RADAR SCATTERING INVESTIGATION

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FOREWORD

This report was prepared by the University of Michigan Radiation Laboratory of the Department of Electrical Engineering, Ann Arbor, Michigan as No. 7462-1-T under Contract No. AF30(602)-3872, Project 6512, Task 651207, for the Rome Air Development Center covering the report period, 30 June 1965 through 31 December 1965.

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This technical report has been reviewed and is approved.

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ABSTRACT

A status report is presented on an investigation to evaluate selected radar cross section measurement ranges. The evaluation procedure involves a comprehensive series of measurements on seven models to be made at five specified ranges at four polarizations and at several frequencies. One of the five ranges will measure eight models and a sixth range will measure only two models. The ranges are discussed and the models to be used are described. Some theoretical radar cross section calculations are presented and a method of analyzing the digital and analog data is given. Existing radar cross section measurement capabilities and limitations are discussed and some recommendations for needed improvements are made. Information is given on future plans for the investigation.

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I

INTRODUCTION

This report covers the first six months (July through December 1965) of a planned 18-month program to evaluate radar cross section measurement capabilities. Deficiencies, if any, are to be noted and recommendations made for any needed improvements.

The evaluation procedure is specified in detail in Exhibit A of the Contract. Summaries and excerpts are given below.

1.1 Objectives

a) To evaluate existing radar cross section measurement facilities.

b) To provide a guide to optimize utilization of existing radar cross section measurement facilities.

c) To identify critical problem areas in radar cross section measurements.

d) To develop plans for attacking the critical problem areas identified.

Special emphasis is to be placed on the measurement of large objects (30' or longer).

1.2 Work Requirements

1.2.1: Experiments to be performed.

A series of radar back scatter measurements shall be performed at the following ranges.

a) Conductron Corporation, Ann Arbor, Michigan
b) Radiation, Incorporated, Melbourne, Florida
c) General Dynamics, Fort Worth, Texas
d) RAT SCAT, Holloman AFB, New Mexico
e) Micronetics, San Diego, California
f) Air Force Avionics Laboratory, Wright-Patterson AFB, Ohio

Measurements shall be performed on five cylinders and three satellite objects at the frequencies shown in Tables I and II. The frequency tolerance is ±0.1 per cent. Four polarization combinations, HH, VV, HV and VH shall be required at all frequencies and both phase and amplitude data shall be recorded for all facilities which have the needed polarization and phase capabilities. Amplitude and phase information is to be provided as a function of target aspect angle through 360^{o} about a plane containing the longitudinal axis of the model. In addition to the analog data, digital data is to be recorded in the finest increments of aspect and amplitude normally available from each of the several ranges. In all cases, measurements are to be made for a single, specified, roll angle except that at one installation (RAT SCAT) the satellite models are to be measured at three roll angles for one frequency and for HH and VV polarizations. The 1/8 scale satellite type object shall be measured only at the General Dynamics Range. Measurements at the Air Force Avionics Laboratory shall be limited to the 1/8 and 1/16 scale cylinders at 1360 and 2720 MHz.

1.2.2: Experimental Control.

The Contractor (University of Michigan) shall prepare and use a standard procedure to insure that the range is in its optimum condition for making measurements scheduled for the day. The Contractor shall establish the fact that target orientation is the same for all measurements at all ranges. Index marks for both roll and pitch shall be provided and any deviations from specified orientation that occur shall be noted.

1.2.3: Models.

The Contractor shall provide five cylinders, the largest of which is to be 32' long and 5' in diameter. The other four cylinders are to be 1/2, 1/4, 1/8 and 1/16 scale models of the larger cylinder.

Other models to be measured are three satellite type objects, the largest of which is 32' long and 5' in diameter. The smaller models are 4/10 and 1/8 scale versions of the full scale satellite. All satellite models are to be government furnished. The Contractor shall be responsible for any needed modifications to insure that the models are roll symmetrical and properly scaled.

1. 2. 4: Theoretical Computations.

The Contractor shall compute expected radar cross section for each of the cylinders under the experimental frequencies and polarization conditions specified. To avoid duplication, the results of a parallel contract, AF33(615)-3166, with the Norair Division of Northrop Corporation shall be used to the maximum extent possible.

1. 2. 5: Data Analysis.

The Contractor shall perform an analysis of all data using the technique most appropriate for the attainment of the stated objective. Comparisons shall be made between measured data and theoretical calculations, between similar measurements at different ranges and between full size and scaled measurements.

Comparisons shall be made of the total performance of the several ranges and any special measurement capabilities that are demonstrated should be noted.

TABLE I: MATRIX OF FREQUENCY VS SCALE FOR CLOSED RIGHT CYLINDER

Scale / Freq. MHz	Full	1/2	1/4	1/8	1/16
170	170	85	-	-	-
340	340	170	85	-	-
680	680	340	170	85	-
1360	1360	680	340	170	85
2720	-	1360	680	340	170

Numbers shown represent equivalent full scale frequency.

TABLE II: MATRIX OF FREQUENCY VS SCALE FOR SATELLITE TYPE OBJECTS

Freq (MHz) \ Scale	Full	4/10	1/8
170	170	-	-
425	-	170	-
1360	-	-	170
425	425	-	-
1062.5	-	425	-

Numbers shown represent equivalent full scale frequency

The six month period covered by this report has been essentially one of preparation for the range evaluation program. Chapter II contains a description of the models and the required modifications on the satellite type objects. In Chapter III the experimental program and the ranges are discussed and information is given on the status of the measurement program. The computation effort is described in Chapter IV together with some preliminary plans for the data analysis.

In Chapter V we present cross section measurement capabilities and limitations and possible improvements. A summary and future plans are presented in Chapter VI.

II
MODELS

2.1 Cylinders

Two types of models are being used in the evaluation. The first is a set of right circular closed cylinders. This shape is well suited for such a program since its scattering pattern is due mainly to two scatterers and it is simple enough that accurate theoretical checks for most aspects of the scattering pattern can be provided. On the other hand it is complicated enough, having many peaks and nulls, to provide a good test for the ranges.

The use of five models, varying in size from full scale to 1/16 scale, makes it possible to check the ability of each range to make accurate measurements over a wide range of model size and operating frequency.

In order to avoid errors in the scaled measurements and in the theoretical-experimental checks, high tolerances were set on the cylinder dimensions. The models were made with sufficient skin thickness and internal bracing to withstand normal handling without deformation or damage. The cylinder dimensions and tolerance are given in Table III. These are essentially as specified in the special instructions that accompanied P. R. No. 65-863.

The two smaller cylinders were made in The University of Michigan machine shops. The 2-foot cylinder was turned on a lathe from a solid bar of aluminum. The 4-foot cylinder was turned from a piece of standard, thick-walled aluminum tubing. No difficulties were experienced in the fabrication or in meeting the specified tolerances.

Due to the close tolerance and large size of the three larger cylinders, considerable difficulty was experienced in finding interested manufacturing concerns who had the capability to fabricate the cylinders. Further time was consumed in getting a purchase order formalized and preliminary drawings approved. About

TABLE III: CYLINDER DIMENSIONS

Length	Diameter+ (inches)	Surface Roughness (welds, rivet heads, etc) (inches)	Surface Irregularity++ (straightness)	Skin Thickness (inches)
32' ± 1/2"	60 ± 1/4	± 0.087	± .033"/ft	0.100
16' ± 1/4"	30 ± 1/8	± 0.043	± .033"/ft	0.050
8' ± 1/8"	15 ± 1/16	± 0.032	± .033"/ft	0.050
4' ± 1/64"	7.5 ± .005	± 0.005	± .005"/ft	0.250
2' ± 1/64"	3.75 ± .005	± 0.005	± .005"/ft	~0.125

+Cylinders are to be circular to within 0.1 per cent of diameter.

++The axis of the cylinder is not to deviate from a straight line by more than .250, .125, .063" for the 32, 16 and 8' cylinders respectively. The ends are to be perpendicular to the cylinder axis to within $1/4^{\circ}$.

the time the manufacturer (Brooks and Perkins, Detroit, Michigan) was given authority to proceed, they experienced a work stoppage due to a strike. They were able to continue the engineering work but more time was lost in rescheduling the work with a suitable subcontractor. On 21 October 1965 Brooks and Perkins let a subcontract with the National Light Metals and Plastic Company of Caro, Michigan. As of the end of this present contract period, none of the cylinders had been completed. A preliminary examination of the 32' cylinder, which was the most nearly completed, showed that it was not meeting the tolerance specifications. The disposition of this problem is now being determined.

The largest cylinders (32', 16', 8') were formed by attaching pre-rolled skins to an inner framework of circular channels. The inner framework for the 32' cylinder included nine 2 1/2"x 1 1/2" x 1/8" channels rolled into circles of the required diameter. The circular forms are supported by longitudinal channels and additional diagonal braces. The skin is held to the framework by flat head rivets. The method of fabrication used for the 16' and 8' cylinders is similar except for a more simple inner framework design. For these cylinders, the rivets were countersunk into the skin in order to meet the surface roughness tolerances. The approximate weights of the 32', 16' and 8' cylinders are 1280, 240 and 27 pounds respectively. Further information on the design of the cylinders is given in Brooks and Perkins Drawings 1086-300, 1086-200 and 1086-100.

2.2 Satellite Type Models

These models, provided by the Government, are designated as satellite type models but henceforth will be referred to as satellites. They differ from satellites due to the numerous modifications they have experienced. It is most appropriate to include these models in the evaluation program since the handling and measurement problems associated with them are more typical of those commonly encountered in the measurement of cross section characteristics of space vehicles.

The full scale satellite (approx. 32' x 5') was shipped to Ann Arbor from the Lockheed Missiles and Space Company. The 0.4 scale model was obtained from General Dynamics/Fort Worth Division. Upon inspection of these models after they had been placed side by side, it was found that the smaller was not a true scale model of the larger. Minor differences were found in the major dimensions and major differences were seen in the details of the engine section. It was also noted that the models were not roll symmetrical. The shape of the satellite models is shown in Fig. 1, and major dimensions are indicated. Values of the major dimensions for the two models are given in Table IV; discrepancies between the dimensions of the 0.4 scale model and 0.4 of the corresponding full scale dimension are shown in the last column.

TABLE IV: MAJOR DIMENSIONS OF 0.4 AND FULL SCALE MODEL SATELLITE

Code No. Fig. 1	Full Scale Model (inches)	0.4 Scale Model (inches)	Discrepancies between 0.4 ~~and Full~~ Scale Models (inches)
1	27.5	10.88	- .12
2	33.0	13.0	- .2
3	63.1	26.56	+1.24
4	17.88	6.88	- .27
5	138.13	55.0	- .25
6	27.88	10.75	- .40
7	50.75	20.0	- .30
8	32.25	13.25	+ .35
9	390.70	156.32	+ .04
A circum.	105.68	40.62	-1.65
B circum.	158.75	63.12	- .38
C circum.	187.62	75.35	+ .31

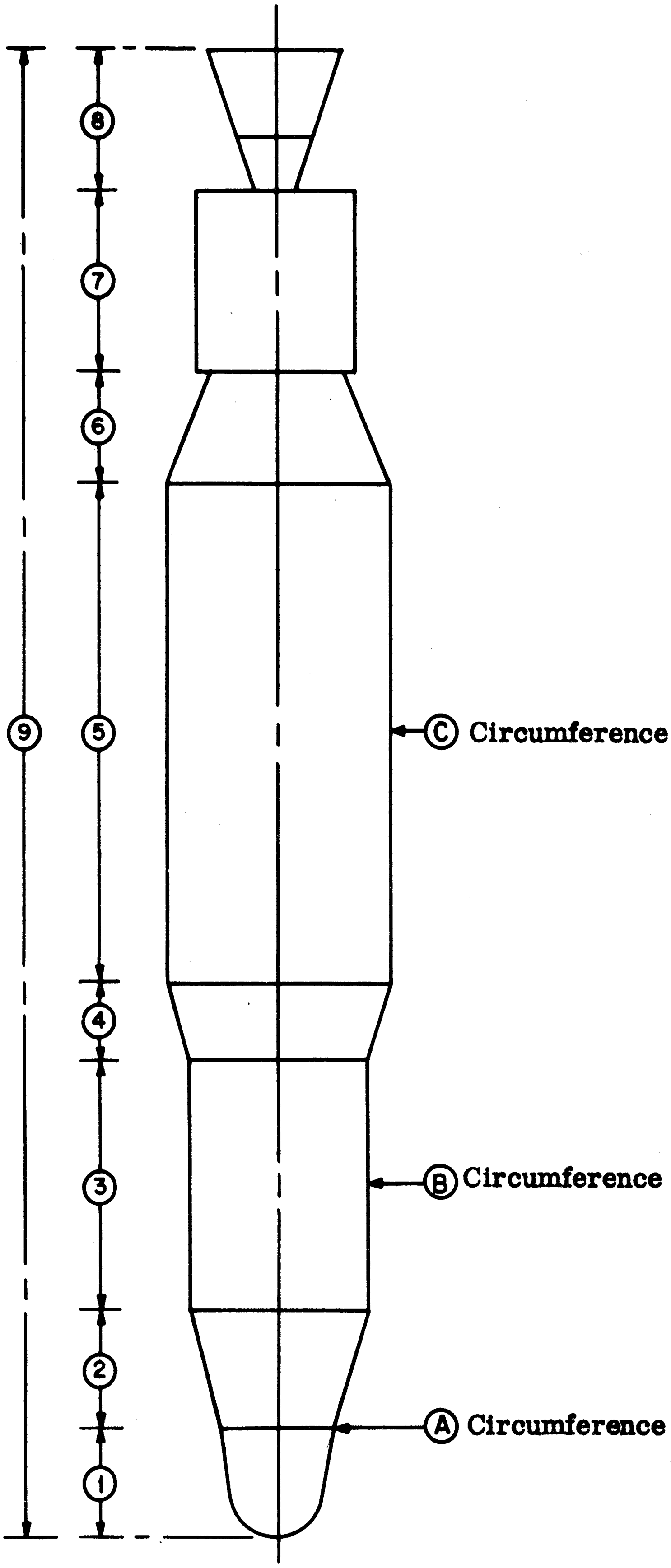

FIG. 1: SATELLITE DIAGRAM (See Table IV for details).

In addition to the errors in dimension in Table IV, several other causes for concern were seen. The nose of the 0.4 scale model was covered with silver conducting paint while the full scale nose was of bakelite or an ablative material. Openings 1/16" wide were found in the seams of the 0.4 scale model. Due to the irregular shape of the engine sections and the presence of cable channels on the sides of the main body, neither satellite was roll symmetrical.

The greatest difference in the two models was in the engine section. The engine of the 0.4 model was more simple and much more exposed than that of the full scale vehicle and the fins on the small model were quite smooth compared to those on the larger model.

After conferences with the sponsor it was agreed that simple modifications would be made to the two satellite models to make them more alike but that no attempt would be made to make them roll symmetrical. To make the models more alike some of the holes on the tapered section of the small model were covered and flat plates were added to cover the sides and aft end of the larger model. These modifications made the two vehicles quite similar in appearance. Figures 2 and 3 are photographs showing the engine area of the large and small satellites after the modifications were complete and Fig. 4 shows a side view of the smaller model.

A calculation was made to determine typical differences that might be expected in the radar cross section of the existing 0.4 model and a perfectly scaled 0.4 model. In the calculations, the satellite was represented by two end-to-end cylinders with dimensions equal to the two major cylinders (see sections 3 and 5 of Fig. 1). For the case of normal incidence and for the highest frequency involved and for dimension errors typical of the largest shown in Table IV, the calculated cross section difference amounted to 8.4 per cent. No attempt was made to change the main body dimensions to obtain a properly scaled model as this would have required major changes in the vehicles.

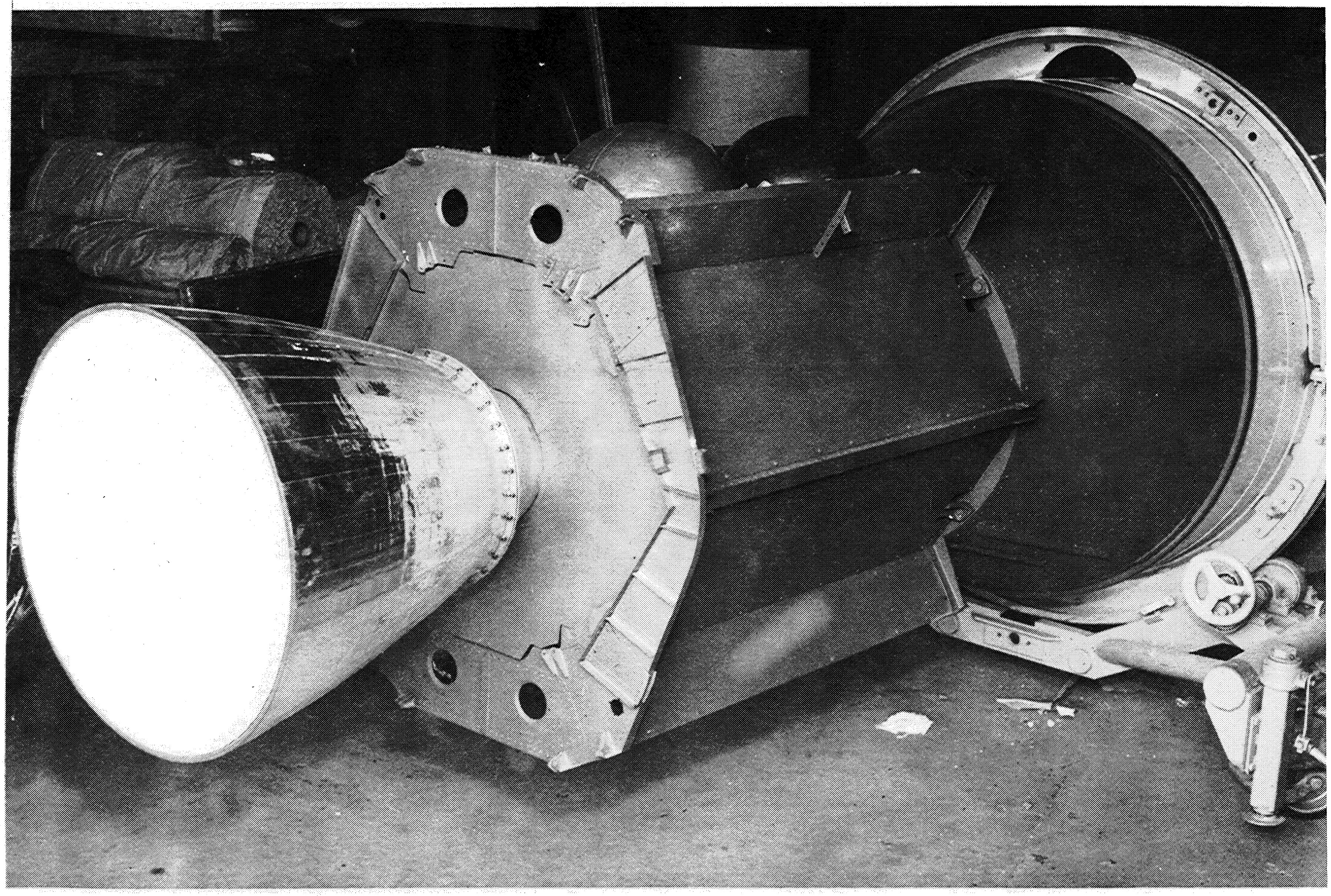

FIG. 2: ENGINE SECTION OF FULL SCALE SATELLITE MODEL

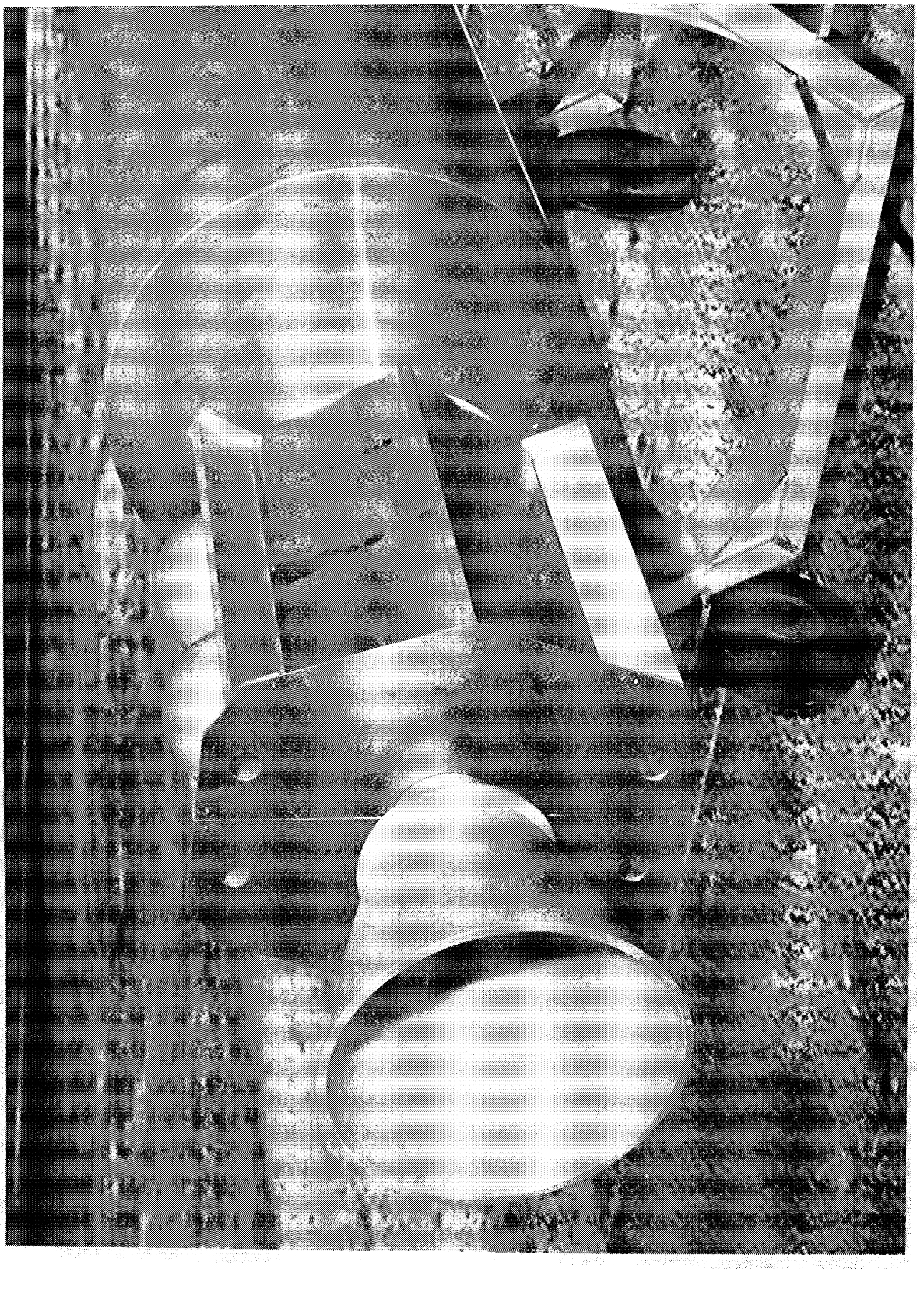

FIG. 3: ENGINE SECTION OF 0.4 SCALE SATELLITE MODEL

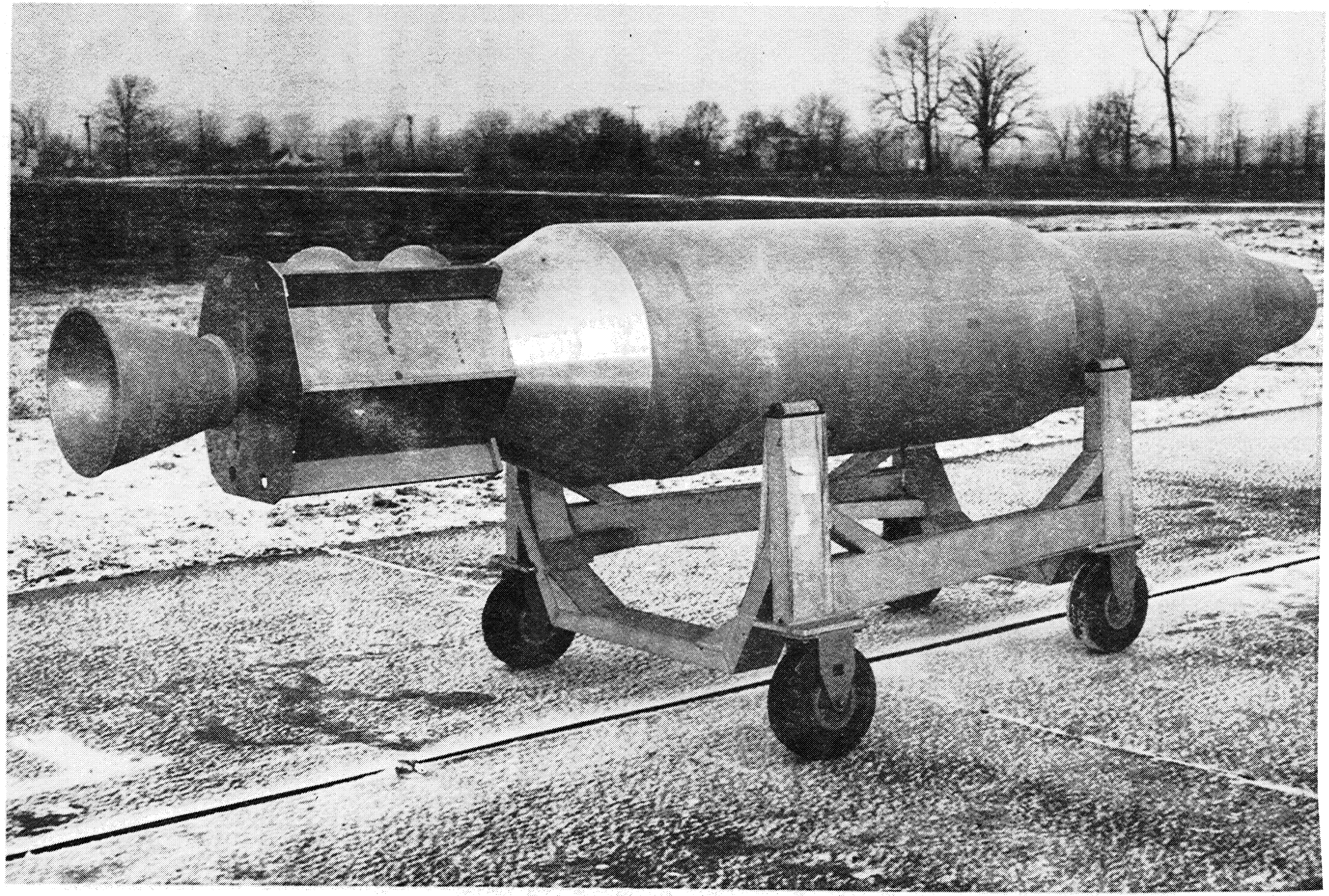

FIG. 4: SIDE VIEW OF 0.4 SCALE SATELLITE MODEL

III

EXPERIMENTAL PROGRAM

A major emphasis under the contract is on the performance of the series of measurements tabulated in Tables I and II. The evaluation of the various ranges depends almost completely upon a critical analysis of the range data. The models to be employed, the frequencies and the polarizations have been closely specified. In addition, each range operator has been asked to follow a standard procedure to insure that his range is in optimum operating condition for each day's measurements. On the other hand, the operator is left free to use his accustomed range geometry and hardware.

As might be expected where large targets and relatively low frequencies are involved, outdoor facilities and the ground plane geometry are to be used in most of the ranges selected for this study. In the ground plane range (Bachman et al, 1963) antenna and target heights are adjusted so as to place the target at the peak of the first lobe formed by the inphase addition of the direct and ground reflected wave. An exception to the above is the range of the Air Force Avionics Laboratory, which is a free space indoor range (Bahret, 1964). In this case, however, only the 2' and 4' cylinders are to be measured and only the higher frequencies are to be employed. In recent months the size of the Avionics Laboratory range has been increased considerably and equipment added to give greater frequency coverage, phase information at some frequencies and more sensitivity and flexibility in pulsed operation.

To some extent, the Micronetics range is also an exception. This is an outdoor range but it is not a typical ground plane range since they endeavor to minimize ground reflections by using a mound of earth in the shape of an inverted "V" which extends along the path between the transmitter and the target. More information on the Micronetics facility is given by Honer and Fortner (1964).

One of the ranges (Conductron Corporation) uses a CW transmitter and employs a balanced bridge to separate the transmitted from the reflected signal. This technique makes it possible to cancel out unwanted reflections due to model support and background scatterers. However, this causes an instability with time. Wren (1964) gives a more detailed report on the Conductron range. Since his report, the frequency coverage at the range has been extended and other improvements have been made. The other ranges plan to use pulsed techniques for all, or almost all, of the required measurements. When pulsed equipment is used the transmitted and received signals are separated in time or range, making it possible to gate out unwanted signals originating outside the range gate containing the target. Blacksmith et al (1965) give additional details on range geometries and on the CW, pulsed and other measurement techniques.

Since complete descriptions of the ranges to be evaluated are not given in this report, it is appropriate to cite additional references which provide descriptions of ranges not already mentioned. The facilities and capabilities of the Radiation Incorporated range are described by Landfried and Williamson (1964). This range is the oldest of those being evaluated and is now operated by Radiation Service Company, a subsidiary of Radiation Incorporated. A description of the General Dynamics/Fort Worth range is given in their brochure (GD/FW 1964). The RAT SCAT range is the newest and probably the most complete of those being evaluated. These facilities are described in some detail by Marlow et al (1965). Additional information on measurements already made and on operating procedures is given in an Air Force brochure (AFMDC 1965).

As already noted, only the two smaller cylinders will be measured at the Avionics Laboratory range. The other five ranges plan to provide complete, or almost complete, amplitude data on all five cylinders and on the two larger satellite models for all of the specified polarization and frequency combinations. In all cases, amplitude data will be provided in both analog and digital form. Phase data will be provided by the General Dynamics range for all frequencies and by the RAT SCAT range for L-band frequencies.

Ideally, on a cross section measurement range, the target is positioned so as to be illuminated by plane waves or in a field closely approximating a plane wave. The most commonly-used criterion requires the target to be far enough removed from the antenna to keep phase errors over the target to $\lambda/16$ or less when it is oriented with its major dimension perpendicular to the direction of propagation. This condition holds when $R = 2D^2/\lambda$ where R is the distance between transmitter and target, D is the major target dimension and λ is the wavelength. Table V shows the values of R thus determined for the models and frequencies to be used on this program. The range operators have not been required to operate at the $2D^2/\lambda$ range but it is assumed that they will operate at, or near, this range if possible and that appropriate corrections will be made to the raw data if ranges very much less than $2D^2/\lambda$ are used.

TABLE V: REQUIRED RANGE DISTANCE (FEET) AS DETERMINED BY $2D^2/\lambda$

Frequency	Model Length (feet)					
MHz	32	16	8	4	2	12.8+
170	354	88	-	-	-	-
340	708	177	44	-	-	-
680	1416	354	88	22	-	-
1360	2832	708	177	44	11	-
2720	-	1416	354	88	22	-
425	885	-	-	-	-	142
1062.5	-	-	-	-	-	354

+0.4 Scale Satellite Model.

The order in which the range evaluation measurements are to be made and the estimate of measurement time required is shown below.

RANGE	EST. TIME (WEEKS)
Conductron Corporation	8
Radiation Service Company	13
General Dynamics/Fort Worth	13
RAT SCAT	6
Micronetics	16 (preliminary est.)
Avionics Laboratory (2 models only)	-

It has been planned that all models will move from one range to the next at one time and all the cost and time estimates have been made on this basis. Due to the delay in getting the three larger cylinders completed, it has been necessary to postpone the formal starting date of the measurement program at the Conductron range. At the end of the present reporting period, the 2' and 4' cylinders and the full scale and 0.4 scale satellites had been delivered to Conductron. Measurements on these models are now in progress.

IV

COMPUTATIONAL PROGRAM AND DATA ANALYSIS

4.1 Introduction

In this chapter the computational analysis for the theoretical and experimental data is discussed. The theoretical model for determining the monostatic scattering cross section of a finite cylinder is based on the physical optics approximation. The governing equation for the physical optics model has been programmed and the results are presented in cross section patterns for the five cases which will arise during the measurements. Digital, as well as analog data is obtained from the experimental tests. Tentative computational techniques, which may be used to process the digital information, are presented. The analog and digital data evaluation procedure is reviewed as it was set forth in the original proposal.

4.2 Scattering Model and Patterns

4.2.1: Monostatic Scattering Cross Section.

The monostatic (or back) scattering cross section of an object is defined as (Blacksmith, 1965)

$$\sigma = 4\pi R^2 \left| \frac{\bar{H}^s}{\bar{H}^i} \right|^2 \tag{1}$$

where $\bar{H}^i$ and $\bar{H}^s$ are the magnetic field intensities of the incident and back scattered fields respectively and R is the distance from the scattering object to the transmitter-receiver location in the far field. For the monostatic case the transmitter and receiver are located at the same position P(R) When the transmitter is placed in the far field, the incident field $\bar{H}^i$ may be treated as a plane wave.

Depending on the polarization of the incident and back scattered field that are being considered in (1), the cross sections are described as either VV, HH, VH or HV where H and V refer to horizontal and vertical polarization of the electric field intensity. The physical optics model is valid only in the small wavelength region where the VV and HH polarizations have the same scattering patterns. Cross polarization effects are not predicted in the physical optics approximation. Some theoretical information on polarization effects will be made available by Norair under their Contract AF33(615)-3166.

In this analysis the scattering object is a finite cylinder of length ℓ and radius a as shown in Fig. 5. Since there is no exact solution for the scattered fields from a finite cylinder, an approximate model is introducted to obtain an expression for the fields. In the approximate model the fields scattering from a cylinder $\bar{H}_c^s$ and a circular flat plate $\bar{H}_p^s$ are summed as phasors to obtain an expression for the total back scattered field.

$$
\begin{aligned}
\bar{H}^s &= \bar{H}_c^s + \bar{H}_p^s \\
\bar{H}^s &= \bar{H}_c e^{j\psi_c} + \bar{H}_p e^{j\psi_p}
\end{aligned}
\tag{2}
$$

where $\bar{H}_c$ and $\bar{H}_p$ are the magnitude and ψ_c and ψ_p are the phase components of the scattered fields from the cylinder and the plate. No attempt is made to consider the scattering contribution from the edge where the cylinder and plate are joined. This omission of the edge effect produces an error in the aspect region near 45^o.

If the back scattered fields of (2) are substituted into (1), then

$$
\sigma = 4\pi R_o^2 \left[\frac{|\bar{H}_c|^2 + |\bar{H}_p|^2 + 2|\bar{H}_c|\,|\bar{H}_p| \cos(\psi_c - \psi_p)}{|\bar{H}^i|^2} \right] \tag{3}
$$

The magnitudes $\bar{H}_c$ and $\bar{H}_p$ are well known and are found in cross section tables (e.g. Oshiro and Su, 1965), but the phase components ψ_c and ψ_p are not easily found. In order to determine the precise value of ψ_c and ψ_p, $\bar{H}_c^s$ and $\bar{H}_p^s$ are evaluated by the physical optics procedure.

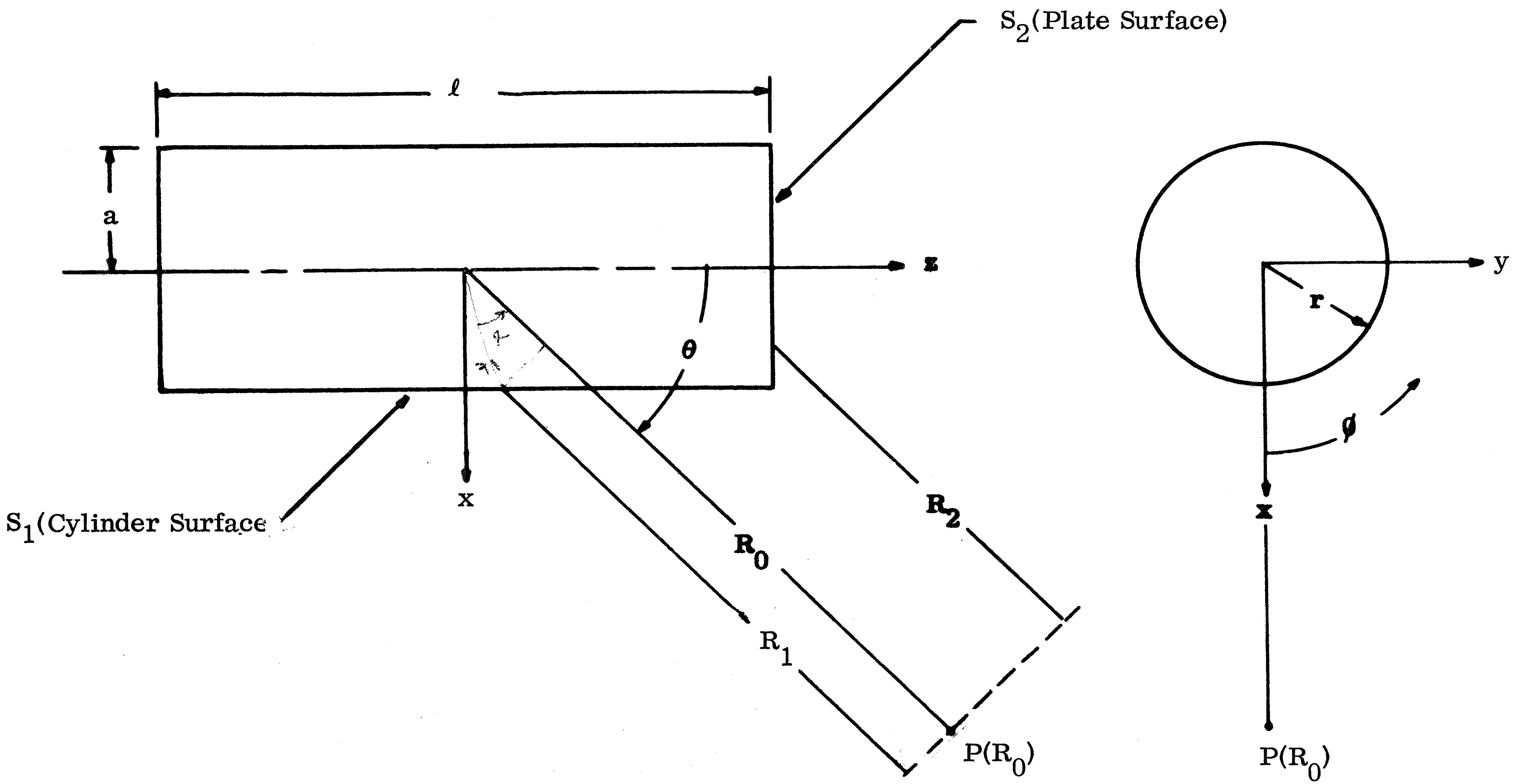

FIG. 5: FINITE CYLINDER GEOMETRY

4.2.2: Physical Optics Model

Assume a plane parallel polarized field is obliquely incident upon a perfectly conducting cylinder of finite length at an aspect angle θ as shown in Fig. 5. The field $\bar{H}^i$ originates at $P(R_0)$ in the far field and in the vicinity of the cylinder is represented as

$$\bar{H}^i = \hat{y}\, H_o e^{jk(z\cos\theta + x\sin\theta)} , \tag{4}$$

where k is the wave number, H_o the harmonic amplitude of the magnetic field intensity, and $\hat{y}$ is a unit vector. Harmonic time dependence has been assumed to be $e^{j\omega t}$.

The surface current density $\bar{J}_s$ generated on the scattering surface by the incident field for the physical model is $\bar{J}_s = 2(\hat{n} \times \bar{H}^i)$ where $\hat{n}$ is the outward normal to the scattering surface. This representation of the current is valid for surfaces which are large and flat compared to a wavelength. As curvature is introduced in the scattering surface, the model becomes less valid. When the radius of the cylinder is on the order of a wavelength ($ka \sim 6$ or smaller) the model no longer applies and polarization effects are noticeable.

Following the procedures outlined by Mentzer (1955), the physical optics expression for the scattered field $\bar{H}^s(R_0)$ is

$$\bar{H}^s(R_0) = \frac{-1}{4\pi} \iint_S 2\,(\hat{n} \times \bar{H}^i) \times \nabla\psi \, dS \tag{5}$$

where S is the portion of the scattering surface illuminated by $\bar{H}^i$ and $\nabla\psi$ is the appropriate Green's function for a conducting body. When kR is large, $\nabla\psi$ is approximately

$$\nabla\psi \cong -j\frac{\hat{R} k e^{-jkR}}{R_o} \tag{6}$$

where $\hat{R} = \hat{x}\sin\theta + \hat{z}\cos\theta$

is the unit vector which is always in the x-z plane in this analysis.

For the finite cylinder the illuminated surface is broken into two parts, the cylinder S_1 and the flat circular plate S_2. Due to the symmetry of the cylinder $\overline{H}^s$ has to be determined only for θ between 0^o and 90^o. When $\theta=0^o$ $P(R_0)$ is located at the end-on position and when $\theta=90^o$, at the broadside position. If S is divided into S_1 and S_2, equations (5) and (6) lead to

$$\overline{H}^s(R_0) = \frac{jk}{2\pi R_0}\left[\iint_{S_1} (\hat{n}_1 x \overline{H}^i) x \hat{R} e^{-jkR_1} dS_1 + \iint_{S_2} (\hat{n}_2 x \overline{H}^i) x \hat{R} e^{-jkR_2} dS_2\right] \quad (7)$$

In the denominator of (7) the far field approximation allows $R_1 \doteq R_2 = R_0$. With the aid of Fig. 5, the desired parameters related to S_1 are

$$\hat{n}_1 = \hat{x}\cos\phi + \hat{y}\sin\phi$$

$$dS_1 = a d\phi dz, \quad -\pi/2 \leqslant \phi \leqslant \pi/2 \text{ and } -\ell/2 \leqslant z \leqslant \ell/2$$

$$R_1 = R_0 - a\cos\phi\sin\theta - z\cos\theta$$

and related to S_2, are

$$\hat{n}_2 = \hat{z}$$

$$dS_2 = r dr d\phi, \quad 0 \leqslant r \leqslant a \text{ and } 0 \leqslant \phi \leqslant 2\pi$$

$$R_2 = R_0 - r\cos\phi\sin\theta - \ell/2\cos\theta \; .$$

The above parameters are substituted into (7) and four integrations are performed. Only one of the integrations is difficult and this is accomplished by taking advantage of the physical optics approximation that 2ka $\sin\theta$ is large in the integral over S_1. The troublesom ntegral has the form

$$\int_{-\pi/2}^{\pi/2} e^{j\beta\cos\phi}\cos\phi\, d\phi \tag{8}$$

where $\beta = 2ka\sin\theta$. When β is large, (8) yields to the method of stationary phase (DeFrancia, 1953) and

$$\int_{-\pi/2}^{\pi/2} e^{j\beta\cos\phi}\cos\phi\, d\phi \rightarrow \left(\frac{2\pi}{j\beta}\right)^{1/2} e^{j\beta} \,. \tag{9}$$

The solutions for the two integrals in (7) are

$$\bar{H}_c^s = \hat{y}\,\frac{H_o\sqrt{ka\,\ell^2\sin\theta}}{2R_0\sqrt{\pi}}\left[\frac{\sin(k\ell\cos\theta)}{k\ell\cos\theta}\right] e^{-jkR_0}\, e^{j\left[\frac{\pi}{4}+2ka\sin\theta\right]} \tag{10}$$

and

$$\bar{H}_p^s = \hat{y}\,\frac{H_o ka^2}{2R_0}\left[\frac{J_1(2ka\sin\theta)}{ka\tan\theta}\right] e^{-jkR_0}\, e^{j\left[\frac{\pi}{2}+k\ell\cos\theta\right]} \tag{11}$$

where $J_1(2ka\sin\theta)$ is the Bessel function of order unity. The phase difference $\psi_c-\psi_p$, which is being sought for (3), can be determined by inspection of (10) and (11) and is

$$\psi_c-\psi_p = 2ka\sin\theta - k\ell\cos\theta - \frac{\pi}{4} \,. \tag{12}$$

With the proper substitution of (10), (11) and (12) into (3) the total back scattering cross section is

$$\sigma = \sigma_c + \sigma_p + 2\sqrt{\sigma_c\sigma_p}\,\cos\left[2ka\sin\theta - k\ell\cos\theta - \frac{\pi}{4}\right] \tag{13}$$

where

$$\sigma_c = ka\,\ell^2\sin\theta\left[\frac{\sin(k\ell\cos\theta)}{k\ell\cos\theta}\right]^2$$

and

$$\sigma_p = \pi(ka^2)^2\left[\frac{J_1(2ka\sin\theta)}{ka\tan\theta}\right]^2 .$$

When ka and kℓ are greater than six (13) becomes a good representation of the monostatic cross section and the VV and HH polarization patterns tend to become indistinguishable.

4.2.3: Cross Section Computer Program

Only five separate calculations are necessary to describe all the experimental scattering patterns which will arise during the cylinder measurements if equation (13) is normalized to a square wavelength.

$$\frac{\sigma}{\lambda^2} = \frac{\sigma_c}{\lambda^2} + \frac{\sigma_p}{\lambda^2} + \frac{2}{\lambda^2}\sqrt{\sigma_c \sigma_p}\,\cos\left[2ka\sin\theta - k\ell\cos\theta - \frac{\pi}{4}\right] \tag{14}$$

and

$$\frac{\sigma_c}{\lambda^2} = ka\left(\frac{k\ell}{2\pi}\right)^2 \sin\theta \left[\frac{\sin(k\ell\cos\theta)}{k\ell\cos\theta}\right]^2$$

$$\frac{\sigma_p}{\lambda^2} = \frac{(ka)^4}{\pi}\left[\frac{J_1(2ka\sin\theta)}{2ka\tan\theta}\right]^2 .$$

The parameters for the five cases of interest are

Case	1	2	3	4	5
ka	1.36	2.72	5.44	10.9	21.7
kℓ	17.4	34.8	69.6	139.2	278.4

In all cases the dimensions of the cylinder are such that $k\ell = 12.8\,ka$.

The output of the computer program gives σ/λ^2 in db as a function of aspect angle θ. For the first three cases θ was listed in 1^o increments. Due to the increased frequency of the pattern oscillations, θ was listed in steps of 0.2^o for case 4 and 0.1^o for case 5.

4.2.4: Cross Section Patterns

Numerical results obtained from (14) for the five cases of interest are expressed as cross section patterns in Figs. 6 through 10. The pattern oscillations due to the cylinder ($\theta > 45^o$) are 6.4 times greater than those due to the circular

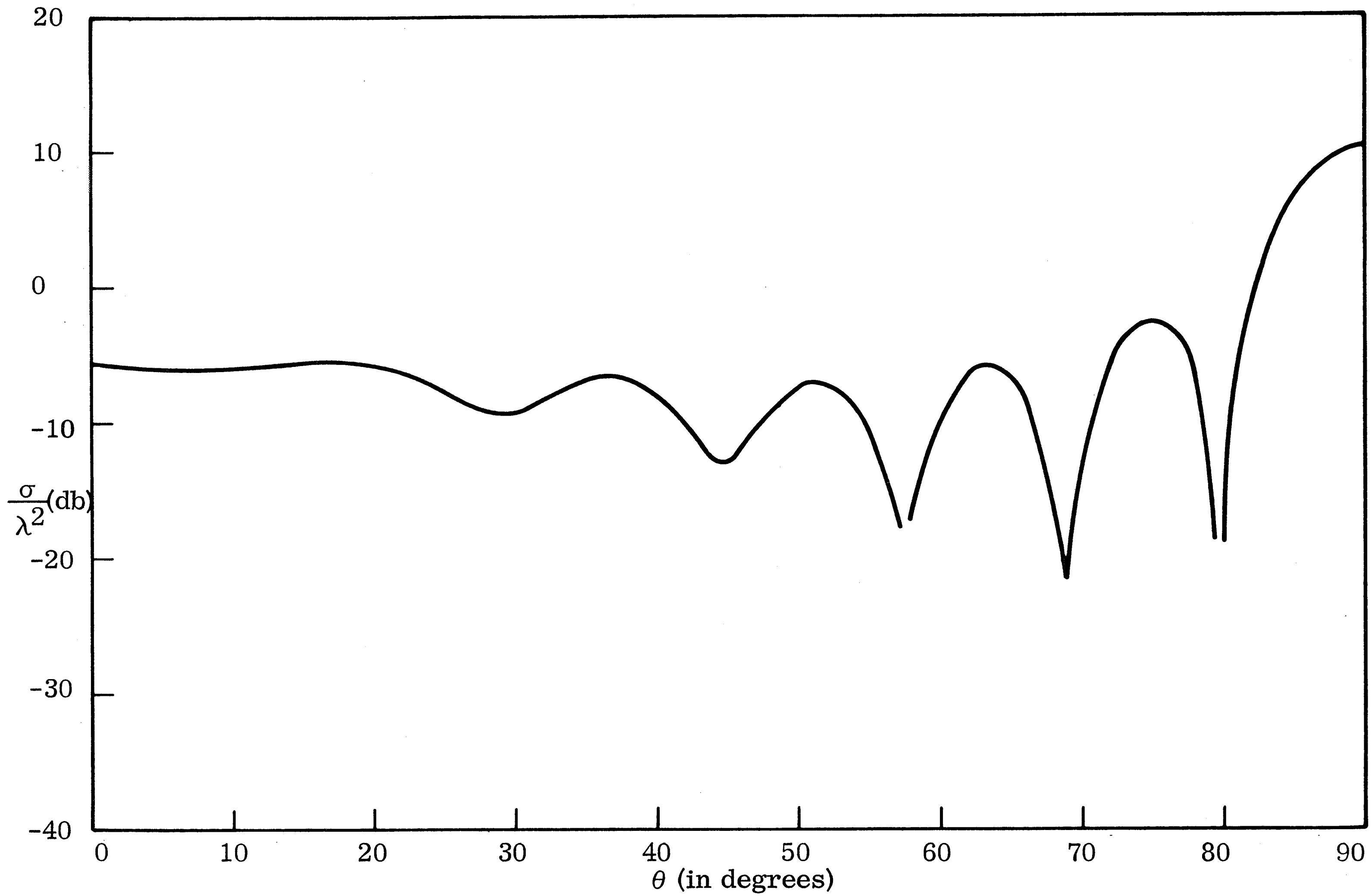

FIG. 6: THEORETICAL PATTERN FOR ka = 1.36 AND kℓ = 17.4

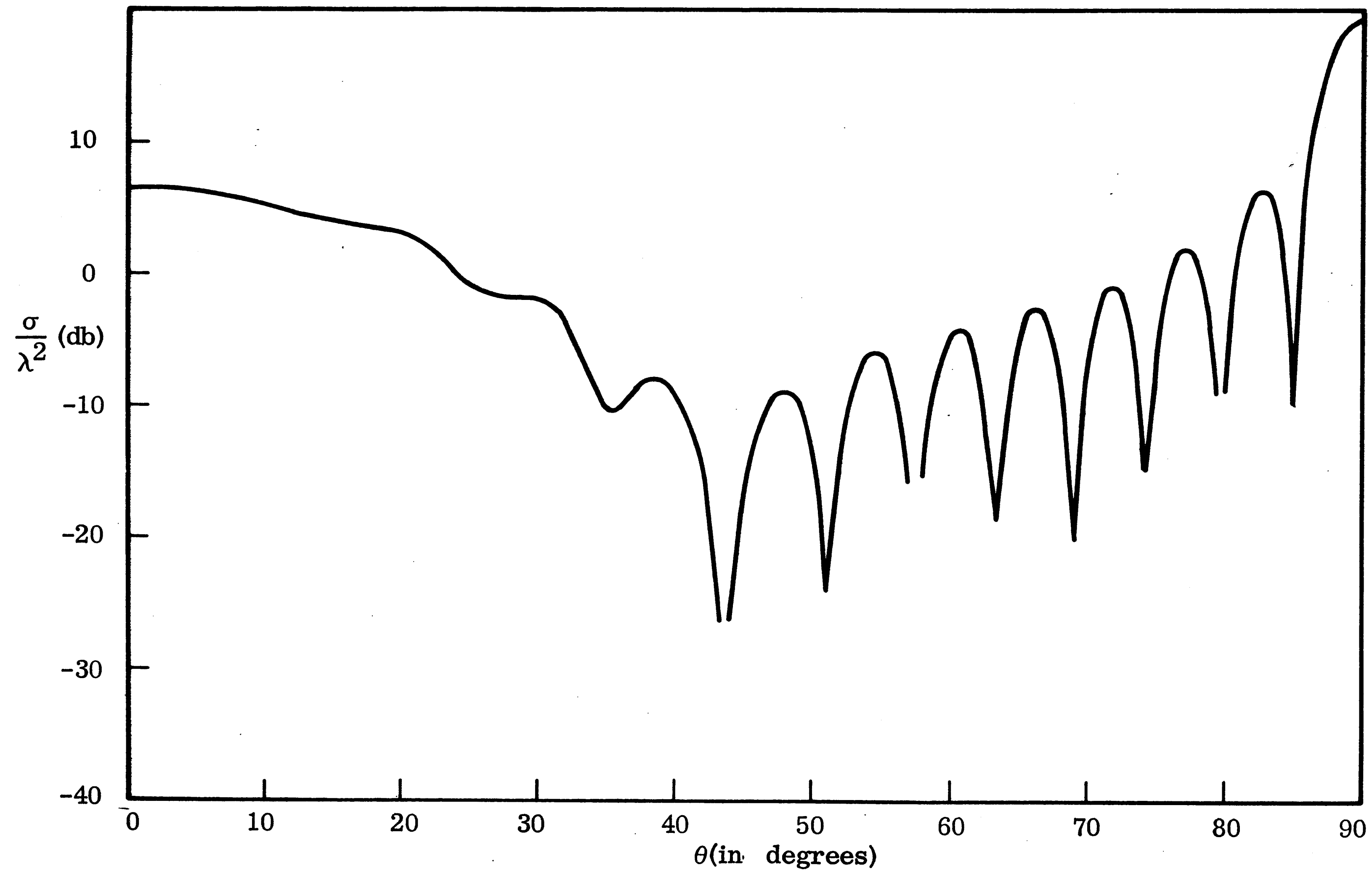

FIG. 7: THEORETICAL PATTERN FOR k a = 2. 72 and kℓ = 34. 8

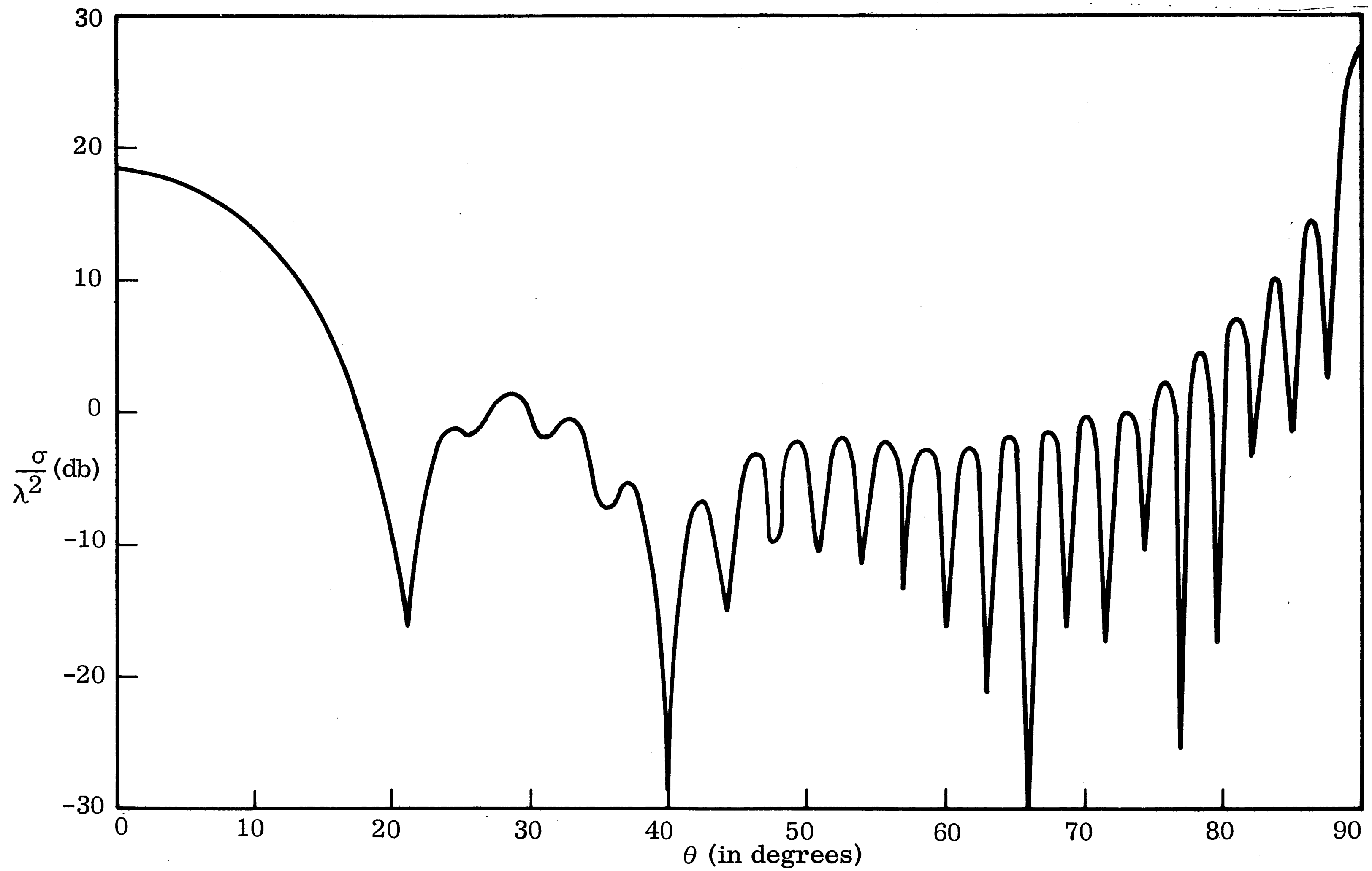

FIG. 8: THEORETICAL PATTERN FOR ka= 5.44 AND $k\ell$ = 69.6

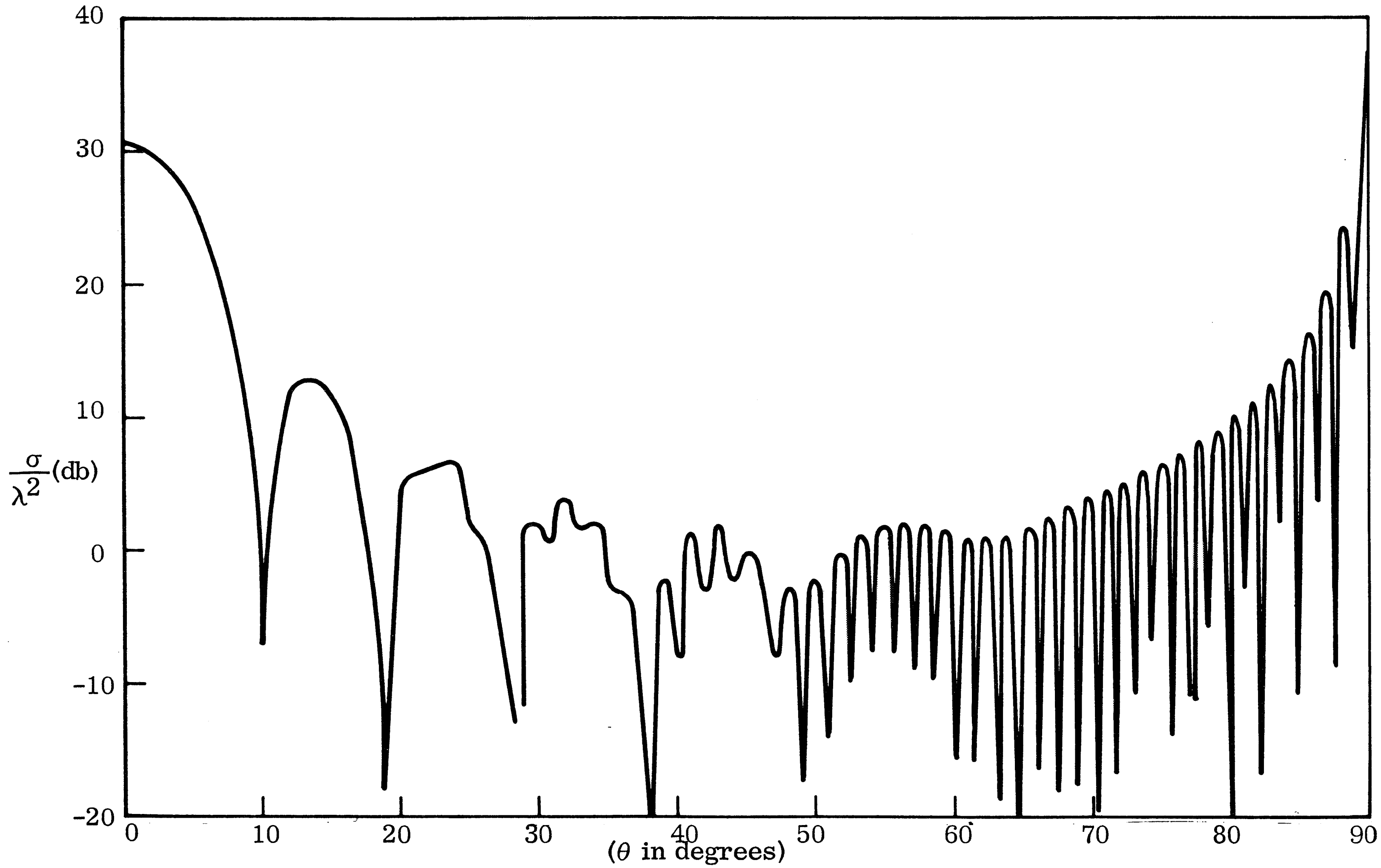

FIG. 9: THEORETICAL PATTERN FOR ka = 10. 9 AND kℓ = 139. 2

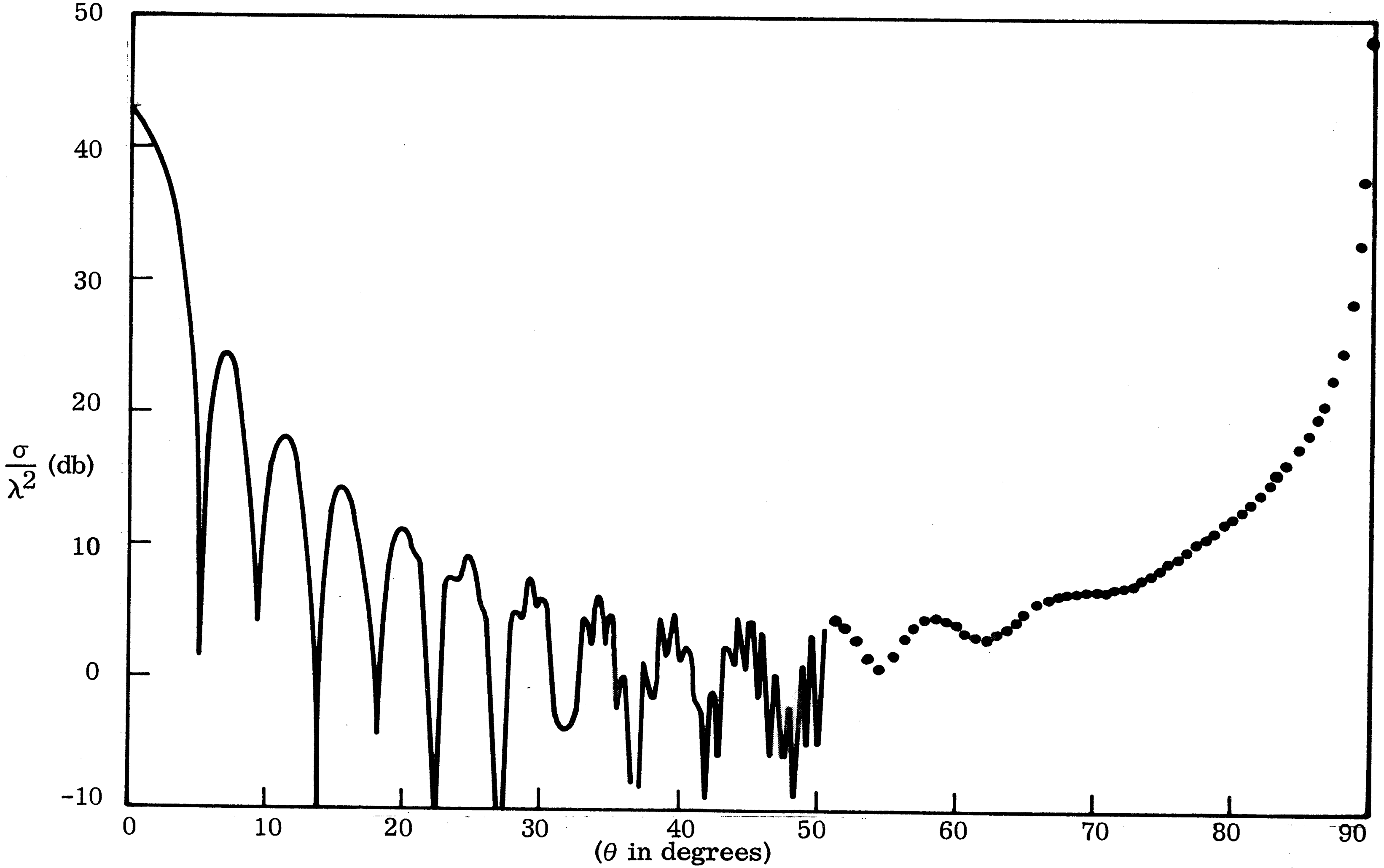

FIG. 10: THEORETICAL PATTERN FOR ka = 21.7 AND kℓ = 278.4

• Indicates Peak Positions for Oscillations with 0.65^o Period.

plate ($\theta < 45^o$). For each successive case of increasing ka, the pattern oscillations double in frequency and the difference between the peak amplitudes at θ=0^o and 90^o decreases. In Fig. 6 the pattern oscillations are so rapid for $\theta > 50^o$, that only the peaks of the lobes are shown.

Cases 1 and 2 are not expected to agree well with the measurements because these do not satisfy the physical optics assumption that ka is large. The experimental VV and HH polarization patterns will differ; in particular the HH patterns will have more rapid oscillations than the VV patterns for θ between 0^o and 45^o. More accurate theoretical information for Cases 1 and 2 is to be made available by Norair with the aid of the "SDT" computer program (Oshiro and Su, 1965).

Case 3 is in the transition region where the physical optics model becomes more meaningful and the differences between the VV and HH patterns become small. In Fig. 11 the experimental pattern for VV polarization and ka = 5.44 is compared with the physical optics theory. Considering that ka < 6 the agreement between the two patterns is not disappointing. In this case only minor differences in the two experimental patterns for VV and HH polarization were observed.

Another comparison between theory and experiment is presented in Fig.12, for ka=7.2 and kℓ=49.7. In this pattern σ is normalized to one square meter rather than a wavelength to be consistent with the experimental pattern which was obtained from Fig. 21 in the report by Oshiro and Su (1965). Note that the agreement is better than for the smaller cylinder case shown in Fig. 11.

The theoretical pattern in Fig.12 was determined from eq. (14) and is in close agreement with the physical optics theory given by Oshiro and Su for the same parameters. All of the side peaks for the theory based on (14) differ by less than 0.5 db from Oshiro and Su's theory, except at θ=34^o where there is 1 db difference.

Cases 4 and 5 are expected to agree well with the test measurements, since ka will be large in both instances. The θ scale in Figs. 9 and 10 is 30 per cent larger than the corresponding scale to be provided by the analog recorders of the

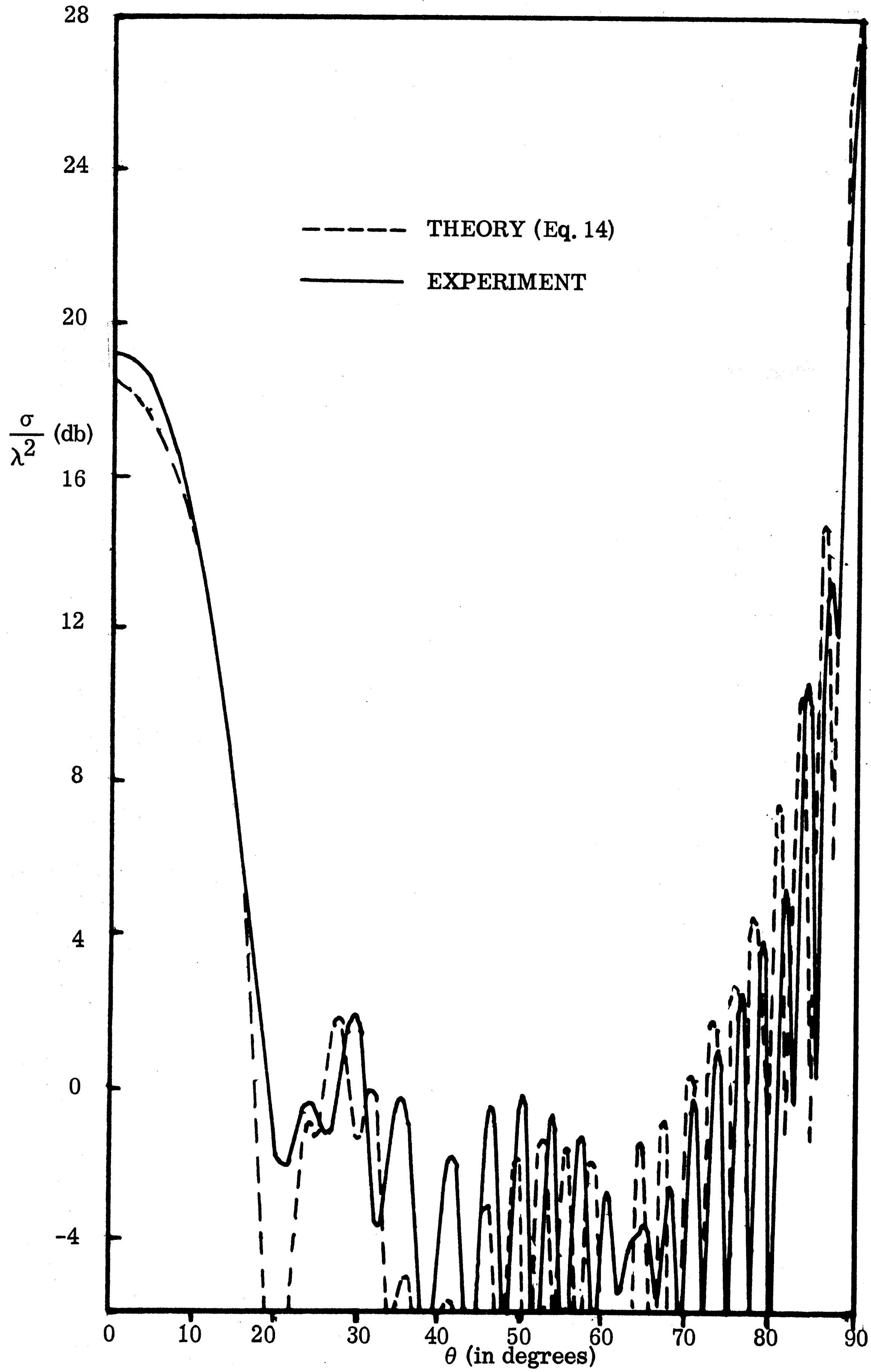

FIG. 11: COMPARISON OF THEORY AND EXPERIMENT FOR ka = 5.4 AND kℓ = 69.6

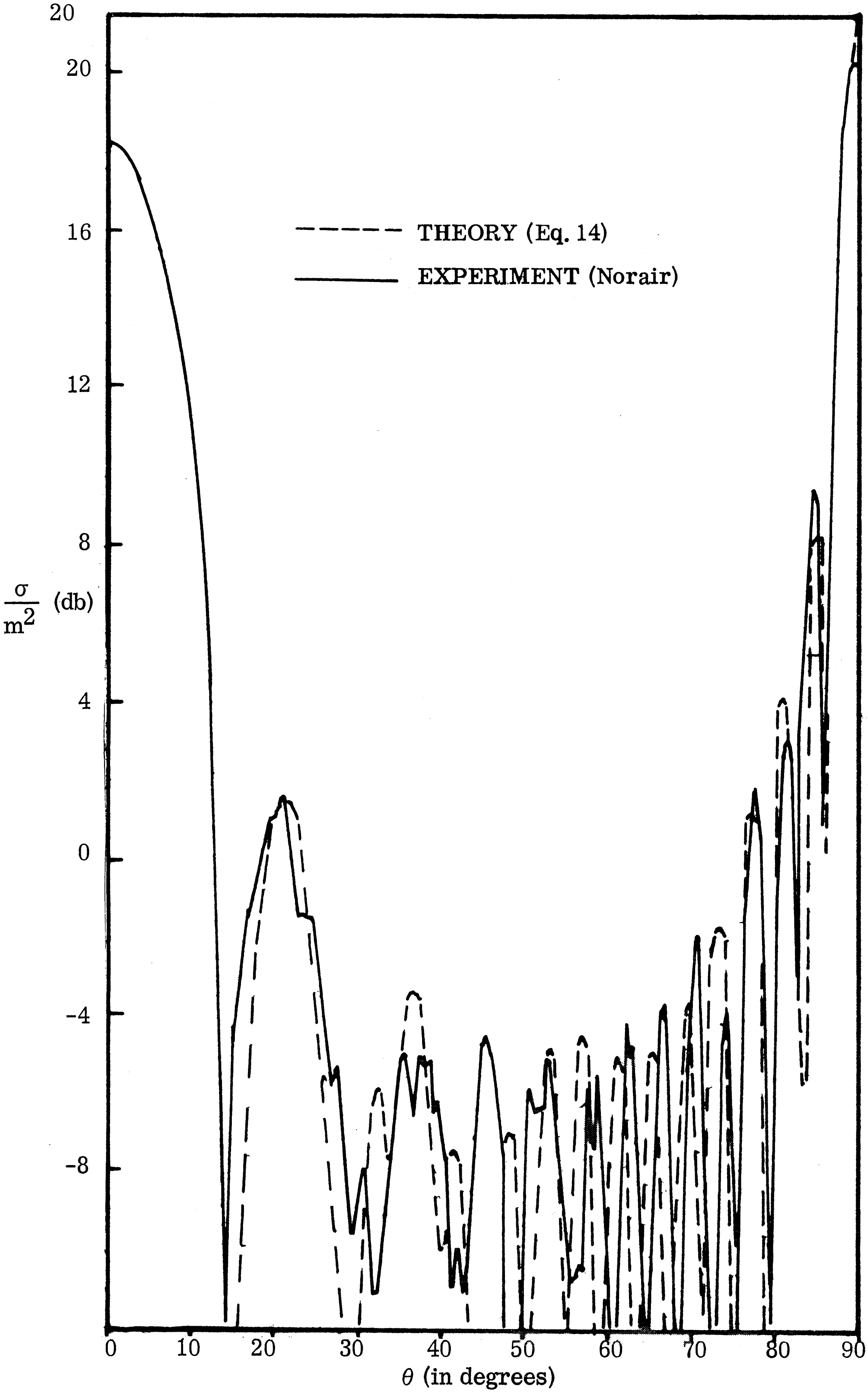

FIG. 12: COMP. RISON OF THEORY AND EXPERIMENT FOR ka = 7.2 AND kℓ = 49.6.

various ranges. The recorder scale will be 18^o per inch as is used in Figs. 11 and 12. Since it is difficult to illustrate the high frequency oscillations of the lobes in Figs. 9 and 10, greater difficulty is anticipated interpreting the fine lobe structure in the analog patterns. Hopefully, the digital information will help alleviate this problem.

4.3 Data Analysis and Evaluation

Preliminary plans have been developed for data analysis and range evaluation. As experimental data is processed the adequacy or deficiency of these plans will become evident. The evaluation techniques to be employed will make use of both analog and digital data.

4.3.1: Analog Data

The analog test patterns will have an angular scale of 18^o per inch and a 40 or 50 db dynamic range depending on the facility. Each test pattern will be judged in three categories.

(1) The patterns will be examined separately and compared with the appropriate theory. Because of the cylinder geometry there should be four regions of symmetry in each pattern. These regions of symmetry will be compared by folding the pattern on itself about either the end-on or broadside locations and viewing it on a light table. The theoretical patterns will be used as a relative guide rather than an absolute measure in the comparison.

(2) A careful comparison will be made between patterns from the same range with the same scaling factors (equal ka and $k\ell$). This test should point out strong and weak features of each range and be a more consistent test than a direct comparison between theory and experiment.

(3) The third test will be a comparison of inter-range data with the same scaling factors. This test should demonstrate similarities and differences among the ranges.

Whenever possible overlays of the patterns will be examined on a light table. After a preliminary study of the data is made, a point system will be chosen to evaluate the test patterns. A relative grading procedure will be used to interpret the point system. Each pattern of each facility will carry a numerical rating. For each facility it will then be possible to assign an average performance figure. Average rating will also be given for each of the models tested and for each frequency scale. This will tend to point out problem areas as well as above average capabilities for each type of measurement.

4.3.2: Digital Data Analysis Procedure

Since digital data will be important, particularly in the cases where ka is large, a tentative method is presented for processing this information. The digital test data will be made available by the ranges on tape or punch cards and should have σ normalized to a square meter as a function of θ in increments of approximately 0.1^{o}. A computer program will take the tape or cards as an input and obtain the mean and peak values of σ for each output interval. At present the output interval is the angular distance between two consecutive nulls in the pattern. For the case where ka = 21.7 this distance would be 0.65^{o}. If it is found that smaller intervals are more desirable, the output intervals can be reduced to the angular distance between a peak and a null.

Digital computer conditional statements can find maxima and minima in the pattern and thereby determine the output interval and pattern peaks. All the input increments that occur during an interval will be summed and divided by the appropriate number to give the average value of σ. At the end of each interval a loop statement will cause the process to repeat itself until all the input data has been analyzed.

An important feature of this program is that no extra input is needed. The test data on the tape or cards has all the necessary information for the program to obtain the peak and average values of σ. The theoretical model can be subjected to the same digital program in order to obtain the corresponding theoretical values.

V

CAPABILITIES: LIMITATIONS AND RECOMMENDATIONS

It will be easier to evaluate the present radar cross section measurement capabilities, to point out inadequacies in the existing systems and recommend needed research or equipment development, at the completion of this investigation. It is possible now, however, to make preliminary comments and observations based on our own experience and inputs from the other range operators. As noted in the Introduction we are mostly concerned with radar cross section measurement problems that occur with large models (30' or more).

There has been an impressive advance in the ability to measure the cross section characteristics of large models during the last few years. Six or seven years ago it was considered a difficult task to measure a 10' model weighing 500 lbs or more. Now, targets 30' or longer and weighing a few thousand pounds are regularly measured. There has been an equally impressive advance in our ability to determine cross section behavior at lower frequencies. Measurements at frequencies lower than L-band were rather unusual before 1960; now several ranges operate at frequencies as low as 200 MHz and the ability to operate below 100 MHz has been demonstrated by a few ranges.

In our opinion, the present investigation will show a very satisfactory capability for measuring cylindrical targets up to 32' in length over the 170 - 1360 MHz frequency range. (1360 MHz is the highest frequency to be employed with the 32' model.) It is quite likely that the results for some of the ranges will be poor for one or more of the frequency or polarization combinations but this study will almost certainly show that accurate measurements of this type are well within the state of the art. Serious measurement problems would appear if the target were a heavy 32' nose cone with a nose-on cross section of less than 10^{-4} m^2. For such a measurement the support column and the background return would begin to be troublesome. These problems will of course become increasingly severe as the cross section to be measured decreases.

Another limitation that quickly becomes apparent in the measurement of 30' models is that imposed by the available length of the existing ranges. If one assumes that the maximum available operating distance is 3000 ft and $R=2D^2/\lambda$ is the appropriate criterion for the far field requirement, it is seen that 1.44 GHz is the highest operating frequency that can be used for a 32' model. In Fig. 13, maximum target size for a 3000 ft range is plotted against frequency.

In planning the measurements to be made during the present study, it was learned that only two of the five ranges had phase measurement capability. Neither of these facilities was able to measure phase over a wide frequency band. This, we consider to be a limitation in existing cross section capabilities. The need of phase data has been demonstrated in two important areas. One of these is in the measurement of the scattering matrix and the other is in the elimination of the effects of the target support by the vector subtraction method (Fritsch and Heart, 1964; Marlow et al, 1965). Scattering matrix data has been obtained on a point by point basis for several years but only recently have we begun to realize some of its potential as the measuring equipment becomes more fully automatic. The most important use for scattering matrix data is in the identification of radar targets. There is a critical need for scattering matrix data both for airborne and space targets and also for land-based targets of interest to the Army. Scattering matrix data can also be used to calculate cross section data when information for many polarizations is required.

Freeny (1965) has demonstrated that it is possible to accurately calculate cross section performance for new polarization combinations; this may prove to be the most economical method of obtaining additional data for large targets.

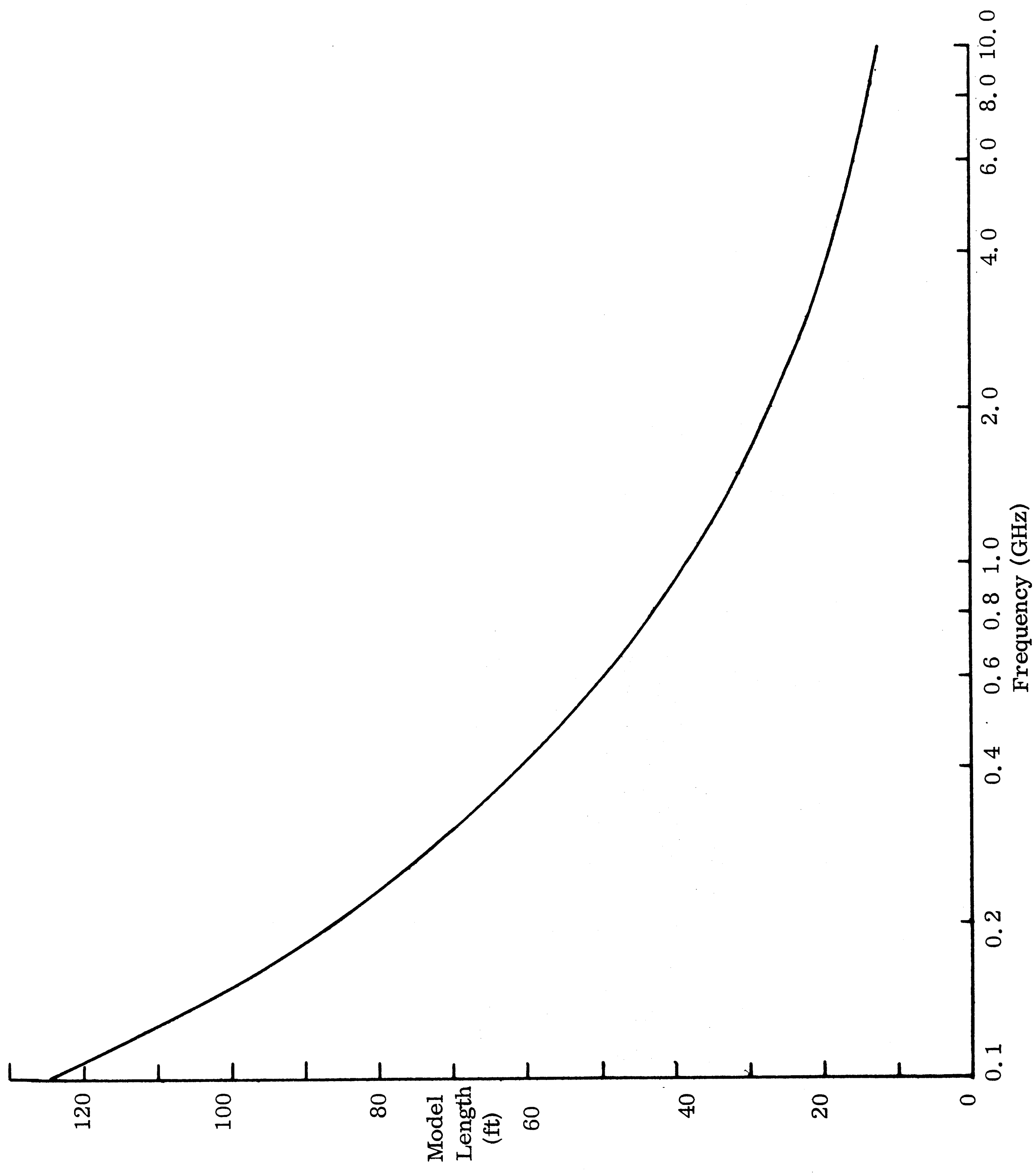

FIG. 13: MAXIMUM MODEL LENGTH VS FREQUENCY FOR 3000' RANGE
$R = 2D^2/\lambda$.

The vector subtraction method of eliminating target support contributions is one of the most important new tools in experimental reflectivity to be developed in recent years. There is little hope that we will soon be able to develop a low cross section support suitable for heavy targets that is superior to the plastic foam support now in use. For the heavier targets, multiple supports or larger diameter supports are needed and both may mitigate against accurate cross section measurements. The vector subtraction technique may well be the best way to upgrade accuracy in this situation or when very low cross section targets are being measured.

Phase data may prove to be valuable for a third reason. As already mentioned, available ranges are not sufficiently long to measure large targets in the far field at the higher frequencies. Future studies will be made to find ways of obtaining satisfactory data at reduced ranges. The availability of phase data would provide an additional parameter which may prove to be important in the derivation of far field data from near field measurements.

The optimum solution to the far field requirement problem is not obvious. Two possible solutions include the use of scaling and the straightforward approach which is to lengthen the range and increase the transmitted power. No doubt it will be necessary to utilize more than one approach since their applicability will tend to depend on the particular measurement problem at hand.

The use of small scale models has, of course, been common since the beginning of cross section studies. The practice of using scale models is attractive both because it obviates the need for working with heavy full scale models and because the required range decreases directly with the scale factor.

Scale models should therefore be employed to the extent possible within the limits imposed by the well-known scaling laws (Sinclair , 1948). If more use of scaling is planned, consideration must be given to the availability of the higher frequencies. Although some facilities have some capability at spot frequencies in the K-band range, the coverage is by no means complete and it is doubtful if adequate power is available for the long ranges that are required. If RAT SCAT is to be the ultimate in cross section capability, its frequency coverage should be extended upward as rapidly as feasible. If, for example, data on a 32' model was needed at 10 GHz, the $2D^2/\lambda$ range would be about 20, 000 feet. If the model was scaled down by a factor of 3. 5 and the measurements made at 35 GHz, the required range would be 5700 feet - much in excess of that now being used. Even at 70 GHz, a range in excess of 2500 feet would be required.

Although ground based X-band radars may not be used against space targets as in the example above, such cross sections may be of interest in space-to-space applications where even higher frequencies may be involved. A similar type of requirement frequently occurs when high frequency cross section data on aircraft is required. Here dimensions of 100 feet or more are common. If S-band data is desired and a 70 GHz scale frequency is used, the range again is in excess (slightly) of 2500 feet.

In summary, we expect to have no difficulty in accurately measuring the cylinders and satellite models at the frequencies and polarizations specified. In order to overcome limitations that would occur if large models having low cross section were to be measured, the effort to develop superior model supports should continue. To implement the vector subtraction method it is recommended that phase measuring capabilities be extended to cover as wide a frequency range as possible. This same phase measuring capability is also needed to provide wider frequency coverage for scattering matrix measurements.

It is obvious that present day ranges, including those at RAT SCAT, are too short to obtain data above L-band on 32' models if the usual far field distance requirements are followed. This limitation can be met for some targets by the use of scale models; for others, it seems to be necessary to have longer ranges. The combined use of scale models and longer ranges of course provides greater flexibility. In going to longer ranges, provision must also be made for higher transmitter power. It is recommended,therefore, that some ranges, preferably the RAT SCAT range, be increased to at least twice the present range with appropriate power increases. The need to double the length of the ranges a second time may be obvious after further study, but , if properly planned, there will be no disadvantage in doing this in two steps.

It is also recommended that frequency capabilities be extended; it is understood that the frequency coverage at RAT SCAT is to be extended to 30 MHz on the lower end. It is recommended that the frequency coverage on the upper end be extended to 35 GHz and on up to 70 GHz if and when economically feasible.

We are aware of the existence of other problems in measuring the cross section characteristics of large models which may or may not prove to be of importance. There is, for example, the scattering by, or coupling to, the underground pedestal pits; this may be troublesome at lower frequencies. Also some difficulties may develop due to the unequal reflection of polarization components. This may cause trouble in measuring circularly polarized, or cross polarized radar cross sections. It is not feasible to make recommendations on these and other border line problems until we have had an opportunity to evaluate the results of the scheduled tests.

VI

SUMMARY AND FUTURE PLANS

We have presented, in the form of a status report, the contract objectives and the progress made toward these objectives. Two of the satellite models to be used in the range evaluation program have been modified to make them reasonably satisfactory as models of the same shape. The two smaller cylinders have been built and these, together with the two satellites, have been delivered to the Conductron measurement range. Difficulties have been experienced in getting the 32' , 16' and 8' cylinders fabricated. The 32' model is nearing completion but a preliminary examination indicates that some dimensional corrections may be required. It is expected that the three cylindrical models will be completed within two weeks or so.

Measurements are in progress on those models now at the Conductron range. Subcontractual agreements with Radiation Service and General Dynamics are almost complete. A formal request has been made to the RAT SCAT range; the range operators have agreed to schedule the measurement program outlined in Chapter I. Preliminary arrangements have been made with Micronetics for measurements on their range.

Under the theoretical program, formulas have been developed and programmed which provide accurate data for the cylinder-frequency combinations with the larger ka values. A physical optics model is used which appears to be entirely adequate for the VV and HH polarization cases for ka values larger than 6 or so. Use will be made of the Norair data, to the extent possible, for the smaller ka cases and for the cross polarization results.

Preliminary plans have been developed by which both analog and digital data may be evaluated and graded. All experimental patterns and digital data with equal ka and polarization conditions will be checked against each other and the corresponding theoretical results. A method for checking the results from one range with another has also been devised.

After a preliminary examination of present cross section measurement capabilities it is concluded that the measurements specified in the study are within the present state of the art: there are, however, deficiencies in ability to measure phase, in the length of existing ranges, and in the frequency band over which they are equipped to operate. Recommendations are made for action to remedy these deficiencies.

6.1 Future Plans

The work yet to be done under this contract has been outlined in detail in earlier sections of this report. All the work is linked closely with the measurement program scheduled for the six ranges. Measurements at the Conductron range should be in full swing during the next month. As the models move on to the Radiation Service Company, the analysis and evaluation of the Conductron data will be underway. Similarly, measurements will be made at General Dynamics, RAT SCAT, Micronetics, and Avionics Laboratory and the data analysis and evaluation will be continued until completed. More attention will then be given to inter-range comparisons and ranking. Final conclusions will be drawn; recommendations will be made, and the findings will be documented and reported as specified.

VII

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13. ABSTRACT

A status report is presented on an investigation to evaluate selected radar cross section measurement ranges. The evaluation procedure involves a comprehensive series of measurements on 7 models to be made at 5 specified ranges at 4 polarizations and at several frequencies. One of the 5 ranges will measure 8 models and a sixth range will measure only 2 models. The ranges are discussed and the models to be used are described. Some theoretical radar cross section calculations are presented and a method of analyzing the digital and analog data is given. Existing radar cross section measurement capabilities and limitations are discussed and some recommendations for needed improvements are made. Information is given on future plans for the investigation.

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There is no limitation on the length of the abstract. However, the suggested length is from 150 to 225 words.

14. KEY WORDS: Key words are technically meaningful terms or short phrases that characterize a report and may be used as index entries for cataloging the report. Key words must be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location, may be used as key words but will be followed by an indication of technical context. The assignment of links, rules, and weights is optional.