is clear that the frequency required to guarantee a given result may increase rapidly as the number of targets increases.

When the relative delays are all multiples of a constant τ_o then the energy ratio given by Equation 19 becomes equal to its maximum possible value for an infinite number of transmitted signals. In fact, any signal of the form

$$e(t) = \Sigma b_n \cos[2n\pi t/\tau_o + \phi_n] \tag{21}$$

is an optimum signal in the sense that it maximizes Equation 19.

It should be noted that the long pulse CW signal considered in the Purdue studies is a member of this set but the "matched transmitter" signal considered in the previous section is not (this becomes obvious when one notes that the signal given by Equation 21 is of infinite duration whereas the matched transmitter signal is of finite duration.

When the transmit signal is constrained to be a series of pulses spaced τ_o apart (some of the pulses may have zero amplitude) the energy ratio becomes

$$R = [\sum_{1}^{M} a_{m_1} \Sigma a_n \Sigma c_\ell c_{\ell-m+n}]/\Sigma c_\ell^{\,2} \qquad (22)$$

where $e(t) = \Sigma c_\ell e_o(t-\ell\tau_o)$.

Even with the restriction that the pulse sequence will be no longer than the target impulse response the matched signal is not optimum although it is very nearly so.

If all of the targets are of equal amplitude and the transmitted pulse train consists of equal amplitude pulses with the number of pulses (N) equal to or greater than the number of targets (M) the energy ratio is given by

$$R_N = \{(N-M)\ M + (2M^2+1)/3\}(M/N) \qquad (23)$$

One should note that for N much greater than M, R approaches the optimum value of M^2 while for large M the matched signal (R_M) approaches $(2/3)M^2$ (-1.76 dB) from above. This means that the matched signal is always within 1.76 dB of the optimum for a target which consists of equal amplitude, equally spaced targets. If the pulse train is made twice as long as the target impulse response Equation 23 shows that the output SNR is 0.79 dB less than the maximum, so that increasing the number of pulses past the matched signal point improves the system performance only slowly.

When the pulse spacings are unequal, but still related by rational numbers, the matched transceiver result can be considerably worse than one might expect. If all of the targets are of equal amplitude but no two spacings are equal, the signal input to the receiver when the matched transmitter is used will consist of M(M-1)/2 unit amplitude pulses, a pulse of amplitude M, and another M(M-1)/2 unit pulses. The pulse train will be symmetric in time. It is a simple matter to show that the system gain is 2M-1 which is considerably less than the optimum gain of M^2 and is less than 3 dB better than the matched receiver (or matched transmitter) gain of M.

As the number of pulses in the transmitted signal is increased, the system gain will also increase, asymptotically approaching that of the optimum system.

In this study, the matched transceiver measurements used only systems employing the matched signal and were therefore suboptimum from the strict standpoint.

2.5 COMPARISON WITH A LONG PULSE SYSTEM

The reference system used in this study is a short pulse radar. Most conventional radars employ pulses which are long compared with the target impulse response. The energy ratio (and peak SNR since this is a system with a matched receiver) is given by Equation 19 with only one frequency component. That is,

$$R_c = \left|\sum_1^M a_m \exp(j\omega_o\tau_m)\right|^2 \qquad (24)$$

where the subscript c denotes "conventional." If all of the amplitudes are approximately equal and the delays (phases) are random it can be shown that the signal represented by the summation in Equation 24 has an envelope that is very nearly Rayleigh distributed for M as small as 6 (c.f., Schwartz et. al. loc. cit. Chapter 9).

Without any knowledge of the target structure one can assume that the phases in Equation 24 will be random for any arbitrary frequency. The mean value of R_c then will become

$$\langle R_c \rangle = \sum_1^M a_m^2$$

which is the same as the maximum SNR for the matched transmitter or matched receiver case discussed previously. Thus, if one chooses a frequency arbitrarily and uses a long pulse system he will do as well half the time as the matched transmitter or matched receiver system. There is also however a good probability that the long pulse response will be much worse. Using the Rayleigh distribution approximation one finds that there is a 25% probability that the long pulse system response will be 3.8 dB or more down and a 10% probability that it will be 8.2 dB or more below that of the matched transmitter system.

Because of this uncertainty in response of a long pulse system to a complex target it is not really meaningful to use the long pulse system as a reference to compare other systems with. It is for this reason that we chose to use a short pulse system for a reference.

SECTION III

MEASUREMENTS

3.1 MEASUREMENT SYSTEM

The measurement system block diagram is shown in Figure 1. The system operation is described in the remainder of this section.

The HP 8620C operating in its CW mode produces a 6 GHz signal.

The HP 215A produces a 1 nsec. video pulse which drives the "I" port of the RELCOM double balanced mixers. It also provides the sync trigger for the oscilloscope and Data Pulse 101 pulse generator.

The 6 GHz is fed to the "R" port of the first RELCOM mixer. When the video pulse correctly biases the mixer, RF is allowed to pass through from the R to L ports thus producing a RF pulse of 1 nsec. A second mixer is used in series to provide sufficient pulse "on to off ratio." The 1 nsec. pulse is next fed to an 8-way power splitter. Each successive port is then delayed by an appropriate amount of time*, and the channels are added back together in another 8-way splitter. Channel number 8 has an attenuator on its output, and can be fed directly to the TWT amplifier for single transmit channel applications.

The summed pulses are next fed to a 10W TWT amplifier to provide sufficient transmit power. The 10 watt pulses are fed through an RF switch which is turned on only long enough for the pulses to pass through and then turned off to eliminate CW TWT noise from the receiver. A second switch is provided for additional TWT noise suppression. These switches are operated at the correct time by the Data Pulse 101 which is synchronized by the HP 215A.

The transmit pulses are next fed through a variable W.G. attenuator and a 30 db coupler. The attenuator controls the transmit signal level and the coupler is for the purpose of monitoring this level.

A circulator provides duplexing for the 4 foot parabolic antenna which is horizontally polarized.

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* The time delays are determined by the target spacings.

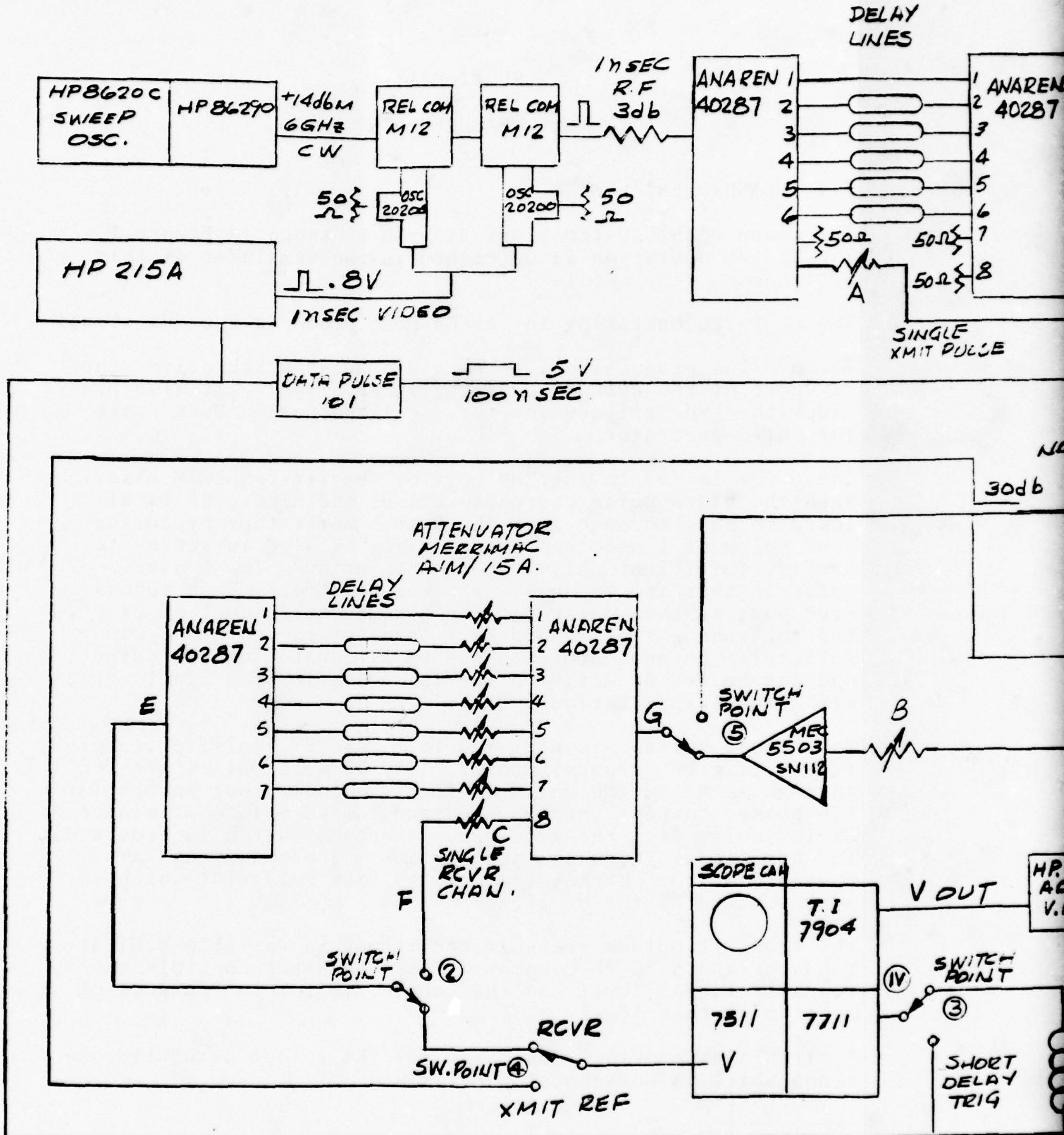
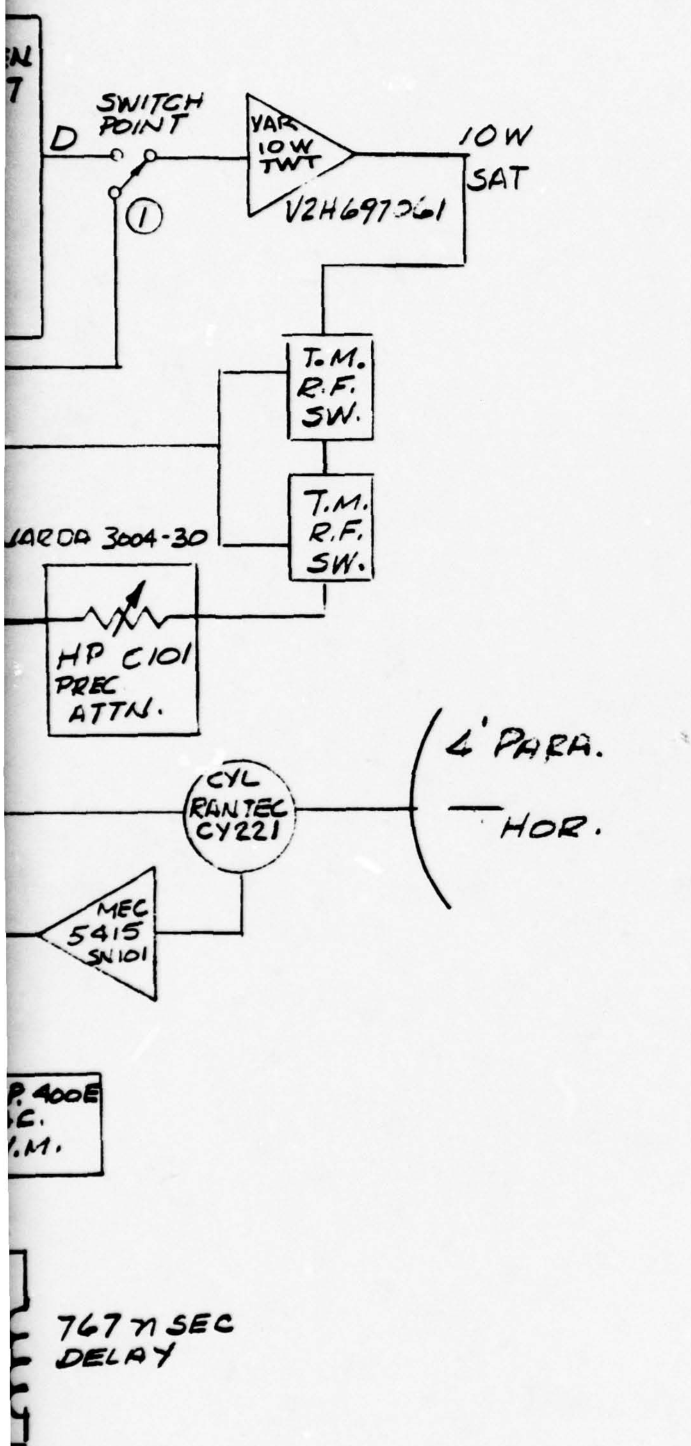


FIGURE 1 MEASUREMENT SYSTEM BLOCK DIAGRAM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VAR 10W TWT
V2H697061
10W SAT
T.M. R.F. SW.
T.M. R.F. SW.
NARDA 3004-30
HP C101 PREC ATTN.
4' PARA.
HOR.
CYL RANTEC CY221
MEC 5415 SN101
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767 n SEC DELAY

2

The received signals are amplified through two TWT's with an attenuator between them to set noise levels in the receiver. The received signal is next fed to another 8-way splitter and each additional channel is also passed through an attenuator for the purpose of setting appropriate receiver channel gains. Channel 8 can be fed directly to the oscilloscope vertical input for single receive channel applications. For matched receiver applications, the other seven channels are added back together in another 8-way splitter.

The receive pulse chain is then fed to the vertical oscilloscope input. The sampling trigger is provided directly to the oscilloscope for the purpose of viewing "early" events from the 215A. The trigger is also delayed 767 nsec. to provide a fixed time delay to enable the viewing of "later" events (i.e., target returns from a 600' range) without relying on long electronic scope trigger delays which are not sufficiently stable for viewing. One or 2 nsec./cm time bases are used.

The vertical output of the scope is fed to a 400E AC voltmeter as a convenient method of measuring scope deflection. A camera is provided for taking pictures of the transmitted and received pulse trains.

The targets were placed on a foam support structure 600' away from the antenna and were 10 square meters cross section lenses with 120° monostatic radar beamwidths.

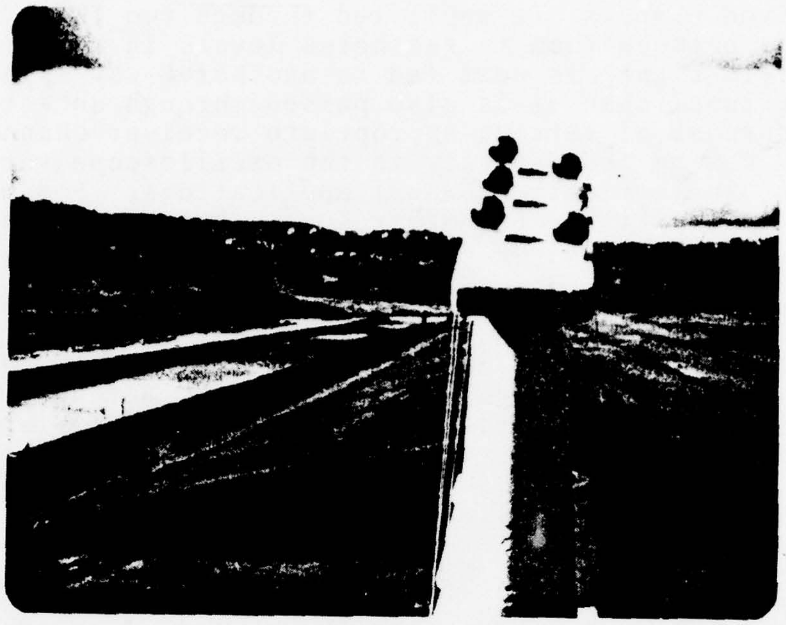
Five target configurations were measured at two aspect angles (0 and 60 degrees). The target configurations consisted of 2, 3, 4, 5, and 6 equally spaced scattering centers. Figure 2 shows the 6 target configurations at the two aspects. As will be noted, at 0° aspect the targets had to be staggered horizontally in order to avoid shadowing by the front targets.

A sixth configuration with three unequally spaced targets was measured at the 60 degree aspect angle. This configuration is shown in Figure 3.

At 0 degrees aspect the targets were spaced one foot in range (2 nsec. in delay) and at 60 degrees the spacing was 6 inches (1 nsec. delay).

3.2 MEASUREMENT PROCEDURES

The measurements, reduced to the simplest form, consisted of determining for each configuration the average transmitted



(a)

(b)

Figure 2 Equally Spaced Target Configuration
a) 0° Aspect; b) 60° Aspect

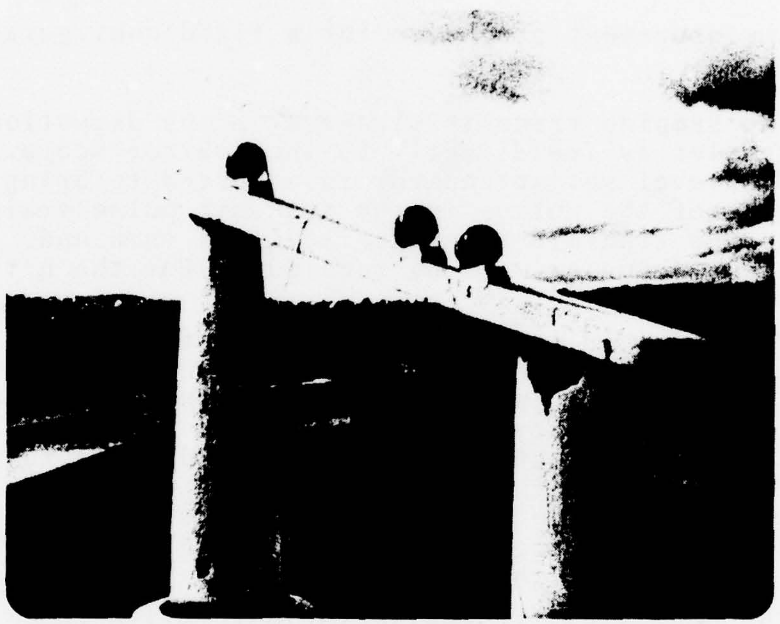


Figure 3 Unequally Spaced Target Configuration

power required in order to produce a specified peak signal-to-noise ratio at the receiver output. The "gain" of a configuration is defined by the ratio of the average power for a single transmit pulse-single receiver channel short pulse system to the average power for the configuration under test. It is to be noted that this is equal to the improvement, under a constant average power constraint, in the peak signal-to-noise ratio when compared to a conventional short pulse system. It is not, however, the improvement when compared to a conventional long pulse system for the reasons discussed in Section 2.5.

The actual measurement procedure for a fixed configuration was as follows:

1. The sampled transmit signal from the directional coupler is fed directly to the monitor scope. The level set attenuator is adjusted to bring each of the pulses in the transmit pulse train to the transmit reference level in turn and the attenuator setting recorded. For the n'th pulse this is T_n.
2. The receiver output is then connected to the monitor scope and the receiver gain set attenuator is adjusted to bring the noise to the noise reference level.
3. The level set attenuator is then adjusted to bring each of the received pulses to the receive reference level in turn and the attenuator setting recorded. For the n'th receive pulse this is R_n.
4. The peak signal-to-noise ratio relative to the reference system and subject to a constant average power constraint is computed from

$$SNR = Max(R_n)/\Sigma(T_n).$$

As part of the permanent record pictures of the oscilloscope displays were taken. The quantitative analysis was however performed by using the readings on the AC voltmeter when the oscilloscope was placed in the manual sweep mode and the horizontal position set to the desired pulse location (or a location containing only noise when appropriate).

The setting and maintaining of the receiver noise level to the reference value was the major continuing source of uncertainty. It is estimated (based upon attempts to reset the level repeatedly while holding all other parameters constant) that the setting of the receiver noise level introduces an uncertainty of ± 0.5 dB. There were also occasions when the RF gain of one of the receiving TWT's was observed to apparently vary by as much as 1 dB in a short time period. These errors are nonsystematic and should cause a zero mean error.

The major systematic error lies in adjusting the phases of the transmit pulses and receiver channels. The phases were adjusted by setting up a situation where a pulse from the line being adjusted is coincident with a single pulse from a previously adjusted line. The length of the new line was adjusted to maximize the sum. This is however, difficult to do with an error of much less than 0.5 dB which corresponds to a 30 degree phase error. It is believed that most of the time the individual phases were adjusted somewhat better than this. The effect of line length errors is to systematically reduce the system gain below theoretical.

The most serious intermittent problem that was encountered was an echo that appeared from time to time on the transmitted pulse. This echo, which was about 10-15 dB below the pulse and delayed about 1 nanosecond, originated in the connection to the circulator. When this echo was present the apparent system gain could be either increased or decreased by several dB depending upon the phase of the echo relative to the pulse. The presence of the echo could not be detected when the transmitted signal was examined since it occurred after the coupler used to sample it. When present however, the echo substantially distorted the symmetry of the received pulse train and this echo was not present when the data contained in this report was taken, but the existence of smaller echoes whose effects were not so obvious cannot be ruled out.

An ever present possibility of error is the human element. The data was taken by adjusting an attenuator to obtain a predefined meter reading and manually recording the attenuator setting. Misreading the meter or attenuator or writing down the wrong number is always a possibility.

3.3 DATA ANALYSIS

3.3.0 GENERAL DISCUSSION

Table I contains the measured and computed gains for the different configurations tested. In a few of the cases the

TABLE I DATA SUMMARY

Configuration	Number			Gain (dB)		Figure
	Targets	Rcvr.	Xmit	Meas.	Theory	
0° Aspect Equal Spacing	2	2	1	3.9	3.0	
	2	1	2	3.5	3.0	81
	2	3	2	4.3	4.8	82
	3	3	1	5.3	4.8	
	3	1	3	4.3	4.8	43
	3	5	3	8.1	8.0	44,84
	4	4	1	5.9	6.0	
	4	1	4	6.1	6.0	45
	4	7	4	9.7	10.4	48
	5	5	1	6.9*	7.0	51
	5	1	5	7.1	7.0	49,50
	5	7	5	12.0	12.2(12.3)	52
	6	6	1	6.5	7.8	58,59,67,68
	6	1	6	7.0	7.8	64
	6	7	6	12.9	13.6(13.9)	65,66
60° Aspect Equal Spacing	2	2	1	3.9	3.0	
	2	1	2	2.0	3.0	
	3	3	1	6.2	4.8	
	4	4	1	6.7	6.0	
	4	1	4	5.9	6.0	
	5	5	1	7.5	7.0	79
	5	1	5	6.7	7.0	75
	5	7	5	11.8	12.2	77
60° Aspect Unequal Spacing	3	3	1	3.5	4.8	
	3	1	3	4.8	4.8	
	3	6	3	4.2	6.7(7.0)	

* Value Corrected for Apparent Gross Error. See Text.

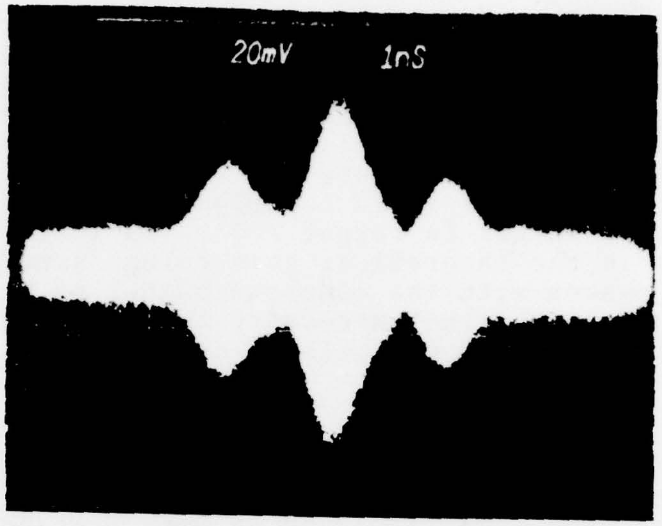
measured gains are averages of two or more measurements. Most, however, represent a single determination.

As discussed previously, the gain as defined here is the maximum signal-to-noise ratio of the test system divided by the maximum signal-to-noise ratio of a single transmit-single receive channel short pulse system with the same average transmitter power. The tabulated results are corrected for the fact that the targets were not all of equal amplitude due to factors such as field taper and partial shadowing as well as actual target to target RCS variation. The values in parenthesis in the theoretical gain column are those that apply to a system with the complete number of receiver channels. Clearly, it is not necessary to implement all of the theoretically required channels to achieve essentially all of the theoretical gain.

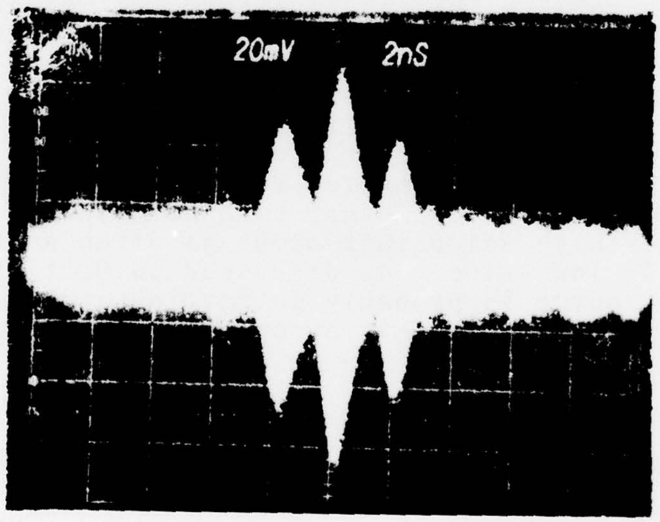
For all of the data taken together, the mean difference between measurement and theory is -0.20 dB with a standard deviation of 0.79 dB. When the unequal spacing cases are excluded the mean error is -0.09 dB with a standard deviation of 0.65 dB. The equally spaced cases with 2 or 3 targets have a mean error of 0.26 dB and a standard deviation of 0.79 dB while the corresponding values for the 4, 5, and 6 target configurations are -0.19 dB and 0.45 dB respectively. Since the standard deviation of the errors is essentially independent of the number of targets and the mean error is quite small it is probable that these errors are primarily associated with the method used to obtain the data rather than with the implementation of the matched system concept. Almost all errors associated with the matched system implementation will decrease the receiver SNR. If these errors were significant therefore, one would expect the observed gain to be systematically less than the computed value. Most of the measurement system errors on the other hand are such as to lead to an apparently high value just about as often as they lead to an apparently low value. As discussed in Section 3.2, the major error source is probably in setting and maintaining the receiver noise with this error accounting for at least $\pm$ 0.5 dB of the total.

3.3.1 EQUALLY SPACED TARGETS

Figures 4 through 8 show pulse sequences for various configurations at 0° aspect. At this aspect the delay between targets is 2 nanoseconds and they are fully resolvable with the 1 nanosecond pulse.

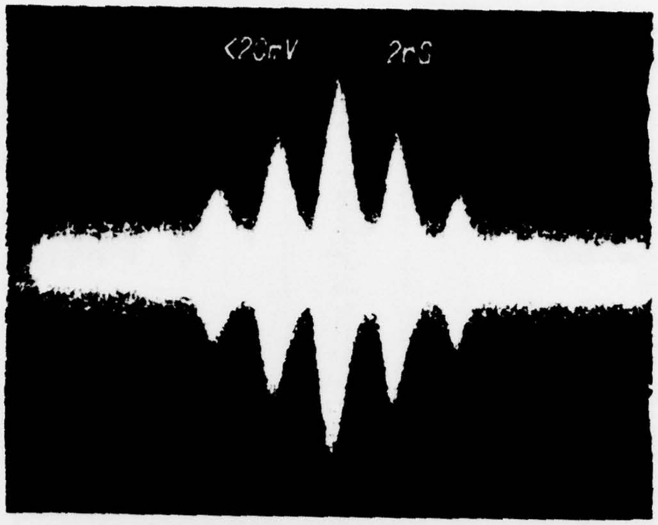


(a)

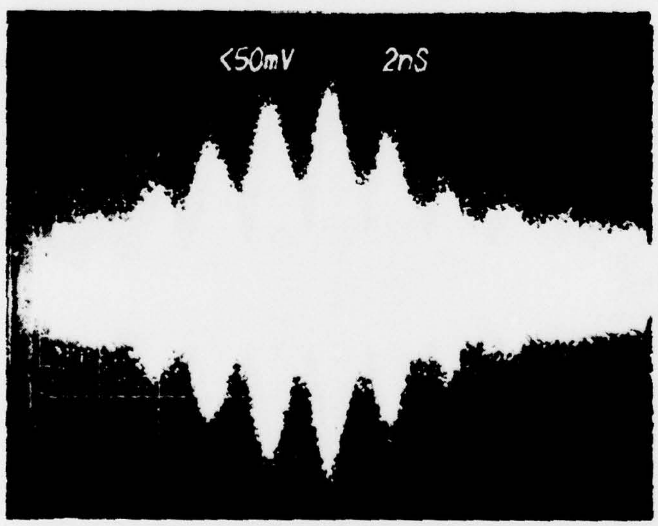


(b)

Figure 4 Two Target Configuration, 0° Aspect
a) Matched Transmitter; b) Matched Transceiver

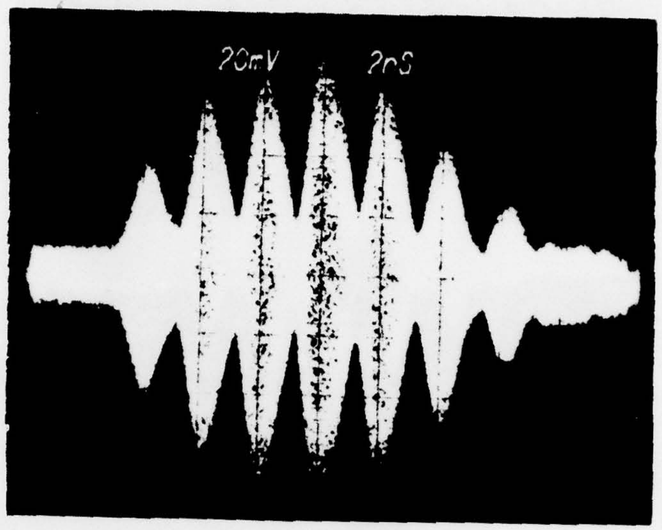


(a)

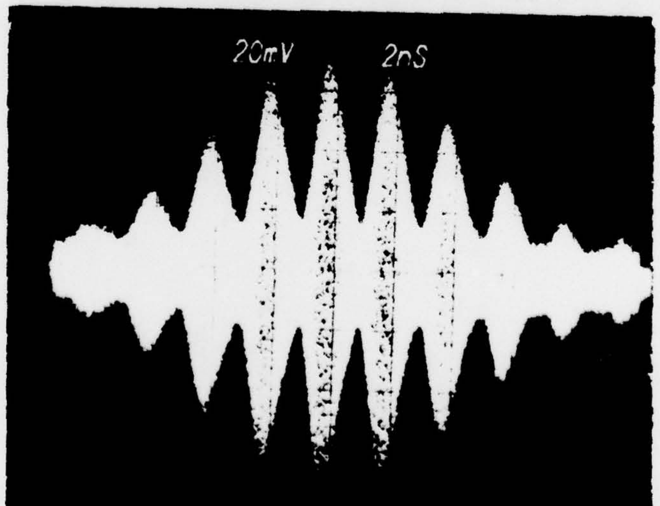


(b)

Figure 5 Three Target Configuration, 0° Aspect
a) Matched Transmitter; b) Matched Transceiver

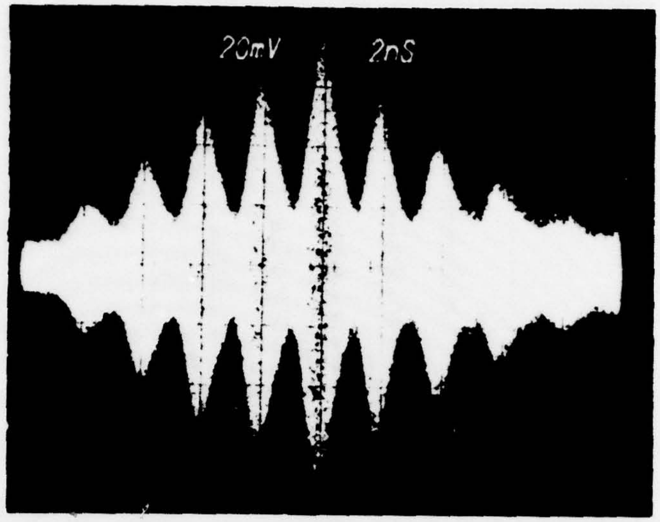


(a)

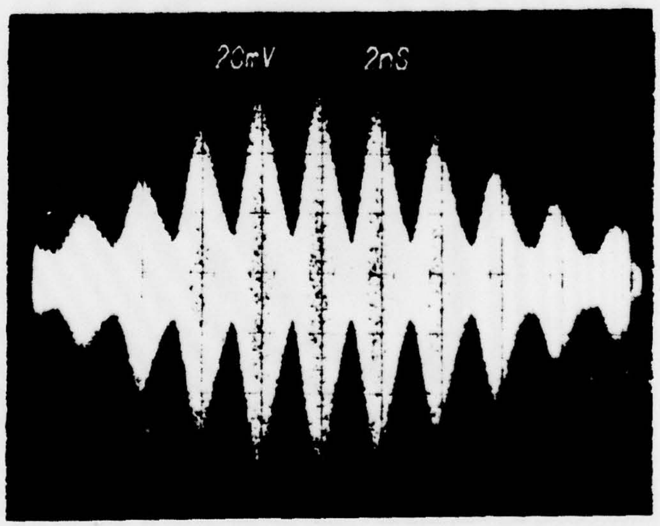


(b)

Figure 6 Four Target Configuration, 0° Aspect
a) Matched Transmitter; b) Matched Transceiver

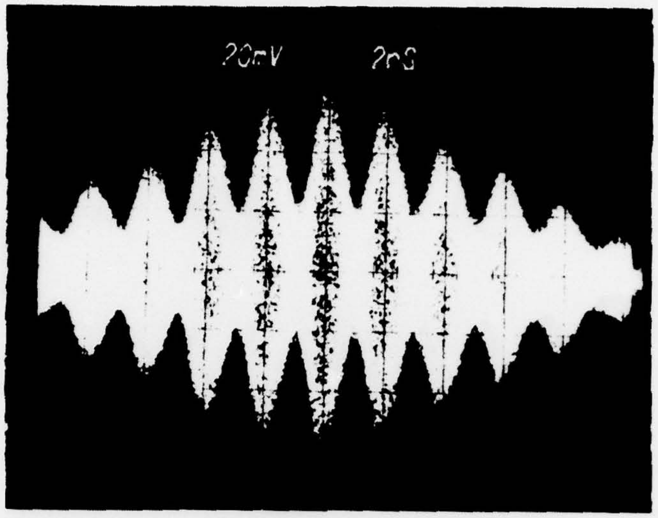


(a)

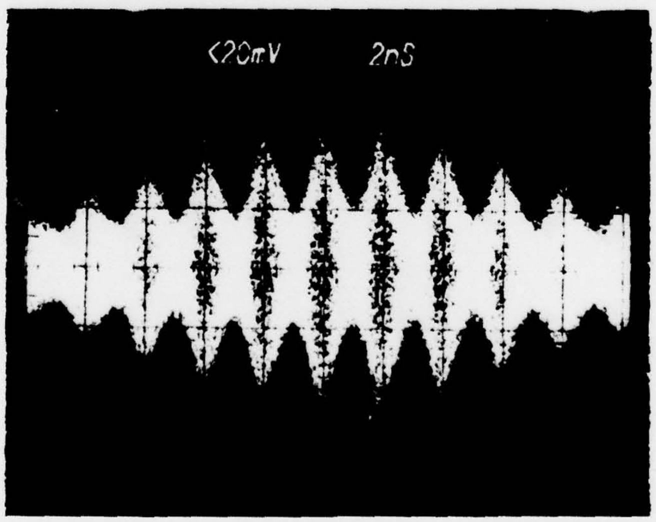


(b)

Figure 7 Five Target Configuration, 0° Aspect
a) Matched Receiver; b) Matched Transceiver



(a)



(b)

Figure 8 Six Target Configuration, 0° Aspect
a) Matched Receiver; b) Matched Transceiver

Generally, the relative amplitudes of the pulses agree very well with the computed values when the actual target cross sections and transmitted pulse powers are used.

As a simple example consider the two target configurations shown in Figure 4. The transmit powers were 13.0 and 12.0 dB respectively and the target cross sections were -6.6 and -7.0 dB respectively.* For the matched transmitter (Figure 4a) the computed pulse levels are 6.4, 11.7, and 5.0 dB respectively while the corresponding measured levels were 6.6, 12.6, and 5.9 dB. For the matched transceiver (Figure 2b) the three largest pulses are computed to be 10.3, 13.5, and 9.6 dB and were measured as 9.2, 13.5, and 9.0 dB.

Examples of the comparison between measurement and theory for a complex configuration are contained in Table II. The agreement for this configuration (6 targets) is in general good except for a few of the pulses in the matched transmitter case. An alternative computation assuming a 45 degree phase error for both the closest target and last transmitter pulse is also included in the table. This agrees somewhat better with the measurements and illustrates the magnitude of effects that can be expected when moderate phase errors add in a worst case mode. Notice that of the higher amplitude pulses only one is changed by more than 0.5 dB by these assumed phase errors.

As indicated by the footnote to Table I, the matched receiver data for the five target configuration has been adjusted for an apparent gross error. The computed and measured pulses for this case are (in dB)

Computed:	-2.6	3.5	6.6	8.9	10.7	8.6	5.7	2.1	-4.0
Measured:	0.0	6.4	9.8	11.4	13.2	10.4	7.5	3.5	?

There is clearly a bias (gross error) in the measured values. Since the first pulse in the sequence is just the single pulse-single receiver channel response of the first target it could have been used to define the reference system for gain computations. When this is done and the result corrected for the noise level change due to the five receiver channels (-7 dB) and the fact that not all of the targets are the same amplitude (+0.7 dB) the value given in Table I is obtained.

---

* In these discussions, the transmit powers and target cross sections are in dB relative to references which are fixed for a given configuration but are otherwise arbitrary.

TABLE II COMPARISON OF COMPUTED AND MEASURED PULSE TRAINS
0° Aspect, 6 Equally Spaced Targets

Conf.		PULSE AMPLITUDE (dB)										
Matched Trans.	Meas		6.4	11.4	13.0	15.8	17.0	15.7	14.7	12.0	10.0	6.5
	Comp		5.5	10.4	13.3	15.0	16.5	17.7	15.4	13.1	10.0	6.2
	Comp*		5.5	9.7	12.7	14.5	16.1	16.4	15.0	12.6	9.4	5.5
Matched RCVR	Meas		3.4	6.0	9.0	10.4	11.0	10.4	8.2	6.2	2.2	
	Comp		3.3	6.4	8.5	10.4	12.0	10.1	8.0	5.4	2.3	
Matched Transcvr	Meas	15.4	19.0	20.7	22.0	23.0	23.0	21.5	20.0	17.0	13.8	7.6
	Comp	14.7	18.2	20.9	22.6	23.4	23.4	22.7	21.2	18.9	15.4	11.2

Trans Pulses: 12.1, 10.9, 11.0, 10.0, 8.8, 7.8 dB

Targets: -6.6, -7.7, -8.4, -9.4, -8.3 -8.0 dB

* Computed Assuming First Target and Last Trans. Pulse Have 45 ° Phase Error.

Pulse sequences at 60° aspect are shown in Figures 9 through 11. At this aspect the target spacing is 1 nanosecond and they are barely resolvable. This is clearly seen in Figure 9 which shows the response of the 5 target configuration when a single pulse is transmitted and single receiver channel is used.

The agreement between theory and measurement is essentially the same for the 60° aspect as it is for the 0° aspect (rms errors = .56 dB and .87 dB respectively) verifying that the technique does not depend upon the individual targets being fully resolvable.

3.3.2 UNEQUALLY SPACED TARGETS

A test of the effects of unequal target spacing was made by using a subset of the 5 target, 60 degree aspect configuration. The targets at positions 1, 4, and 5 were used giving delays of 1 and 3 nsec. between returns. The return pulse sequence when a single pulse was transmitted was 1, 1, 0, 0, 1. The matched transmitter response was 1, 1, 0, 1, 3, 1,0, 1, 1 and the matched transceiver response was 1, 2, 1, 2, 8, 8, 3, 8, 15, 8, 3, 8, 8, 2, 1, 2, 1. The computed matched transmitter gain is 4.8 dB and the computed matched transceiver gain is 7.0 dB.

The receiver portion of the theoretical matched transceiver has seven channels. However, due to time pressures only the first six were implemented reducing the theoretical matched transceiver gain to 6.7 dB. Pictures of the matched receiver and most of the matched transceiver response are shown in Figures 12a and 12b respectively.

The measurement results are presented in Table I. The matched receiver and matched transmitter results are acceptable. The matched transceiver result appears however to contain a gross error of some sort. The individual pulse amplitudes in the train were not recorded in this case so that it is not possible to make the sort of self-consistency check that was made in the case of the other large error detected. The relative amplitudes seen on the scope picture (Figure 12b) are however very close to the theoretical values reinforcing the belief that an undetected change in the gain of the signal detection system of perhaps 2 dB occurred and the matched transceiver really did work as predicted.

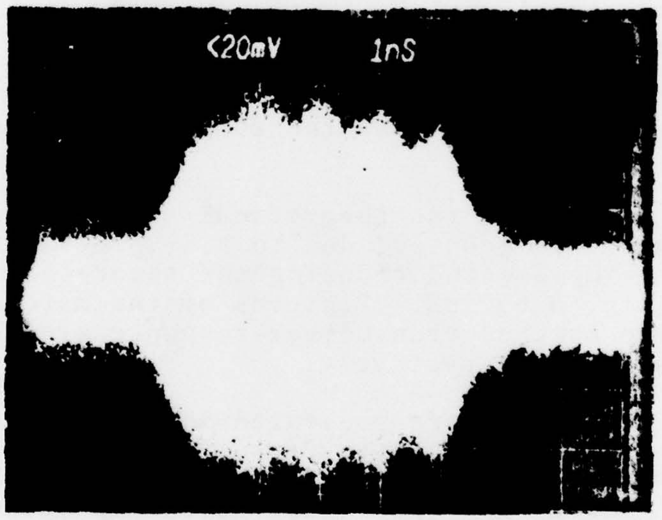
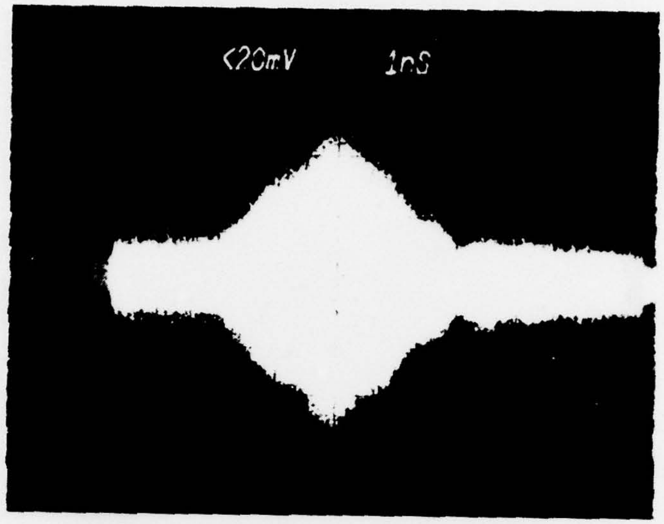
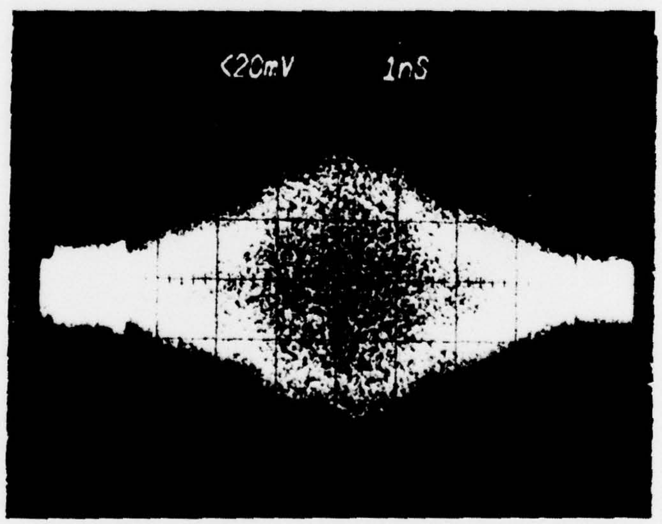


Figure 9 Five Target Configuration, 60° Aspect Reference System

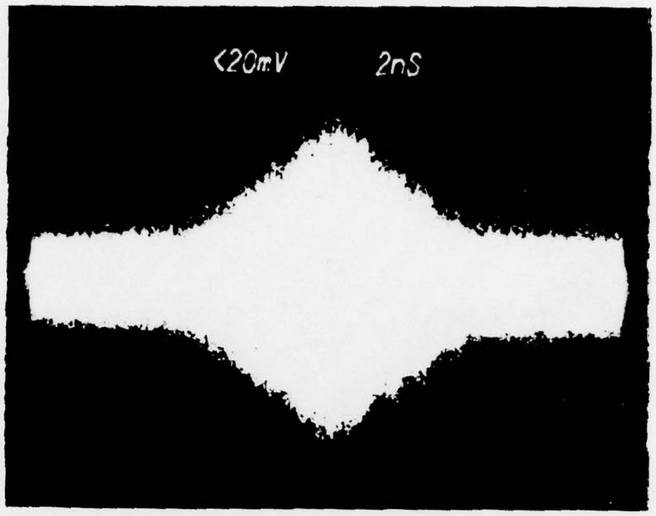


(a)

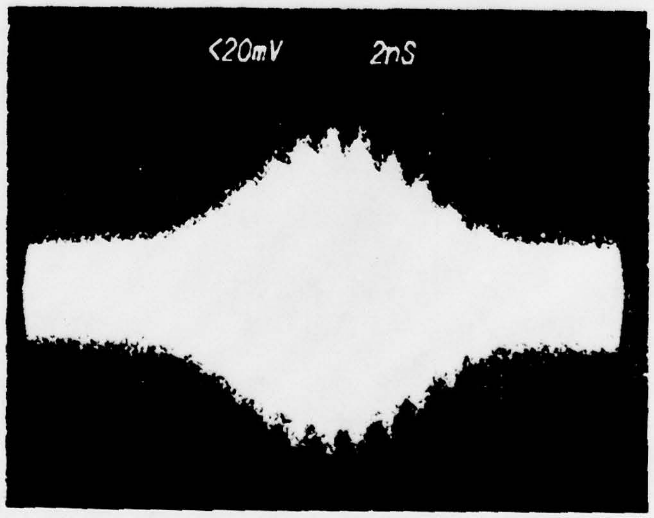


(b)

Figure 10 Matched Receiver, 60° Aspect
a) Two Targets; b) Four Targets

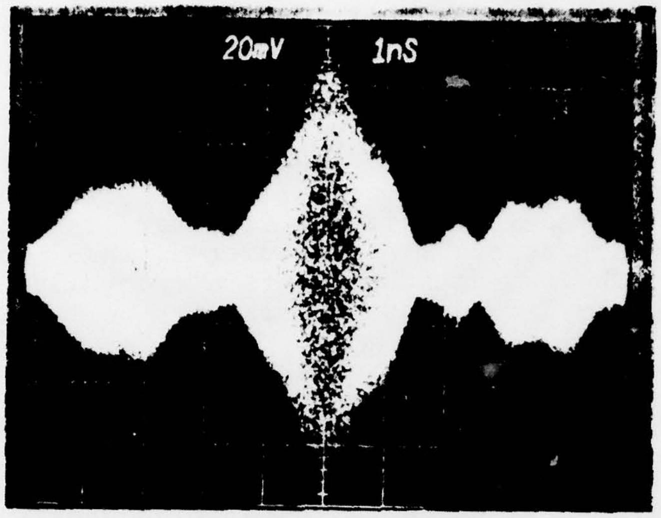


(a)

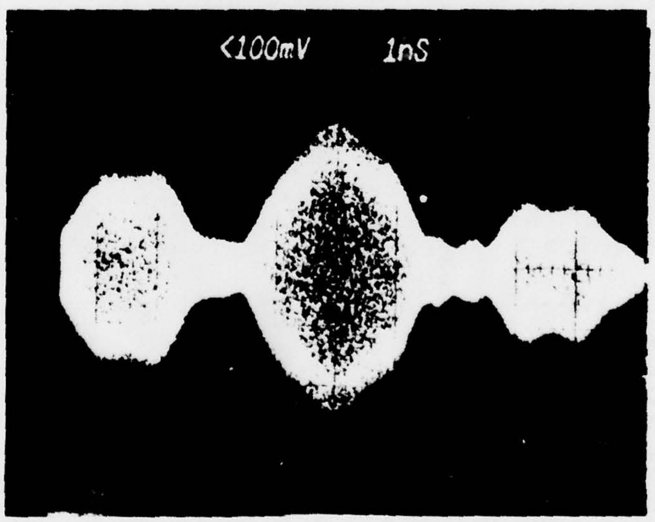


(b)

Figure 11 Five Target Configuration, 60° Aspect
a) Matched Receiver; b) Matched Transceiver



(a)



(b)

Figure 12 Unequal Spacing Responses
a) Matched Receiver; b) Matched Transceiver

SECTION IV

CONCLUSIONS AND RECOMMENDATIONS

4.1 CONCLUSIONS

The results of the measurements presented in Section 3.4 verify theoretical predictions of radar cross section enhancement when the radar pulse train and receiver are matched to the target impulse response. As predicted, this enhancement is greater when the target subelements are equally spaced in range than when they are unequally spaced.

Three types of systems were investigated experimentally. These are denoted by "matched transmitter", "matched receiver", and "matched transceiver." The matched transmitter (transmitter pulse train matched to the target impulse response) and matched receiver (receiver impulse response matched to the target impulse response) give the same enhancement in SNR relative to a single pulse-single receiver channel conventional short pulse system. The SNR gain approaches 10 log(N) dB (where N is the number of discrete targets) when the targets are of nearly equal amplitude. The matched transceiver is defined as a system which utilizes the matched transmitter pulse sequence and a receiver that is matched to the target response to this transmitter signal. As shown in the theoretical discussion this system is not the best possible short pulse system (which would require an infinitely long pulse train) but its response is within 2 dB of the optimum if the targets are of equal amplitude and are equally spaced. If the targets are unequally spaced however, the matched transceiver performance degrades dramatically and in the worst case is only 3 dB better than the matched transmitter or matched receiver system.

The difference between measurement and theory was, in general, less than 1 dB.

Two major sources of difficulty in implementing the concepts were encountered and are likely to be problems in any future hardware. These are the requirements for phase matching (the pulses contain several RF cycles so phases must be matched) and the sensitivity of the technique to time echoes of the pulse. Any echoes of the pulse are enhanced in the same manner as the pulse itself and may act to either increase or decrease the output SNR. This will be especially true if multiple echoes occur so that special efforts must be made to suppress all reflections in the RF and video portions of the system.

4.2 RECOMMENDATIONS

The results of this program have shown that it is indeed possible to achieve the predicted cross section enhancement if the target impulse response is known and sufficient time is available. In any real world application, however, the target response will, at best, be known only within limits and the time available to configure the system will be short. Consequently, an investigation, both theoretical and experimental, of real time adaptive implementations is recommended.

The theory indicates that a long pulse system with a suitably chosen frequency may offer substantial advantages in certain respects. The Purdue studies have extensively examined theoretically the results for such a system with several canonical target models. It is recommended that a long pulse swept frequency system be used to verify these results experimentally.

In the course of making these measurements experience with such a system will be gained which will aid in evaluating the relative practicality of long pulse and short pulse signal enhancement techniques.

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