

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

by

RAJINDER K. KHURANA

B.Sc. Engg., Panjab University, INDIA, 1974

A MASTER'S REPORT

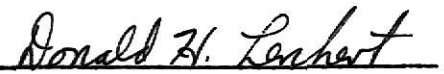
submitted in partial fulfillment of the
requirements for the degree

MASTER OF SCIENCE

Department of Electrical Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1976


Major Professor

LD
2668
R4
1976
K53
C.2

205

TABLE OF CONTENTS

Document

Chapter		Page
I	Introduction	1
II	Design of the Experiment	7
	2.1 Introduction.	7
	2.1.1 Physical Equipment	11
	2.2 Equipment Modification and Calibration.	21
	2.3 System Calibration.	27
	2.3.1 Need for Calibration	27
	2.3.2. Calibration Procedure	28
	2.4 Definition of Variable	29
	2.4.1 Independent Variables.	29
	2.4.2 Dependent Variables...	37
	2.5 Experimental Design	37
	2.6 Procedure for Data Collection	42
III	Analysis of Data	46
IV	Conclusions.	55
	Appendix I	57
	Appendix II	61
	References	64
	Acknowledgements	
	Abstract	

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

**THIS IS AS
RECEIVED FROM
CUSTOMER.**

LIST OF FIGURES

Figure		Page
1	Picture of Targets	12
2	Floor Plan of Radar Range.	13
3	Block Diagram of Radar System.	15
4	Theoretical Value for the Radar Cross-Section of an Alluminium Target with Radius of .1 Meter. .	17
5	Dimensions of Calibration Target	23
6	Transmission and Receiving Carriers.	24
7	Offset Point on Calibration Target	26
8	Particular Response Characteristics.	32
9	Pulse Format	33
10	Particular Transmitter and Receiver Set-Up	34
11	Typical Replicate.	39
12	Plot of Response Variables	49

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

* 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^{*}, but considerable for

^{*}The transmitted wave was also vertically polarized.

horizontally polarized radiation^{**}. 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

^{**}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° to 65° . 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:

*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 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 cm^3 * of target volume. Relative permittivity of 2.8)

*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.

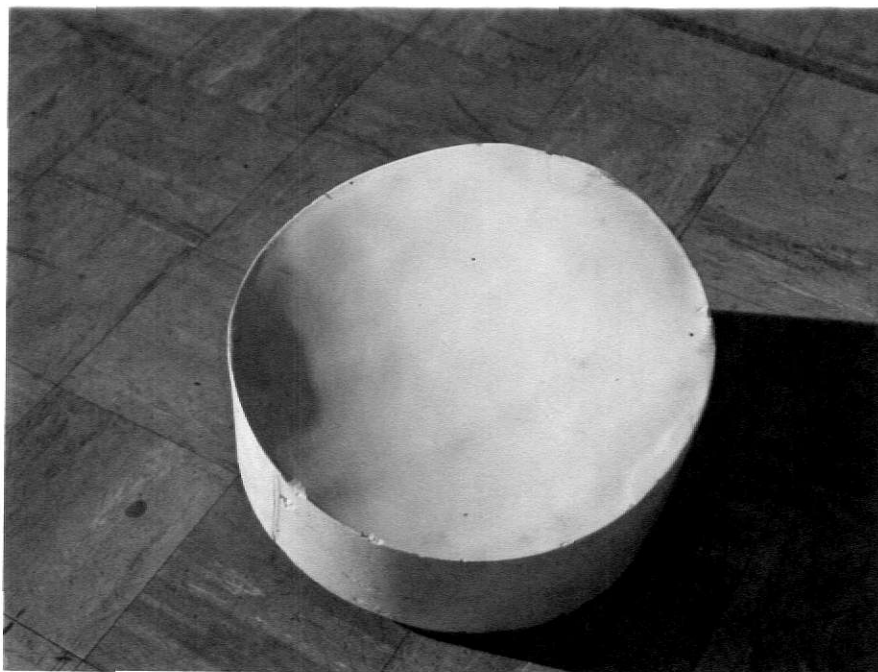


Fig. 1. Picture of targets.

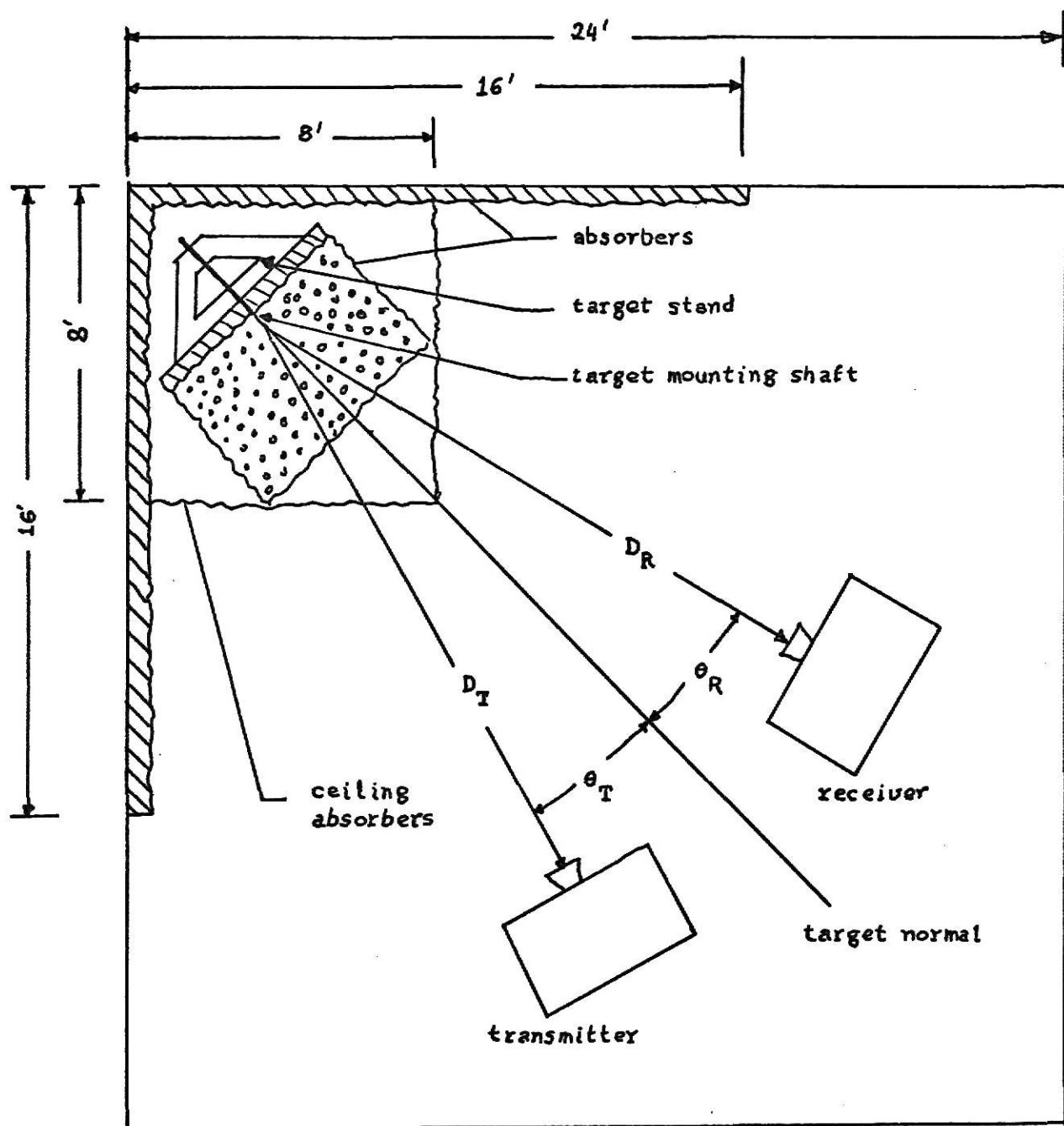


Figure 2. Floor plan of the radar range.

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, λ 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)²; e.g., cm²).

θ_T and θ_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)²) 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

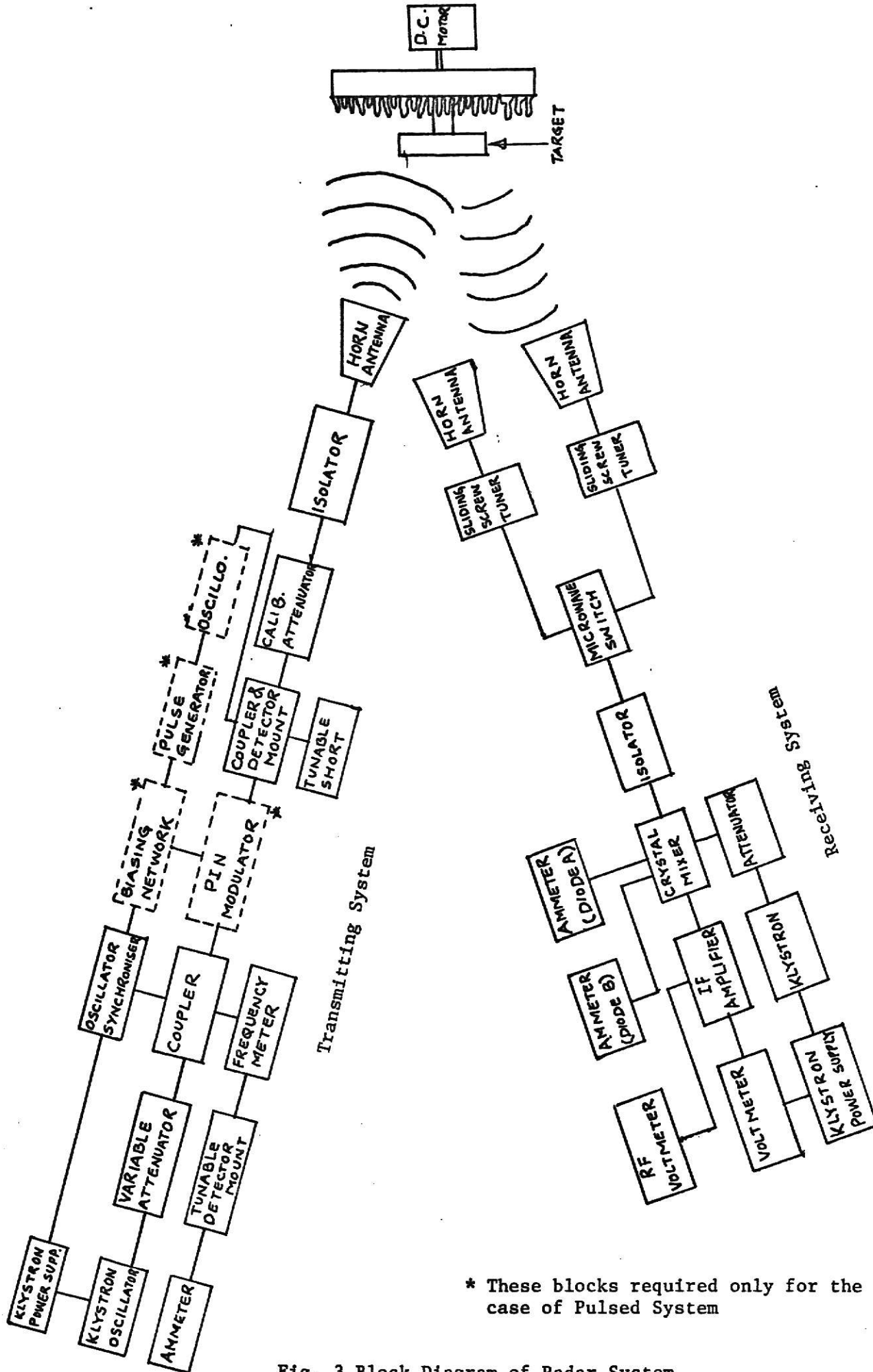


Fig. 3 Block Diagram of Radar System

θ_T and θ_R . A typical variation of the radar cross-section $\sigma_D(\theta_T, \theta_R)$ with respect to θ_R for a fixed θ_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 cm^2); σ is the radar cross-section of the target (also measured in units of 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 θ_R for fixed θ_T . And, of course, for metal targets, the intensity of cross-polarized response function (P_{rc}) is zero, as is σ_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 (σ_C or σ_D) can be measured in our experimental set up because of

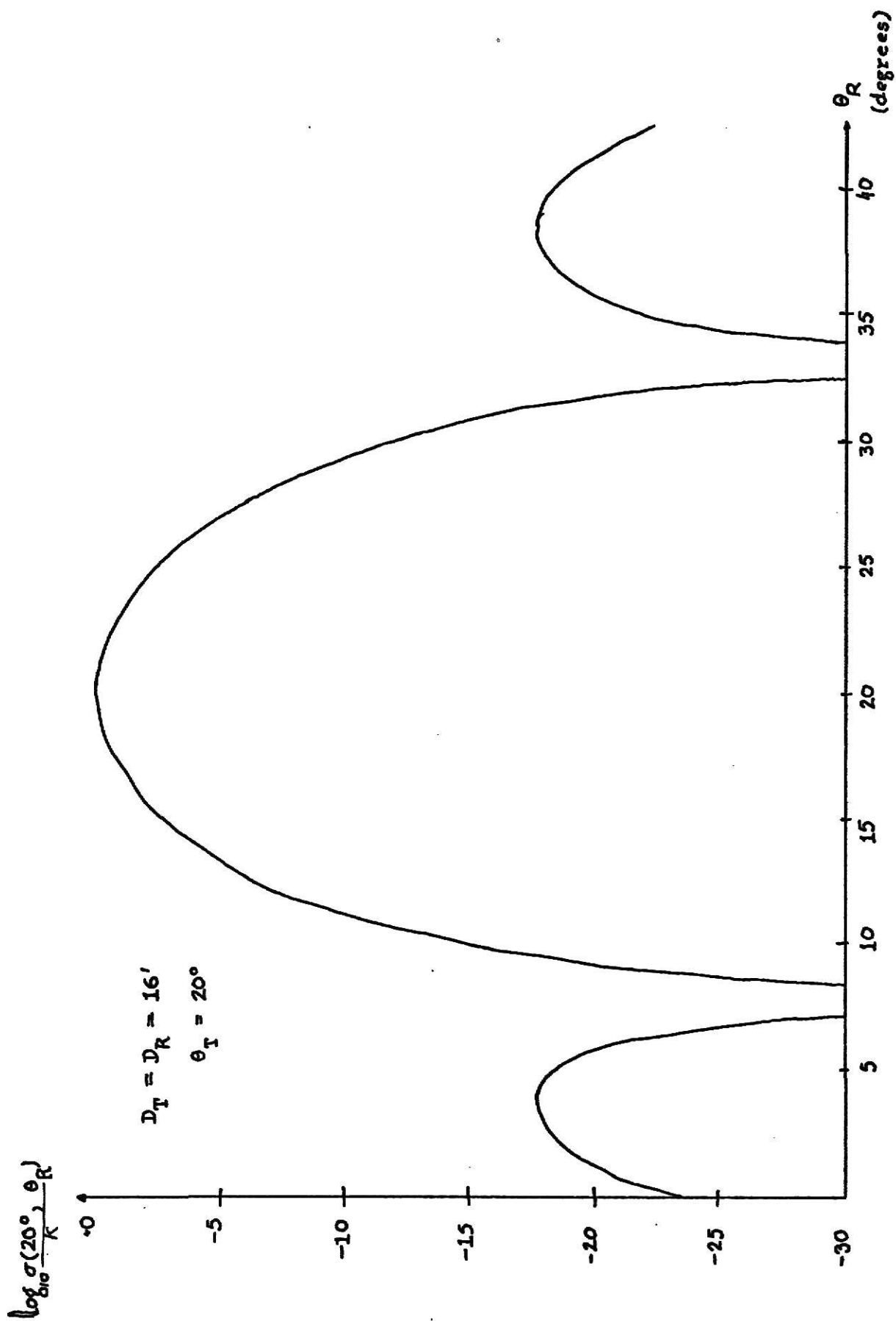


Figure 4. Theoretical value for the radar cross-section of an aluminum target with radius of .1 meter.

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 , λ , θ_T , a , K_o , A are fixed.

If we replace all these by a constant ' α ', 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 θ_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 θ_R at some constant level but it can be measured along with a response function (or response variable). This variable θ_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 β_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 ϵ_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.

(2) A noticeable amount of rotational "wobble" was observed in the previous calibration targets. It was also noted that the face of the planar calibration target and the shaft supporting it were not perpendicular to each other. Due to this error in the calibration target, Funke [16] probably observed fluctuations in the RF voltmeter reading for a fixed set up; at least, these fluctuations are present in his data.

To remedy this source of error, a new aluminum calibration target has been made. This has been carefully machined from aluminum slab material, 5.8 cm in thickness and then machined to dimensions shown in Fig. 5. The back of the target is bolted to the hub, and is used to mount the target on the rotating shaft. Complying with the rule of thumb given in [21] concerning the minimum range at which targets must be placed for accurate measurements of radar cross-section, the radius of the target has been chosen to be 0.1 m (corresponding to $D_T = D_R = 16'$).

(3) It was also observed in the previous experimental set up that the platform carriers supporting the transmitter and receiver waveguide sections were not stable. If one tried to set up the transmitting or receiving antenna at a particular angular position as marked on the floor then it was possible that the actual location of the platform was in error by as much as 2° . In other words the equipment platforms were not rigid.

To remedy this, new stable stands of proper dimensions have been made (see Fig. 6). These have been provided with levelling screws, with lock nuts, so that the carriers can be made rigid at a particular angular position and placed at the proper height so that the center of the

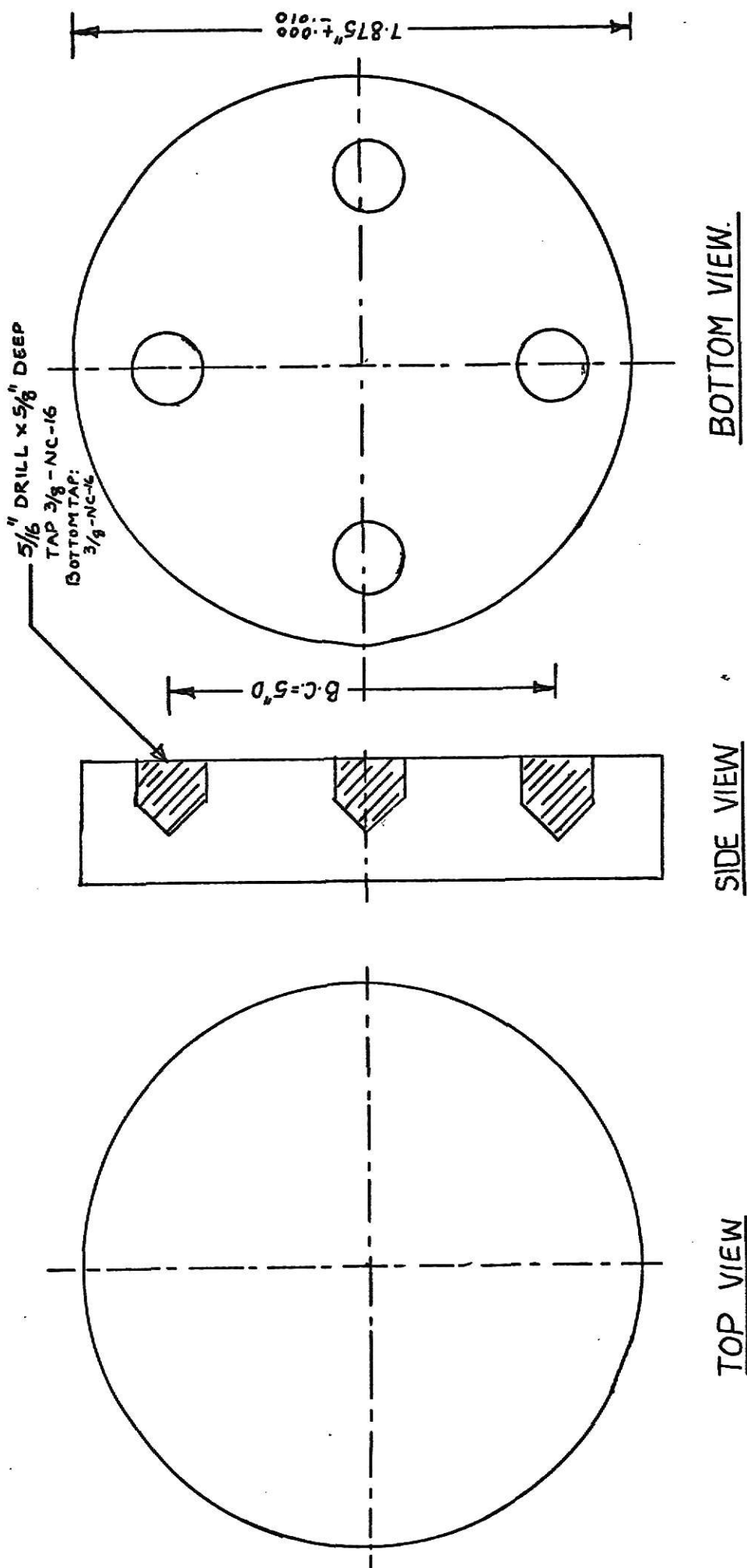


Figure 5. Dimensions of calibration target.

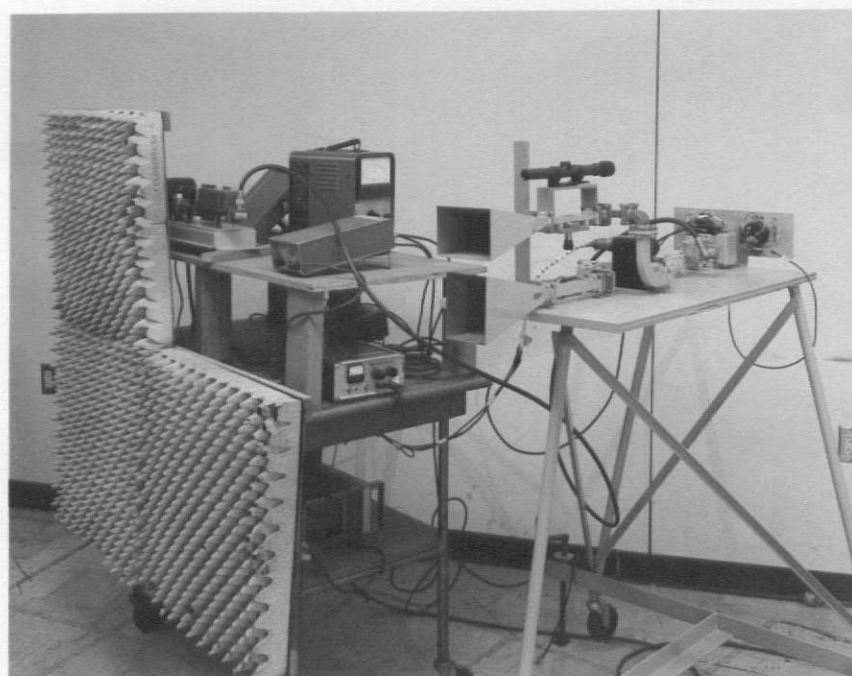
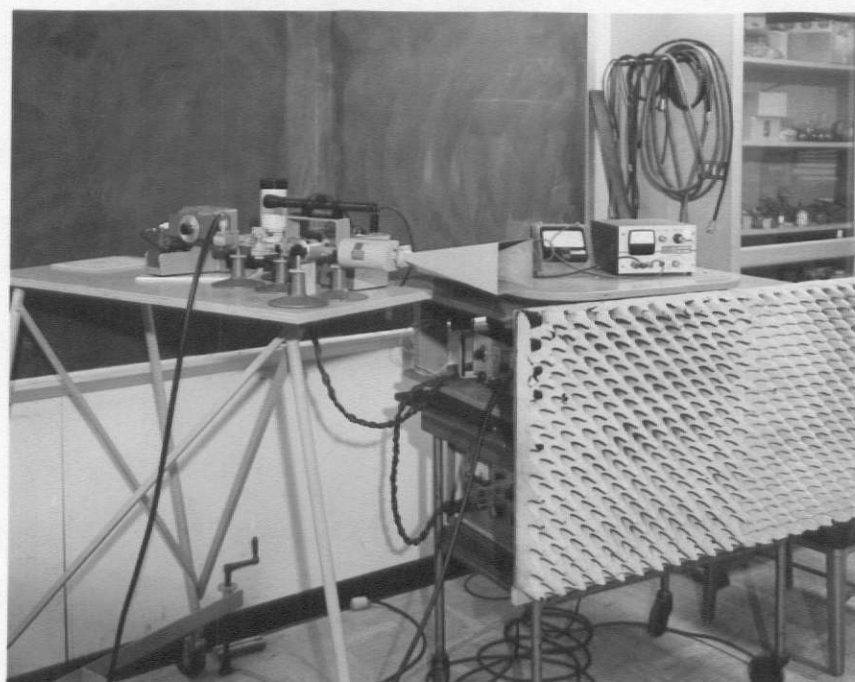
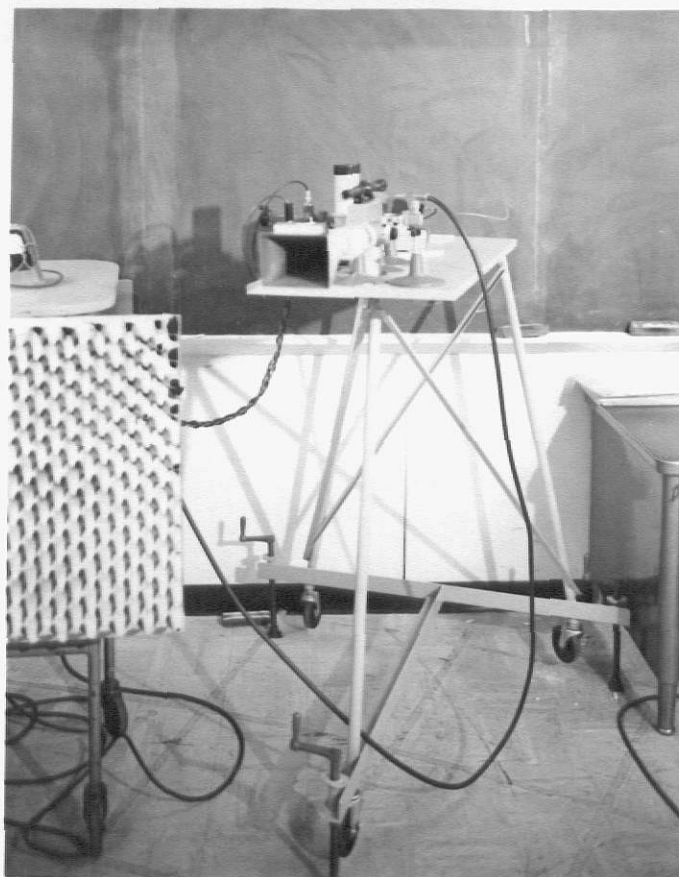


Fig. 6 Picture of transmitting and receiving carriers.



antennas can be adjusted to the center of the targets.

Each carrier has also been provided with a bubble leveller so that the axis of the antennas can be made parallel to the horizontal reference plane which is in turn at right angles to the face of the target.

(4) Furthermore, the horizontal angular markings on the floor and the target support stand were checked with the help of a surveying transit and were found to be in misalignment. To correct for this misalignment error, new angular markings have been placed on the floor. The level as well as the orientation of the target support stand have been so adjusted that the target is normal to the line of wave propagation (i.e. centre of the shaft supporting the target) and the zero degree mark on the floor are parallel to each other and coincident. This procedure ensures that there is no misalignment of the target itself and the angular lay-outs on floor.

(5) In order to reduce the misalignment while adjusting the height of the carriers (by means of levelling screws) so that the center of the transmitting and receiving antennas are at the center of the target, telescopic rifle sights have been mounted on the waveguide sections as shown in Fig. 6. Thus when an off-set point on the target and the center of the cross-hairs of the telescopic sight overlap then the waveguide is not only normal to the target surface but the center line of wave propagation is aimed at the center of the target (see Fig. 7).

(6) Since statistical techniques are to be used to investigate a possible significant difference between two different (pulsed and CW) types of radars, then replication and randomization of the order in which

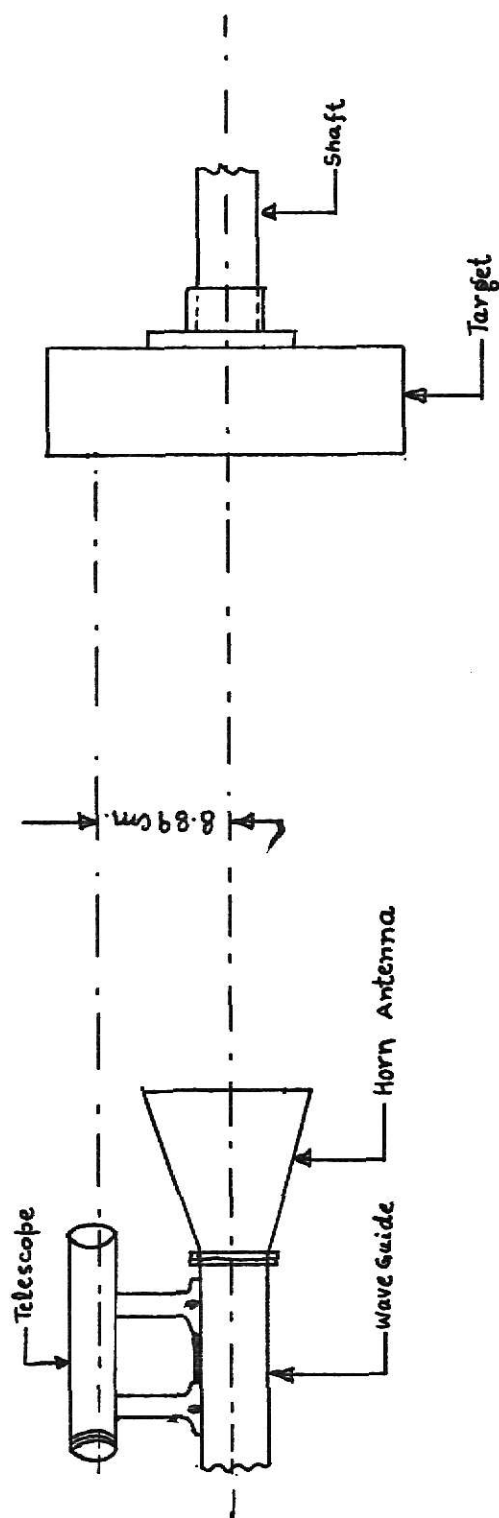


Figure 7. Offset point on calibration target.

data are taken is necessary (because these are the two fundamental principles on which the statistical model is based). At least three replicates of each set of data should be taken, and the order in which the data will be taken, for a particular set, should be randomized by using a random number table.

In short, the above improvements in the experimental set up were made in order to reduce the size of the random error term in the experiment, when performed.

2.3 SYSTEM CALIBRATION

2.3.1 Need for calibration:

The response variable in this experimental set up is the normalized received power (both P_{rNd} and P_{rNC} ; i.e. direct and cross-polarized). Since the numerical value of the transmitted power is not known, so as a consequence, the received power cannot be measured in absolute units. A Boonton model 91 DA sensitive RF voltmeter is used to obtain a measure of the received power. This voltmeter indicates a voltage value (both in dB and volts), which is proportional to the amount of received power at its input terminals, and a corresponding DC voltage value which can be measured at the DC output terminals of RF voltmeter by means of a digital DC voltmeter. Whether we read off the RF or the DC voltmeters, we obtain only a number which is proportional to the received power. It is consequently necessary to calibrate the whole system in such a manner that the number read off the DC voltmeter can be related to the received power in relative units, dB (since we cannot measure in absolute units). The 750 B calibrated attenuator on the transmitter is

used to calibrate the system so that it reads in dB. This value of dB is relative to the zero setting of calibrated attenuator.

2.3.2 Calibration Procedure:

One of the standard aluminum targets (20 cm diameter; 5.8 cm thick) is used during the calibration procedure. The transmitter and receiver are placed at standard calibration conditions (Appendix I). The Narda 750 B calibrated attenuator is then used to reduce the amount of transmitter power. This in turn reduces the voltage value indicated on the DC voltmeter (as a consequence of reduction of rms value on RF voltmeter since for a particular range on the Boonton RF voltmeter, the rms value as indicated on the meter and corresponding DC output have a linear relationship). The amount of attenuation in dB for a particular setting of 750 B attenuator is found from the calibration curve of the attenuator; hence points on the different voltage scales of the voltmeter can be calibrated to indicate the received power in dB.

The above procedure is adopted for both the pulsed and the CW radar systems. The different settings of the 750 B calibrated attenuator are used in random order by using a random number table (see Appendix II). For each radar system, graphs are plotted between dB value of the calibrated attenuator and the DC output as indicated on the digital voltmeter. The corresponding points on graph are joined by a straight line.

Hence whenever data is taken and a number read off the voltmeter, the corresponding dB value of received power can be found from the calibration curve for that particular range.

A typical format of data sheets for system calibration for the two schemes is presented on the following page.

2.4 DEFINITION OF VARIABLES

2.4.1 Independent Variables:

The independent variables in an experiment (also known as "controlled" or experimental variables) are variables which are believed to affect the response (measured) variables in some way. The different independent variables of interest in the present experiment are taken to be:

(1) Target Material:

Modulation schemes are to be compared based on the scattering of EM waves from different planar, homogeneous and inhomogeneous targets (of different internal structure and surface type) which in general means targets of different electrical permittivities. Since it is a common property of electromagnetic waves that they get scattered by different amounts from targets of different structure and composition, hence we choose the target material as one of the variables affecting the response variables. The different materials to be investigated in the complete experiment will be (i) aluminum (ii) Plater of Paris (iii) Plaster of Paris + embedded styrofoam pellets. This variable is presently a qualitative one; although if enough different materials were used, a quantitative measure could be stated in terms of electrical permittivities.

(2) Thickness:

The depth of penetration of the incident electromagnetic wave in a particular target apparently depends on (i) the frequency of

DATA SHEET

Fluke 8000A Digital Multimeter; KSU Asset No. EE 279990 Serial No. 06979
 Boonton Model 91DA, sensitive RF voltmeter; KSU Asset No. EE 146883.

SYSTEM CALIBRATION FOR PULSED MODE

No.	Dial Setting of 750 B Attenuator	Order of Setting	Current in diode A of mixer	XMTR Frequency GHZ	DC Voltmeter Scale	DC Voltmeter Reading (volts)	RF voltmeter scale	RF voltmeter Reading (volts)	Setting of Variable Attenua- tor on Transmitt.	DB value from graph of Cal.
1	00	23								
2	20	17								
3	60	08								
4	95	36								
5	120	09								
6	130	22								
7	145	28								
8	160	01								
9	172	02								
10	190	35								
11	205	25								
12	220	29								
13	235	31								
14	252	11								
15	275	20								
16	300	32								
17	315	21								
18	332	14								
19	340	10								
20	357	37								
21	364	12								
22	379	26								
23	395	34								
24	407	19								
25	428	38								
26	442	03								
27	459	07								
28	463	13								
29	479	33								
30	481	27								
31	497	18								
32	509	05								
33	524	16								
34	538	30								
35	549	04								
36	561	06								
37	567	15								
38	570	24								

transmission (ii) the material of the target construction. The high frequency of transmission (8.857 GHz) in the present experiment ensures that the depth of penetration will be small (because depth of penetration of electromagnetic waves is inversely proportional to frequency) but one cannot give the exact numerical value. Moreover, the frequency is fixed in this experiment, so it cannot be considered a variable. But on the other hand, the thickness of the target should be such that the backscattered wave is representative of reflection solely from the target material itself and not from the combination of the target and the metal hub supporting the target on the rotating shaft. To investigate the effect of thickness of target on the received reflected power, two thicknesses of target have been chosen: (i) 5.8 cm (ii) 15 cm this causes the target thickness to become one of the variables in the experiment.

(3) Surface Type:

It is known that the form of the target surface affects both the power and the shape of the reflected radar wave. However, it is not known what the interactive effects of the surface conformation and the material composition are. In order to discern the effect of target surface on the received power, the following different surface types will be studied experimentally: (i) Planar (ii) Laminar cut surface with different depths and widths of cuts (iii) Random (Gaussian generated) surfaces.

(4) Rotation of Targets:

Targets are to be placed in rotation about a horizontal axis by a small DC gear driven motor, at approximately $1\frac{1}{2}$ - 2 rpm. The

purpose is to measure, on an x-y plotter (in case of plaster targets), both direct and cross-polarized responses as functions of the angle of target rotation. Such responses will then be manually integrated to determine an effective (mean) direct or cross-polarized response. The effective (mean) response is assumed to be a measure of the particular characteristics of the particular target (material, density, dielectric properties, surface characteristics, volumetric characteristics, etc.). For example, the response from the target might be as follows:

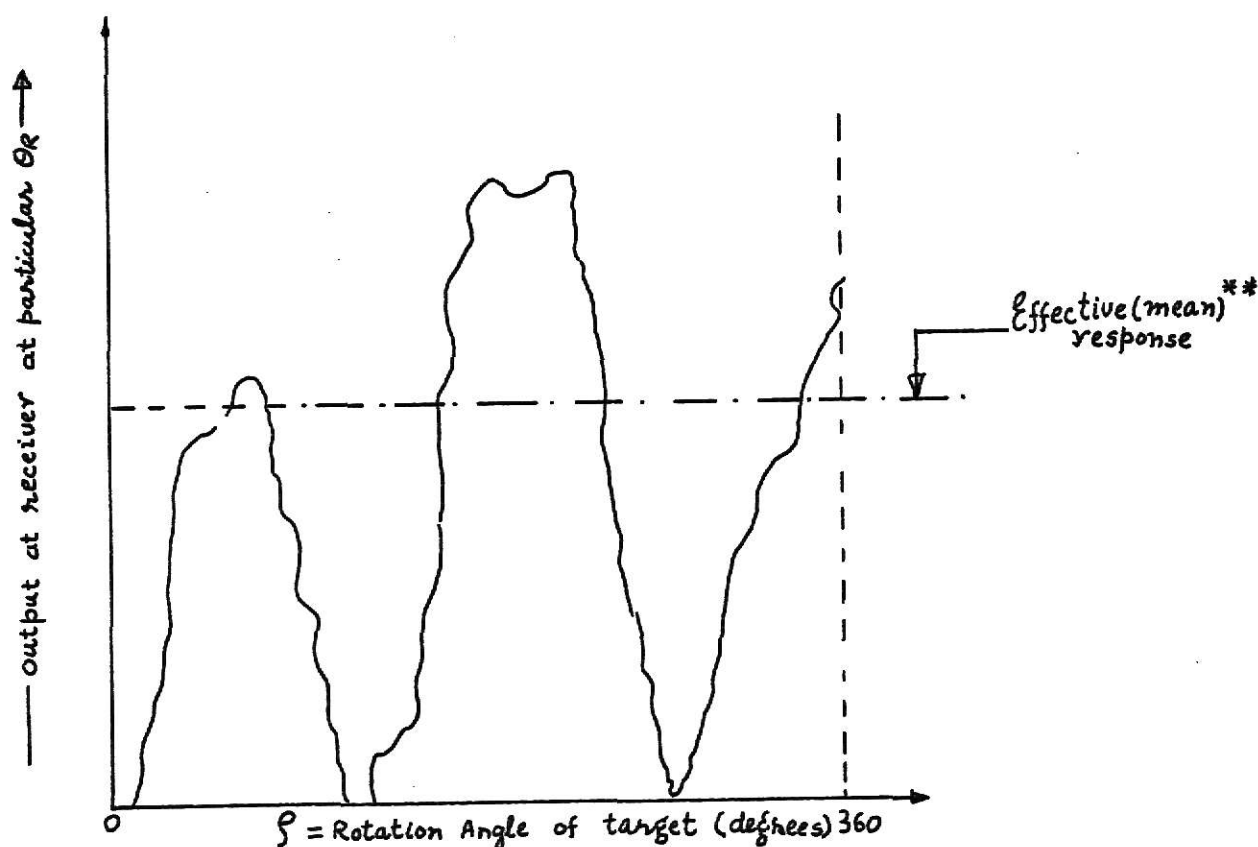


Figure 8. Particular response characteristics

* Obtained by integrating the actual response and dividing by θ ; thus particular response $(\theta_T, \theta_R) = 1/360 \int_0^{360} f(\theta) d\theta$

The above response would be typical for some particular

- (a) Target, as a random one^{*}
- (b) A particular transmitter angle, $\theta_T = 20^\circ$ say
- (c) A particular receiver angle, $\theta_R = 15^\circ$ say
- (5) Modulation scheme:

The general purpose of the immediate experiment is to determine if a continuous wave type of target illumination will provide useable information concerning target definition and structure (internal characteristics) instead of a pulsed mode of target illumination. More particularly, if CW illumination is used, then simpler radar transmitting and receiving equipment installations can be used. Thus the principal purpose at this time is to find out if there is any statistically significant difference in the responses of two systems; viz (i) a pulsed wave system and (ii) a continuous wave system.

For a pulsed wave system, a typical pulse format is as follows:

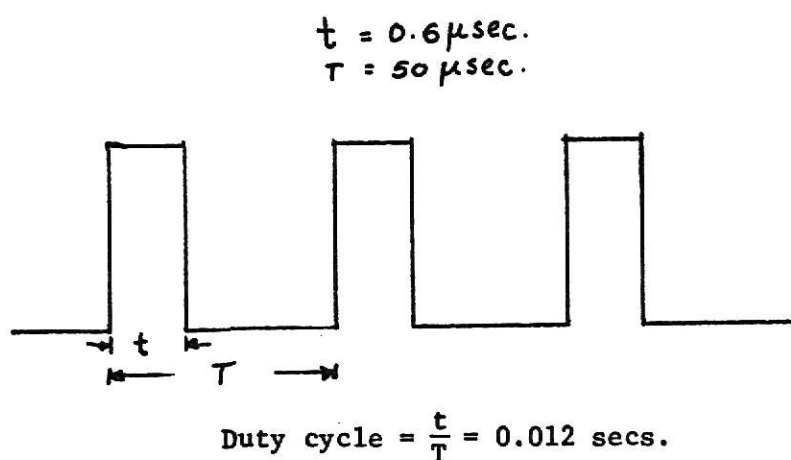


Figure 9. Pulse format

^{*}Or random with a specified (given) density and backing surface.

(6) Covariable:

Since the response (P_{rc} or P_{rd}) is a function of the horizontal angle of transmission with respect to the target normal (θ_T) and of the angle of reception with respect to the target (θ_R), it is planned to locate the transmitter at a fixed location of $\theta_T = 20^\circ$ to the normal to the target plane, and then place the receiver at several locations which varies the receiver angle from $\theta_R = -5^\circ$ to $\theta_R = 45^\circ^*$ at increments ($\Delta\theta_R$) of 2.5° .

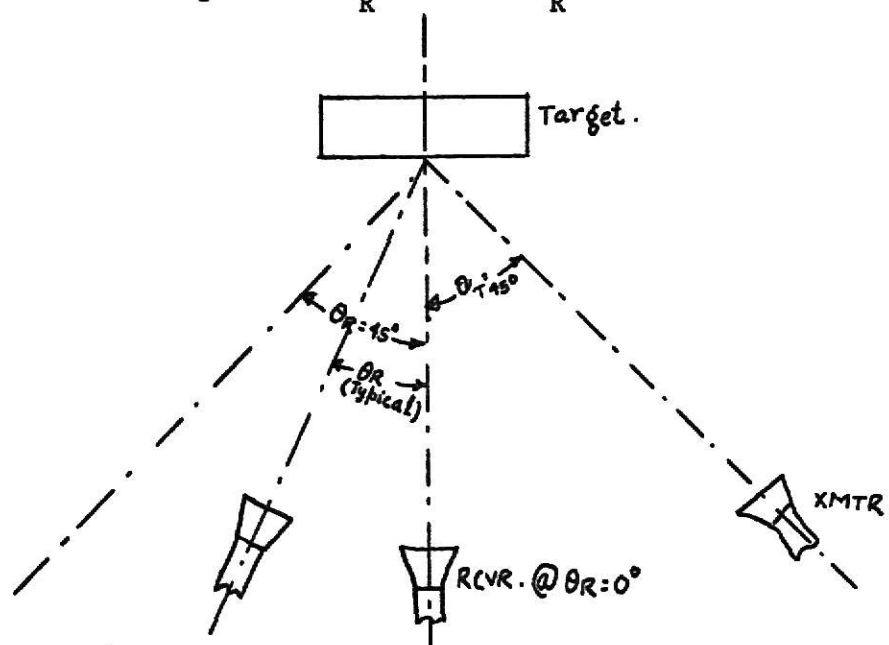


Figure 10. Particular transmitter and receiver set up.

* There are two reasons for keeping the upper limit of θ_R at 45° : (i) Due to physical limitations of the laboratory where the experiment is to be performed, one cannot go beyond 45° (ii) At angles of 45° and above, one cannot make out whether (a) the reflected wave is coming from the target front surface or from the target sides since at these angles the receiver sees the sides as well as the target front surface (b) the receiver horn starts getting into the field of transmitter horn.

At each receiver location, the following data will be taken:

$P_{rd}(\theta_T, \theta_R)$ = direct (in phase) component of received power

$P_{rc}(\theta_T, \theta_R)$ = cross-polarized component of received power

θ_T = constant = 20°

θ_R = horizontal angle.

(Also other necessary data to indicate transmitter and receiver are functioning properly).

There are 21 receiver locations (from -5° to 45° at 2.5° intervals). Hence there are the same number of data points for each reading of each of the variables $P_{rd}(\theta_T, \theta_R)$ and $P_{rc}(\theta_T, \theta_R)$.

It would have been desirable to randomize all the controllable variables in this experiment. However, this would have needlessly complicated the experiment and required an excessive amount of time. Some of the controllable variables were believed capable of being set without appreciable error between settings (e.g., the planar targets could be repeatedly set on the mounting shaft in almost precisely the same vertical plane because of a reference point placed on the floor which in turn could be "tied" to the target with a plumb-bob. This probable error in this setting, on the order of $1/16"$ (0.158 cm) in 16 feet (487 cm), is very small in comparison to the radar wavelength of the system (approximately 3.38 cm) or the probable error due to an error in horizontal angular displacement, which is of the order $1/8"$ (0.32 cm) in 32 feet (975 cm) or 0.0003 radians (0.019 degrees). What is being said here, effectively, is that there are several sources of experimental error; however, it is believed that these sources (except the co-variable, θ_R) produce errors now so small (after the equipment modification) that complete randomization of the experiment need not

be considered vital. However, the one variable that could not be so controlled is the covariable, θ_R , and for this reason the horizontal angular settings of the receiver have been taken in random order.

2.4.2 Dependent Variable:

In this composite experiment, the dependent variables are:

(i) Normalized direct-polarized received power [P_{rNd}] (ii) Normalized cross-polarized received power [P_{rNc}]. The received power will be measured by the DC voltmeter. Correspondingly the value of received power in dB will be obtained from the calibration curve corresponding to (i) the range setting of RF voltmeter (ii) type of modulation scheme. After obtaining the data for each desired angular position of receiver, each value will be normalized with respect to the value of received power corresponding to $\theta_T = \theta_R = 20^\circ$.

2.5 EXPERIMENTAL DESIGN

As can be deduced from the general definition of the problem and the definition of several variables in the experiment, there are not only several experimental variables (factors) present but also several levels of each of these factors. Normally, if interaction were suspected, it would be desirable to completely randomize the entire experiment, and perform it according to a factorial design. However, we recognize, for example, that not every target type (surface and thickness) is made from every type of material, so it is not possible to investigate all possible interactions with respect to target "mixes".

What is of interest here is the relative performance of continuous wave responses versus pulsed wave responses, in the presence of various types of targets and target materials, as a function of the covariable, θ_R . This type of performance comparison can be adequately investigated by using a hierarchial experimental design, Hicks [22], in which a covariable is embedded. In such a design, we conceive of the hierarchial variables as (i) target material, (ii) target thickness and (iii) type of target surface. Thus, for any given target material, a subclassification would be the target thickness, and then within these two classifications, a second level of subclassification, the type of surface. As an example, an aluminum target having a thickness of 5.8 cm and a planar machined surface would constitute a particular hierarchial subdivision.

It is presently contemplated that the experiment will eventually examine responses from at least four types of materials (i.e., the variable "material" is programmed at four levels; $k = 1, 2, 3, 4$):

$K = 1$ aluminum alloy

$K = 2$ Pure plaster of Paris (Relative permittivity of 3.2; loss tangent of .01 and vol. app. 21936 cm^3)

$K = 3$ Plaster of Paris plus styrofoam pellets, (density = 500 styrofoam pellets in approximately 21936 cm^3 of target volume)

$K = 4$ Plaster of Paris plus styrofoam pellets (density = 2500 styrofoam pellets in approximately 21936 cm^3 of target volume).

Two nominal (mean) thicknesses (l) of target are presently contemplated:

$l = 1$ mean target thickness = 5.8 cm

$l = 2$ mean target thickness = 15 cm.

As to the type of surface, several possibilities exist. For the present, it will suffice to describe three types of target surfaces, each of which may affect the direct and cross-polarized reflected waves in different manners. This subclassification is presently taken to have only three levels ($m = 1, 2, 3$) although more levels can be added to the overall experiment later. The present minimum number of levels of investigation are:

- $m = 1$ Planar reflecting surface, generated as plane as possible and at right angles to the supporting shaft by fine, finished machining and polished in a lathe;
- $m = 2$ Random, Gaussian surfaces, generated by the method described by Funke [16];
- $m = 3$ Planar surfaces that are cut by parallel laminar cuts, so as to present "a ridged" reflecting surface to the incident wave.

Possible subclassification under $m = 2$ above (random surfaces) would be targets with different mean random heights and different variations in heights. Possible subclassification under $m = 3$ above (laminar cut surfaces) would be targets having different depths of cut, different widths of cut, and different spacings of cuts.

These variables can be initially investigated in a hierarchical experiment. For a typical replicate, the design is illustrated in Fig. 11. Note that within any treatment combination (K, ℓ, m) , the covariable, θ_R , is embedded as a result of the functional relationship prescribed by Eq. (2.8) between the response variables, P_{rNd} and P_{rNc} and the covariable θ_R .

The random error in the entire experiment is measurable only when the experiment is replicated at least twice. Better precision of estimation

REPLICATE

REPLICATE No. (A_j): (j = 1,2,3) ("blocks") (Randomization occurs within replicates)

TYPE OF MODULATION (M_j)

TYPE OF RESPONSE (P₁ or P₂): Direct Polarized (P_d) Cross Polarized (P_c)

Material Homogeneity of Target (affects of dielectric "effect"); i.e., Material of construction of target. (Symbol H _k)	k = 1 = Aluminum		k = 2 = Plaster		k = 3 = Plaster + Styro balls, density #1		k = 4 = Plaster + Styro balls, density #2	
	l = 1 Existing Calibration Target thickness=5.8cm	l = 2 Future: thick on order of 15 cm.	l = 1 5.8 cm	l = 2 (Future) ~ 15 cm	l = 1 5.8 cm	l = 2 Exist'g 15 cm effect-five thickness	l = 1 5.8 cm	l = 2 Exist'g 15 cm effect-five thickness
Type of Surface (i.e., planar, cut in laminar grating, random generated surface) 1 = planar 2 = laminar cut * Symbol S _m 3 = random	m = 1	m = 2*	m = 3	m = 1	m = 2*	m = 3	m = 1	m = 2*
*Special cases of #2 are variations in (a) depth of cut, (b) spacing of grating								
Covariable (θ _R):								
Condition 1								
(n)								
2								
3								
4								
5								
6								
7								
8								
9								
10								
11								
12								
13								
14								
15								
16								
17								
18								
19								
20								
21								

on the random error can be had if the number of replicates is increased. Here, at least three replicates ($i = 1, 2, 3$) should be taken. Each replicate is treated as a "block" in the experimental design.

Based on a "block" (replicate) design of the experiment and the hierarchical nature of the variables, the mathematical model of the experimental design used in this experiment may be stated as follows:

$$\left. \begin{array}{l} (P_{rNd}(\theta_T, \theta_R)_{ijklmn}) \\ (P_{rNc}(\theta_T, \theta_R)_{ijklmn}) \end{array} \right\} = \mu + M_i + A_j + H_k + T_l + S_m + \beta_i[f'(\theta_R)_n] + \epsilon_{ijklmn} \quad (2.11)$$

The symbols in the mathematical model stand for the following above mentioned variables (or factors in the block design):

(i) (P_{rNd}) and (P_{rNc}) : P_{rNd} and P_{rNc} are the response variables.

They are the normalized direct and cross-polarized components of the EM wave backscattered from the particular target.

Both P_{rNd} and P_{rNc} are measured in relative units of power i.e. decibels.

(ii) μ : The overall mean of the experiment for the particular modulation scheme.

(iii) M_i : The effect due to the type of modulation in the transmitter ($i = 1 = \text{Pulsed}$; $i = 2 = \text{continuous wave}$).

(iv) A_j : The effect of the j^{th} replicate on the response variable (here $j = 1, 2, 3$).

(v) H_k : The effect on the response due to the type of material under investigation;

$k = 1$ = aluminum alloy.

$k = 2$ = solid plaster of Paris target (of volume approximately 21936 cm^3).

$k = 3$ = plaster of Paris plus styrofoam pellets (density = 500 styrofoam pellets in approximately 21936 cm^3 of target volume).

$k = 4$ = plaster of Paris plus styrofoam pellets (density = 2500 styrofoam pellets in approximately 21936 cm^3 of target volume).

If need be, different types of materials can be put under experimental study. The only change in the hierarchial design will be that there will be another column on the right of the four material columns indicated in Fig. 11.

(vi) T_l : The effect due to the target thickness;

$l = 1$ = target of thickness 5.8 cm.

$l = 2$ = target of thickness 15 cm.

(vii) S_m : The effect on the response due to the type of surface;

$m = 1$ = planar surface.

$m = 2$ = Laminar cut surface.

$m = 3$ = random (Gaussian generated surface).

(viii) $\beta_f[f'(\theta_R)_n]$: θ_R is the independent continuous variable known as the covariable. $f'(\theta_R)$ is the function of θ_R and is $\left[\frac{Z'}{Z} - \frac{J_1(Z)}{J_1(Z')}\right]^2$, where $Z = K_0 a(\sin\theta_R - \sin\theta_T)$. 'f' is the logarithmic transformation (base 10) to be applied to $f'(\theta_R)$ to get a linear relationship of

Eq. (2.10). β_n is the constant; $n = 1, 2, 3, \dots, 21$ = the particular angle of θ_R .

- (ix) ε_{ijklmn} : The random error term in the experiment. The usefulness of the conclusions drawn from the experiment depends upon the value of the random error term (which should be small). This cannot be determined until the analysis of data is performed. However, random error can be reduced by minimizing the identifiable sources of error.

2.6 PROCEDURE FOR DATA COLLECTION

In order to verify the proper operation of the system while taking data, the following procedure is followed:

- (1) Turn on the equipment, transmitter and receiver, and allow it to warm up for one hour.
- (2) During warm up time, mount the standard target on the shaft. Move the transmitting and receiving antennas to the standard calibration conditions (Appendix I). Boresight the transmitting and receiving antennas, at this particular condition, according to the boresighting procedure (Appendix I).
- (3) At the end of warm up period, set up the transmitter and receiver according to the respective set up procedures (Appendix I).
- (4) After verification of the transmitter and receiver equipment set ups and boresighting, check for the following points before recording voltmeter reading:
 - (i) Search light on the front panel of oscillator synchronizer is off.

- (ii) By means of frequency meter, make sure that transmitter frequency is 8.857 GHz. (In order not to reduce the effective transmission power in the desired direction, detune the frequency meter after verification of frequency).
- (iii) Current in diode 'A' of the mixer is .7 mA.
- (iv) Target is rotating

After checking for the above mentioned points, record the reading of the digital voltmeter (recording to be made on x-y plotter if target is inhomogeneous) for both direct and cross-polarized positions* of the receiving antenna. Also record the other necessary information required according to the columns of the data sheet.

(5)** Remove the standard target from the shaft and mount the target under investigation.

(6) With transmitter antenna at angular position of $\theta_T = 20^\circ$, move the receiving antenna at the angular position as determined from the random number table or data sheet (this angular position is between -5° to 45° at intervals of 2.5°) and boresight it as before.

* For setting up at cross-polarized position, simply lift the receiver and place the standard aluminum block under the microwave switch and bolt it at that position.

** Because of the harmful effects of electromagnetic radiations to human body; turn off the transmitter power (beam voltage) while replacing the target. Turn the beam voltage 'ON' at the completion of this step.

(7) Before taking data at this position of the receiver, follow the procedure as in step (4) above.

(8) After the completion of data taking (not to exceed 8 hrs.), set up and boresight the transmitter and receiver at standard calibration condition and record the reading on voltmeter by following step (4). [This reading is taken to ensure that the system had not had a major shift in characteristics while the data was being taken].

(9) Before turning off the main power at the end of data taking, first turn off the beam voltage of the klystrons and then turn off the main power.

A typical format of data sheet is shown on next page.

CHAPTER III

ANALYSIS OF DATA

3.1 Introduction

Chapter II presented the design of the experiment and the mathematical model of the experimental design. Furthermore, it also presented the procedure for taking data. The purpose of this chapter is to demonstrate the method of handling the data and the consequent analysis of it. For this purpose, data for the 10 cm radius aluminum target has been analysed, for both pulsed and CW modulation schemes. The data for the pulsed system were obtained from Funke's dissertation [16], and the data for the CW system were collected before the equipment was modified and the experiment was rigourously designed from a statistical viewpoint. Because of the small number of available data points, these data have been analysed by an abbreviated Doolittle method (Wine[23]) and the rest of the analysis has been undertaken manually.

3.2 Statistical Model

Equation (2.11) is a mathematical model for the experimental design developed in Chapter II. To demonstrate the method of analysis, only an aluminium target of 10 cm radius has been considered here. Hence, the full covariance model in (2.11) is not fully applicable, and a reduced model has been derived from the mathematical model to apply to the available data. The reduced model is:

$$Y_{in} = \mu + \beta_1(X_{in} - \bar{X}) + M_1 + \epsilon_{in} \quad (3.1)$$

where $Y_{in} : P_{rNd}(\theta_T, \theta_R)_{in}$, measured in dB.

μ : overall mean of the experiment.

$$X_{in} : 10 \log_{10} \left[\frac{J_1(Z)}{Z} \cdot \frac{Z'}{J_1(Z')} \right]^2;$$

where $Z = K_o a (\sin \theta_R - \sin \theta_T)$

$Z = K_o a (\sin \theta_R - \sin \theta_T)$ when $\theta_T = \theta_R = 20^\circ$

\bar{X} : mean of X_{ij} values

β_1 : regression coefficient (slope)

M_i : effect due to type of modulation

($i=1$ =plused system; $i=2$ =continuous wave system)

ϵ_{in} : random error term in the experiment.

The data, to be analysed, are given in tabular form on the following page. A graphical sketch of independent (X_{in}) and dependent (Y_{in}) variables is also given in Fig. 12.

3.3 Analysis of Covariance

Equation (3.1) is the covariance model for the data to be analysed.

Since the primary objective is to discern the effect of two different modulation schemes on the response variable, the effect of the covariable (θ_R) on the response variable has to be removed before the effect of modulation schemes can be evaluated statistically.

TABLE OF DATA TO BE ANALYZED

n	θ_R (degrees)	$X_{in} = 10 \log_{10} \left(\frac{J_1(Z)}{Z} \cdot \frac{Z'}{J_1(Z')} \right)^2$ $i = 1, 2$	$Y_{1n} (=P_{dB}^{rNd})$	$Y_{2n} (=P_{dB}^{rNd})$
1	0	24.1412	19.3	-
2	2.5	18.2271	17.0	-
3	5.0	18.1213	18.2	17.4
4	7.5	34.6509	20.2	22.0
5	10.0	14.5527	13.2	21.4
6	12.5	6.7636	6.8	9.02
7	15.0	2.7281	2.5	5.06
8	17.5	0.6470	0.23	1.68
9	20.0	0.0000	0.00	0.0
10	22.5	0.6260	0.91	1.55
11	25.0	2.5528	3.41	2.91
12	27.5	6.0535	7.50	5.70
13	30.0	12.0689	10.0	9.85
14	32.5	26.4694	21.6	25.3
15	35.0	22.0304	19.5	19.9
16	37.5	17.7301	19.3	-
17	40.0	18.3784	18.2	-
18	42.5	22.3611	19.1	-

**THE FOLLOWING
PAGE IS CUT OFF**

**THIS IS AS
RECEIVED FROM
THE CUSTOMER**

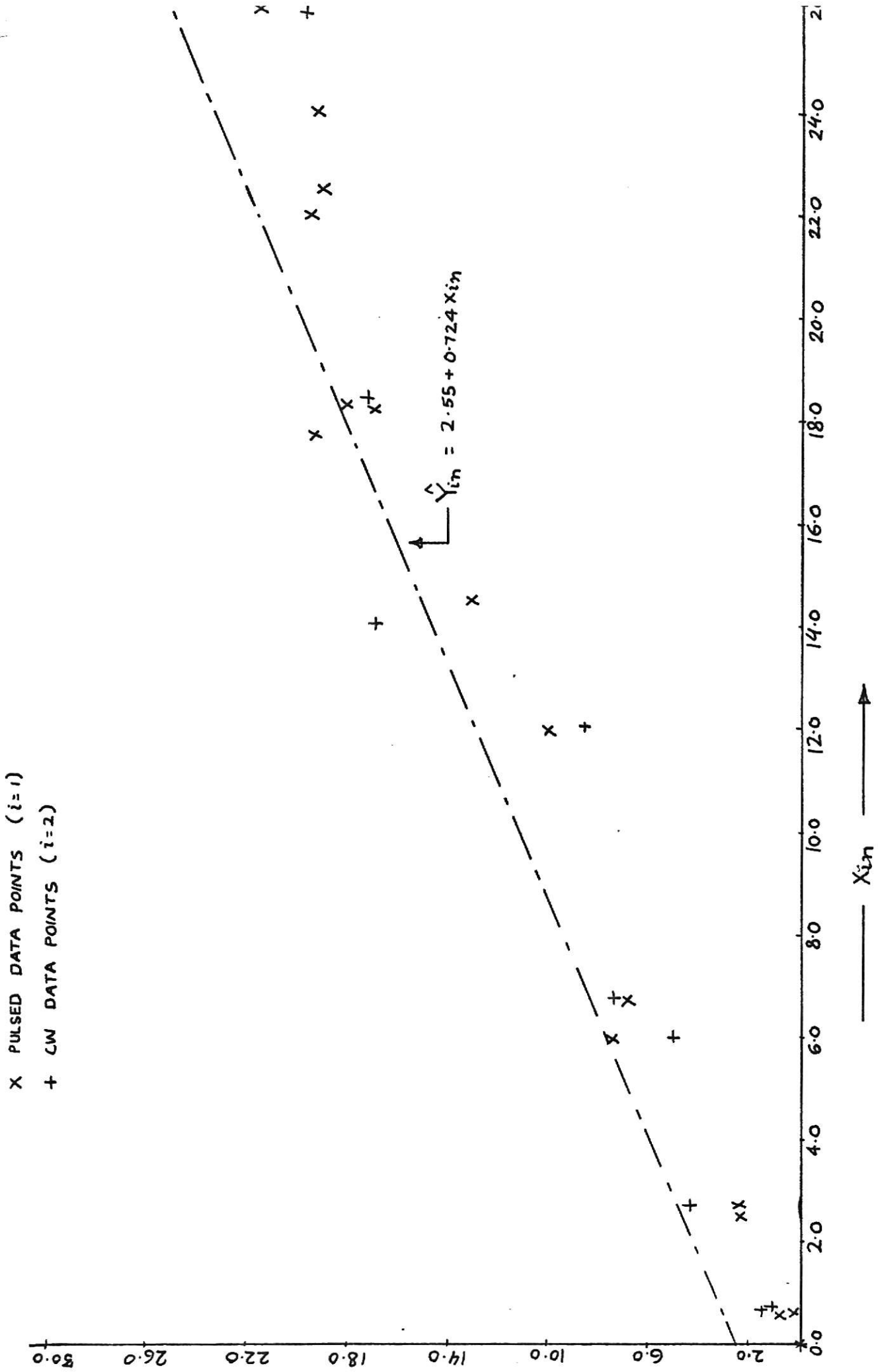


Fig. 12. Plot of Response Variables

In order to discern the difference between the modulation schemes, the analysis is performed in two steps:

Step I: 'Test for the equality of slopes of the two regression lines for the two modulation schemes'.

In this step, the hypothesis to be tested is:

$$H_0 : (\beta_1)_1 - (\beta_1)_2 = 0$$

$$H_a : (\beta_1)_1 - (\beta_1)_2 \neq 0$$

where

$$(\beta_1)_1 = \text{slope of pulsed data in (3.1)}$$

$$(\beta_1)_2 = \text{slope of CW data in (3.1)}$$

By the abbreviated Doolittle method, the estimate of the slope of regression lines is:

$$(\hat{\beta}_1)_1 = b_1 = 0.7199$$

$$(\hat{\beta}_1)_2 = b_2 = 0.7282$$

Since the common population variance is unknown, the pooled error variance, used as an estimator of the population variance, is found from the relation:

$$\hat{\sigma}_e^2 = s^2 = \frac{SSres_1 + SSres_2}{(n_1 + n_2 - 4)} \quad (3.2)$$

where $SSres_1$ = residual sum of squares for pulsed modulation data
 $SSres_2$ = residual sum of squares for CW modulation data
 n_1, n_2 are the number of data points for the pulsed and CW data, respectively.

$$\begin{aligned} \text{Hence: } s^2 &= \frac{102.8621 + 130.2848}{17 + 12 - 4} \\ &= \frac{233.1469}{25} = 9.3258 \end{aligned}$$

The appropriate statistical test for testing the null hypothesis $H_0 : (\beta_1)_1 - (\beta_1)_2 = 0$ versus $H_a : (\beta_1)_1 - (\beta_1)_2 \neq 0$ is the student "t" test, with $(n_1 + n_2 - 4)$ degrees of freedom. The test statistic [23] is:

$$t(25) = \frac{b_1 - b_2}{s \sqrt{\frac{1}{SS_1} + \frac{1}{SS_2}}} \quad (3.3)$$

where SS_1 = sum of squares of pulsed modulation data

SS_2 = sum of squares of CW modulation data

b_1, b_2 = estimates of the slopes β_1 and β_2 from the Doolittle analysis.

$$\begin{aligned} \text{hence: } t(25)_{\text{test}} &= \frac{0.7199 - 0.7282}{(9.3258)^{1/2} \sqrt{\frac{1}{1622.9263} + \frac{1}{1368.1240}}} \\ &= \frac{0.0084}{(9.3258)^{1/2} (.0006161 + .007309)^{1/2}} \\ &= 0.0741 \end{aligned}$$

From tabulated values of the "t" distribution, at an assumed $\alpha = .05$ level of significance with 25 degrees of freedom, the comparative statistic is $t(25)_{\alpha = .05} = 1.708$.

Since the test statistic $t_{\text{test}} = 0.0741$ is very small compared to $t_{\alpha = .05} = 1.708$, the test fails and we cannot reject the null hypothesis H_0 . The result is that we must assume both the regression lines are parallel and have equal slopes.

Step II:

Having accepted the hypothesis that the slopes of the two regression functions are equal, we may now test the hypothesis that the intercepts are equal. The appropriate hypothesis are:

$$H'_0 : (\beta_0)_1 - (\beta_0)_2 = 0$$

$$H'_a : (\beta_0)_1 - (\beta_0)_2 \neq 0$$

which is equivalent to testing the hypotheses,

$$H'_0 : \mu_1 - \mu_2 = 0$$

$$H'_a : \mu_1 - \mu_2 \neq 0$$

where μ_1 and μ_2 are the means of the data for the two modulation schemes. Note that the subscripts 1 and 2 represent the modulation schemes, where

1 = pulsed modulation, and

2 = continuous wave modulation

In order to test the above hypothesis, it is necessary to pool the data (Wine [23], pp. 558-561), which results in a covariance model with common slope β_1 . In this model, the modulation effect is explicitly stated, thus:

$$Y_{in} = \mu + \beta_1 (X_{in} - \bar{X}) + M_i + \epsilon_{in} \quad (3.4)$$

where

Y_{in} : response variable

X_{in} : covariate value

μ : the experimental mean

M_i : treatment effect (modulation scheme: $i = 1$, pulsed; $i = 2$, CW)

β_1 : common slope of the covariable

\bar{X} : mean of all the X_{in} values.

Equation (3.4) is analogous to equation developed in Chapter II but with only one treatment term (M_i) instead of the others (A_j , H_k , T_l , S_m). The effect of this is to force the other effects (if they exist) into the random error term, ϵ_{in} .

With the present data, the effects M_i ($i=1,2$) can be estimated and the hypotheses can be tested as follows:

$$H'_0 : M_1 = M_2 \text{ (no difference in modulation schemes)}$$

$$H'_a : M_1 \neq M_2 \text{ (significant difference between modulation schemes)}$$

The appropriate method of testing these hypotheses is by analysis of covariance, using an F-test on the modulation scheme mean square. The statistical test is made by an analysis of covariance, as follows:

Effect	Degrees of Freedom (df)	Sum of Squares	Mean Square	F (test value)	F ($\alpha = .05$)
Total (uncorrected)	29	6244.9479	—	—	—
Corrections:					
Mean (β_0)	1	4438.6974	—	—	—
Covariable ($\beta_1 \beta_0$)	1	1569.3877	—	—	—
Corrected	27	236.8628	—	—	—
Modulation type (M_1)	1	3.6550	3.6650	0.409	4.23
Residual	26	233.1978	8.9691	—	—

where error mean square (EMS) = $\sigma\epsilon^2$ = experimental error:

$$= \frac{233.1978}{26} = 8.9691$$

The F-statistic for testing H_0 is

$$F(1,26) = \frac{\sigma\epsilon^2 + K \sigma_m^2}{\sigma\epsilon^2} = \frac{3.6550}{8.9691} = 0.409$$

From the tabulated values of the F distribution, $F(1,26)$ at a significance level, $\alpha = .05$, is 4.23.

Since .409 is small compared to 4.23, one cannot reject the null hypothesis that there is no significant difference due to the type of modulation used.

In conclusion, we must conclude that there is no statistical difference between modulation schemes. However, this may be merely due to either:

- (i) insufficient data, or (ii) too large an experimental error.

As an example of (ii) above, the standard deviation corresponding to error mean square is:

$$\sqrt{\text{EMS}} = \sqrt{\sigma_{\epsilon}^2} = (8.9691)^{1/2} = 2.99$$

and the difference in the 'means' of modulation schemes is:

$$\begin{aligned}\Delta\mu &= \mu_1 - \mu_2 = 2.8565 - 2.2405 \\ &= 0.6160\end{aligned}$$

Accordingly, the coefficient of variability for this effect is:

$$C_v = \frac{\sqrt{\text{EMS}}}{\Delta\mu} = \frac{2.99}{0.6160} = 4.85 \text{ or } 485\%$$

This statement shows that in these data the experimental error is approximately five times the magnitude of the effect being examined.

In order to "see" a statistically significant difference between modulation schemes, one should have a coefficient of variability on the order of 5-10% instead of 485%. The fundamental conclusion of these early data, then, is that the variability of the experiment must be drastically reduced in order to discern any significant difference in modulation schemes.

CHAPTER IV

CONCLUSIONS

In order to discern the possible "statistically significant difference" in the reflection interpretations between continuous wave and pulsed wave radar systems, a hierarchical experimental design has been presented, in which a covariable is embedded. Since the strength of both the direct and cross-polarized reflected waves depends upon the type of target from which they are reflected, the experimental design contemplates the use of targets of different material, composition and surface type. Both independent and dependent variables, in the experiment, have been defined and based on their hierarchical nature, a mathematical model of the experimental design has been laid down.

Since the experimental results are weighed against the random error term in the experiment, the experimental set up has been drastically modified to reduce foreseen sources of random errors. A procedure has also been given for system calibration and for taking data.

Based on an analysis of covariance, (in Chapter III) there appears to be no effect of the type of modulation scheme (pulsed and CW) on the response variable (Y_{ij}). This is possibly due to the error variance being large compared to the effect due to modulation schemes at the level of significance (α) of .05. In other words, with 95% confidence, we can say that the effect of the type of modulation on the received power is not measurable by the data. The same result could come from insufficient data.

On the other hand, it has also been concluded in Chapter III that the coefficient of variability of the modulation effect is 485%. But in statistical terminology, in order to "see" the treatment effect (modulation scheme in the example illustrated in Chapter III) on the response function, the coefficient of variability should be on the order of 5-10% for the experiment, if the conclusions are to be based on more solid grounds.

In conclusion, the error variance in the example illustrated in Chapter III, is probably too large. It should be emphasized that these data have been analysed here for illustrative purposes only, and the conclusions that derive from the analysis are probably not valid, nor are they to be used as predictive results. They demonstrate data reduction methods only.

APPENDIX I

TRANSMITTER ADJUSTMENTS

- (1) (a) For operational set up of klystron power supply, refer to 'sequence of operation' section of the 'Instruction Manual' (for Narda model 438 klystron power supply) and proceed according to steps 2 through 7, skipping step 3.
(b) The beam voltage and reflector voltage should be adjusted so that the transmitter frequency is 8.857 GHZ. (Check this frequency with the frequency meter provided). While adjusting these two voltages, make sure that the sum of these two voltages does not exceed 750 volts because this high a voltage may damage the klystron.
(c) When operating in pulsed mode, set the modulation switch on the front panel of power supply to 'external' position and when in CW mode, set it to off position.
- (2) (a) For set up and operational procedure for 'Oscillator Synchronizer', refer to Handbook for model DY-2650A oscillator synchronizer (Art 2-3.1-Frequency Stabilization).
(b) Set the modulation sensitivity of oscillator synchronizer to 0.12-0.25 Mc/μ by adjusting the function switch provided at the rear panel of the synchronizer.
- (3)* (a) Adjust the pulse generator to give a pulse width of .6μ sec (at 3 dB point) and pulse repetition frequency of 20 KHZ.

* This adjustment required only for pulsed mode of operation.

- (b) Before connecting the output of pulse generator to PIN modulator, through wave shaping network, check the pulse width and repetition frequency on the oscilloscope.
 - (c) Adjust the DC voltage for wave shaping network at 4.5 V with current limit below 15 mA.
 - (d) Further observe the pulse shape on oscilloscope through the wave shaping network, check the pulse width and repetition frequency on the oscilloscope.
- (4) Set the variable attenuator provided with the klystron to a value above 5 db. (Set it at that particular value and do not disturb it then on). If it is set at a value lower than 5 db then output will be distorted since the isolator is not able to handle output power above this level.
- (5) Set the calibrated attenuator at position of 300.

RECEIVER ADJUSTMENTS

- (1) (a) Adjust the repeller to ground voltage (which is sum of beam and reflector voltage) of local oscillator klystron to -725 volts. By this adjustment, the IF frequency out of the mixer will be below 40 MHz, the upper frequency limit of the IF amplifier provided at the output of the mixer.
- (b) Set up the modulation switch to CW, amplitude and frequency settings may be arbitrary.
- (2) Set the attenuator, provided with the local oscillator klystron, so that current through diode 'A' of the mixer is .7 mA.

(3) Set the amplification switch of the IF amplifier ('HP' wide-band amplifier) to 40 db.

BORESIGHTING PROCEDURE

(1) Bring the receiving (or transmitting) antenna over the angular position (marked on floor) at which it is required.

(2) Drop down a plumb bob from the center of the face of the antenna and move the carrier till the tip of the plumb bob is exactly over the desired angular mark (this mark is intersection of 16' radius point and that particular angular line) and that the pointer at the back of the carrier is also over that same angular line.

(3) Turn the jack screws to lift the carrier off the floor.

(4) Look through the eyepiece of the gun sight, provided above the waveguide section, and stop turning the jack screws when the off-set mark on the target approximately falls at the cross-hairs.

(5) Make slight adjustments of the jack screws till the following conditions are met:

(a) The off-set mark on the target falls exactly at the center of the cross-hairs.

(b) Wooden platform of carrier is levelled (as observed from bubble levellers provided on the waveguide section).

(c) The center of the face of the antenna and the center of the back of the carrier are exactly over a particular angular line (as observed by means of plumb bob).

(6) Tighten the lock nuts and go through step (5) above, again.

(7) The transmitter (or receiver) antenna is now set at the position desired.

This completes boresighting adjustment.

CALIBRATION CONDITIONS

During calibration conditions, following settings should be made:

- (a) Transmitter antenna at $\theta_T = 20^\circ$.
- (b) Receiving antenna at $\theta_R = 20^\circ$.
- (c) Distance of transmitting and receiving antennas from center of target, i.e. $D_T = D_R = 16'$.
- (d) The standard calibration target is 10 cm radius, 5.8 cm thick planar aluminum target.

APPENDIX II

Procedure for randomizing the order of data collection:

First of all choose some random number base (10,000 in present case). This means that the range of random numbers which can be assigned to the data points is from 0 to 9999. Since all the data points are equally probable, divide the total range by the number of data points (21 in present case of data collection and 38 for system calibration). This means the total range is divided into different subsets of equally probable ranges. Assign these ranges to the data points, in order. After this start from any point from random number table. If for example first number picked up from table is 400 then find the range in which this number 400 lies and assign number '1' to that data point, under 'order' column. Proceed in this manner till all data points have been covered. These tables for the present set up are provided on following pages:

RANDOMIZATION OF THE SETTINGS OF
CALIBRATED ATTENUATOR (ON TRANSMITTER)
FOR PLOTTING THE CALIBRATION CURVES

No.	Dial Setting	Assigned Random Number Range	Order of Setting
1	00	0 - 262	23
2	20	263 - 525	17
3	60	526 - 788	08
4	95	789 - 1051	36
5	120	1052 - 1314	09
6	130	1315 - 1577	22
7	145	1578 - 1841	28
8	160	1842 - 2104	01
9	172	2105 - 2367	02
10	190	2368 - 2630	35
11	205	2631 - 2893	25
12	220	2894 - 3156	29
13	235	3157 - 3420	31
14	252	3421 - 3683	11
15	275	3684 - 3946	20
16	300	3947 - 4209	32
17	315	4210 - 4472	21
18	332	4473 - 4735	14
19	340	4736 - 4999	10
20	357	5000 - 5262	37
21	364	5263 - 5525	12
22	379	5526 - 5788	26
23	395	5789 - 6051	34
24	407	6052 - 6314	19
25	428	6315 - 6577	38
26	442	6578 - 6841	03
27	459	6842 - 7104	07
28	463	7105 - 7367	13
29	479	7368 - 7630	33
30	481	7631 - 7893	27
31	497	7894 - 8156	18
32	509	8157 - 8420	05
33	524	8421 - 8683	16
34	538	8684 - 8946	30
35	549	8947 - 9209	04
36	561	9210 - 9472	06
37	567	9473 - 9735	15
38	570	9736 - 9999	24

ORDER OF SETTING OF RECEIVING ANTENNA AT
ANGULAR POSITIONS FOR PURPOSE OF COLLECTING DATA

No.	θ_R Degrees	Assigned Random Number Range	Random Order of Setting of Receiving Antenna		
			Replicate		
			I	II	III
1	-5°	0 - 475	21	11	04
2	-2.5°	476 - 951	20	01	03
3	0.0°	952 - 1428	04	07	17
4	2.5°	1429 - 1904	16	18	15
5	5.0°	1905 - 2380	06	13	18
6	7.5°	2381 - 2856	13	03	10
7	10.0°	2857 - 3332	10	19	08
8	12.5°	3333 - 3809	12	04	19
9	15.0°	39.0 - 4285	18	08	07
10	17.5°	4286 - 4761	09	02	14
11	20.0°	4762 - 5237	01	05	12
12	22.5°	5238 - 5713	05	17	13
13	25.0°	5714 - 6189	17	10	06
14	27.5°	6190 - 6665	11	14	16
15	30.0°	6666 - 7141	14	15	01
16	32.5°	7142 - 7618	08	21	11
17	35.0°	7619 - 8094	07	06	21
18	37.5°	8095 - 8570	03	09	05
19	40.0°	8571 - 9046	02	16	09
20	42.5°	9047 - 9522	15	12	02
21	45.0°	9533 - 9999	19	20	20

REFERENCES

- [1] A. K. Fung, "Scattering Theories and Radar Returns," University of Kansas, Center for Research, Inc.,; Engineering Science Division, Report No. 48-3, 1965A.
- [2] F. J. Janza, "The Analysis of a Pulsed Radar Acquisition System and a Comparison of Analytical Models for Describing Land and Water Radar Return Phenomena," Sandia Corporation Monograph SCR-533; January, 1963.
- [3] T. S. Trowbridge and K. P. Reitz, "Average Irregularity Representation of a Rough Surface for Ray Reflection," Journal of the Optical Society of America, Vol. 65, May, 1975, pp. 531-536.
- [4] J. Renau, P. K. Cheo and H. G. Cooper, "Depolarization of Linearly Polarized EM Waves Backscattered from Rough Metals and Inhomogeneous Dielectrics," Journal of the Optical Society of America, Vol. 57, April, 1967, pp. 459-466.
- [5] J. W. Rouse, "The Effect of the Subsurface on the Depolarization of Rough Surface Backscatter," Radio Science, Vol. 7, October, 1972, pp. 889-895.
- [6] Hoekstra, Pieter and Dennis Spanogle, "Backscatter from Snow and Ice Surfaces at Near Incident Angles," IEEE Trans. Antennas Propagat., Vol. 20, November, 1972, pp. 788-790.
- [7] Rosenbaum, Shalom and L. W. Bowles, "Clutter Return from Vegetated Areas," IEEE Trans. Antennas Propagat., Vol. 22, March, 1974, pp. 227-236.

- [8] M. W. Long, "On the Polarization and Wavelength Dependence of Sea Echo," IEEE Trans. Antennas Propagat., September, 1965, pp. 749-754.
- [9] M. W. Long, "On a Two-Scatterer Theory of Sea Echo," IEEE Trans. Antennas Propagat., Vol. 22, September, 1974, pp. 667-672.
- [10] F. T. Ulaby, "Radar Measurements of Soil Moisture Content," IEEE Trans. Antennas Propagat., Vol. 22, March, 1974, pp. 257-265.
- [11] F. T. Ulaby, "Radar Response to Vegetation," IEEE Trans. Antennas Propagat., Vol. 23, January, 1975, pp. 36-45.
- [12] F. T. Ulaby, T. F. Bush and P. P. Batlivala, "Radar Response to Vegetation II: 8-18 GHz Band," IEEE Trans. Antennas Propagat., Vol. 23, September, 1975, pp. 608-618.
- [13] F. T. Ulaby and P. P. Batlivala, "Diurnal Variations of Radar Backscatter from a Vegetation Canopy," IEEE Trans. Antennas Propagat., Vol. 24, January, 1976, pp. 11-17.
- [14] F. T. Ulaby, L. F. Dellwig and Thomas Schmugge, "Satellite Microwave Observations of the Utah Great Salt Lake Desert," Radio Science, Vol. 10, November, 1975, pp. 947-963.
- [15] Kumar Krishen, "Reflection from Rough Layers," Ph.D. Dissertation, Kansas State University, 1969.
- [16] Jimmy L. Funke, "The Depolarization of Electromagnetic Waves Backscattered from Inhomogeneous Media," Ph.D. Dissertation, Kansas State University, 1974.
- [17] William B. Weir, Lloyd A. Robinson and Don Parker, "Broadband Automated Radar Cross-Section Measurements," IEEE Trans. Antennas Propagat., Vol. 22, November, 1974, pp. 780-784.

- [18] Merrill I. Skolnik, "Introduction to Radar Systems" New York:
McGraw-Hill Book Company, Inc., 1962.
- [19] John Neter and William Wasserman, "Applied Linear Statistical Models,"
Illinois: Richard D. Irwin, Inc., 1974.
- [20] K. E. Kemp, "AARDVARK Reference Manual," Contribution 209,
Department of Statistics; Statistical Laboratory; Kansas Agricultural
Experiment Station, Kansas State University, 1973.
- [21] J. R. Mentzer, "Scattering and Diffraction of Radio Waves, "
Massachusetts: Harvard University Press, 1959.
- [22] Charles R. Hicks, "Fundamental Concepts in the Design of Experiments,"
New York: Holt, Rinehart and Winston, 1973.
- [23] R. L. Wine, "Statistics for Scientists and Engineers,"
NJ: Prentice Hall, Inc., 1964.

ACKNOWLEDGMENTS

I wish to express my gratitude to my major advisor, Dr. D.H. Lenhart, for his guidance. I am also indebted to Dr. L. E. Bussey, of the Department of Industrial Engineering, for his invaluable advice, guidance and encouragement throughout the course of writing this report. I do not have words to thank Dr. Bussey for his honest labor. Thanks are also due to Drs. D. R. Hummels and N. Ahmed for serving on the graduate committee. Dr. W. W. Koepsel, chairman of Electrical Engineering Department, also deserves thanks for providing financial aid.

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

by

RAJINDER K. KHURANA

B.S., Engg., Panjab University, INDIA, 1974

AN ABSTRACT OF MASTER'S REPORT

submitted in partial fulfillment of the
requirements for the degree

MASTER OF SCIENCE

Department of Electrical Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1976

ABSTRACT

For comparing the response characteristics of pulsed and continuous wave radar systems, a hierarchical experimental design has been presented, in which a covariable is embedded. Since the random error in the entire experiment is measurable only when the experiment is replicated at least twice, then three replicates of the experiment should be taken to reduce the size of the random error. Based on a "block" (replicate) design of the experiment and the hierarchical nature of the variables, the mathematical model of the experimental design has been presented. A step by step procedure has also been presented for system calibration and for taking data.

The procedure for the analysis of data has been illustrated by making use of data which were collected before experiment was rigorously designed from a statistical viewpoint. For these data, a conclusion regarding the effect on the response function of the type of modulation (pulsed or CW) cannot be put on a solid basis because of the large coefficient of variability in the data. This accounts for the reason for undertaking the equipment modification as outlined in this report. The conclusions that derive from the present analysis cannot be used as predictive results; they merely demonstrate data reduction methods.