

AN EXPERIMENTAL DESIGN FOR A STATISTICAL COMPARISON  
BETWEEN PULSED AND CONTINUOUS WAVE RADAR SYSTEMS

by

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A MASTER'S REPORT

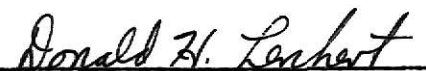
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**THIS BOOK  
CONTAINS  
NUMEROUS PAGES  
WITH DIAGRAMS  
THAT ARE CROOKED  
COMPARED TO THE  
REST OF THE  
INFORMATION ON  
THE PAGE.**

**THIS IS AS  
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## CHAPTER I

### INTRODUCTION

The problem of scattering of electromagnetic or accoustic waves from a rough surface is of interest in a number of different fields. In particular, the problem occurs in the sensing of reflected radar waves from rough ground or from the sea. The prediction and interpretation of radar reflections obtained from various terrain types is important in designing radar mapping systems and radio altimeters.

Experimental studies in the past few years have examined the presence of the depolarized\* or cross-polarized component of the electromagnetic waves that are back-scattered from rough surfaces. The back-scatter phenomena is considered important because it is thought that if the scattering phenomena can be explained theoretically and experimental results correlated with the theory, then depolarized backscatter information can be used to make analytical predictions concerning the terrain or other scattering medium, which is not present in the direct-polarized backscatter.

#### Previous Work

Most of the existing rough surface scattering theories are based on the Kirchoff method, geometric optics method, or small perturbation

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\*When the polarization of backscattered electromagnetic wave is in quadrature to that of transmitted wave then it is known as cross-polarized backscatter. It is known as direct-polarized backscatter when the transmitted and backscattered electromagnetic waves have the same polarization.

method. Summaries of these methods as well as extensive bibliographies on the scattering theories can be found in the works of Fung [1] and Janza [2]. Although these theories have had limited success in explaining the direct-polarized scatter from rough surfaces, they fail to explain the depolarized scatter measured in experimental studies. Trowbridge and Reitz [3] have presented a new ray model for the reflection of electromagnetic radiation from the interface of a randomly rough target surface in contact with air. This derivation considers the surface to be composed of microareas not only randomly oriented but also randomly curved. But again, no attempt has been made to account for the presence of the depolarized component of electromagnetic wave backscattered from a rough surface.

A few authors have recently published papers suggesting that the depolarized scatter does not originate at the surface but from scattering within the volume of the reflecting medium [4,5]. Intuitively, this approach seems to explain the differences between theoretical predictions and actual experimental measurements. The scattering theories assume a homogeneous scattering medium and only those reflections which take place at the surface are considered. On the other hand, most natural targets such as earth terrain are inhomogeneous. Thus, the possibility of volume scattering exists.

Hoekstra and Spanogle [6] measured the radar backscatter from snow and ice surfaces at frequencies of 10 and 35 GHz. They observed that the backscatter was dependent on temperature, and that the effect was small for vertically polarized radiation<sup>\*</sup>, but considerable for

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<sup>\*</sup>The transmitted wave was also vertically polarized.

horizontally polarized radiation<sup>\*\*</sup>. On the other hand, at 10 GHZ, the backscatter of horizontally polarized radiation was approximately 10 dB higher than the return from vertically polarized radiation.

While the experiment conducted by Hoekstra and Spanogle [6] was required for the design of a terrain avoidance system for surface effect vehicles operating on the arctic pack ice, Rosenbaum and Bowles [7] have presented an analytical-stochastic model capable of predicting relevant statistical scattering features of electromagnetic (EM) waves propagating within vegetated environments (such as a forest). The presence of the environment is manifested in the modifications it imposes upon the effective propagation features of the incident as well as the scattered radiation. Since the scattered losses reduce the efficiency of the channel, and in addition, the mean wave experiences an effective slow-down, there is a modification in the back-scattered radiation due to target composition.

In yet another experiment on radar cross-section per unit area of the sea at 6.3 GHZ and 35.0 GHZ, conducted by Long [8,9], the results indicate that the sea echo is primarily caused by two scattering mechanisms: (i) a wind-dependent fine structure of the sea that partly depolarizes the backscattered echo and has a scattering cross-section which depends on wavelength, and (ii) essentially smooth reflecting surfaces (facets) that are contained within the wave structure. The composite theory for rough surfaces developed recently in both the United States and Soviet Union predicts the average radar cross-section

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<sup>\*\*</sup>The transmitted wave was horizontally polarized.

of sea echo for transmitting and receiving horizontal polarizations never exceeds that for vertical polarization. However, measurements at near grazing incidence in Long's [9] experiment yield average HH (the horizontally polarized transmission and reception) cross-sections that sometimes exceed average VV cross-sections, and the observations reported indicate that reflections from facets is the cause.

Ulaby [10,11,12,13] has conducted measurements of vegetation backscatter to determine the utility of radar in (i) mapping soil moisture through vegetation and (ii) mapping crop types. It has been observed from the data that soil moisture estimation is best accomplished at incident angles near nadir, with low frequencies, while crop discrimination is best accomplished using two frequencies at incident angles ranging from  $30^\circ$  to  $65^\circ$ . It was also observed that the backscattering co-efficient exhibited a definite diurnal variation pattern which is insensitive to polarization but sensitive to frequency and angle of incidence. Also, a high degree of sensitivity of backscattering coefficient of soil surfaces to soil moisture variations is further confirmed from data acquired over the Great Salt Lake desert area by sensors aboard Skylab and Nimbus 5, [14].

To investigate some of these phenomena, experimental work has been done by Krishen [15] and Funke [16] in the Electromagnetic Research Laboratory at Kansas State University, Manhattan, Kansas. Their objective was to study the scattering behavior of plane electromagnetic waves. The studies have basically examined scattering from homogeneous and inhomogeneous targets. The targets used by Funke [16] were designed by a computer generating program to have a random gaussian surface.



This was accomplished using a random generator for surface heights and specifying particular means and variances of the heights. The experimental set up, used by both Krishen and Funke [15,16], in the laboratory, included an x-band pulsed radar set, in which the beam was reflected from the target. To approximate the "real world" situation in the laboratory, a pulsed radar system was used; in which, for example an airborne pulsed radar would obliquely scan the terrain below, and also one can obtain peak power from the system, on the order of megawatts. [But recently, Weir [17], has developed a new technique for making rapid radar cross-section measurements over wide frequency bands. The Hewlett-Packard (HP) automatic network analyser, which measures scattering parameters at discrete frequencies over a wide band and corrects for system errors before presenting measured data, has been adapted to obtaining RCS (Radar Cross-section) measurements].

Because of the obvious potential for savings in terms of both money and equipment if a continuous wave system was used instead of a pulsed wave system to investigate the significance of depolarized back-scatter, this experiment is posed an extension to previous work in the laboratory.

The immediate purpose of this present study is to design an experiment to determine if a statistically significant difference exists between continuous wave (CW) and pulsed radar systems, in which the back-scattering of electromagnetic waves occurs from planar, homogeneous and inhomogeneous targets.

This report is organized into several chapters. This first chapter presents the introduction to the problem, and explores some of the relevant prior theoretical and experimental work on the interpretation of

direct and cross-polarized radar reflections.

Chapter II presents an overall experimental design for the conduct of this and future extensions to the prior work of Funke [16] reported in Chapter I. The fundamental question raised by this experiment (namely, "is there a 'measurable difference' in reflection interpretations between continuous wave systems and pulsed wave system?") requires the use of statistical techniques and a carefully controlled experimental environment in order to discern the possible existence of such "differences." Accordingly, the experiment has been rigorously designed from a statistical viewpoint. Much of the physical equipment in the experimental set up has been drastically modified in order to reduce known or foreseen sources of random error. The guiding principle in the experimental design is to reduce the "final" random error in the experiment to as small a value as reasonably possible, so that if a real "difference" exists between continuous wave (CW) and pulsed wave reflections, it can be detected against the experimental error. This chapter also sets forth the method of system calibration. A step-by-step check-list procedure for setting the instruments at their initial points, which must be done before data are recorded, is provided. Also, the method of data taking is described.

In Chapter III, the procedure for analysis of the data is illustrated by making use of some data which were collected before the design of the experiment was undertaken.

Chapter IV presents the conclusions which may be drawn from the present study.

## CHAPTER II

### DESIGN OF THE EXPERIMENT

#### 2.1 Introduction

The specific experimental design undertaken in this report is for an experiment much larger and more comprehensive than that illustrated in Chapter III. The design of the complete and entire experiment has been undertaken here, and is developed and reported herein, not only as a specific framework for the reduced form reported in Chapter III, but also to serve as a guide for future extensions to the present experimental work. In this manner, the present data and results can be directly incorporated in the continuing larger experiment as portions of it are accomplished in the future. The whole undertaking should thus be considered an on-going experiment to be performed in segments, but which can be analyzed segmentally as performed, and again as an entity when the entire experiment is ultimately completed.

The general purpose of the entire composite experiment is to determine whether or not any statistically significant difference can be discerned between the response characteristics of two different types of radar systems: one, a pulsed wave system, and the other, a continuous wave (CW) system when the incident wave is reflected from a series of calibrated targets.

Because of the tendency of some types of radar targets to cross-polarize the reflected waveform of the incident beam, two types of responses are of interest throughout the entire experiment. First, the

portion of the reflected waveform that is polarized in-phase with the beam incident to the target is of interest, since it is this portion of the reflected waveform that describes the geometric form of the target.

Second, the portion of the reflected waveform that is cross-polarized with respect to the incident beam is also of interest, since there is theoretical and empirical evidence that this cross-polarized reflection can be used to interpret the composition of the target material; i.e. it is perhaps indicative of the target material, its density and water content. Hence, throughout the entire experiment, two variables should always be measured; namely, the intensity and form of (i) the in-phase reflected (or back-scattered) wave, and (ii) the cross-polarized reflected wave, symbolically represented by  $P_{rd}$  and  $P_{rc}$  respectively.

Since the target material apparently affects the cross-polarized component of the reflected wave more than it affects the direct polarized component, it would seem desirable to investigate a series of targets composed of different materials, and hence (electrical) permittivities. Furthermore, it is known that the form of the target surface affects the nature of the reflected radar wave, particularly the direct-polarized component. However, it is not known what the interactive effects of surface conformation and material composition are; this certainly indicates the necessity for the performance of a series of tests in which targets of different surfaces, different materials and different combinations of materials and surfaces are used. Furthermore, there may be a volumetric effect; i.e. a modification of the reflected wave due to the depth (thickness) of the target itself. Funke [16] noted, for example, that anchor bolts in some of his plaster targets, at a depth of about 10 cm from the

target surface, modified the cross-polarized form of the reflected wave.

Hence, there are at least three effects that should be varied in any comprehensive investigation of reflected wave interpretation. These effects are due to (a) target material (composition) (b) target surface conformation and (c) target thickness. Accordingly, this experiment in its fully developed form contemplates the use of several types of targets, which can be described briefly as follows:

1. Planar Aluminum Targets (to be used as calibration targets)

(a) 20 cm diameter; 5.8 cm thick (approximately 1.7 wavelengths at 8.857 GHz)

(b) 20 cm diameter; 15 cm thick (approximately 4.4 wavelengths at 8.857 GHz)

2. Solid Plaster of Paris Targets (\*Relative permittivity of 3.2; loss tangent of .01; propagation loss of about .35 dB/in)

(a) 20 cm diameter, 5.8 cm thick

The different surface types to be investigated are:

(i) Planar surface

(ii) Laminar cut surface with various:

(aa) Depths of cuts

(bb) Width of cuts

(iii) Random (Gaussian generated) surfaces

(b) 20 cm diameter, 15 cm thick

The different surface types to be investigated are:

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\*For detailed description refer to Funke [16], pp. 80 and 119.

- (i) Planar surface
  - (ii) Laminar cut surface with various;
    - (aa) Depths of cuts
    - (bb) Width of cuts
  - (iii) Random Gaussian generated surfaces
3. Plaster-of-Paris targets with styrofoam pellets randomly embedded to provide an inhomogeneous target (density = 500 styrofoam pellets in approximately  $21936 \text{ cm}^3$ \* of target volume)
- (a) 20 cm diameter, 5.8 cm thick
    - (i) Planar surface
    - (ii) Laminar cut surface with various;
      - (aa) Depths of cuts
      - (bb) Width of cuts
    - (iii) Random Gaussian generated surfaces
  - (b) 20 cm diameter, 15 cm thick
    - (i) Planar surface
    - (ii) Laminar cut surface with various;
      - (aa) Depths of cuts
      - (bb) Width of cuts
    - (iii) Random (Gaussian generated) surfaces
4. Plaster-of-Paris targets with styrofoam pellets embedded to provide a second inhomogeneous target (density 2500 styrofoam pellets in approximately  $21936 \text{ cm}^3$ \* of target volume. Relative permittivity of 2.8)

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\*Considering target of radius 21.4 cm and average height of 15.24 cm. For detailed description refer to Funke [16], pp. 80 and 119.

- (a) 20 cm diameter, 5.8 cm thick target with following different surface types:
  - (i) Planar surface
  - (ii) Laminar cut surface with various:
    - (aa) Depths of cut
    - (bb) Width of cuts
  - (iii) Random Gaussian generated surfaces
- (b) 20 cm diameter, 15 cm thick with following different surface types:
  - (i) Planar surface
  - (ii) Laminar cut surface with various:
    - (aa) Depths of cuts
    - (bb) Width of cuts
  - (iii) Random Gaussian generated surfaces

The typical pictures of the various targets are shown in Fig. 1.

#### 2.1.1 Physical Equipment:

Figure 2 shows the floor plan of the laboratory where the radar system is located. The target mounting shaft, supported by a target mounting stand and connected to an electric motor, to rotate the target about a horizontal axis, is located in one corner of the laboratory. In the corner where target stand is located, the walls are covered by echo absorbing material to reduce unwanted reflections. A surveying transit has been used to place angular markings on the floor and to align the target mounting shaft to the markings on the floor.

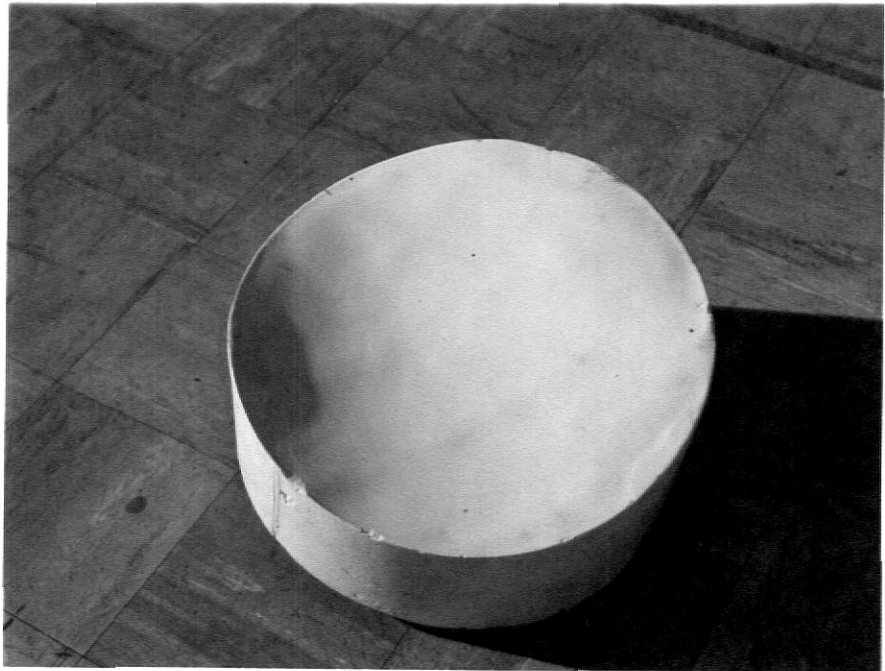


Fig. 1. Picture of targets.



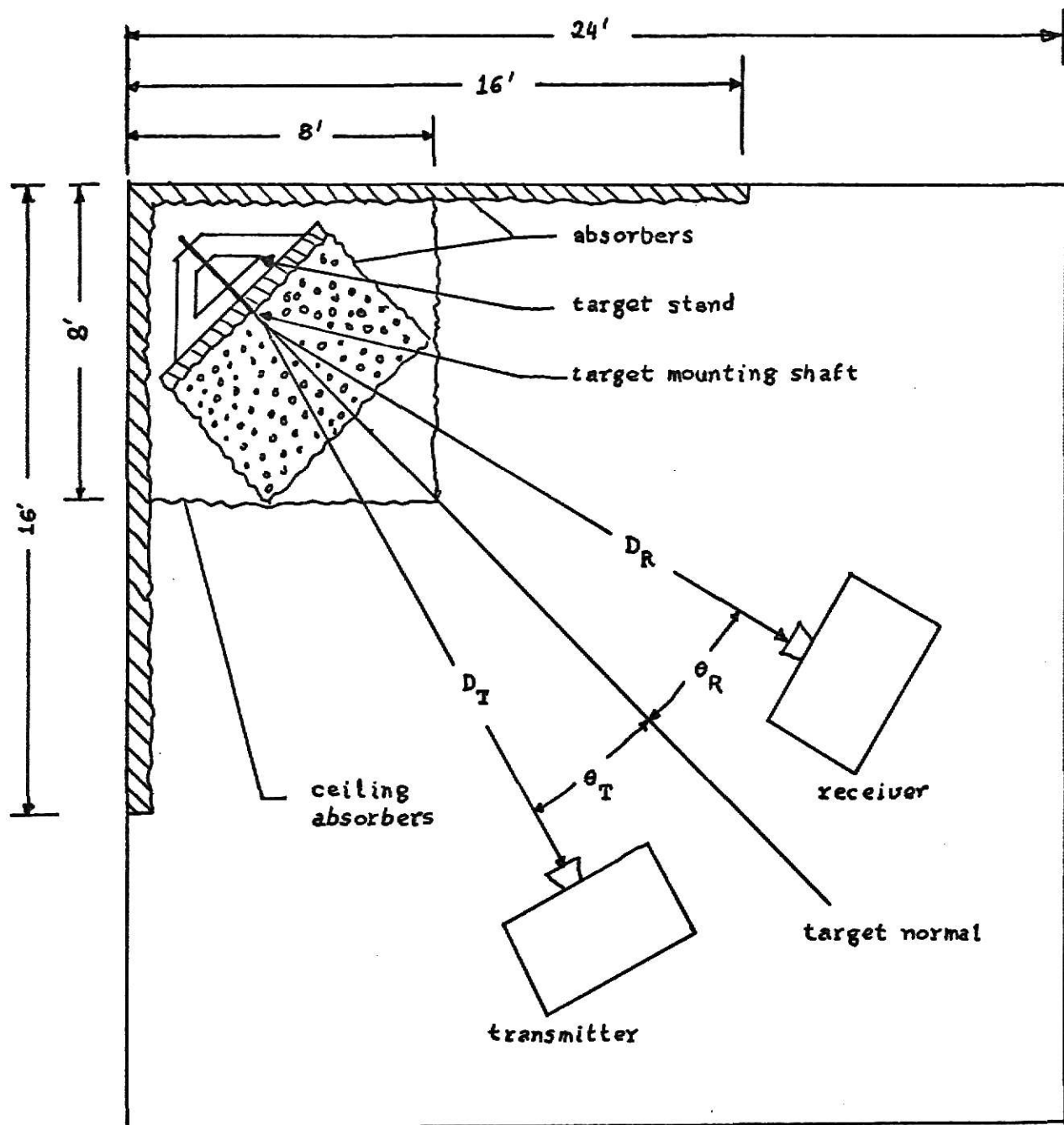


Figure 2. Floor plan of the radar range.

A simplified block diagram of the radar system, used in this experimental set up, is given in Fig. 3. The transmitting and receiving waveguide sections of the radar system are mounted on movable tables (carriers) so that angular measurements with respect to the target can be taken easily. The radar system parameters and reasons for choosing their particular values are given in [16].

Equation (2.1) gives the theoretical expression for the radar cross-section of circular metal targets as given by the method of physical optics.

$$\sigma_C(\theta_T, \theta_R) = 0$$

$$\sigma_D(\theta_T, \theta_R) = \frac{4\pi A^2 \cos^2 \theta_T}{\lambda^2} \left[ 2 \frac{J_1(K_0 a (\sin \theta_R - \sin \theta_T))}{K_0 a (\sin \theta_R - \sin \theta_T)} \right]^2 \quad (2.1)$$

where  $A$  is the area of the target,  $a$  is the radius of the target,  $\lambda$  is the wavelength of the incident radiation,  $K_0$  is the propagation constant of free space, and  $J_1$  is the Bessel function of the first kind of order 1.

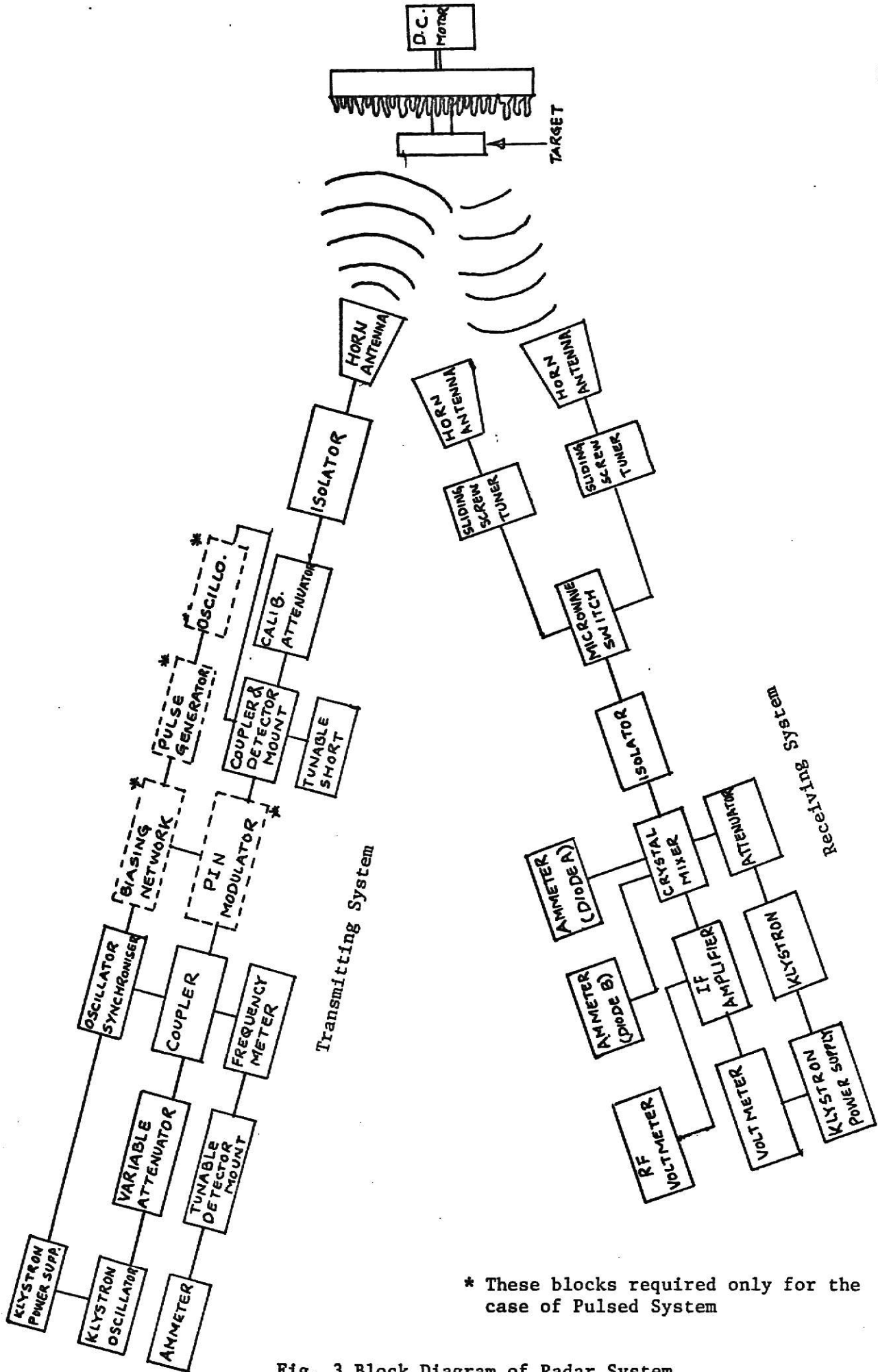
(It should be noted that (2.1) has dimensions of (distance)<sup>2</sup>; e.g., cm<sup>2</sup>).

$\theta_T$  and  $\theta_R$  are angles of transmission and reception as shown in Fig. 2.

$\sigma_D(\theta_T, \theta_R)$  is the radar cross-section of the target (in units of (linear measure)<sup>2</sup>) when the incident and reflected beams have the same polarization.

$\sigma_C(\theta_T, \theta_R)$  is the radar cross-section of the metal target when the incident and reflected beams are in quadrature to each other and is zero.

From (2.1), it can be seen that for a fixed transmission frequency and a fixed target cross-section, the radar cross-section is dependent on



\* These blocks required only for the case of Pulsed System

Fig. 3 Block Diagram of Radar System

$\theta_T$  and  $\theta_R$ . A typical variation of the radar cross-section  $\sigma_D(\theta_T, \theta_R)$  with respect to  $\theta_R$  for a fixed  $\theta_T$  is shown in Fig. 4.

The fundamental form of the radar equation (Skolnik [18]) is given by:

$$P_r = \frac{P_t G_t A_r \sigma}{(4\pi D_T)^2 (4\pi D_R)^2} \quad (2.2)$$

where  $P_t$  is power transmitted (measured in units of watts);  $G_t$  is the gain of transmitting antenna;  $A_r$  is the effective capture area of receiving antenna (measured in units of  $\text{cm}^2$ );  $\sigma$  is the radar cross-section of the target (also measured in units of  $\text{cm}^2$ );  $D_T$  and  $D_R$  are respectively the distances of transmitting and receiving antennas from the target (measured in units of cm) and  $P_r$  is the power received (in units of watts).

For our experimental set up,  $G_t$  and  $A_r$  are fixed.  $D_T = D_R (=R)$  is also fixed, as is clear from Fig. 2. So for fixed transmitter power, the power received is directly related to (or is indicated by) the radar cross-section of the target. Since the intensity of reflected beam (i.e. power received) is the primary response function under investigation so, as a consequence, Fig. 4 also represents the variation of the direct polarized response function ( $P_{rd}$ ) as a function of  $\theta_R$  for fixed  $\theta_T$ . And, of course, for metal targets, the intensity of cross-polarized response function ( $P_{rc}$ ) is zero, as is  $\sigma_C$  i.e. the radar cross-section for cross-polarization.

Because neither the absolute value of reflected power,  $P_r$  (more specifically  $P_{rd}$  and  $P_{rc}$ ), nor the absolute value of the radar cross-section ( $\sigma_C$  or  $\sigma_D$ ) can be measured in our experimental set up because of

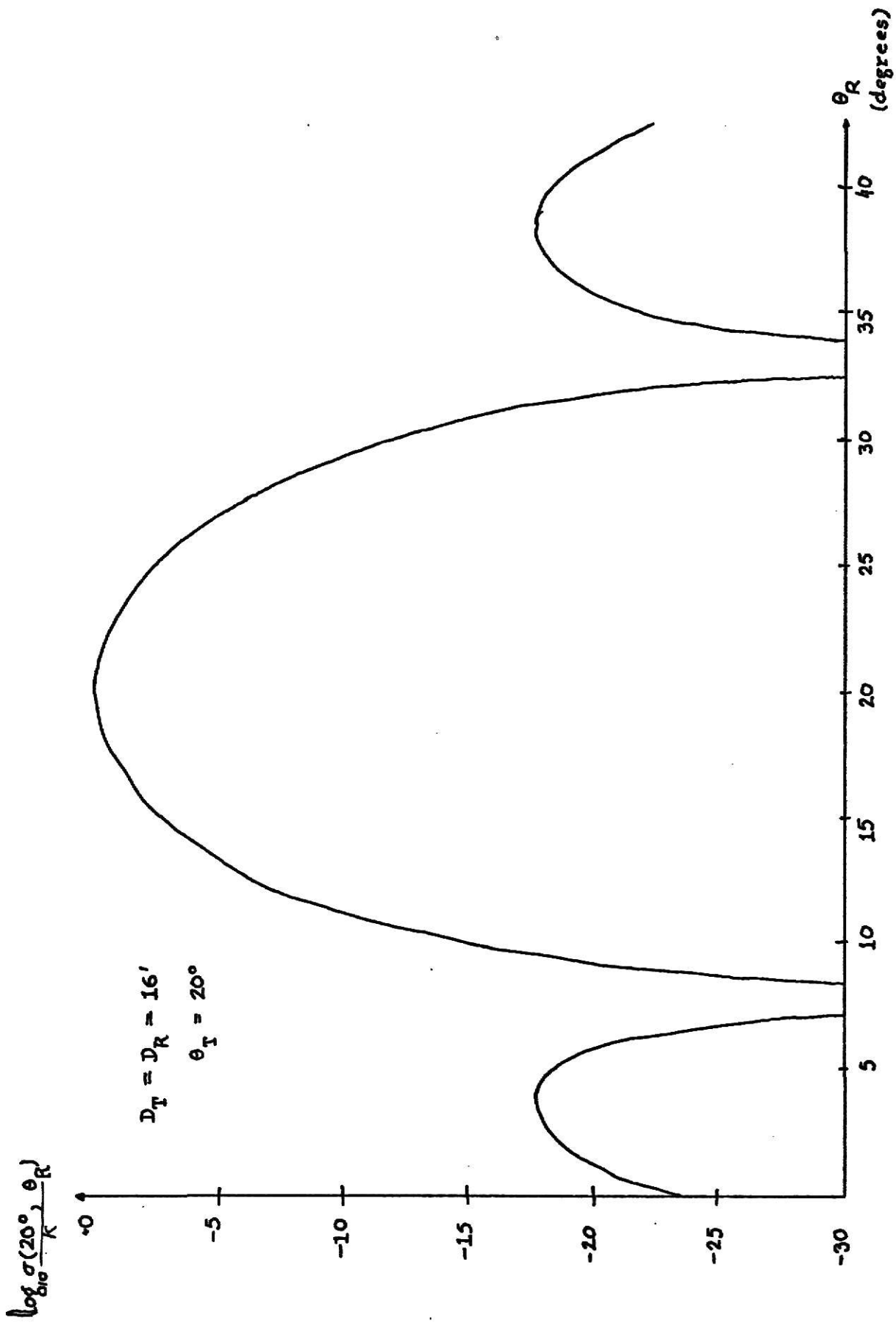


Figure 4. Theoretical value for the radar cross-section of an aluminum target with radius of .1 meter.

the lack of proper equipment, it is necessary that we use a relative measure of reflected power (or radar cross-section) as a substitute measure. This relative measure is established via a set of "system calibration curves," which are described in Section 2.3. The power output data, originally taken in terms of output voltage at the receiver, is converted via calibration curves into received power, relative to calibrated unattenuated transmitter power at  $\theta_T = \theta_R = 20^\circ$ , measured in dB.

Because this received power measurement is a measure relative to transmitted power at the time of observation, and because no absolute control can be maintained on the level of transmitted power with respect to time, and because the transmitted power can vary during the day and from day-to-day, then there is no guarantee of the absolute level of received power at any given time. Hence, to make the data comparable, relative power measurements need to be normalized with respect to the maximum value of relative received power at  $\theta_T = \theta_R$ . When this is done, then Eq. (2.2) must be placed in normal form as follows:

Substituting Eq. (2.1) into Eq. (2.2), we get

$$P_{rd} = \frac{P_t G_t A_r}{(4\pi R)^2} \cdot \frac{4\pi A^2 \cos^2 \theta_T}{\lambda^2} \left[ 2 \frac{J_1(K_o a(\sin \theta_R - \sin \theta_T))}{K_o a(\sin \theta_R - \sin \theta_T)} \right]^2 \quad (2.3)$$

as mentioned above, in our case,  $G_t$ ,  $A_r$ ,  $R$ ,  $\lambda$ ,  $\theta_T$ ,  $a$ ,  $K_o$ ,  $A$  are fixed.

If we replace all these by a constant ' $\alpha$ ', then we get:

$$P_{rd} = P_t \cdot \alpha \cdot \left[ 2 \frac{J_1(z)}{z} \right]^2 \quad (2.4)$$

where  $Z = K_o a(\sin\theta_R - \sin\theta_T)$  and  $P_{rd}$  is in watts. Hence, our normalizing factor is:

$$P'_{rd} = P_t \cdot \alpha \cdot \left[ 2 \frac{J_1(Z')}{Z'} \right]^2 \quad (2.5)$$

where primed values in (2.5) correspond to  $\theta_R = 20^\circ = \theta_T$ . Upon dividing (2.4) by (2.5) we get

$$\frac{P_{rd}}{P'_{rd}} = \frac{P_t \cdot \alpha \cdot \left( 2 \frac{J_1(Z)}{Z} \right)^2}{P_t \cdot \alpha \cdot \left( 2 \frac{J_1(Z')}{Z'} \right)^2} \quad (2.6)$$

or

$$\frac{P_{rd}}{P'_{rd}} = \left( \frac{J_1(Z)}{J_1(Z')} \cdot \frac{Z'}{Z} \right)^2 \quad (2.7)$$

where both  $P_{rd}$  and  $P'_{rd}$  are measured in watts. If we take  $10 \log_{10}$  of both sides of (2.7) we have:

$$10 \log_{10} \frac{P_{rd}}{P'_{rd}} = 10 \log_{10} \left( \frac{J_1(Z)}{J_1(Z')} \cdot \frac{Z'}{Z} \right)^2 \quad (2.8)$$

or, since  $10 \log_{10} (P_{rd}/P'_{rd}) =$  the power ratio measured in decibels, (2.8) becomes:

$$(P_{rd})_{db} = 10 \log_{10} \left( \frac{J_1(z)}{J_1(z')} \cdot \frac{z'}{z} \right)^2 \quad (2.8a)$$

Since the primary purpose of this report is to investigate the response characteristics of two different systems mentioned above, the effect of the variable  $\theta_R$  on the response function has to be removed in the statistical analysis. As is clear from (2.1) and Fig. 4, it is not possible to control the variable  $\theta_R$  at some constant level but it can be measured along with a response function (or response variable). This variable  $\theta_R$ , in statistical terms, is known as the covariable, since it "runs along" with the response variable, [19]. A method has been utilized in this report to remove the effect of this co-variable on the response function and then to investigate the possible significant difference between two different (pulsed and CW) types of radar systems. This method of analysis of the data is known as "covariance analysis". Furthermore, since it is easy to apply this method to linear mathematical functions, Eq. (2.7) has been placed in linear form by applying a transformation to it. The transformation applied is a logarithmic transformation; i.e. by taking the logarithms of both sides of (2.7). In this fashion (2.7) is converted to Eq (2.8). Noting that the left side of Eq (2.8) is simply relative power measured in decibels, we have

$$P_{rNd} = 10 \log_{10} \left[ \frac{z'}{z} \cdot \frac{J_1(z)}{J_1(z')} \right]^2 \quad (2.9)$$

where  $P_{rNd}$  is normalized direct-polarized power ratio, measured in dB. equation (2.9) is of the form

$$Y = \beta_0 + \beta_1 X \quad (2.10)$$

where  $\beta_0$  is initially taken as zero, and where

$$Y = P_{rNd}; \quad X = 10 \log_{10} \left[ \frac{z'}{z} \cdot \frac{J_1(z)}{J_1(z')} \right]^2; \quad \beta_1 = \text{a slope.}$$



The appropriate regression model used to remove the covariable effect is then

$$\hat{Y}_i = \hat{\beta}_0 + \hat{\beta}_1 X_i + \epsilon_i$$

where  $\hat{Y}$ ,  $\hat{\beta}_0$  and  $\hat{\beta}_1$  are estimates derived from least-squares analysis and  $\epsilon_i$  is the error term. The covariance analysis can be performed by using the "AARDVARK" subroutine in the computer library of the IBM 370 computer facility on the campus of Kansas State University [20], and utilizing (2.10) as the regression equation for the observed data.

## 2.2 Equipment Modification and Calibration

Several sources of possibly large random errors were identified with the previous experimental set ups [15,16] in the electromagnetic research laboratory. Because of these, it was deemed necessary to modify the experimental set up before taking data for this experiment. The under-mentioned equipment and set up errors were identified and the modifications were made to reduce the magnitude of some of the "uncontrollable" errors:

(1) It was suggested by Funke [16] that the electromagnetic waves backscattered from the target may form standing wave patterns in the transmitter waveguide, thus reducing the effective transmitter power. In order to improve transmitter stability and performance, an isolator has been inserted between the transmitting antenna and the calibrated attenuator of the transmitter. This tends to reduce the formation of standing waves since a 2 dB improvement in the received power has been observed.