EVALUATION OF SELECTED RADAR CROSS SECTION MEASUREMENT RANGES

Volume I: Range Parameters, Range Evaluation, Problem Areas and Recommendations

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FOREWORD

This final technical report was prepared by the University of Michigan Radiation Laboratory, Dept of Electrical Engineering, Ann Arbor, Michigan 48108 under contract AF 30(602)-3872, Project 6512, Task 651207. The work was performed during the period July 1965 through April 1968 under the direction of Professor Ralph E. Hiatt. The number used by the contractor to identify this report is 7462-1-F. The project engineer was D. M. Montana, Rome Air Development Center, EMASP, Griffiss Air Force Base, NY 13440.

ACKNOWLEDGEMENT

The authors are pleased to acknowledge the contributions of Dr. T.B.A.Senior on several phases of the program. Thanks are due to Mr. Tony Hsu for his considerable help in reading **patterns and** organizing the data. Special thanks are due Dr. George Gruver for his contribution in the Interpretation of Scattering Phase Measurements included in this report.

Distribution of this report is limited because it discloses the current U.S. state of the art in radar reflectivity measurements.

This technical report has been reviewed and is approved.

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ABSTRACT

A program under which selected radar cross section measurement ranges were evaluated is described. Some details are given on the test models involved and on the test procedures used. Test results are summarized and the ranges are assigned ratings according to their performance in an evaluation that includes many points of comparison. Problem areas in radar cross section measurements are outlined and some recommended solutions are given. Some suggestions for the optimum utilization of radar cross section ranges are given for the benefit of the potential range user.

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This report presents data resulting from the first comprehensive evaluation of radar reflectivity ranges. Prior to this time there has been no means of determining the ability of any reflectivity range to produce data of specified accuracy; nor has there been any attempt to quantitatively compare these ranges or compare any specific range with theory to establish levels of proficiency in production measurements. This report therefore constitutes a baseline criteria for radar reflectivity range use which will benefit all government agencies whose mission require radar cross section (RCS) measurements of aerospace vehicles. The report was intended to and may be used as a guide in securing RCS data of high quality, in a timely manner and at a reasonable cost. No other reference of this type has ever been available to the radar reflectivity community. The recommendations presented, if adopted by the ranges, should insure future RCS measurement data of consistently higher quality and greater usefulness.

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I

INTRODUCTION

This report is Volume I of a three part report summarizing the results of work accomplished under Contract AF30(602)-3872. The objectives of this project were:

1) To evaluate existing radar cross section measurement facilities.
2) To provide a guide to optimum utilization of existing radar cross section measurement facilities.
3) To identify critical problem areas in radar cross section measurements.
4) To develop plans for attacking the critical problem areas identified.

Special emphasis was placed upon the measurement of large objects (30' and longer).

This volume is intended to contain information of general interest to potential users of radar cross section ranges. It discusses the relative merits of the radar range facilities involved in the study. A short history of the investigation appears in Chapter II and serves to acquaint the reader with some of the problems encountered during the contract. Chapter III is a comparison of the radar ranges in several categories. In Chapter IV, we discuss problem areas and possible solutions, and in Chapter V some brief comments on optimum utilization of ranges are given. The important conclusions to the investigation are summarized in Chapter VI.

The measurement techniques, the measurements themselves and the evaluation of the data are discussed in Volumes II-a and II-b of this Final Report. Volume II-a contains a detailed description of tests performed on five cylinders while Volume II-b presents the results on the satellite models.

II

SHORT HISTORY OF THE MEASUREMENTS PROGRAM

2.1 Description of the Project

We present here a brief chronicle of the measurements program and itemize some of the reasons which caused the original scheduling to slip. We will single out the major errors committed early in the contract so that other potential radar range users, who may well encounter the same problems, may benefit from our experience.

The work requirements of this program called for a series of radar back scatter measurements to be made at the ranges operated by the contractors listed below:[*]

Conductron Corporation, Ann Arbor, Michigan
Radiation Incorporated, Melbourne, Florida[**]
General Dynamics, Fort Worth, Texas
RAT SCAT, Holloman Air Force Base, New Mexico
Micronetics Incorporated[***], San Diego, California
Air Force Avionics Laboratory, Wright-Patterson Air Force Base, Ohio.

With the exception of Micronetics, all the outdoor ranges make use of the ground plane geometry in their measurements. In the typical ground plane range, the antenna and target heights are adjusted so that the target is placed at a peak of the first lobe formed by the in-phase addition of the direct and ground reflected waves as shown in Fig. 2-1 (Bachman et al, 1963). At Micronetics the ground reflections are minimized by using a mound of asphalt in the shape of an inverted V which extends along the path between the transmitter and the target.

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[*] For the convenience of the reader we will refer to these organizations in the remainder of the report as: Conductron (CC), Radiation Services (RSC), General Dynamics (GD/FW), RAT SCAT (RSS), Micronetics (MC) and Avionics Laboratory (A L).

[**] The reflectivity range operated by Radiation Incorporated is now an independent organization called Sigma Incorporated.

[***] This organization was later changed to Micronetics Division, Teledyne Incorporated, Teledyne Systems Company.

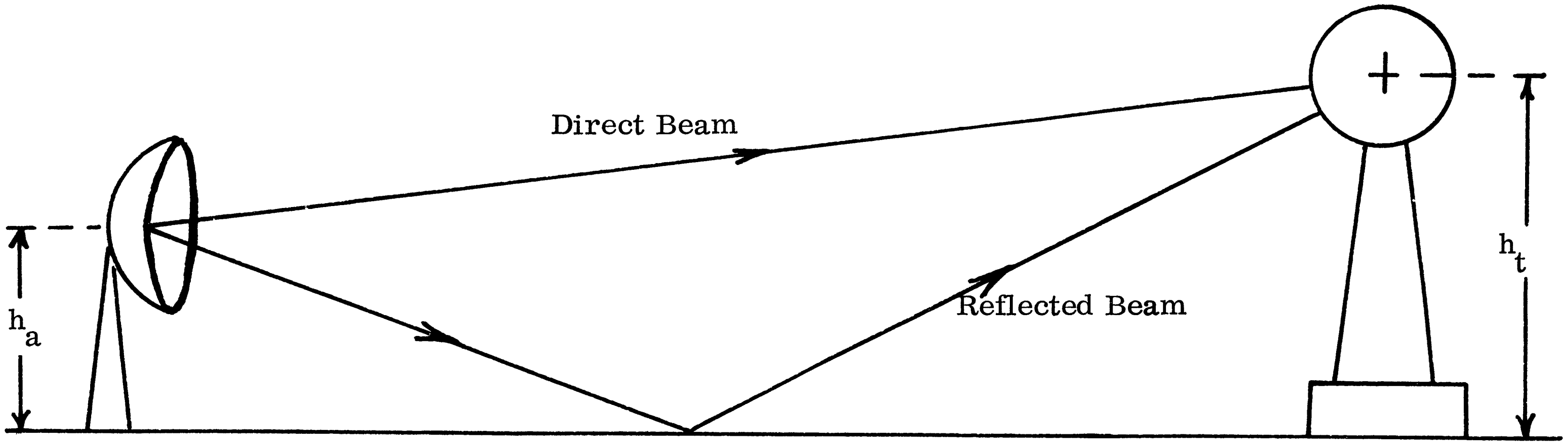

FIG. 2-1: GEOMETRY FOR TYPICAL GROUND PLANE RADAR CROSS SECTION MEASURING FACILITY.

With this arrangement the target and antenna heights are not as critically dependent on one another as with the conventional ground plane geometry.

Conductron Corporation uses a CW transmitter and employs a balanced RF bridge to separate the transmitted signal from the received. The other four ranges used pulsed radar systems with pulse widths between 1.0 and 0.1 microseconds and repetition rates on the order of a few KHz. When pulsed equipment is used the transmitted and received signals are separated in time and range, making it possible to gate out unwanted returns originating outside the target area. Blacksmith et al (1965) give more details on these types of systems and measurement techniques.

All the ranges have similar systems for recording amplitude data in analog form on rectangular pattern paper. The dynamic range of the recorders is 40 or 50 dB depending on the facility (Table II-1). Digital data are also recorded, and at two of the ranges, phase information is recorded. The type of equipment used at each range is also indicated in Table II-1.

For more detailed information on the ranges, the reader is referred to the following: (Conductron, Wren 1964), (Radiation Services, Landfried and Williamson 1964), (General Dynamics, 1968), (RAT SCAT, Marlow et al 1965), (Micronetics, Honer and Fortner, 1964), (Avionics Laboratory, Bahret, 1964), as well as more recent sources listed in the References.

Measurements were performed on five cylinders and three satellite objects at the frequencies shown in Tables II-2 and II-3. The frequency tolerance was to be ± 0.1 percent. Four polarization combinations, HH, VV, HV and VH were required at all frequencies and both phase and amplitude data was to be recorded for all facilities which have the needed polarization and phase capabilities. In the above abbreviations, H and V refer to horizontal and vertical respectively. The first letter indicates the transmitted and the second letter indicates the received polarization. Amplitude and phase information was to be provided as a function of target aspect angle through

TABLE II-1: SOME CHARACTERISTICS OF THE SITES

Site	Trans-mitter	Max Range Used (ft.)[1]	Geometry	Type Data Recorded	Dynamic Range	Digital Equipment
CC	CW	200	Ground Plane	Amplitude	40 db	Paper Tape
RSC	Pulse	1000	Ground Plane	Amplitude	40 db	Punch Cards
GD/FW	Pulse	1800	Ground Plane	Amplitude Phase	50 db 360°	Paper Tape
RSS	Pulse	1200[2]	Ground Plane	Amplitude Phase (L-band)	50 db 360°	Paper Tape
MC	Pulse	600[3]	Direct	Amplitude	40 db	Magnetic Tape

[1] Desired maximum range 2840' for the 32' cylinder at 1360 MHz.

[2] RAT SCAT has a 2400' range but did not use it to measure the full scale cylinder at 1360 MHz.

[3] Micronetics has a 1000' range but did not use it to measure the full scale cylinder at 1360 MHz.

TABLE II-2: MATRIX OF FREQUENCY VS SCALE FOR CLOSED RIGHT CYLINDER.

Scale Frequency 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-3: MATRIX OF FREQUENCY VS SCALE FOR SATELLITE TYPE OBJECTS.

Scale Frequency MHz	Full	4/10	1/8
170	170	–	—
425	–	170	—
1360	–	–	170
425	425	–	—
1062.5	—	425	—

Numbers shown represent equivalent full scale frequency

360^o about a plane containing the longitudinal axis of the model. Phase data were to be provided only if the ranges were normally equipped to measure phase (see Table II-1). In all cases, measurements were to be made for a single, specified roll angle except that at one installation (RSS) the satellite models were to be measured at three roll angles for one frequency and for HH and VV polarizations. The 1/8 scale satellite type object was to be measured only at GD/FW. Measurements at AL were limited to the 1/8 and 1/16 scale cylinders at 1360 and 2720 MHz. Because of this limitation, the AL facility was not evaluated in the same sense as the other facilities. However, the data obtained there were useful as an additional yardstick for the study.

In order to make a comparative evaluation of the ranges it was planned to have each measure the radar backscatter from a standard electromagnetically simple physical object for which theoretical cross section computations could also be made (a cylinder in several scaled dimensions) and a more complex representative utilitarian target (full-scale satellite and two scaled models). The cylinders were furnished by the Radiation Laboratory. The largest is 32' long and 5' in diameter. The other four cylinders are 1/2, 1/4, 1/8 and 1/16 scale models of the larger cylinder. All satellite models were furnished by the United States Air Force. The full-scale satellite was obtained from Lockheed Missiles and Space Company and the two scaled models were obtained from General Dynamics/Fort Worth. The largest of the satellite models is 32'6" long and 5' in diameter. The smaller models are 4/10 and 1/8 scale versions of the full scale satellite.

The target dimensions and weights are summarized in Table II-4. The 4/10 scale satellite was probably the least satisfactory with respect to details in structure and craftsmanship. Some of the cross section ranges noted this in their reports. More information on dimensions and tolerances for the cylinders are given in Vol. II-a, and by Hiatt and Smith (1966). Some detailed information is also given there, and in Vol. II-b the discrepancies between the 4/10 scale satellite and the full-scale model are listed.

TABLE II-4: DESCRIPTION OF THE MODELS USED IN THE MEASUREMENTS.

Model	Diameter (Inches)	Length (Feet)	Approximate Weight (Pounds)
Cylinder	60.0	32.0	1300
Cylinder	30.0	16.0	250
Cylinder	15.0	8.0	30
Cylinder	7.50	4.0	30
Cylinder	3.75	2.0	25
Full Scale Satellite	59.6 (max.)	32.6	900
4/10 Scale Satellite	24.0 (max.)	13.0	250

We knew before any measurements could be made on the satellite targets that they would have to be modified if we expected to be able to scale the data obtained from one model to another. The engine of the full scale model was somewhat exposed and because the fine engine details were not reproduced in the 4/10 scale model, it seemed best to remove some of the parts of the large model and shield others with conducting flat plates. After making these changes, it was still obvious that the 4/10 scale model was not an exact scale model of the larger satellite. It was our opinion, however, that the differences were not sufficient to warrant the considerable time and effort that would be required to perfect the scale. After consultation with the sponsor, it was agreed that the measurements should proceed without further changes. In the meantime, we arranged to have the five cylinders constructed. Eventually the models were ready for measurement, although not all at the same time, and we began shipping them to the cross section ranges. The radar data obtained from the tests are described, analyzed and compared in Volumes II-a and II-b of this Final Report; a summary of the results from these tests is presented in Chapter III of this volume. The Radiation Laboratory was responsible for monitoring the performance of the ranges but the measurements themselves were made by the operators of the individual ranges.

In addition to comparing the measurements of each object at each range, comparisons were made at the Radiation Laboratory between the measured data and theoretically computed cross sections for the cylinder models. For this purpose, theoretical calculations based on a physical optics model provided by the Radiation Laboratory and digital computations provided by the Norair Division of Northrop Corporation under its contract with the Air Force Avionics Laboratory (AF33(615)-3166) were used.

2.2 Delays and Slippage in Schedules

The logistics involved in assembling the models and routing them from one range to another was far simpler than, say, a military operation, but it is nonetheless instructive to examine our plans as summarized in Fig. 2-2. Each line there represents a particular model or group of models and each box represents the location of a cross section range or the site of model origin. In the early months of the investigation we planned that all the models would converge at the Conductron range and would be measured before the winter of 1965 had set in. As we will see, the three largest cylinders were fabricated by Brooks and Perkins of Detroit, the two smallest in University of Michigan shops and the full scale and 4/10 scale satellites originated at Lockheed Missiles and Space Company (Sunnyvale) and General Dynamics/Fort Worth, respectively.

After measurements at Conductron, the models would be shipped south to Radiation Services, then westward to General Dynamics. The two smallest cylinders would then be shunted north to Wright-Patterson AFB while the remainder of the models would advance to RAT SCAT. In due time, the smaller cylinders would rendezvous with the main convoy of models at RAT SCAT after which the entire phalanx would press on to Micronetics in San Diego. After measurements there, the full scale satellite would embark on its last leg of the journey, heading back to Sunnyvale, while the rest of the models would be destined for RAT SCAT.

It will be quickly apparent to anyone keeping abreast of our progress that our schedule began slipping at the very beginning. Our first task was to solicit official quotations from several local fabricators for construction

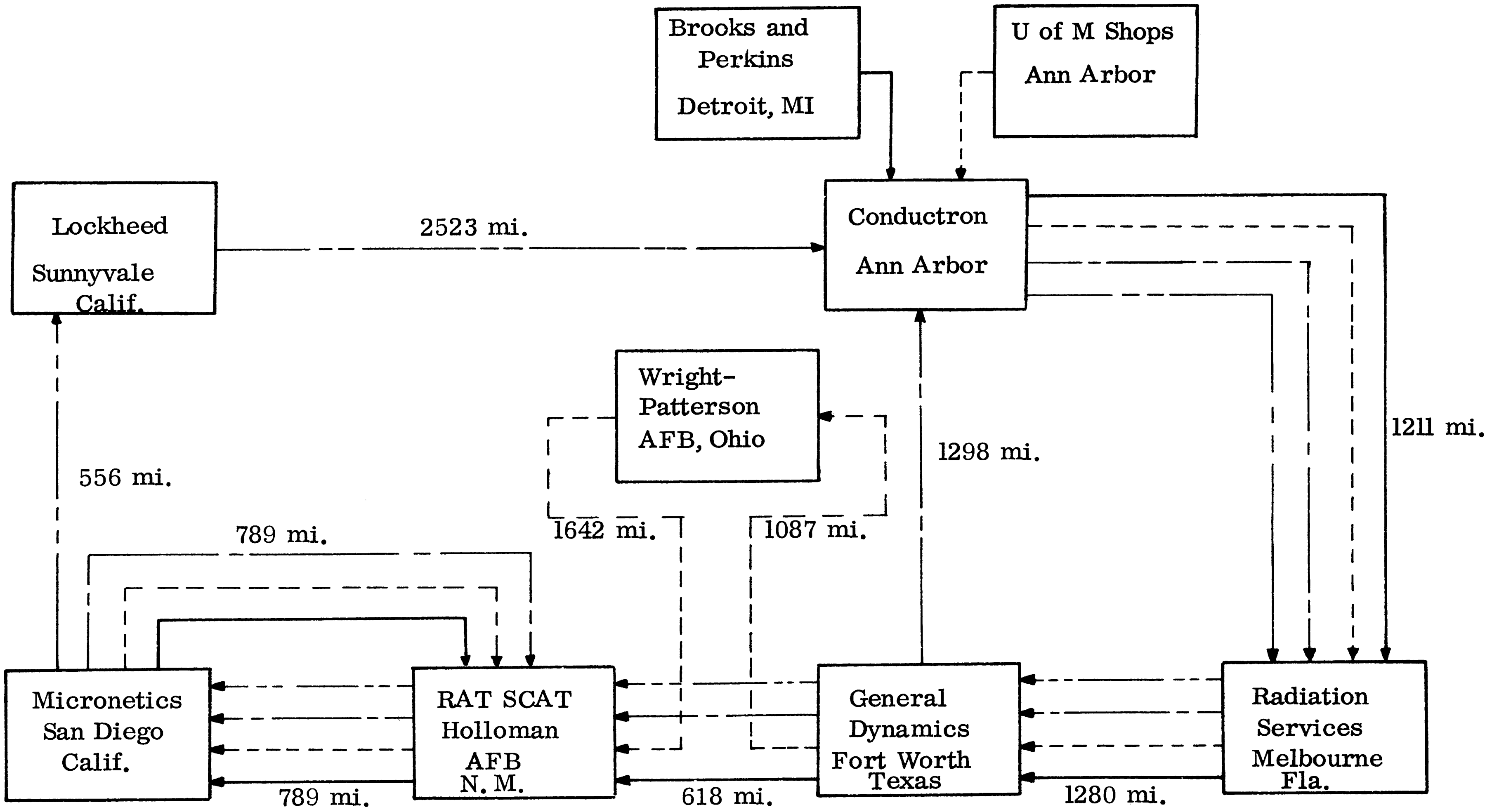

FIG. 2-2: TEST PROGRAM BEGAN WITH ASSEMBLY OF ALL MODELS TO BE MEASURED AT CONDUCTRON RANGE. —— 3 Large Cylinders, - - - 2 Small Cylinders, — - — 4/10 Scale Satellite, —— - - —— Full Scale Satellite.

of the three largest cylinders required for the study. We requested these quotations be submitted to us by 30 July 1965, but none responded within the stated time. From this point on, our story is one of delays — the schedule slippage can be determined from Fig. 2-3 where we present our original plans (from the first Monthly Status Report, 7462-1-L, August 1965) together with the rate at which progress was actually made (shaded portion).

After the official quotations had been received, we felt Brooks and Perkins, Incorporated (B-P) of Detroit Michigan would do the best job of producing the three largest cylinders and an order was placed with them. In September 1965, we learned that B-P had encountered labor troubles and its non-salaried employees had struck the company. In an attempt to meet its obligation, B-P sub-contracted the construction job to National Light Metal and Plastic Tile Company of Caro, Michigan and fully expected the finished products would meet specifications. National Light Metal, however, found it difficult to meet our tolerance requirements and we subsequently relaxed them, but retained realistic specifications. When we inspected the 32' cylinder on 9 February 1966, we saw that it failed to meet even the relaxed specifications. To get the project under way, we accepted the model in spite of its shortcomings, with the proviso that the 16' and 8' models fully meet the specifications.* Brooks and Perkins announced the completion of these two smaller models on 4 April 1966 and after inspection, they too, were accepted. The model construction phase of the program was thus completed about five months later than originally planned.

We did not anticipate the delay in model procurement, nor perhaps, did B-P. It was primarily due to labor strife and B-P was an innocent victim. We feel, on the other hand, that B-P could have sensed trouble afoot before it actually occurred and could have alerted us that a delay might be imminent.

The late model procurement had a lasting effect on the measurement program. Our plan was to provide Conductron with a complete set of models

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*As judged from radar cross section measurements of the 32' cylinder, the decision proved to be a sound one.

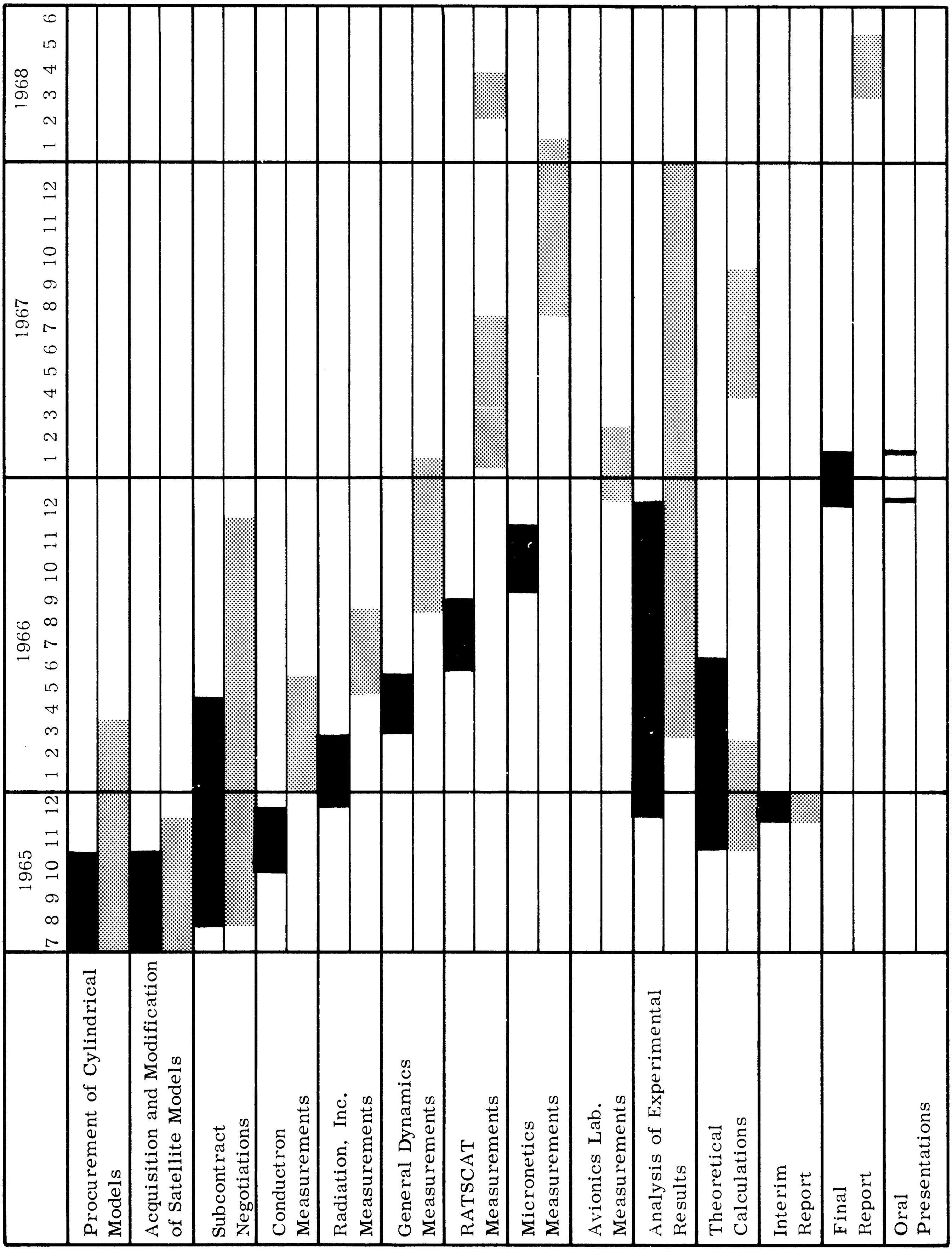

FIG. 2-3: COMPARISON OF PLANNED AND ACTUAL FLOW OF WORK.

before the capricious Michigan winter had set in and thus permit Conductron to finish its measurements well ahead of adverse weather conditions. But, due to lack of models (as well as modifications that had to be made upon the satellite targets), the Conductron work was started early in January 1966, and took place through practically all of that winter and most of the following spring. The measurements were finished on 26 May 1966, more than five months beyond schedule, the precise delay encountered in model procurement.

Radiation Services received the models shortly and discharged its measurement obligation in a scant two or three weeks beyond the estimated time allocated. We note that it began measurements before Conductron had finished because some models had been shipped onward to expedite the program. Measurements were finished in Florida on 10 August 1966, barely five months beyond schedule, again the amount of model procurement delay. Thus far, our schedule had slipped only by the initial delay and neither Conductron or Radiation Services had contributed to further delays. We note in passing that the price for the data provided by Radiation Services, whether measured in dollars or in range time, was the best that any range provided.

After receiving the models from Radiation Services, General Dynamics of Fort Worth did nothing with them for almost two months. At about this point we began to realize that we had made a mistake in scheduling; it takes a finite amount of time to transport the models between ranges and, moreover, some ranges want to examine the models, decide how to set up the range, and otherwise prepare for actual measurements after accepting the models from the trucker. After GD/FW eventually started work, it finished in less than three months, and thus its actual range time (measurement time) was less than that of any other facility. The delay between receipt of models and commencement of measurements, however, amounted to two months and our scheduling had slipped to about 7 1/2 months by 11 January 1967.
During the journey from GD/FT to RAT SCAT in mid January 1967, some of the models were damaged but the people at RAT SCAT were able to make all necessary repairs. In the interim, the two smaller cylinders were shunted

from GD/FW to Wright Field, were measured, and sent on to RAT SCAT by the first of March 1967.

We were unaware at the time, but very serious delays were in store for us after all the models showed up at RSS. Measurements were started there on 17 March 1967, 9 1/2 months beyond schedule, and because RSS declared it must discharge measurements with higher priority than ours, the slippage grew worse. In the summer of 1967, the models were still at RSS; after four months, and in exasperation, we arranged to ship them onward to Micronetics in San Diego, after which they could be returned to RSS for the possible completion of measurements there since this would eventually be their final destination anyway.

Micronetics began measurements early in August 1967, eleven months beyond the target date of our tattered schedule. As at other ranges, the work at MC was delayed by weather, higher priority measurements, and equipment failure. With the exception of one model and one frequency, the tests at MC were completed by 23 January 1968. The data on the 32' cylinder at 170 MHz were not obtained because the Micronetics crew lost the 32' cylinder from atop its column and the model was severely damaged. We will comment on this event later.

All the cylinders except the damaged 32' cylinder were then shipped to RSS to await completion of the test program. The 32' cylinder had already been completely measured there and detaining it for repairs at MC was no problem. In addition to these four cylinders, the 4/10 scale satellite was also shipped to RSS and the large satellite was returned to Lockheed in Sunnyvale, California. Thus, by the first of February 1968, RAT SCAT once again had all the models necessary to complete its test program.

The models remained untouched at RSS for a month. The sponsor then decided that the measurement phase of the program should be terminated by mid-March 1968 whether the work was completed or not. Upon being made aware of this decision, RSS rearranged its schedules and completed the measurements within the above time limit.

In summary, the delay in cylinder construction led a parade of subsequent delays, but was unavoidable and unforeseeable ; we ascribe the blame to no one. The delays that we experienced at the radar cross section ranges were due to (in the order of their importance), 1) adverse weather, 2) higher priority work, 3) the tendency of range operators to do very careful, and thus time-consuming work, since the results would be a badge of their competence, 4) finite shipping time between ranges and 5) preliminary range preparation. We were especially disappointed in RAT SCAT's inability to meet schedules but we could do no more than periodically prod them with anxious questions about measurement progress. It should be noted, however, that they were probably forced to pay closer attention to government priority ratings than the other ranges.

2.3 A Few Mistakes

We made most of our errors early in the contract and they were largely confined to model handling and transportation. It turned out that the two larger models (32' cylinder and full scale satellite) each occupied more than half a standard trailer and there was not enough room left in either trailer to accommodate the 16' cylinder. Consequently, portions of no fewer than three trailers were required for a complete shipment of the test models and two of them generally had an "exclusive use" rate for freight charges because more than half the trailer was required. The minimum "exclusive use" charge is based on a load of 12,000 or 14,000 pounds (it seems to depend on the particular freight route used) and since our models were much lighter than this, the shipping charges far exceeded our original estimates. Had we been able to fit all the models into a single trailer, the exclusive rate would have reduced our costs by 15 percent, but the final costs turned out to be about double our original estimates. The total weight of the shipment was less than 4000 pounds and the actual per mile costs per cwt listed in Table II-5 are based on this weight.

TABLE II-5: SHIPPING COSTS OF THE MODELS

Shipped From	Distance (Miles)	Cost (Dollars)	Cost/Mile (Dollars)	Cost/Mile/cwt. (Dollars)
Detroit to				
Melbourne to	1211	1244	1.025	.0256
Fort Worth to	1280	1795	1.401	.0350
Holloman AFB to	618	1410	2.280	.0570
San Diego	789	1903	2.380	.0604

A second error was our underestimation of the amount of abuse a shipment receives in the trucking process. On the first major leg of the trip, the loading was supervised by a Radiation Laboratory engineer and the models were received in good condition at Melbourne Florida; only the 4/10 scale satellite was damaged, and it was easily repaired. Between Melbourne and Fort Worth much more model damage was noted. An end plate of the large cylinder had received two or three dozen small pits due to contact with either another object loaded in the same trailer or the walls of the trailer itself; the forward retaining ring of the carriage supporting the full scale satellite had been damaged, and the nose cone of the 4/10 satellite needed repainting. Between Fort Worth and Holloman Air Force Base, the 16' cylinder had received a dent in its flank, the 4/10 scale satellite had been damaged again, and the shipping carriage for the full scale satellite needed repairs for the second time.

The full scale satellite was cradled in a large metal framework equipped with small jack-stands and dolly wheels. This fixture had a pair of heavy rings that encircled the model and clamped it tightly to the framework, and is apparently a universal support for handling the vehicle. It was a difficult piece of cargo to load or unload in trailers and difficult to handle with fork-lift equipment because the support fixture was shorter than the model it supported and was relatively open framework. Although the satellite was shipped in two pieces, with the smaller piece in an open crate, the loading process was often cumbersome.

The 32' cylinder was carried by a relatively weaker structure that did little more than support the model and keep it from rolling about the trailer. The shipping pallet was simply a pair of longitudinal timbers spanned transversely at three points by heavy plywood cradles in which the cylinder rested. The pallet was fitted with four lifting eyes that were apparently seldom used, and the model was strapped down by three belts at the points of support. The 16' cylinder was borne by a similar, but smaller, skid and the 4/10 scale satellite was shipped in a closed crate. The three smaller cylinders shared a foam-padded plywood box not unlike a coffin.

We were not concerned about the relative openness of the shipping skids for the two larger objects (the cylinder and full scale satellite) because both models were much stronger than any container would have been. It appears, however, that we were not careful enough in our efforts to protect the models. The large cylinder was originally covered by a pair of heavy tarpaulins and this should have been adequate but these were apparently not in place between Melbourne and Fort Worth. Even the 4/10 satellite model was damaged and since it was protected by its own crate, we wonder how stout a packing crate must be. It appears that no matter how much attention is given to designing a protective shipping container, models will be damaged unless loading and unloading is supervised, or if adequate loading equipment is not on hand. A simple device would be an unloading dock, or if this is too costly for a cross section range to possess, even a long unloading ramp would suffice. A few dollars worth of block and tackle would be a worthwhile investment. Several of the cross section ranges had, or could have quickly built, lifting equipment to hoist models from the trailers, but the trailers were all covered and the models had to be withdrawn horizontally from the rear.

RANGE COMPARISONS

In this chapter we examine the capabilities and performance of the five ranges from several points of view and, based on our findings, we assign ratings as appropriate. Our examination is divided into five areas and the results are contained in five tables. Note that these groupings are not considered to be of equal importance.

3.1 Facilities, Techniques and Procedures

Table III-1 is one list of ratings by which the five cross section ranges may be compared and the reader will note that each basis of comparison is a question. The ratings themselves do not specifically answer the question but are intended only to indicate how well the individual ranges performed in each instance. Twelve points of comparison are listed, but not in any particular order, and the potential range user will have to judge for himself which of the comparisons are important to his own needs. The ratings run from A through E and indicate our assessment as follows:

A = Very good; B = Good; C = Acceptable; D = Barely Acceptable; E = Intolerable

Note that only two entries in Table III-1 have the lowest possible rating of our scale of value. We will now briefly discuss each point of comparison.

3.1.1 Frequency

A University of Michigan engineer measured the seven frequencies which were used at each radar cross section range with a superheterodyne frequency meter. The device uses a zero beat technique in which an unknown signal is compared with a harmonic of a known internally generated signal. Since four of the five ranges used pulsed systems, the measurement was really that of the center frequency of a power spectrum; not all the ranges produced the same pulse shape. Two of the ranges were able to hold frequency within 0.02 percent (RMS over the seven frequencies), two held it under 0.1 percent, and one slightly exceeded the ± 0.1 percent which was the limit specified in the subcontracts. It appears that frequency errors are the least troublesome aspects of radar cross section measurements. Radiation Services used 2712 MHz in place of

2720 MHz due to its inability to obtain the correct frequency source. This caused no noticeable errors in the data at this frequency for the cylinder models. An error of this size (approximately 0.3 %) in frequency for the satellite targets might have caused some fluctuation in the satellite data due to the location and nature of the scattering centers on these models.

TABLE III-1: COMPARISON OF FACILITIES, TECHNIQUES AND PROCEDURES

Basis of Comparison	CC	RCS	GD/FW	RSS	MC
1 How closely did they hold frequency to specifications?	A	B	A	A	A
2 Were they in the far field?	E	C	B	C	D
3 Did they maintain a good log?	B	B	A	A	C
4 How long did it take to record a pattern of the large model?	C	C	B	B	A
5 How long were the models held at the range?	B	A	D	E	D
6 Did they use good measurement procedures?	B	B	A	B	D
7 How did they handle cross polarized calibration?	B	B	B	B	B
8 Are there handling facilities adequate for large models?	B	C	A	A	A
9 Do they have enough sheltered storage?	B	B	A	A	B
10 Are they confident of their data?	B	B	A	C	C
11 How good was the data format?	C	B	A	A	B
12 How good was the final report?	A	A	B	D*	C
Average	B-	B	B+	B	B-

* RAT SCAT was originally given a mark of E because its report was not available for evaluation at the end of the contract. The RAT SCAT final report was received on July 8, during the final revision of this volume but this was far too late to be of use in our analysis of the data. We note that the report it finally submitted was good (B) but a grade of D has been assigned because the report was not available for our use.

3.1.2 Near Field Effect

We have rated all five ranges on their far field distances, for the largest models only, since this is one of several gauges with which data are judged. For a 32' target at a frequency of 1.36 GHz, the required far field distance ($2L^2/\lambda$) between the target and antennas is about 2840 feet; the actual distances used for this measurement are shown in Table III-2.

TABLE III-2: DISTANCES USED FOR THE LARGEST MODEL WERE ALWAYS LESS THAN $2L^2/\lambda$.

Range	R, Distance Used (Feet)	$\frac{R\lambda}{2L^2}$
Conductron Corporation	200	0.07
Radiation Services	1000	0.35
General Dynamics/Ft. W.	1800	0.63
RAT SCAT	1200	0.42
Micronetics	600	0.21

Accepted practice calls for $R\lambda/2L^2$ to be equal to or greater than unity. Note that Conductron's measurements were performed well in the Fresnel zone and this seems to be characteristic of CW systems due to the relatively low power. (Low power requires that the target be close for sufficient sensitivity in the receiving system.) General Dynamics/Fort Worth used the greatest distance of all ranges, and RAT SCAT used only 50 percent of its range capability; we were not told why RAT SCAT did not use its full 2500' range capacity. Although Micronetics has a 1000' range, it chose to measure the 32' cylinder at 600' and this introduced a serious near field distortion in the broadside return at 1360 MHz.

3.1.3 Log

The intent of a log is to provide a history that may be consulted to find the answers to questions that often arise after an experiment has been completed and the apparatus dismantled. It can describe the conditions under which a measurement was made and is thus a simple method of bookkeeping that will identify raw data. It can also be a repository for other raw data that the observers perhaps would not even consider data. Not all the ranges were diligent in maintaining good logs, but if they had been, we would later be able to find the answers to what appeared at the time to be unimportant questions.

Examples

What percent of range "down time" is due to wind?
How often do birds destroy patterns by flying through the range gate?
How many times must the grass be mowed during the summer months?
How many patterns are destroyed by man-made disturbances such as automobiles, airplanes or Channel 7 ?
Why are less than maximum range distances used when they cause near field distortions?

The answers to many of these questions can be found in some of the logs, while others will tell only the frequency, polarization, and pattern number.

3.1.4 Measurement Time

Many of the radar cross section ranges involved in this investigation use digital recording equipment which slows down the actual measurement time considerably, but one range, Micronetics, used a magnetic recorder that scarcely affected recording time at all. Since it is possible for signals to drift in both amplitude and phase in the duration of a measurement, the actual measurement time is, admittedly in a small way, a quality factor for data. It might also be a measure of the total time required by a range to complete a measurement program. We note, however, that the range that finished all its measurements in the shortest time required the longest time to record a single pattern.

3.1.5 Total Range Time

By total range time we mean the length of time that a given range consumed between the receiving the first, and shipping the last, model to be measured. Radiation Services scored best on this critical question and RAT SCAT scored poorest of all the ranges.

3.1.6 Measurement Procedures

Most of the ranges used the commonly accepted measurement procedures. Model alignment and orientation were carefully checked at all ranges and support columns appropriately guyed at most of them. All ranges made preliminary probes of the structure of the incident field over the volume occupied by the targets, in both horizontal and vertical planes. Some ranges took it upon themselves to measure the effects of target roll, looking for asymmetries in the models that could cause errors. Some ranges were very careful about their model support columns and fashioned elaborate fixtures that supported the smaller models on slender foam fingers, much like a professional waiter carries his tray. Micronetics was surprisingly casual and plopped its models atop a fat column with perfect innocence; the operators of this range later discovered that more care is required than they had first supposed.

3.1.7 Calibration Techniques

All the ranges calibrated their co-polarized patterns with spheres and Micronetics supplemented the calibration with disks. (In a co-polarized measurement the polarization of the transmitting and receiving antenna are the same). All the ranges except Conductron pre-calibrated their patterns; this permitted them to label the pattern amplitude grid in convenient scales so that radar cross sections in dB relative to a square meter (dBsm) may be read directly from the patterns without the need for interpolating or counting dB's from a calibration level. While this admittedly makes the patterns easier to read, it also demands very careful observance of gain and attenuator settings and maintenance of a good log. Conductron installs the calibrating device after a measurement and the user of the data must execute mental gymnastics in order to determine the radar cross section in dBsm. The data, however, are more or less raw and are likely to contain fewer human errors than the pre-calibrated data of other ranges.

Calibration of the cross-polarized data varied from range to range. Conductron calibrated against the copolarized return from a sphere. With a sphere as a target and with the antennas cross-polarized, fine polarization adjustments were made to minimize the return. The level of the cross-polarized return was obtained by referencing it to the copolarized return while maintaining the frequency and power level constant. To verify the fact that the system was properly cross-polarized when this procedure was followed, use was also made of a 45^o inclined wire. Radiation Services calibrated a 45^o inclined wire against a sphere; GD/FW and RSS used a corner reflector stationed outside the range gate. The cross-polarized return of this secondary standard was calibrated against the copolarized return of a sphere. In addition, GD/FW used a 45^o inclined dipole as an alternate standard. Micronetics used a corner reflector as a secondary standard and carefully re-checked the calibration with an inclined wire. General Dynamics occasionally used an "electronic reference" composed of an appropriately attenuated sample of the transmitted signal piped directly to the receiver, but only for the very low frequencies. This reference was calibrated against a sphere.

3.1.8 Handling Facilities for Large Targets

RAT SCAT appeared to have more equipment than the other ranges for handling large targets and GD/FW was also well equipped, but with older and less sophisticated gear. Micronetics recently acquired its own crane (Fall, 1967) but Radiation Services had to rent a crane for its large models. Conductron used a large A-frame to hoist and carry large models and, though adequate, was often cumbersome to use.

3.1.9 Sheltered Storage

All of the ranges had provisions for sheltered storage of large models, and the ratings we assign are chiefly of degree. Both RAT SCAT and GD/FW had large sheds on wheels that served as shelter as well as model installation and retrieval equipment. The others had sufficient enclosed buildings to accommodate the models, but if several large models must be received at some of the ranges, conditions could become crowded. We should point out that the climate in San Diego and New Mexico is relatively dry and models will not ordinarily suffer from outdoor exposure. We learned, however, that sudden and severe storms can erupt and pelt the desert with raindrops the size of grapes, and that the blowing alkali can abrade the skins of some targets. At Fort Worth, Melbourne and Ann Arbor, rainfall is more frequent and in these locations shelter is more desirable. All the facilities could adequately house classified models.

3.1.10 Confidence in Data

The General Dynamics/Fort Worth people were probably the most competent and confident of all the range personnel with respect to their techniques and results. The strongest test was that of cross-polarized data collection and GD/FW executed the measurements with aplomb. The Micronetics personnel were wary of even their co-polarized patterns and Conductron and Radiation Services personnel were suspicious only of their cross-polarized data. The RAT SCAT people were noncommittal about their work and they kept their esteem for the patterns more or less to themselves.

3.1.11 Data Format

Radar cross section ranges are virtually at the mercy of the equipment vendors in regard to the form of recorded analog data. All the ranges submitted radar cross section patterns on standard sized charts (~11" x 20") and these patterns must be either photographically reduced to manageable size for inclusion in reports, or be submitted in a separate folder of unmanageable size. All the patterns were approximately the same size, but often inter-range comparisons could not be made directly because the patterns were not exactly the same size. Thus, for purposes of inter-range comparison, we had to examine every pattern and read off certain data, such as broadside, end-on, and first sidelobe amplitudes, and the positions of various important nulls of the patterns. The lists of such data then had to be compared against each other for different ranges. The effort required in this comparison led us to conclude that the format in data presentation is a problem area and we will discuss it further in the next chapter. The grades for Item 11 in Table III-1 are based on how easy we found it to read and interpret the data.

3.1.12 Final Reports

Each of the ranges submitted a final engineering report at the end of the subcontract period and we have decided to compare them. Both Conductron and Radiation Services included some theoretical discussions, the former to account for near field effects and the latter to present some results for comparison with theory. General Dynamics and Micronetics presented no theoretical discussions, but merely explained and described the experimental results. Conductron failed to discuss cross polarized calibration procedures and Micronetics omitted any mention of its range crew dropping the 32' cylinder. We feel this latter omission to be ill advised since an organization should admit its mistakes. A discussion of the cause of the accident and means for avoiding such accidents in the future would have been in order.

3.2 Accuracy of Cylinder VV and HH Data

Without question, data accuracy is an important, probably the most important, criterion to be considered in evaluating range performance. This and the next two sections are devoted to an examination of measurement accuracy. Attention is given first to the data resulting from the co-polarized (VV and HH) measurements on the cylinders.

Cylinder data, in the form of patterns and tabulated results are presented in considerable detail in Volume IIa. The co-polarized data are analyzed and evaluated based on five points of comparison with the results presented in the form of tables and display graphs. Here we summarize the results in Table III-3 with a brief discussion of the points of comparison. (This is a duplicate of Table VI-4 in Volume IIa.) In this table we include entries from Avionics Laboratory (AL), who provided data only for the two and four foot cylinders, the smallest models used in the program.

The constant ka row in the table results from the comparison of end-on and broadside returns from one cylinder-frequency combination with another cylinder frequency combination having the same ka value where $k = 2\pi/\lambda$ and a is the radius of the cylinder. Where equal ka values are involved with a

TABLE III-3: SUMMARY OF RANGE TESTS FOR FIVE POINTS OF EVALUATION. Numbers indicate errors 1 dB or less for the range listed.

Range / Test	CC	RSC	GD	RSS	MC	AL
Constant ka (52 possible)	40	46	43	45	41	4 (of possible 4)
End-on Polarization (18 possible)	17	18	18	16	17	4 (of possible 4)
End-on Theory (36 possible)	17	30	24	27	33	4 (of possible 8)
Broadside Theory (36 possible)	21	30	34	33	15	8 (of possible 8)
Special Low ka Test (74 possible)	36	53	52	46	30	not evaluated
Total Number of Errors (216 possible)	131	177	171	167	136	20 (of possible 24)
Percent	60	82	79	77	63	83
Grade	D	B	C	C	D	B

2 to 1 size difference the cross section of the larger model will be 6 dB higher than that of the smaller model. Out of the eighteen model frequency combinations to be measured (Table II-2) there are thirteen equal ka pairs with a 2 to 1 size ratio. Each of these have two aspects, 0^{o} and 90^{o} and two polarizations to be compared. This provides for a total of 52 points for intra-range comparison for each facility. We show in Table III-3 the number of comparison points that deviate from 6 dB by less than 1 dB. We consider this to be a critical test; the ratings range from 39 to 46, neither poor nor excellent.

The next row, End-on Polarization, summarizes a comparison based on the theory that the HH and VV returns for end-on aspects should be equal. The theory is completely dependable and errors must be charged to calibration errors or other improper range procedures. There is a single comparison for each frequency-range combination making it possible for each range to have eighteen readings with less than 1 dB error. The ratings are good here with four of the major ranges having no more than one error greater than 1 dB. All four of the Avionics Laboratory's values had less than 1 dB error.

The third row, labeled End-on Theory, is based on data presented in Table VI-1 and earlier figures in Volume IIa. The entries in this row are the number of errors under 1 dB between the theory and the measured end-on returns for both polarizations. This is seen to be a more sensitive test than the end-on polarization comparison; note that only one of the major ranges (MC) rates an A grade. More information on the theory and experiment as well as a plot showing the distribution of errors is given in Volume IIa.

In the fourth row (Broadside Theory), we present the results obtained when the measured broadside returns are compared with the theoretical estimates. Since broadside returns depend upon polarization, the errors were determined separately for each polarization based on data presented in Figures 6-2 and 6-3 of Volume IIa. The entries we show in Table III-3 of this report represent the average for the two polarizations. Two of the major ranges,GD/FW and RSS,as well as AL,rate an A on this test. Two other ranges, CC and MC,do poorly, partly as a result of errors caused by using insufficient range length. This and other sources of error are discussed in Section 6.2 of Volume IIa.

In the fifth row of Table III-3, the results of a special low ka test are presented. Special attention was given to certain measurements involving the ka value of 1.36 where unusually large discrepancies were found in the experimental data. The experimental data along with the theory are contained in Figures 6-7 to 6-10 of Volume IIa and a detailed discussion of the comparison is contained in Section 6-4 of that report. The experimental data are VV and HH measurements of the 16-foot cylinder at 170 MHz and the 4-foot cylinder at 680 MHz. The theory used is obtained from the Norair SDT program. Comparisons are made at 5^o intervals from 0^o to 90^o with certain omissions to avoid extreme nulls in the pattern. The scores given in this test,as shown by the entries in row five range from medium to poor. Possible causes for the unusually poor performance on these tests are discussed in the next chapter of this report as well as in Section 6-4 of Volume IIa.

Some final comments on the comparison of the co-polarized cylinder data are in order. Table III-3 encompasses and summarizes the results from almost all of the analyses performed on these data. The data represent a major part of the results from the entire program and they have proven to be the most satisfactory when used as a basis for comparing range performance. The tests represented by the individual rows show that three of the outdoor ranges rather consistently earned the three highest ratings and this is also shown in the row which indicates the accumulated rating. From this we see that Radiation Services comes out as number one and General Dynamics and RAT SCAT are within five percent of the number one position. These three ranges rank well above Conductron and Micronetics on the basis of these accuracy tests.

3.3 The Reliability of Cross Polarized Measurements on Cylinders

With the increasing need for cross polarized RCS data, it is important to consider the ability of the various facilities to make such measurements with the necessary reliability. We are not satisfied with our method of judging ability to perform cross polarized measurements. It is shown in Chapter VII of Volume IIa that there should be no VH or HV return from true cylinder models for the aspects measured. As observed elsewhere in these reports, we now know that other models or other aspects for these models would have provided a much better basis for judgement.

Under the test conditions employed, the recorded VH or HV return should have been random in nature and at a level close to the background return. The actual return was not random; in fact it rather closely resembled the VV or HH return except that its level in dBsm was on the order of 25 to 30 dB lower. We concluded that the return presented was essentially the co-polarized return attenuated by an amount equal to the isolation level between the VV and HH polarizations of the antenna(s) and associated rf components.

Since we could not judge performance on the basis of the form of the patterns we have used the only other available criterion, the amount of isolation between the co-polarized and the cross polarized return. This value was obtained by subtracting the near broadside VH return from the HH return and similarly the HV return from the broadside HH return. This is discussed in further detail in Volume IIa and in Tables VII-3 and VII-4 of that report, where all isolation levels so determined are presented. In Table III-4 we present only the values obtained by averaging the dB values from the above tables. A maximum of 36 VH and HV tests were considered in the isolation evaluations. The RAT SCAT and Radiation Service facilities completed all 36 tests. Table III-6 in a later section, shows the number of measurements made by all ranges.

TABLE III-4: RATING ON CROSS POLARIZED MEASUREMENTS ON CYLINDERS.

Range	Average Isolation Between Co-Polarized and Cross Polarized Broadside Returns	Grade
CC	32.2	C
RSC	30.7	C
GD/FW	27.2	D
RSS	31.5	C
MC	25.7	D

The required isolation needed to perform satisfactory cross polarized measurements is subject to question. It depends of course on the target being measured and the required accuracy. Based on our experience, we feel that a 30 dB isolation level is the minimum acceptable, hence we somewhat arbitrarily equate this to a grade of C and assign other grades accordingly.

Our position on this aspect of the evaluation should be restated. We consider the <u>ability</u> to perform accurate cross polarized measurements very important. The specified cross polarized tests <u>do</u> <u>not</u> provide a good basis for judging the ranges' capabilities to make such measurements. This is discussed further in the cross polarization chapters in Volumes IIa and IIb.

3.4 The Accuracy of the Satellite RCS Data

In earlier chapters we have described the satellite models to be measured in this evaluation and the frequency model combinations involved are shown in Table II-3. Four of the ranges were able to measure the full scale and the 0.4 scale satellite at two frequencies and four polarizations each. GD/FW was asked to make the same measurement and was to measure the 1/8 scale satellite at a third frequency and with four different polarizations. The frequency-model combinations were such that two pairs of equal ka values could be obtained.

A considerable amount of data on the satellite tests is presented in Chapter III of Volume IIb and in Chapter IV of that volume and the data are analyzed and evaluated. For that reason and in order to avoid having any classified information in this report our discussion of the satellite data here will be brief.

In both the constant ka tests and in the inter-range tests, comparisons are based on RCS values at nose-on, broadside and tail-on. Hence, in the constant ka tests for VV and HH polarizations, twelve intra-range comparison points were possible. For perfectly scaled models, an 8 dB difference in RCS values should have been measured. In Volume IIb we present the values obtained and show the distribution of errors, categorized in 2 dB steps. The grade we assigned as a result of our evaluation was based on the number of errors less than 2 dB. We used a more relaxed standard here than for the cylinder data since we are dealing with a target more complex and more difficult to measure. We wanted also to allow for the effect of possible modeling errors in the scaling. The results are given in Table III-5.

TABLE III-5: RATING ON SATELLITE RCS MEASUREMENTS

Range	Co-Polarized Tests		Cross Polarized Tests
	Constant ka	Inter-Range	
CC	D	D	? ?
RSC	C	C	? ?
GD/FW	D	B	? ?
RSS	D	B	? ?
MC	E	C	? ?

In the inter-range tests of the co-polarized measurements, we have available four patterns for each of two polarizations and with three aspect angles being examined we thus have 24 points to be compared with the average value. These data for all five ranges are contained in Tables IV-4 through IV-6 in Volume IIb. From these data we determine the deviations between the measured and average values and show the distribution of errors arranged in steps of 1.5 dB. The assigned letter grade which appears in the second column in the above table is based on the number of errors less than 1.5 dB. Modeling errors are not a factor in the inter-range tests, thus a more restrictive standard than that used for the constant ka tests is appropriate.

In Volume IIb we present a substantial amount of cross polarized data. The data are analyzed and we use several approaches in an attempt to evaluate the HV and VH data. We finally decided that it is not feasible to rate the cross polarized data due to the small number of samples and the wide divergence that exists in patterns that should be identical. We acknowledge that the lack of agreement may be due in part to modelling inaccuracies, a factor that is particularly difficult to evaluate in cross polarized measurements. Modeling inaccuracies, however, should not effect the inter-range comparisons but here the position and the level of the major lobes showed too little agreement to give any credence to an average value. It is possible that a single pattern in the various comparison tests or even all of the RCS patterns of one range are the correct and accurate patterns but we doubt this very much. We doubt if any of the cross polarized satellite data should have an accuracy rating of better than 3 dB.

3.5 Ability to Make Specified Measurements

In this section we note and summarize the ability of the ranges to make the measurements specified in this program. In evaluating a range's performance on the basis of accuracy, we did not, in most cases, include as a factor the inability to perform some of the measurements. At the start of the program, the range operators were advised that they should respond to the request for proposal on an "as is" basis. They were not asked, for example, to add phase measuring equipment to their facilities to accommodate this program. Information on this and other capabilities are, however, needed by the potential user as he attempts to determine the range most suited for his needs. Table III-6 contains a summary of our information on the ability of the five ranges to perform the measurements which were specified in this program. Much of this information is given elsewhere in this or the companion reports, e.g. Table II-1 of this report. With respect to the co-polarized amplitude measurements, entries there less than 100 % in the case of Conductron are due to the lack of acceptable patterns where near field problems were particularly severe. For Micronetics, the same explanation holds, and in addition two measurements were not made as a result of severe damage to the 32 foot cylinder on that range.

TABLE III-6: ABILITY TO MAKE PHASE AND AMPLITUDE MEASUREMENTS SPECIFIED IN TABLES II-2 AND II-3

Range	Amplitude Measurements		Phase Measurements
	Co-Polarized	Cross Polarized	
CC	38/44	20/44	None
RSC	100 %	100 %	None
GD/FW	100 %	40/46	100 %
RSS	100 %	100 %	L Band Only
MC	42/44	40/44	None

Both Conductron and General Dynamics elected to omit some of the cross polarized measurements since the antenna systems were not well suited to provide the needed isolation. For Micronetics, the explanation given for the co-polarized measurements holds here also. As noted here and as was stated at the start of the program, three of the ranges do not make phase measurements and the RAT SCAT range provides phase data only at L Band (1000 to 2000 MHz in this case).

3.6 Summary

In this chapter we have compared the performance of the ranges based on information introduced here as well as data presented elsewhere in this report and in Volumes IIa and IIb. Our examination of the capabilities and performance of the ranges has been based on five points of comparison. In four of these we have made an attempt to assign a letter grade indicating our estimate of the rating of each range. For the fifth area, having to do with the ranges' ability to perform the specified measurements, we provide a summary Table III-6. As indicated earlier, these points of comparison are not of equal importance. In Table III-7, we summarize the results of the range comparison and show the letter grade resulting from the first four ratings. Here we introduce a weighting factor to indicate our estimate of the relative importance of each of the four grades. In assigning the weighting factor, we were influenced also by our ability to judge range performance on the basis of the data available. This accounts to some extent for the smaller factor associated with cross polarized data and the satellite data. Judging from his specific requirements, the potential range user can, of course, substitute his own weighting factor and may thus see a lower rated range as best choice for his work.

TABLE III-7: RANGE COMPARISON SUMMARY

Range	Facilities Techniques and Procedures	Accuracy		
		Cylinder Data		Satellite Date
		Co-Polarized	Cross Polarized	
CC	B-	D	C	D
RSC	B	B	C	C
GD/FW	B+	C	D	C
RSS	B	C	C	C
MC	B-	D	D	D
Suggested Weighting Factor	2	4	1	2

IV

IDENTIFICATION OF PROBLEM AREAS AND RECOMMENDATIONS FOR IMPROVEMENT

We have had the good fortune of seeing range results coalesce at the Radiation Laboratory preceded by fairly comprehensive reports by Radiation Laboratory engineers who visited the ranges and observed actual measurements. The measurements, and the corroborating trip reports of these engineers, have delineated some distinct problem areas, and in this chapter we summarize our estimation of them and give our suggestions on possible improvements.

First, and foremost, is the problem of the accuracy of the data. Whether it is adequate or deficient depends, of course, upon the data user, but in several instances, it seems deficient. This is particularly true in the case of an object whose return is not easily predictable theoretically. We state that three requirements must be met to minimize measurement errors and much of this chapter is devoted to a discussion of these requirements.

We present additional comments on other problem areas most of which are not closely related to the measurement errors being analyzed here. We discuss cross-polarized measurements, phase measurements, digital recording systems, data display practices, range time estimates and weather problems.

4.1 Measurement Errors

There may be some disagreement on the required degree of accuracy in radar cross section measurements. In considering the present program many users would be satisfied with the accuracy of the data obtained for the cylindrical models if the near field data were excluded. These data, however, may lack the accuracy desired in some applications even when the near field errors are disregarded. The seriousness of the accuracy problem becomes apparent when the satellite data is examined. A sample of this is given in Fig. 4-1 for one angle of incidence. (The polarization and absolute dBsm scale is omitted for security reasons; see Volume IIB for details.) Note that in this sample, the results obtained by different ranges for the same model and frequency differ by as much as 8 dB. Additional errors equal or greater in magnitude are shown in Volume IIb. It is difficult to assign grades to the satellite data because no theoretical analysis is available for complex targets like these to substantiate what the cross sections should be.

Based on these results it is obvious that a careful examination of the cause of measurement errors is needed and, along with this, recommendations should be made how they can be minimized.

Three requirements must be met to insure accurate measurements. They are:

1) Adequate equipment and facilities.
2) The use of proven measurement procedures.
3) Careful, experienced and well-motivated operating personnel.

Let us consider these three requirements.

4.1.1 Equipment and Facilities

It is our opinion that the performance of the equipment and facilities used in these tests proves that accurate measurements can be made and show also that no major deficiency exists in the equipment and facilities except for the cases where there is a near field problem. Evidence of this is seen in Fig. 6-3 of Volume IIa. Note the results for ka = 1.36 involving model lengths of 16, 8, 4 and 2 feet. Five ranges each contributing four measurements participated in this series of tests. All of these 20 datum points agree within ±1 dB of the theory and are consistent among themselves.

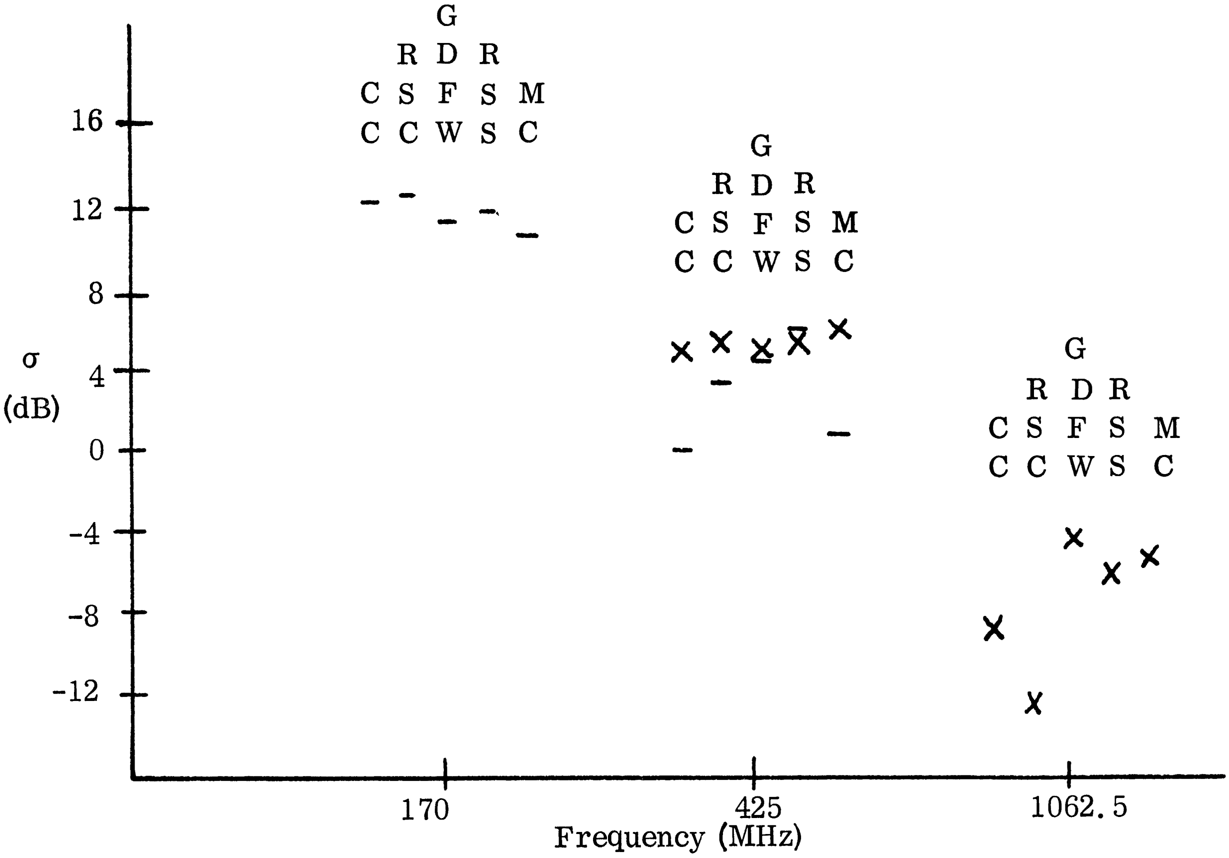

FIG. 4-1: FULL SCALE (—) AND 4/10 SCALE (✕) SATELLITE DATA FOR FIXED ASPECT ANGLE AND POLARIZATION

4.1.1.1 Near Field Measurements. Since the near field problem is the major source of error associated with equipment and facilities we now consider it in some detail. None of the radar cross section ranges measured the largest cylinder at 1360 MHz at the generally accepted distance of $2L^2/\lambda$. We were not told why the required far field criterion was not satisfied, but in some cases it was a problem of receiver sensitivity; in others the fixed pit locations limited the range and in a few cases it appeared to be just a matter of indifference to recommended procedures.

As range is decreased from the standard $2L^2/\lambda$ the first effect to be noticed is that the nulls begin to fill in, especially the first nulls off broadside. All the nulls of the pattern become shallow, but since pattern levels are low for intermediate aspect angles, the effect is often not noticeable. As range is decreased further, the sharp broadside lobe becomes wider and eventually splits into two or more perturbations superimposed over a broad variation of the pattern. The magnitude of the return decreases at the same time. By this time, the first and second, and possibly third, nulls off broadside have completely disappeared and even the returns at intermediate aspects are affected in some measure. Finally, if the range is decreased enough, the broadside echo drops below that of end-on for the cylinder patterns.

Near field measurements are more often encountered at CW radar cross section ranges than at pulsed ranges. This is due in part to the relatively low power levels that are available in CW sources. Even if the higher power were available, the poor isolation between transmitted and received signals could be a problem. Good isolation is possible in a pulsed system because there is no transmission during reception but CW systems depend on cancellation schemes to achieve isolation and these are highly dependent on frequency stability. Pulsed systems have another major advantage, when long ranges are involved, in their ability to gate out all unwanted foreground and background reflections except those near the target. For these reasons pulsed systems are much better than CW for making cross section measurements of large targets. This fact was pointed out in the first comprehensive study made of cross section measurement techniques (Fails and Fubini, 1949).

In discussing the limitations of CW ranges for measuring large targets at higher frequencies one should note that the CW system has advantages in other situations. Many present day targets are small and have extremely low radar cross sections. For sensitivity reasons it is important to work at the minimum range consistent with far field requirements. Ranges as short as 10 to 20 feet may be suitable and these are easily achievable for CW systems. The minimum range for pulsed systems is limited by the receiver recovery time and in most cases it is well in excess of the above figures. As noted above, with a pulsed system it is possible to gate out unwanted reflections except those near the target. In a CW system when working at close ranges, reflections from the pedestal and those near the target will tend to be of most concern. An inherent characteristic of the CW system is its ability to cancel out such reflections. A phase coherent pulsed system is also able to cancel out these reflections but only a few such systems exist.

One recommended cure for the near field problem is quite straightforward: namely, design the equipment and range so that the target can always be in the far field. There is no simple rule that relates range length deficiencies to cross section error since this is a function of the target. The $2L^2/\lambda$ distance is adequate or more than adequate in most cases. For a complete discussion of this question see, for example, Kouyoumjian and Peters (1965).

Another recommendation should be considered since, even though the above solution is straightforward, it is not always practical to operate at $2L^2/\lambda$. It is easy to see that the $2L^2/\lambda$ rapidly becomes inconveniently large ($\sim$ 38 miles) when the cross section of a 100' airplane at X-band (λ = 0.1ft) is needed. A range of almost 4 miles is needed even if a 1/10 scale model and a λ of 3 mm is used. To help find a solution to this problem, an intensive study should be made to find an accurate method of transforming near field measurements to far field results. Some work has been done on this problem, (see, for example, Kay (1954) and Crispin and Siegel (1968)).

To summarize with respect to the first requirement, we believe it has been adequately demonstrated that the equipment and facility are sufficient to insure satisfactory accuracy if proper procedures are followed. Further comments will be made on the equipment in a later section but the points to be discussed are not closely related to measurement errors.

4.1.2 Measurement Procedures

Any outline of procedures is subject to modification to better fit the characteristics of a particular range or measurement problem. Admitting this limitation, it is believed that the following outline will help reduce measurement errors.

4.1.2.1 The Transmitter. Whether CW or pulsed, the transmitted signal should be stable in amplitude and free from signals of spurious frequencies. The source must be stable in frequency and this requirement is particularly important for the CW system since to a large extent it determines the degree and the duration of the balance or isolation in the system. The required isolation is a function of the target cross section and range and typical numbers range from 90 to 115 dB; a frequency stability of one part in 10^7 or better is needed.

Sources with even higher frequency stability are needed in pulsed systems employing phase coherence. Phase coherence has been incorporated into pulsed systems (e.g. GD/FW and part of the RAT SCAT system) for the measurement of phase and to help cancel unwanted reflections emanating from within the range gate.

Use should be made of an oscilliscope or spectrum analyzer to be sure that the transmitted spectrum is up to specifications. This, together with a check of the frequency and amplitude stability and the absolute level of the transmitted power will in general be sufficient to insure the satisfactory performance of the transmitter. The frequency and power stability should be monitored prior to the beginning of a series of runs for a time period equal to twice that of a normal run. A good check is to retrace the second pattern over the first. If there is a close overlay, one thus obtains a check of the stability of the entire system. In recording any 360^o pattern, the operator has an opportunity to check stability by noting whether or not the starting and stopping point (e.g. $\pm$ 180^o) coincide to within 1/4 dB or so. If not the pattern should not be accepted. It is a useful practice to have the scope or spectrum analyzer and a frequency meter or counter available to continuously monitor the power level, the signal spectrum and the frequency of a sample of the transmitted power.

Except for isolated instances where components failed, the transmitters caused little trouble in this series of measurements; the transmitters are not a likely source of significant measurement errors.

4.1.2.2 Receiving and Analog Recording System. The receiver must have the required sensitivity, stability and linearity. The receivers and recorders used on present day ranges are commonly comprised of a superheterodyne receiver and a Scientific Atlanta rectangular recorder such as their model 1520. For the receiver itself, use is made of custom-made equipment or one of the Scientific Atlanta series 1600 receivers or modifications thereof. These receivers have a sensitivity ranging from -95 to -110 dBsm for the frequency range involved in these tests and this is comparable to the sensitivity of the receivers specially designed for the pulsed transmitters. The receiver-recorder systems have a dynamic range usually selectable at 40, 50 or 60 dB and they are rated to be linear in dB to ± 1/4 dB.

The following checks should be made at the start of each series of runs or when poor performance occurs.

a) Check the stability of the receiver -- this will ordinarily be done along with the stability check of the transmitter unless separate checks are found necessary.

b) Determine the sensitivity; a value below the rated level is an indication of a malfunction in the system.

c) Check the response of the recorder servoloops that operate the pen and the chart azimuth motion. Amplitude errors are caused both by a sluggish as well as by a too tight control.

d) Check the linearity of the receiver-recorder combination. This can be done with a signal generator or by the use of a precision rf attenuator when receiving a signal from a large cross section target. It is reasonable to demand linearity good to within $\pm$ 1/4 dB over the dynamic range being used. If there is a problem, separate checks of the receiver and recorder should be made.

e) To the extent possible, check to see that the digital system is operating satisfactorily. This will be discussed further in a later section.

f) For those ranges where phase is measured, the associated receiving and recording system should be checked for linearity. Use may be made of a calibrated phase shifter. For a more complete check, the phase of a rotating off—center sphere may be recorded and checked against theory.

g) The synchronization between turntable position and recorded azimuth angle should be within $\pm 0.10^{\circ}$; an occasional check should be made.

With a reasonable amount of care and attention, the receiver-recorder system should not be a source of error. We have seen no indication that it was a source of error in this series of measurements.

4.1.2.3 Turntable and Model Support. The turntable should be capable of supporting the weight and lateral stress imposed by the target and supporting structure with azimuth and elevation deflections no greater than $\pm 0.1^{\circ}$ whether at rest or while rotating. In order to provide for guys when needed, the diameter of the rotating table should be an appreciable fraction of the target length. Along with the requirement for size and rigidity, there is a need for minimum RCS. This is accomplished by the use of an absorber covered turntable level with or below the surface of the ground. Even so, it is frequently necessary to cover exposed parts with radar absorbing material (RAM). This will be mentioned again as we discuss background. It is fortunate that with the typical ground plane system the turntable is not illuminated as strongly as the target. The axis of rotation of the turntable must be adjustable. In general, it must be tilted toward the antenna so that it will be perpendicular to the effective center of radiation.

When the target and frequency are known, the range distance, R, is selected according to the far field requirement and the proposed target height, h_t, is selected according to the equation

$$h_t = \frac{R\lambda}{4h_a}$$

where h_a is the antenna height, λ is the wavelength and the geometry is shown in Fig. 2-1. The quantity, h_t, is subject to further considerations depending upon the field probe to be described in the next section. Assuming the correct h_t is known, the model support must be chosen so that it is sturdy enough to provide secure support for the model but small enough and so shaped that its RCS will be 30 dB (hopefully) below the significant cross section values to be measured. Supports are generally made of styrofoam or Pelaspan but in some cases where h_t and λ are large, fiberglass tubes are used.

It is desired also that the area of contact between the target and pedestal be a minimum to avoid undesired coupling. This can be accomplished by tapering the column to a smaller diameter at the top or by the use of "fingers" which make contact with the target. By coupling we refer to the interaction between the target and the support. It has been shown that the RCS of a long target can be significantly effected when there is opportunity for a strong surface wave to be propagated in the foam structure adjacent to the model (Senior and Knott, 1964). Ordinarily the supports are symmetrical about the axis of rotation but where low cross section shapes are being measured and where it is more important to have an accurate reading on the low part of the RCS pattern (e.g. the nose region of a re-entry vehicle) asymmetrical supports are used. This may be accomplished by tilting the column or by shaping its cross section to provide a lower than average return in the low RCS part of the pattern to be measured.

The final selection of the support is dependent on its performance when the background checks are made.

Based on the generally satisfactory background levels that were measured with the supports in position we conclude that the supports did not significantly contribute to measurement errors. The background measurements would not include possible coupling effects. With a large RCS target and relatively small support columns we believe this would also be insignificant.

4.1.2.4 Field Probe. The field probe is one of the most important checks associated with RCS measurements RCS measurements are based on the assumption that the model is illuminated by a plane wave. Since this occurs only in free space and at infinity we must settle for an approximate plane wave condition. At a distance of $2L^2/\lambda$, the approximation is considered to be sufficiently good barring perturbations due to the intervening ground or other scatterers. Since the effect of the ground and other scatterers can not always be accurately predicted they must be measured. Experience has shown that for the ground plane geometry it is generally possible to predict the azimuth field with some accuracy but the ground constants and their effect are not sufficiently well known to allow a reliable prediction of the elevation pattern except for its general shape.

Once the tentative target height is selected, the antenna(s) whose height has already been selected, is adjusted in azimuth and elevation for maximum signal at the point to be occupied by the center of the target. The field strength is then measured on a vertical line through the target center. If the target center does not coincide with the peak illumination, the support column height is changed or the antenna is adjusted and the vertical field is again probed. When the height is finally selected, a more thorough field mapping is needed to be sure that the field is uniform over the volume to be occupied by the model. This is accomplished by moving a small antenna vertically at selected (10 or so) stations along the horizontal axis of the model. This is the line that would coincide with the axis of the model if it were on the support with its horizontal axis in the broadside position. The horn is ordinarily moved by a pulley arrangement in a framework provided for this purpose and the signal received is recorded by hand or plotted automatically. In place of the receiving antenna probe, some ranges use a sphere and the two way signal strength is measured. Some ranges are accustomed to probing the horizontal field by rotating a sphere on the turntable at the proper height with the sphere several feet off center. This is adequate only if it covered the entire field of interest. Since the reflection coefficient of the ground varies with polarization it is important to probe the field with both vertical and horizontal polarization. The uniformity of the far field power level is advertized by some ranges to be

± 0.5 dB. over the volume to be occupied by the model. With this degree of uniformity it is not likely that errors in RCS measurements of the model would exceed 1.0 dB. The error could be zero if the average illumination level over the illuminated portion of the model for all aspects was zero dB and if the calibration sphere had an average illumination of the same value. It should be noted, however, that field probes showed variations up to 1 dB for one range and up to 2 dB for another. Moreover in most cases the field was not probed as a function of range from the point occupied by the center of the model. The importance of this had not occurred to us until recently. Assume the 32 foot cylinder is being viewed end-on. It appears that we have no information on the average illumination over the 5 foot diameter circle occupied by the end of the cylinder and this illumination determines almost completely the end-on RCS. This cross section is calibrated against a sphere which would be located 16 feet down range from the end of the cylinder viewed end-on.

Traditionally we have not been much concerned about this; in a "free space" range the relative power (round trip) is proportional to $1/R^4$ and when R is very large compared to the model length this factor is insignificant. It is not completely insignificant for a 32 foot model at a 200 ft range as was used by Conductron. The $1/R^4$ effect over half the model length amounts to about 1.4 dB. We are more concerned, however, about the behavior of the field in the range direction where the ground plane geometry is involved. It is easy to suspect that the field variations at the position occupied by the cylinder end might be as large or perhaps much larger than those found elsewhere. End-on illumination is not likely to average out to equal the illumination on the calibration sphere partly because of the $1/R^4$ effect.

We think this may account for the fact that there are greater discrepancies in end-on values than in the broadside values. We note also that Micronetics, which has the nearest approximation to a free space range, had the best results for their end-on values. From Table VI-1 of Volume IIa it is seen that 92 percent of their end-on returns were within 1 dB of theory. The corresponding average for the other 4 ranges is 68 percent. Conductron whose end-on illumination may have suffered both due to the ground plane geometry and the $1/R^4$ effect had only 47 percent of its values within 1 dB of the theoretical prediction.

In summary, we recommend that the usual procedures for probing the field be carefully followed. It should include vertical and horizontal coverage for all polarizations to be involved and it should cover the volume to be occupied by the model -- not only for the broadside but also for the end-on position. A field uniform to within ± 0.5 dB is a desired objective but for large targets this may not be achievable. It is important that significant deviations in excess of 1/2 dB be noted in the pattern log, especially if an area large enough to illuminate an important scattering center is involved.

4.1.2.5 Background Evaluation. After the field probing is complete, with the selected model in place and the transmitter, receiver and recording systems properly operating, the turntable should be rotated to determine the contribution due to the background. For this test the CW system will be tuned to minimize the background contributions. In the pulsed system, all reflections outside the range gate will be largely excluded. The background return will be plotted on the recorder and calibrated in terms of dBsm. The acceptable background level is dependent on the accuracy required. It introduces errors by adding in or out of phase with the desired signal. The upper and lower limits of the error are plotted in several references, see for example Fig. 3 of Blacksmith et al (1965). A background of -20 dB may cause errors of about ± 0.9 dB while the maximum error for a -30 dB background is less than 1/2 dB. If the background is not sufficiently low a search should be made to determine the cause. Any extraneous scatterers should be removed. For a CW system this includes any scatterers illuminated by the antenna; for a pulsed system scatterers in the range gate should be removed or covered with RAM. If this does not reduce the background sufficiently, the target support might be temporarily removed, if this is feasible. This move will indicate whether or not the support column is satisfactory. For low cross section measurements, the return from a styrofoam column can be considerably decreased for a spot frequency by adjusting, or tuning its diameter (Senior et al, 1964). If further adjustments are needed, a careful examination of the turntable is in order. Additional RAM or improved RAM should be added to cover exposed areas. If a RAM covered barrier is being used, a minor adjustment in its position may be needed.

Once the background is properly cleaned up, further changes should not be necessary until a frequency change or some change in the physical set up is made, but background checks should be made several times each day. For a CW system, checks are made after each pattern.

In the present series of measurements, the background was not high enough to cause errors of more than 1/2 dB in the broadside and end-on returns. This is based on a background -25 dB below the end-on return. More typical values are -35 dB. One exception to this should be noted. At GD/FW, the interference due to an outside electronic source was particularly troublesome at 170 MHz. It was erratic in time and amplitude but was frequently high enough to add spikes to the patterns submitted. A number of reruns were made in hopes of obtaining a clean pattern. This interference was troublesome but easily recognizable; it did not add to the tabulated measurement errors.

At this point it is important to note another possible source of error. It is related to background but would not be measured in the background tests just described. We refer to secondary reflections which strike nearby scatterers before or after being reflected by the target. If scattered towards the receiving antenna, these will cause errors in measured RCS values. Rays being scattered as intended by the "mid-area" in the ground plane geometry are, of course, not to be considered here.

Scatterers most likely to cause trouble might be the edges of the turntable pit or nearby rough areas on the ground. These will be more strongly illuminated where frequencies and targets combine to form low ka or kℓ conditions thus resulting in wide beam scattering from the target. In the present series this might be expected to cause more trouble when the 16 foot cylinder is measured at 170 MHz and perhaps with the 8 foot and 4 foot models at 340 and 680 MHz since for these cases ka is small and the antenna beamwidth tends to broaden. It is not feasable to predict the effect of this secondary scattering and since it will not be detected in the standard background checks, another test is needed. A rotating off-center sphere will give some clue to the presence of secondary reflections but this will not be quantitative since the sphere scattering pattern will differ from that of the model. The nose rock test commonly used in anechoic room RCS measurements and used by Conductron on its outdoor range would indicate more specifically whether or not secondary reflections were effecting the RCS of the model being measured. This consists of moving the target toward or away from the antenna with the target on the support and rotated to the aspect of interest. A movement of a wavelength or so is needed to allow for the in-phase and out-of-phase addition of the contribution of the unwanted scatterer. Zero change in the RCS value shows that there is no problem. An alternate method is to run the pattern at ranges R, $R + \lambda/4$ and $R + \lambda/2$. If secondary reflections are indicated they should be eliminated or their presence and the extent of their contribution should be noted. Changes which may remove secondary reflections include small change of height, variations and the adjustment or addition of RAM and (of course) the removal of any suspect scatterers.

Judging from the data it is not possible to prove or disprove that RCS errors were caused by secondary reflections. Since the measurement errors are more pronounced for low ka and low frequency tests there is good reason to suspect that secondary reflections were a contributor. Our only data which includes results at range R and R + $\lambda/4$ is from Conductron for the 2 foot cylinder at 2720 MHz for VV and HH. See Fig. 4-2 for the VV patterns. The differences in RCS for the two ranges are less than 0.2 dB for broadside and end-on values. The variation amounts to 1 dB in the first end-on side lobe for VV. In this test ka = 2.72, so we are not dealing with our smallest ka value; this and the high frequency would lead us to expect only minor errors from secondary reflections. It indicates, we think, the likelihood of more pronounced effects under less favorable conditions suggested above.

For those ranges that can not move their turn table in range, an alternative is to move the model longitudinally on its support. This can give the desired R + $\lambda/4$ change for near nose-on and tail-on aspects but it will have little effect on the broadside aspects. It will, however, help also to indicate the presence or absence of coupling with the support which we mentioned in 4.1.2.3.

4.1.2.6. Calibration Procedures. The commonly accepted method of determining the absolute level of a scattering pattern is to compare its return with that of a standard scatterer. The preferred standard scatterer is the precision sphere since it presents no orientation problems and its RCS has been accurately calculated. In most ranges where pulsed systems are used the calibration is accomplished before the pattern is run. A

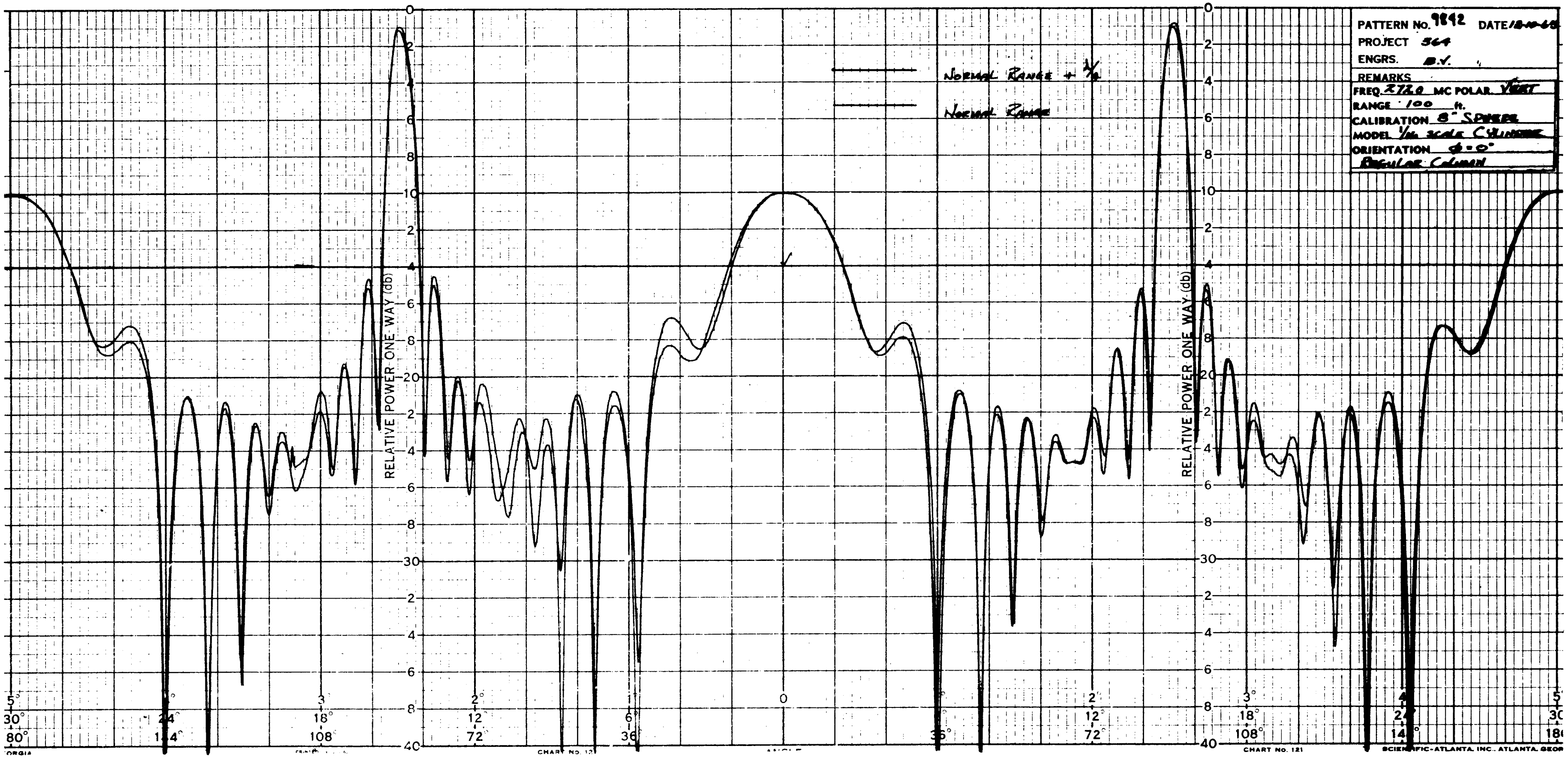

FIG. 4-2: RCS PATTERN FOR TWO FOOT CYLINDER, 2720 MHz ,VV POLARIZATION , FROM CONDUCTRON CORPORATION RANGE. Shows effect of secondary reflections.

suitable sphere, preferably one with an RCS within 10 dB or so of the target's average cross section is placed on the support column and the receiver gain is usually adjusted so that 0 or some multiple of 10 dBsm coincides with a 10 dB line on the pattern paper. At the start of a series of runs, it is advisable to use two or three standard spheres selected so that their returns are well distributed in the dB range of the pattern to be recorded. This not only provides a second check on the linearity of the system but it also checks range performance for different scattering patterns. On CW ranges the procedure is essentially the same except that the calibration is more commonly done after the pattern is run.

Some pulse ranges, use a secondary or transfer standard located outside the range gate that contains the target. By calibrating the transfer standard in dBsm, the system can be checked before and after each pattern simply by moving the range gate. A recheck should be made with the sphere after several hours or several patterns. If the sphere and secondary standard do not recheck, the patterns taken since the previous sphere calibrations should be invalidated.

Cross polarized patterns must be calibrated by other means since a sphere theoretically has no cross polarized return. This will be discussed in more detail in Section 4.2.1; briefly however, the cross polarized pattern may be calibrated against the co-polarized (HH or VV) return of a sphere or against the return of a 45° inclined wire. For a 45° inclined wire the return for VV, HH, HV and VH are equal.

If 1 dB accuracy is required, we believe a more elaborate type of standard is needed in many cases. As has been stated above, the measurement errors on the satellite models were large, much higher than for the cylinders. We have concluded that most range operators will stay with a model until they measure an accurate scattering pattern providing they have reliable information on the true pattern. The accurate pattern is obtained by removing effects about the range or the equipment that contribute to error until the desired accuracy is obtained. This is not possible when working with a satellite or similar complex model since its scattering characteristics can not be predicted accurately. Even if all the above guide lines are carefully followed, one would have no way of knowing that his results were correct. To help improve this situation it is proposed that a series of standard scatterers be developed that tend to approximate typical targets being measured. Closed circular cylinders would be appropriate for satellite models for example. Two should be used, so chosen that they would bracket the target return with an upper and lower bound.

The procedure might be as follows: Carefully perform all of the range checks then measure the pattern of one of the cylinders whose end-on and broadside values are known. If the test cylinder doesn't perform according to theoretical predictions, start over again and repeat until a good pattern is obtained from the first cylinder. As a further check on the facility and procedures, measure the second cylinder. If this does not check according to theoretical predictions find the reason and repeat until the correct patterns can be obtained from the two cylinders one after the other.

The complex (satellite) model should now be measured using all the care exercised on the cylinders. Additional patterns should be taken until it is demonstrated that a satisfactory repeat pattern can be taken after the model has been removed and replaced on the support column. If this proves to be difficult due to sensitivity to frequency, roll or pitch alignment, a study should be made to determine the degree of sensitivity to these factors. Proper control of the factors causing the sensitivity should then make it possible to produce the desired repeat pattern. Following this, one of the two standard cylinders should be run again. With this procedure one should be able to state that the satellite pattern was as nearly correct as the final repeat pattern on the cylinder. If the cylinder pattern did not repeat sufficiently well, all or part of the process should be repeated until a satisfactory check pattern is obtained.

It is obvious that this procedure will be time consuming and costly but it should produce patterns of unknown scatterers to which a reliable confidence rating can be assigned. It is recognized that the intended use of scattering data does not, in many cases, require the accuracy that would result from this costly procedure. Based on a "cost effectiveness" philosophy the user of the scattering data must decide how many dollars he is able to spend to achieve a given degree of accuracy.

4.1.2.7 Preliminary Analysis of Data. Before they are released, all data should be reviewed by a qualified analyst experienced in RCS analysis and familiar with experimental procedures as well. The average range operator can be expected to determine if a pattern is acceptable from the standpoint of background noise, pattern symmetry, apparent calibration accuracy and repeatability, but in many cases he will not be able to make a very accurate prediction of the expected scattering pattern. We believe that the cylinder data obtained in this program benefited from this type of preliminary analysis and such an analysis should probably be done by a man who, to some extent, acts as an inspector. He should be a little apart from the operating crew and willing to take a purely objective point of view in deciding if data is acceptable.

4.1.3 The Range Crew

We stated earlier that to insure accurate RCS measurements, the requirements included adequate equipment and facilities, proven measurement procedures and a careful, experienced, well-motivated range crew. We feel that this third requirement is an important as the other two but once this is recognized and acknowledged, little more needs to be said. Some range operators say that there is still some "black magic" in the art of producing good patterns. This may be true to some extent - an operator will learn the fine points about the equipment and procedures only by experience with the system.

The need for careful and dedicated workers is obvious. We believe that they require a good understanding of the users' requirements, and where feasible, a knowledge of the ultimate use of the data. This may help to solve another problem; too often a user will ask for measurements or accuracy that he doesn't need. A detailed discussion between a technical man representing the user and the range operator and the analyst will help to eliminate confusion and delineate the more important aspects of the requirements. Such procedures will help to maintain the needed motivation of the range operators.

4.2 Other Problem Areas

In this section we review other problems which became apparent during the program. Some deserve early attention, some are in the nuisance category and some, such as the weather problem, we can't do much about.

4.2.1 Cross Polarized Measurements

Some of the ranges were well prepared for cross polarized measurements while others had to do some homework. It can be shown that the cross polarized return from a perfectly conducting right circular cylinder is zero if measured in a principal plane, but none of the data produced by the ranges approached this. One can argue that the support column, ground reflections, and imperfect models have some depolarizing effect and hence contribute to a cross polarized return, but we feel it is the impurity of the illuminating wave that causes most of the trouble. We are told by antenna experts that even good pyramidal horns emit a cross polarized component that is down only 30 dB or so from the dominant polarization. Even if a perfect feed (ellipticity of zero) horn is used with a parabolic dish, the reflecting surface, as well as the feed support struts, will cause some depolarization. It is not surprising, then, that most of the cross polarized patterns are near facsimiles of HH or VV patterns, or possibly combinations of both. The cross polarized data are analyzed in Volume II-a and we concluded there that the purity, or ellipticity of the transmitted wave, was no better than 20 to 30 dB for most radar cross section ranges.

A study should be made to determine how much isolation is needed between the direct and cross polarized radiation to obtain satisfactory results for most practical cases. For cylinders and principal plane patterns, 30 dB is not enough to produce the expected random pattern. It might, however, be enough for targets having a large amount of cross polarized return. The fact that General Dynamics/Fort Worth have been able to use its cross-polarized data and scattering matrix techniques to calculate scattering data for new polarizations (later verified experimentally) is evidence that their cross polarized data is accurate enough.

Once we learn the amount of needed isolation, the factors contributing to the inferior isolation should be determined and appropriate remedies could then be made. One possible remedy would be to add polarization gratings to the antenna aperture to screen out the unwanted polarization. When the antenna problem is solved, attention should then be given to the range. It is quite likely that the ground plane range and possibly the pedestal add considerably to the cross polarized return. Perhaps the following test has been made, but if not, it would be informative to do the following. With a good linearly polarized pick up antenna in free space and in the far field, measure the polarization ellipticity from the transmitting antenna. Then make the same measurement with the pick up antenna at the target location on the ground plane range. If the results differ, a study should be made to eliminate this effect of the ground plane if possible.

4.2.2 Phase Measurements

Up to now, little has been said about phase measurements. As was stated in the original University of Michigan proposal, we planned to make little or no use of the phase data in our evaluation of the ranges. As a matter of fact, we have made no use of the phase data. This is partly because only two ranges were able to provide phase data and then for only part of the frequencies. It is difficult or impossible to make good use of phase data unless it is properly calibrated against a reference point that can be identified. From what we have been able to determine and from informal conversations with General

Dynamics/Fort Worth personnel, the phase data they provided were not adequately calibrated. RAT SCAT submitted phase data for the 32' and 16' cylinder at 1360 MHz only.

Despite this we consider it very important that the major ranges have the ability to provide phase data over a wide frequency range. The need for phase data is well known. The primary requirement for phase data is in the measurement of the scattering matrix. Scattering matrix data have 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 measurement equipment becomes more fully automatic. The most important use for scattering matrix data is in the identification of radar targets. Considerable efforts are being made to solve the inverse scattering problem and part of this effort is concerned with scattering matrix measurements. Scattering matrix data can also be used to calculate cross section data when information for many polarizations is required.

Phase data are also of use in the vector subtraction method that has been used to cancel out target support contributions. Another potential use for phase data may be in the solution of the far-field requirement problem. Phase data provide an additional parameter which may prove important in the derivation of far field measurements when only near field data is available.

4.2.3 Digital Recording Systems

Three kinds of digital recording systems were used at the various ranges to provide stored digital data for use in data analysis or for reproducing the analog patterns. Three ranges used punched paper tape, one used punched cards, and one used magnetic tape (see Table II-1). The punched cards were the slowest (since a pattern can be run no faster than the data can be punched on the cards) and they occasionally contained punching errors that had to be manually corrected later. The cards can be processed by computer directly. Punched paper tape was not much faster than the cards, but suffered serious problems due to frequent breaking. The paper tape often broke during recording as well as during the later read-out of the stored information. Magnetic tape was the fastest since the rate of information storage is very high, and patterns could be obtained rapidly as the range crews felt was physically safe for the targets installed on the pedestal. In earlier installations, paper tape systems may well have been the best means of obtaining digital data but with the proven superiority of magnetic tape a change to it is in order. In addition, the Air Force should determine the preferred data format and advise all ranges accordingly.

Another problem with digital data became obvious during the program. There are few opportunities for the range operator to adequately check the performance of the digital equipment. From time to time his data may be checked out by others at the computing center but this will generally occur too late for the range operator to correct any errors that may exist. Equipment should be readily available at the range to allow frequent checks of the accuracy and adequacy of the digital data. The analog output of the D to A converter should be on a scale identical to that of the original analog pattern to allow for quick checks by the use of overlays.

4.2.4 Data Display.

Data users can be classified into two groups: those who roll up their sleeves and work with cross section patterns, reading off amplitudes to the nearest tenth of a decibel and positions to the nearest 1/2 degree; and those who make only a cursory inspection of a pattern, noticing amplitudes to the decibel or two and positions within five degrees. Data users of the first kind are particularly keen on detail and would prefer to use original patterns to work with while those of the second kind look for gross effects and leave the details to users of the first kind. There are many more of the latter than the former.

A typical raw analog pattern is of the order of 11" x 20" in size and may have 40, 50, or 60 dB full scale amplitude range. To include such a pattern in a report means that it must either be photographically reduced in size by about 50 percent, or that the final report be in two separate volumes (one part being the text printed on standard 8 1/2 x 11 paper; the other being the 11 x 20 patterns), or that the patterns be included in the standard size report as foldouts. None of these solutions is ideal.

Our solution is to have the recording equipment modified to produce not only its regular size patterns but also patterns whose overall size is about 5 x 9 inches. Such a pattern could be read with nearly the same precision as the present sizes are and it would be far easier to reproduce. When there is a particular concern for detail, the larger patterns could still be used.

Another small, but annoying, problem is the lack of standard sizes of chart paper grids. This is not ordinarily a problem, but in our investigation many inter-range comparisons had to be made which could not be simply done because of the variety of amplitude scales used by the five radar cross section ranges. This variation is illustrated in Table IV-1, in which we have compared the amplitudes of the various range patterns' scales. The full scale amplitude range of the chart paper in all cases covered 9 7/8 inches; this makes more sense when one realizes it is precisely 25 centimeters. Here we recommend that a standard be established so that all 40 dB paper has the same grid size; similarly for 50 dB and 60 dB paper. In an evaluation such as ours, it would make sense to insist that all ranges supply their data on identical chart paper.

TABLE IV-1: COMPARISON OF RANGE PATTERN SCALES.

Range	Full Scale Pattern Deflection (dB)	Smallest Division (dB)
Conductron	40	1. 0
Radiation Services	40	0. 5
General Dynamics/FW	50	0. 5
Micronetics	40	1. 0
RAT SCAT	50	0. 5

Finally, with regard to data display, there is a small problem that CW ranges experience in post-calibration. It is tradition at CW ranges that the calibration standard is installed or measured after the pattern of the desired target has been measured and this calibration level generally does not coincide with any convenient amplitude scale on the chart. The ranges using pulsed systems, on the other hand, pre-calibrate their patterns and thus assign convenient amplitudes to the scale printed on the chart. This makes it easy to read values off the pattern in dBsm, or any other desired unit, with scarcely any effort. The post-calibration technique, on the other hand, requires that the cross section of the calibration target be first ascertained and this rarely turns out to be a convenient number, either in dBsm or dB λ^2 , and then the difference between its level and an amplitude on the pattern must be counted relative to the calibration level.

The solution is obvious. CW ranges could, if they desired, pre-calibrate their data like the pulsed ranges do. The two measurements (of the target and of the calibrator) take place next to each other, in time, and it matters little which is done first. In fact, patterns could be both pre- and post-calibrated at CW ranges. The net result is that radar cross section patterns produced at CW ranges would be much more readable.

4.2.5 Underestimating Range Time.

In the summer of 1965 we solicited the five cross section ranges for quotations and the particulars of their responses are shown in Table IV-2. The measurement times seemed reasonable, although GD/FW and MC required a full four to eight weeks more than the other ranges. It should be noted that the measurements to be provided for the quotations were not the same for each range. Most of the ranges declined to bid on phase measurements while others could not provide cross polarized data at certain frequencies. Table IV-2 is intended only to show the original estimates of range time according to the preliminary quotes submitted to us.

Note that we have included the lead time each range required in order to prepare for the measurements; this varies from 2 weeks for Conductron to as long as three months for Micronetics . We more or less assumed that the lead time was a negligible factor in the measurements program because we had encountered model procurement delays early in the investigation and had kept the various ranges informed of expected delivery dates for the models. Apparently however, our assumptions were wrong because the measurements at most of the ranges required approximately the sum of estimated measurement time plus estimated lead time.

TABLE IV-2: SUMMARY OF RANGE QUOTATIONS

Range	Lead Time	Measurement Time	Quotation Good For	Cost
Conductron	2 wks	8 wks	--	39, 872
Radiation Serv.	2 mo.	7 wks	45 days	16, 674
General Dyn.	2 mo.	3 mo.	75 days	46, 880
Micronetics	3 mo.	4 mo.	90 days	62, 200*
RAT SCAT	--	6 wks	-	GFE

*The $62, 000 quotation was later revised to $38, 700.

By the beginning of 1967, we had advised the ranges of delays due to model procurement problems and many of them had revised their estimated range time; Conductron held to its 8-week estimate, GD/FW stood by its 13-week estimate, Radiation Services now asked for 13 weeks, Micronetics asked for 16 weeks and RAT SCAT 6 weeks. If we add the lead time originally requested by each range to its revised range time estimate, we obtain the numbers listed in the first column of Table IV-3. The ranges required from 19 to 28 weeks to receive the models, measure them and ship them out again.

TABLE IV-3: REVISED SUMMARY OF RANGE QUOTATIONS

Range	Lead Time + Estimated Range Time (Weeks)	Actual Range Time (Weeks)
Conductron	10	21
Radiation Services	22	21
General Dynamics/FW	22	19
Micronetics	29	26
RAT SCAT	39	28

We hasten to caution the reader against judging the ranges too harshly on the basis of Tables IV-2 and IV-3. It might appear the Conductron and Radiation Services badly underestimated their range times but we believe the 21-weeks they each used does not reflect their true performance. The models dribbled into each range over a 12-week period and it is therefore not entirely their fault that they had the models longer than estimated.

Both General Dynamics/Fort Worth and RAT SCAT, on the other hand, had been informed of measurement progress at preceding ranges and could have been better prepared for measurements when the models finally appeared. Both these organizations waited a full eight weeks after receiving the models before commencing their measurements. General Dynamics discharged its obligations a scant eleven weeks after starting measurements, however, RAT SCAT felt it advisable to release the models to Micronetics long before its measurements were done. Micronetics made a few token measurements after receiving the models but its work was performed in short spurts interrupted by long delays due to weather, equipment trouble and "higher priority" committments.

Twenty-odd weeks seem to be a long time to obtain 92 radar cross section patterns, but this is typically the time we encountered. Had the measurements been of entirely unknown targets (by "unknown" we mean targets whose returns could not have easily been predicted theoretically) the range times might have been much less. Since each cross section range knew it was part of an evaluation program, each probably took much more time than it might have ordinarily.

It is difficult to make a significant recommendation that will help to solve this problem. One might offer a cash incentive for every week a range finishes ahead of a schedule and impose penalties for every week it consumes beyond the promised schedule. To avoid delays due to higher priority measurements, one should make use of ranges with as small a work load as possible, other things being equal. If the need is great enough, the price paid per measurement can be raised to increase the level of competition and the number of ranges .

4.2.6 Weather

We grossly underestimated the effects of weather and apparently so did some of the range operators. Regardless of location or season, the weather was hostile. The wind was the worst offender, since it always threatened to blow the models off their support columns and, in one case, this actually occurred with disastrous results. Conductron's CW system required the quietest of conditions and its work was done almost exclusively at night. General Dynamics/Fort Worth had the boldest operators who even made a few measurements in 15 to 20 knot winds. Yet range managers tend to ignore weather when they bid a job and the evidence lies in the fact that no range completed its work in the time specified in its quotation. Thus, we learned that quoted range time estimates are usually unreliable; models will be detained at a range from a minimum of two weeks to as much as several months longer than specified in an official quotation.

With respect to weather advantages, and range location, we feel that the weather tends to be more adverse at the Conductron range location. To a large extent, however, this was compensated for by the "try harder" attitude of the range personnel as evidenced by the extensive amount of their night work. Poor weather was given as a frequent cause of delay by Radiation Services, RAT SCAT and Micronetics. For this series of measurements, we would rate these locations as nearly equal with respect to time lost due to weather and General Dynamics would receive a slightly higher rating.

Our recommendation in connection with the weather problem is to allow for delays due to weather; a minimum of 25 percent lost time would seem to be a reasonable estimate.

4.3 Summary

In this chapter we have pointed out problem areas, discussed the source of the problems when known and to the extent possible we have made recommendations for solutions. The major problem area is the lack of measurement accuracy. We suggest that accurate measurements can be obtained (1) if one has adequate equipment and facilities, (2), if proven operation procedures are used, and (3) if the range is operated by careful experienced and well motivated personnel. We conclude that the equipment and facilities are adequate except for the near field limitation. We list the major steps to be followed in our suggested measurement procedure, call attention to specific problem areas, and we briefly discuss the importance of a qualified range crew. Other problem areas not so closely related to measurement accuracies are also discussed.

It would be helpful at this point to be able to pinpoint the several problem areas and cite the specific deficiencies at each range that caused their results to be less than perfect. Except for a few instances this can not be done. One of the easiest problems to identify has been mentioned, perhaps too many times. We refer to the near field problem. This problem exists at the Conductron range and it was well recognized by them and it was treated very thoroughly in their report. This limitation, which in their case is difficult to overcome, did not prevent them from producing quite satisfactory data in many of their measurements. Perhaps more to be criticized are those organizations who had long ranges available but still worked at near field distances and turned in some faulty data as a result. Micronetics and to a lesser extent RAT SCAT and Radiation Service measured targets at distances less than L^2/λ when longer distances were available.

Another less critical deficiency that is easy to identify is the pattern errors due to rf interference experienced by GD/FW in its 170 MHz measurements. This, too, is a well recognized problem and errors due to it are easily corrected.

It is not possible, however, to tie down the causes of the bulk of the measurement errors and link the problems to one or more specific range. We believe that the situation is too complex to do this. In our opinion there are two or three probable causes of errors in addition to those just mentioned.

Judging from the random nature of the errors it is quite possible that all the ranges were deficient in one or more ways and these deficiencies could well have varied with model size or frequency.

It is our opinion that most of the errors not already mentioned are due to (1) lack of uniform field, (2) secondary reflections, (3) insufficient attention to test procedural details. The first point was discussed in detail in 4.1.2.4. We show that a field variation of n dB could result in an error of about this magnitude if it happens to occur over much of the position to be occupied by a principal scatterer. To our knowledge few of the range operators examine their field in the target-antenna direction and it is in this direction that errors in this field pattern could be linked directly to changes in the RCS values. This problem could exist on any range but it is more likely to exist on the ground plane ranges than on the Micronetics range.

Secondary reflections, discussed in 4.1.2.5 are a known major source of errors in anechoic room RCS measurements and are almost certain to exist, although to a lesser extent, on outdoor ranges. Evidence of this was cited; its presence is shown by measuring the RCS pattern at two slightly different ranges. Its presence will sometimes (but not always) be indicated by rotating a sphere off center. The common background check where the support column only is rotated will not reveal the effect of secondary scattering. Until proven otherwise, one should assume that all five of the ranges experienced some inaccuraces due to secondary reflections.

We have mentioned also that measurement errors are caused by insufficient attention to test procedural details. Examples of this are seen in Fig. 5-3 of Volume IIa where VV and HH RCS values for end-on aspects are presented. All those involved are aware that the HH and VV values should be equal and yet there are two instances where the values differ by 1.75 dB and another with a difference of 2 dB. Had the operators been aware and concerned about this discrepancy they would have been able to acertain the cause and correct the errors. In the same figure GD/FW submits data which are quite suspect. Its data for the two foot cylinder at 1360 MHz is well below the theoretical value and about 8.5 (rather than 6) dB below its 680 MHz data for this value of ka. Precision cylinders are involved here so the fault cannot be with the models. We believe that these and other inconsistencies which could be pointed out are due to insufficient attention to details that would have become obvious had the operators been more alert.

One further point should be mentioned. The satellite data were considerably poorer than the cylinder data. There is a tendency to claim that this is largely due to imperfect models. It is agreed that the models did not scale as well as desired.

There were, however, two opportunities to compare the full scale and 4/10 scale models at the "same" ka value, namely in the 170/425 MHz and the 425/1062.5 MHz measurements where the first frequency in each case is that used for the full scale model. The differences and similarities which occurred in the first two patterns should have been repeated in the second two patterns. We found a number of inconsistencies in making these comparisons. These data and further discussion is found in Volume IIb of this Final Report.

In Section 4.1.2.6 we discussed calibration procedures at considerable length and suggested that other standard shapes such as cylinders should be used. We think of these auxiliary standards more as a method of checking performance over the entire pattern. We do not question the present calibration procedure for determining the RCS of a target if the system and the range are operating ideally.

V

GUIDE TO THE CHOICE AND UTILIZATION OF RADAR CROSS SECTION MEASUREMENT FACILITIES

As was stated in the introduction, one of the objectives of this study was to provide a guide to optimum utilization of existing radar cross section measurement facilities. We have interpreted this to mean that a guide should be provided for the user or customer who requires the service of a range facility. While we believe that this entire report serves as such a guide, we provide in this chapter a list of guidelines which we think are most pertinent. In most cases we consider these points to be rather obvious and would expect most users to produce a somewhat similar list after a little consideration.

5.1 Guidelines for Range Utilization

5.1.1 Adequacy of Facilities

The user should satisfy himself that the physical facilities are adequate for his needs - check the following points by inspecting the facilities and the results of previous measurements.

a) Be sure that the operating frequencies available at the range include those required in the planned measurements.

b) Polarization capability; some ranges are unable to measure cross polarized return or even co-polarized returns, except for vertical and horizontal planes.

c) Antenna-to-target distance; to date there is no completely satisfactory method for eliminating deficiency in range length. If accuracy is important and good data is required for all aspects, the $2L^2/\lambda$ formula should be applied. The near field effects begin to be intolerable for ranges less than L^2/λ.

d) Signal-to-noise; this is most important for low cross section targets. Transmitter power and receiver sensitivity should be sufficient to prove a 20 dB S/N for critical data points. Expected cross sections and the range distance are, of course, important factors in any S/N computation.

e) Extraneous reflections: The range should be as free as possible of unwanted reflections and means must be available to cancel out or gate out those which do exist. When accurate results are required, tests should be performed to map the field over the volume to be occupied by the target. A "quick and dirty" method for assessing background effects is to note the return of a sphere rotating on the target support in an off-center position. Choose a sphere whose return is less than or comparable to the critical values in the pattern to be measured. See also 4.1.2.4 and 4.1.2.5.

f) Target support: The target support must be designed so as to eliminate the possibility of dropping the model under all reasonable circumstances. Equally important it must not significantly affect the return from the target. This is not a critical problem for the models measured in this series but it is a major problem for low cross section targets and it has been discussed widely in the literature. See, for example, Blacksmith et al, 1965, as well as 4.1.2.3.

g) Calibration standards: The standard procedures for calibrating radar cross section returns are well known, and should be satisfactory for nominal accuracy for co-polarized returns. For measurements where accuracy is of critical importance refer to the discussion in 4.1.2.6. For calibrating cross polarized returns, secondary standards such as a 45^o inclined wire should be used which in turn may be calibrated against the co-polarized return of a sphere.

h) Determine if the analog plots are adequate in dynamic range and angular extent.

i) Digital data: If required, magnetic tape or punch cards are preferable, depending on the user's own read-out equipment. Check to see that amplitude and angle increments are compatible with requirements.

j) Phase measuring capability, if required: Be sure that phase data can be calibrated in a meaningful and usable manner.

5.1.2 Range Personnel

The user should satisfy himself that the range supervisor and operating crew are experienced, competent and concerned about doing a good job. It is advisable for the customer to have an experienced representative on hand at the start of the measurements. A mutual understanding of the objectives and good rapport between the customer and range operators will help ensure a well-motivated crew and more accurate data. It is most desirable that the staff at the range facility include a qualified analyst who is available to answer questions concerning the data. He should examine the data periodically and point out obvious, or even subtle, errors in the measured results.

5.1.3 Costs

Price quotations should be solicited from two or more ranges. Quotations for the measurements involved in this program differed by a factor of 3.7. This factor was later reduced; the highest bidder reduced their quotation by more than 35 percent after a second solicitation. There is by no means a one-to-one relationship between cost and results.

5.1.4 Schedules

If the user has a tight time schedule, he should make a special effort to negotiate an agreement to ensure that the schedule will be met. This procedure will, in most cases, eliminate delays resulting from work on other programs. As a partial protection against delays due to weather, the user can arrange to have his measurements made in that part of the country which traditionally has good weather for the time interval in question.

5.2 Range Selection by a Potential User

Shopping for precisely the "right" radar cross section range to use is much like shopping for a major household appliance. The typical consumer expects the appliance to be durable, perhaps with a life expectancy of 15 years, and he therefore seeks to make as wise a selection as possible. The potential range user has much the same outlook, since he will probably have his target measured only once.

Ideally we would like to present the potential range customer with a survey that tells him precisely which range to use but, because of the limited scope of the contract, we can do so only in general terms. This is because not all the ranges in the United States capable of measuring our targets were included in the investigation and only two basic shapes were used in the study. The reader must bear in mind that our conclusions are valid only for cylindrical or roughly cylindrical targets.

Since the potential user is likely to be interested in range performance for large targets and low frequencies, Table V-1 below has been generated from data evaluated in Volume IIa of the final report. In this table we present the same information in two different matrices. The numbers listed refer to the number of errors one dB or less, as judged by a comparison of theory and experiment, committed by the ranges in their end-on and broadside radar cross section measurements. Note that GD heads the list for the large cylinders, but falls last for small cylinders. Note also that RSC takes first place for the lowest frequency and ties for first place for the highest frequency. The table suggests that GD should be given the task of measuring large cylinders, that any of the other four can handle the smallest cylinders, and that RSC is the choice for both high and low frequencies (but not for all intermediate ones).

TABLE V-1: LIST OF THE NUMBER OF ERRORS 1 dB OR LESS WHEN MEASUREMENTS COMPARED WITH THEORY FOR END-ON AND BROADSIDE. The same data are presented in both halves of the table but are categorized differently in each case.

Cylinder Size (feet) or Frequency (MHz)	CC	RSC	GD	RSS	MC	Total Possible
32	4	9	13	11	8	16
16	8	16	17	15	10	20
8	7	15	13	15	13	16
4	11	12	10	11	10	12
2	8	8	5	8	7	8
170	2	7	4	4	2	8
340	4	10	10	9	6	12
680	12	11	16	14	12	16
1360	11	17	15	18	14	20
2720	9	15	13	15	12	16

Optimum range selection depends a great deal on the kind of information required (for example, amplitude or phase or both), the accuracy demanded, the price the customer is willing to pay, and the delay he will tolerate before he gets his data. Assume, for example, that a satellite target is to be measured at the frequencies spanned in our investigation and that the quality of the ranges has not changed since our targets were measured. By stipulating certain conditions, listed in column 1 of Table V-2 below, we postulate the range selections in column 2, based on our evaluation of range performance.

TABLE V-2: RANGE SELECTION FOR A VARIETY OF REQUIREMENTS. None of the ranges can satisfy all the requirements.

Requirement	Range Selection
RCS amplitude with emphasis on accuracy	RSC, GD, RSS
Amplitude and phase at L-band	GD, RSS
Amplitude and phase at all frequencies	GD
Amplitude at lowest cost	RSC
Amplitude recorded on mag tape	MC
Very large targets	GD
Small targets	CC, RSC, RSS, MC, AL
Low frequencies	RSC

Finally we urge the reader to examine ranges other than those considered in this report. Depending upon the size of his targets and the frequencies of interest, there may be a dozen other ranges capable of performing the measurements. Some range descriptions and points of comparison can be found in Fritsch (1963), Buie and Mills (1963) and in the Radar Reflectivity Measurements Symposium (1964). From these descriptions, one feels that the Boeing (Wichita) and Lockheed ranges could have measured all but the largest cylinder, but these ranges were not specified in our contract.

VI

CONCLUSIONS

In the Introduction, four objectives were listed, the first of which was to evaluate selected radar cross section measurement facilities. We did this in Chapter III based on data and opinions contained therein, and on the more complete data in Volumes IIa and IIb of this Final Report. To obtain an overall performance figure we rated the ranges from A to E for several points of evaluation, but in Chapter III these ratings were grouped into four major areas.

Some of the areas are much more significant than others and it is doubtful if a group of experts would agree on their relative importance. The cost of measurements (Table IV-2) is also significant. A summary of our evaluation is given in Table III-7, which we repeat here. Our own

TABLE III-7: RANGE COMPARISON SUMMARY

Range	Facilities Techniques and Procedures	Accuracy		
		Cylinder Data		Satellite Date
		Co-Polarized	Cross Polarized	
CC	B-	D	C	D
RSC	B	B	C	C
GD/FW	B+	C	D	C
RSS	B	C	C	C
MC	B-	D	D	D
Suggested Weighting Factor	2	4	1	2

estimate of the relative importance of the areas of comparison and our ability to judge based on the data available is indicated by a weighting factor which we introduced into the table. Any potential user should, of course, assign a weighting factor in accordance with the requirements of his particular needs. With certain exceptions such as inability to measure phase or insufficient range, all five of the facilities are able to make the measurements required. If the facilities are adequate, the most important requirements are to exercise extreme care in checking out range characteristics (field probe, background and secondary reflection effects) and the experience, competence and motivation of the personnel involved.

We note that range personnel and management change with time and it may be of interest to point out some of the major changes that have taken place during the three years of this evaluation. Radiation Services Company was sold to Sigma Incorporated by Radiation Incorporated and Micronetics was bought by the Teledyne Company. High level and intermediate management changes have occured at Conductron Corporation, on the range and in the front office. Thus to a certain extent the findings of this investigation are dated,which points out the importance for range users to maintain an up-to-date person-to-person contact with the cross section facilities.

Other objectives were to identify critical problem areas and present plans for their solution. Several problems were cited in Chapter IV and to the extent possible, recommendations were given for their solutions. In examining the data, we are impressed with the evident accuracy of some of the measurements. On the whole, inter-range and intra-range comparisons are good and the theory is supported by the measurements. On the other hand, we find range-to-range deviations greater than 3 dB for some of the cylinder results but, more distressing, are the satellite data in which differences as large as 10 dB exist between the returns from the same model measured at two different ranges. We conclude that a range user cannot expect accurate results for a target whose return cannot be accurately predicted theoretically. The problem of measurement errors was discussed at length in Chapter IV and, briefly, we feel that the customer must insist, with appropriate motivation, on much more care than currently is practiced in following through good measurement procedures. The major steps to be followed in RCS measurements were discussed in 4.1.2 not the least of which is the repetition of measurements to insure higher accuracy, a costly proposition. The customer should ask for all the data, both good and bad, to acquaint himself with the measurement problems and results.

Another critical problem occurs in measurements of large targets with insufficient target distance. This is a well-known problem with a well-known answer but it remained an obvious cause of error in this series of measurements. Aside from the obvious recommendation that all measurements should be made at a distance equal to or reasonably close to $2L^2/\lambda$, two other recommendations are made. A considerable effort should be made to develop much longer ranges at existing or new facilities so that large models can be measured at high microwave frequencies. Second, an effort should be made to exploit, if possible, near field data to produce far field results.

Most ranges are incapable of making phase measurements. As was pointed out in Chapter IV, phase data are needed to calculate scattering matrices, to study discrimination problems, to help eliminate errors in cross section measurements due to the pedestal support, and possibly to help calculate far field data from near field measurements. We recommend that ranges equip themselves for phase measurements as this becomes economically feasible.

Other problems considered in Chapter IV included cross polarization measurements, data display, digital recording techniques, weather problems, and inaccuracies in estimates on measurement schedules.

A problem area which was not discussed since it was not pertinent to this series of measurements, is the inadequate frequency coverage of outdoor ranges measuring large targets. There is a growing interest in radar cross section data just above and in the HF band and although some capabilities exist, they are usually makeshift setups. The difficulties in working at these frequencies are severe and demand careful equipment design.

We saw very little evidence of measurement capabilities at K-band or millimeter wavelengths and there is a need for more and better facilities to accomodate these frequencies. As shown in Chapter IV, millimeter frequencies will be needed for X-band and higher frequency measurements of large models. We believe that the RAT SCAT range at least should be equipped to make measurements at long ranges at these frequencies.

Another objective was to provide a guide to the selection and optimum utilization of radar cross section measurement facilities. It is felt that this information is contained in all parts of this report . To set them out more clearly, however, they are listed in Chapter V separately.

With the responsibility for evaluating these five radar cross section ranges, we play the part of the umpire and have been, perhaps, supercritical. In order to make comparisons we have used a more precise yardstick than is generally required. Most of the data would be considered satisfactory for a majority of applications and we emphasize that the ranges were asked to participate in these tests with as is facilities. They were not to make additions or modifications in order to increase their ability with respect to frequency coverage, cross polarized measurements, phase measurements or digital records. Ranges which had some problems with these measurements may well be able to provide more accurate data in other measurements.

VII

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APPENDIX I

INTERPRETATION OF SCATTERING PHASE MEASUREMENTS

Introduction

This appendix contains a discussion of scattering phase measurements in terms of (1) the physical significance of scattering phase, (2) the relationship between measured phase and target geometry, (3) the removal of phase terms resulting from the reference phase center being different than the target rotational center, and (4) applications of scattering phase measurements.

Scattering phase measurements are routinely measured in conjunction with cross section measurements throughout all bands of operation of the range radars at the Fort Worth facility of General Dynamics. The interpretation of phase data in some cases is indeed difficult, however, in many cases a simple position error of much less than a wavelength may introduce a non-linear component of phase which can virtually mask the actual target phase if the effect of the undesired term is not removed.

As a result of the extensive set of phase measurements which were obtained for RADC under Contract AF30(602)-67-C-0074, the Fort Worth Division has established criteria which result in minimizing the apparent anomolies observable in phase data. The removal of these apparent anomolies has resulted in a significantly better understanding of the physical significance of phase data.

ANALYSIS OF SCATTERING PHASE DATA

In general, the amplitude of the energy scattered from a scattering center is sensitive to the polarization of the incident wave. This fact can be demonstrated through the use of the plots contain in Figure 1 which is reproduced from Reference 1. Examination of these two plots reveals that the shape of the curve of σ_1 versus aspect angle is essentially the same at both vertical and horizontal polarizations. However, in the case of vertical polarication it is observed that the magnitudes of σ_2 and σ_3 differ by many dB except near $\theta = 45$ degrees where they are both about 17 dB below σ_1. Thus, in the case of vertical polarization, the scattering from scattering center S_1, is dominant except in the regions near end on and broadside. Note, however, that near end-on S_1 and S_3 are quite close together - relative to their separation along the RLOS - so that the location of the phase center must always be somewhere on the end of the cylinder in this aspect region.

Similarly, near broadside, σ_1 and σ_2 become nearly equal and at $\theta = 90$ degrees they are equal in magnitude and scatter in-phase as a result of being equal distances from the radar.

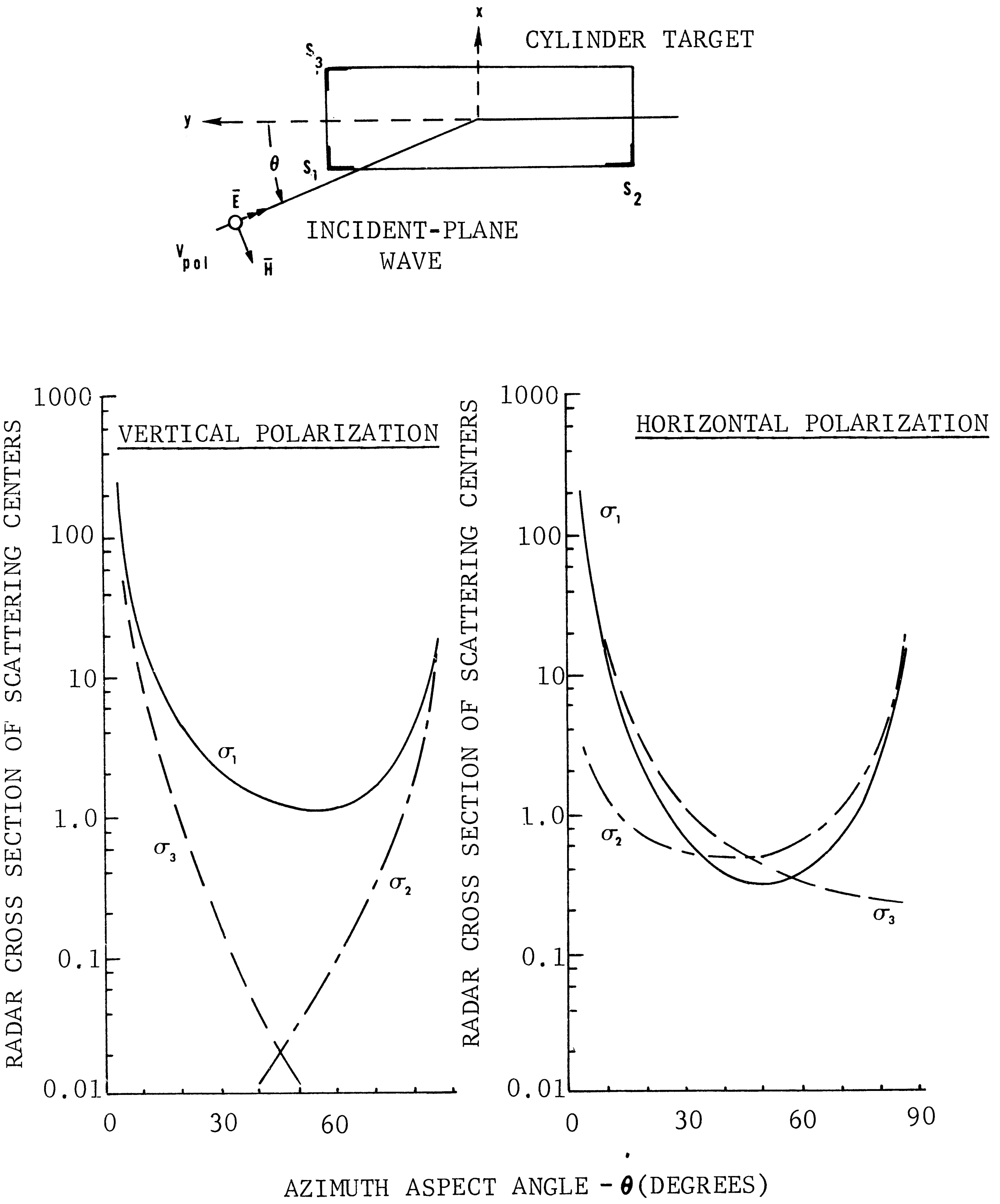


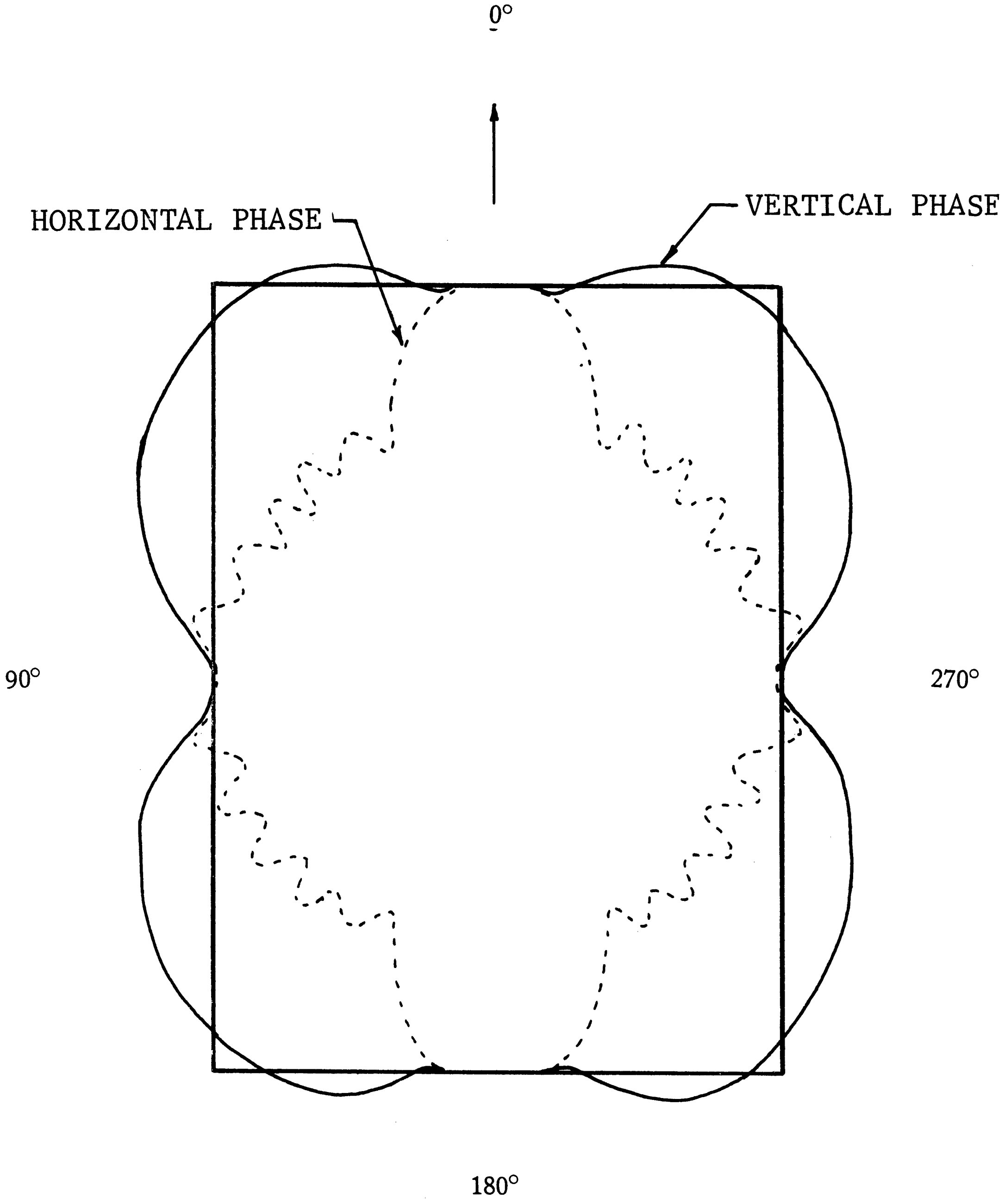
Fig. 1 RADAR CROSS SECTION OF SCATTERING CENTERS ON CYLINDER FOR VERTICAL AND HORIZONTAL POLARIZATIONS ($\beta = 0$)

As a result of the fact that, at vertical polarization, S_1 is the dominant scattering center throughout all aspect regions in the interval between 0 and 90 degrees, the location of the target phase center will always be located very near to the projection of S_1 onto the RLOS. Figure 2 shows a polar plot of the measured phase center location, obtained through use of vertical polarization, superimposed on a scale drawing of the target cylinder. The distance from a point on the phase plot to the center of the polar coordinate system is the phase center location at that aspect angle. The measured data shown in Figure 2 was reproduced from Figures 3-8 and 3-10 of Reference 2.

In the case of horizontal polarization, the data in Figure 2 indicates that a broad region of aspect angles exists in which S_1, S_2, and S_3 exhibit similar values of cross section. Thus, at aspect angles where any pair of these scatterers are approximately the same magnitude and 180 degrees out of phase, the phase center would necessarily be closest to the third scatterer. The following example will be used to explain this phenomena.

The projection of S_1 onto the RLOS is given by

$$x_1 = r_1 \cos (\theta - \gamma_1)$$



8.313 INCH CYLINDER
6.320 INCH DIAMETER
f = 5.975 gHz
Phase scale: 1 inch Radial = 360.

Fig. 2 MEASURED PHASE OF CYLINDER (REFERENCE) and the projection of S_3 onto the RLOS is given by

$$x_3 = r_3 \cos (\theta + \gamma_3)$$

where r_i is the distance from S_i to the center of the target (assumed to be coincident with the center of rotation of the target in this case), and γ_i is the angle r_i makes with the target axis. Whenever the difference between x_1 and x_3 equals an odd multiple of $\lambda/4$ and σ_1 equals σ_3, the effects of these two scatterers cancel leaving S_2 as the predominate scatterer. This may be formulated as

$$|x_1 - x_3| = r\left|\cos (\theta - \gamma_1) - \cos (\theta + \gamma_3)\right| = (2n + 1) \frac{\lambda}{4}; n=0,1,2---$$

Applying a trigonometric identity then,

$$2r\sin\theta\sin\gamma = (2n + 1)\frac{\lambda}{4}; n=0,1,2---$$

Since $2r\sin\gamma$ is the diameter of the cylinder, this equation can be reduced to

$$\sin \theta_{13} = (2n + 1)\frac{\lambda}{4D}; n=0,1,2---$$

A similar derivation can be used to establish the angles θ_{12} at which $x_1 - x_2$ is a odd multiple of $\lambda/4$. In this case

$$\sin \theta_{12} = (2n + 1)\frac{\lambda}{4L}; n=0,1,2---$$

when L is the cylinder length. It should be noted, however, that two scattering centers S_i and S_j will effectively cancel only if both conditions:

$$\sin \theta_{ij} = (2n + 1)\frac{\lambda}{4L_{ij}};n=0,1,2---$$

and

$$\sigma_i = \sigma_j$$

are satisfied, where L_{ij} is the separation between S_i and S_j. The amount of cancellation achieved can be expressed as

$$\sigma_R = -10 \log \quad (1 - \delta_{ij})^2 + 4 \sin^2 \frac{\phi_{ij}}{2}$$

where

$$\delta_{ij} = \frac{\sqrt{\sigma_i}}{\sqrt{\sigma_j}}$$ and ϕ_{ij} is the relative phase angle.

In computing δ_{ij} by convention the denominator is numerically greater. If $\phi_{ij} = 0$, then $\sigma_R = -20 \log (1 - \delta_{ij})$.

If $\delta_{ij} = 1$, impying that $\sigma_i = \sigma_j$ then

$$\sigma_R = \infty$$

corresponding to complete cancellation. Similarly, if σ_i and σ_j differ by 10 dB, only 3.3 dB of cancellation can be obtained. Thus, assuming that σ_i is the larger of σ_i and σ_j, then the effective cross section of the pair in the case where $\phi_{ij} = 180$ degrees is given by

$$\sigma_{ij(eff)} = \sigma_i - \sigma_R : \phi_{ij} = 180 \text{ degrees}$$

Unless $\sigma_{ij(eff)}$ is considerably less than the cross section of the third scatter S_k, then the phase center may remain associated with the pair S_i and S_j. This is always the case for vertical polarization since σ_2 and σ_3 differ by many dB. Figure 2 also shows a plot of measured horizontal phase. At the end-on aspects, the phase center is attached to the near end, as is that measurement at vertical polarization, and the phase center tends to remain attached to the end of the cylinder as the end rotates away from the radar. However, less than 10 degrees off of end-on the phase center location becomes influenced by scattering from S_2 and begins to move inside of the volume of the cylinder. It must be pointed out, however, that there may exist 2π ambiguities in the regions where the phase center tends to oscillate.

Comparison or the horizontal and vertical phase of a cylinder readily shows that the vertical phase is more easily interpretable from a physical standpoint. It is quite easy for example to identify the predominant scatterer by simply selecting a point on the polar phase plot and drawing a line through this point perpendicular to the radar-line-of-site.

The point, or more exactly, the region where this line intersects the target body represents the predominent source of the scattered energy at the selected aspect angle. It will be noted that this procedure will unerringly result in the selection of the closest corner to the radar in the case of the vertical polarization data contained in Figure 2. Note, however, that these data also serve to point out that the scattering from a curved edge does not eminate directly from the closest point on the edge but a region along the curve.

Unfortunately, the interpretation of measured phase data may be complicated by the fact that symmetrical targets may be positioned so that the center of the target is not coincident with the axis of rotation. When this occurs, a term proportional to the vector position of the reference point relative to the center of rotation is added to the actual phase. Analytically, the measured phase may be expressed as follows:

$$\psi_m(\theta) = \psi(\theta) - 2k\cos\beta/2 \; R \cos(\rho - \theta) + \psi_c \qquad (1)$$

where

$\psi_m(\theta)$ is the measured phase

β is the bistatic angle

$\psi(\theta)$ is the theoretical phase obtained in the absence of any physical displacement

ψ_c is a phase bias introduced during calibration

R, ρ are the polar coordinates of the phase center with respect to the geometrical reference position

θ is the aspect angle.

The derivation of Equation 1 is contained in Reference 3 along with a detailed example of its use with measured phase data of a cylinder, a frustrum, and a frustrum-cylinder. Three equations are necessary to solve for the three unknown R, ρ, and ψ_c. In the case of the cylinder only two are required as a result of symmetry. The values of $\psi(0)$ and $\psi(180)$, corresponding to the two end-on views, must be identical, therefore

$$\psi_m(180) - \psi_m(0) = 4k\cos\beta/2R\cos\rho \tag{2}$$

and the ψ_c term drops out. Similarly, although the exact value of $\psi(90)$ and $\psi(90)$ may not be known as a result of the curvature of the cylinder, their values must be equal. Hence

$$\psi_m(-90) - \psi_m(90) = 4k\cos\beta/2R\sin\rho \tag{3}$$

In order to solve these two equations for R and ρ the values of

$$\left[\psi_m(180) - \psi_m(0)\right] \text{ and } \left[\psi_m(-90) - \psi_m(90)\right]$$

must be determined from the measured phase plots. The phase data subsequently shown in Figure 2 was obtained through use of a cylinder and the C-band coherent radar at the Fort Worth Division Scattering Range. These data were corrected through the use of Equations 2 and 3

The values of R and ρ whose effects are observed in the data obtained on the 16 foot cylinder at 340 megahertz were published on pages 378 and 380 in Reference 4 for evaluation by the University of Michigan. The values of these parameters are determined as follows using the vertical polarization data.

$$\psi(-90) - \psi(90) = 289 \text{ degrees}$$

$$\psi(180) - \psi(0) = 40 \text{ degrees}$$

Using $\beta = 0$ and $\lambda = 2.89$ feet and converting 2π to 360 degrees results in

$$R \cos\rho = 0.0803$$

and

$$R \sin\rho = 0.58$$

Therefore

$$\rho = \tan^{-1}\left[\frac{0.58}{0.0803}\right]$$

and

$$R = \frac{0.58}{\sin\rho}$$

Numerical results for R and ρ are

$$R = 0.586 \text{ feet}$$

$$\rho = 82.12 \text{ degrees.}$$

Figure 3 contains a polar diagram showing, to scale, the 16 foot cylinder positioned at a distance of 0.586 feet from the center of rotation at an angle of 82.12 degrees. The measured phase

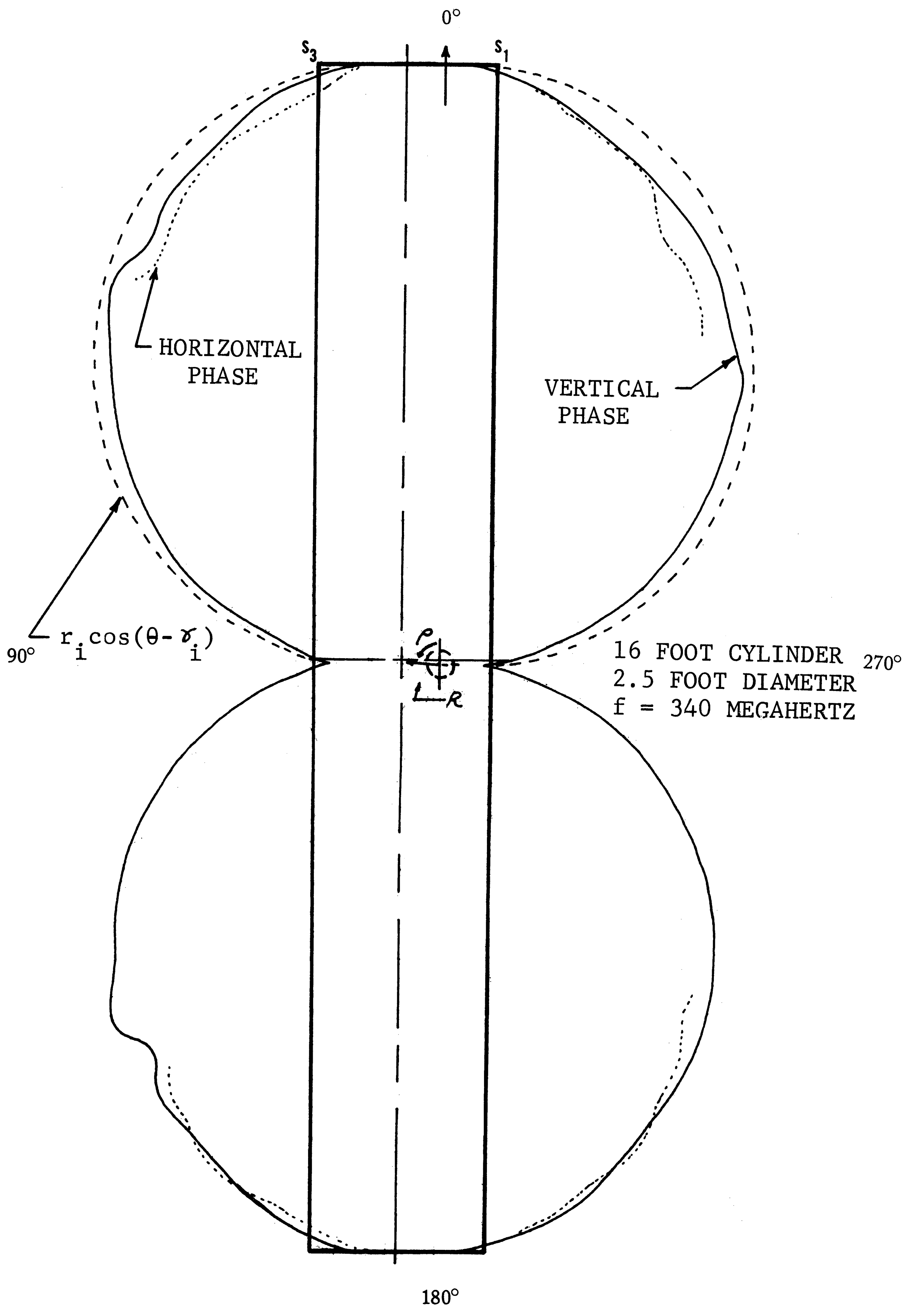


Fig. 3 MEASURED PHASE OF 16 FOOT CYLINDER AT 340 mHz

obtained through use of vertical polarization is shown superimposed on this diagram. Figures 4 and 5 contain the measured phase plots reproduced from Reference 4. As in the case of the data in Figure 2, the scattering center is observed to be slightly internal to the corner of the cylinder. The dashed curve in Figure 3 is a plot of the values of $r_i\cos(\theta - \gamma_i)$ over the aspect interval from -90 to 90 degrees. In this function, r_1 represents the distance of the scattering center at S_1 from the center of rotation and γ_1 the angle r_1 makes with $\theta = 0$ degrees. Similarly r_3 is the distance between S_3 and the center of rotation and γ_3 is the angle r_2 makes with $\theta = 0$. The values of these parameters are as follows:

$r_1 = 8.09$ feet $\quad \gamma_1 = 5$ degrees

$r_3 = 8.28$ feet $\quad \gamma_3 = -12$ degrees

The plot of $r_1\cos(\theta - \gamma_1)$ represents the phase center location which would be obtained if S_1 were the only scattering center illuminated over the aspect interval between 0 and 90 degrees. The plot of $r_3\cos(\theta - \gamma_2)$ is a plot of the location of the phase center based on the assumption that S_3 is the only scattering center illuminated over the interval between 0 and -90 degrees. The difference between the computed curve and the measured curve represents the effects of neglecting the other scattering centers on the target and the fact that each scattering center is a region rather than a discrete point.

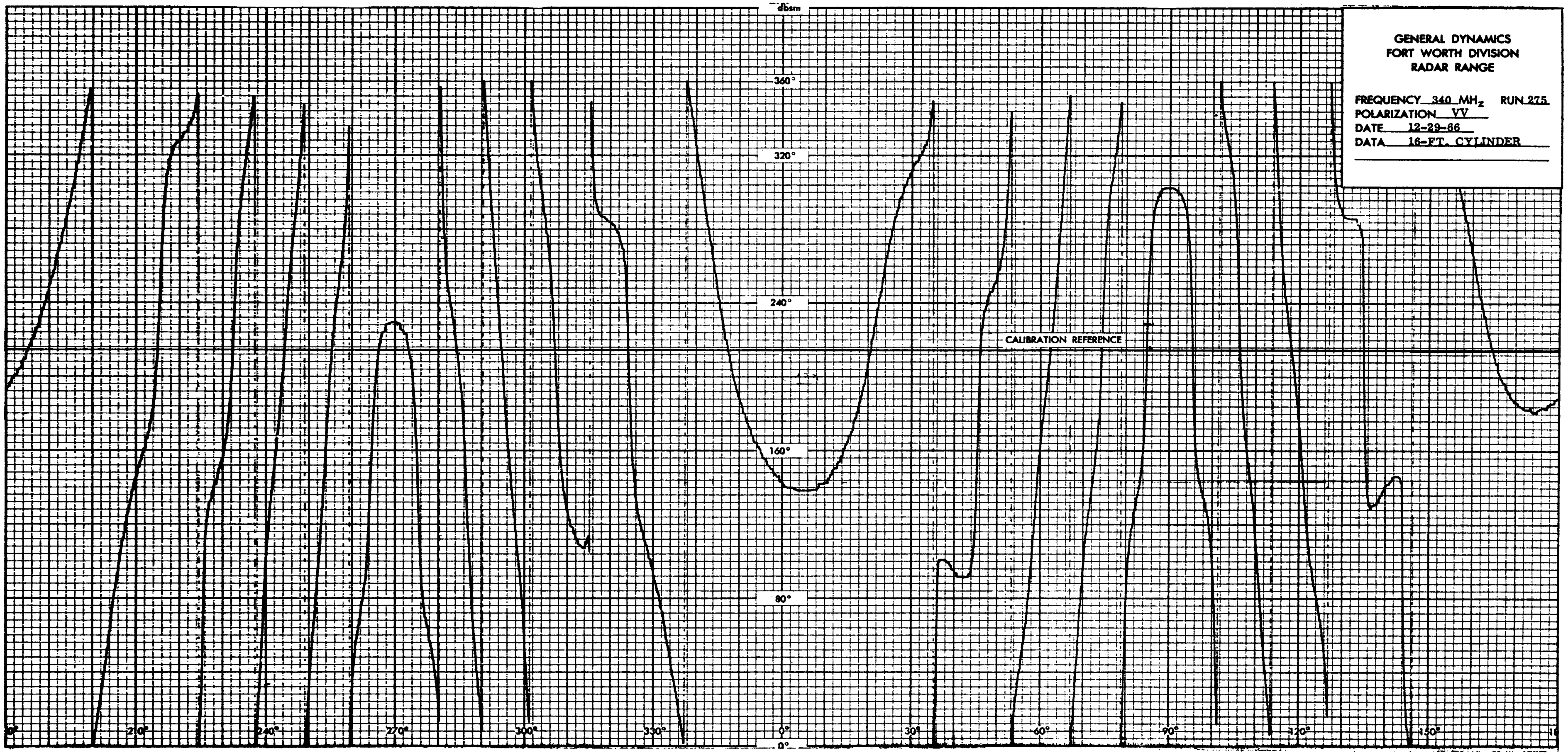


Fig. 4 MEASURED PHASE FOR 16-FOOT CYLINDER - VV POLARIZATION

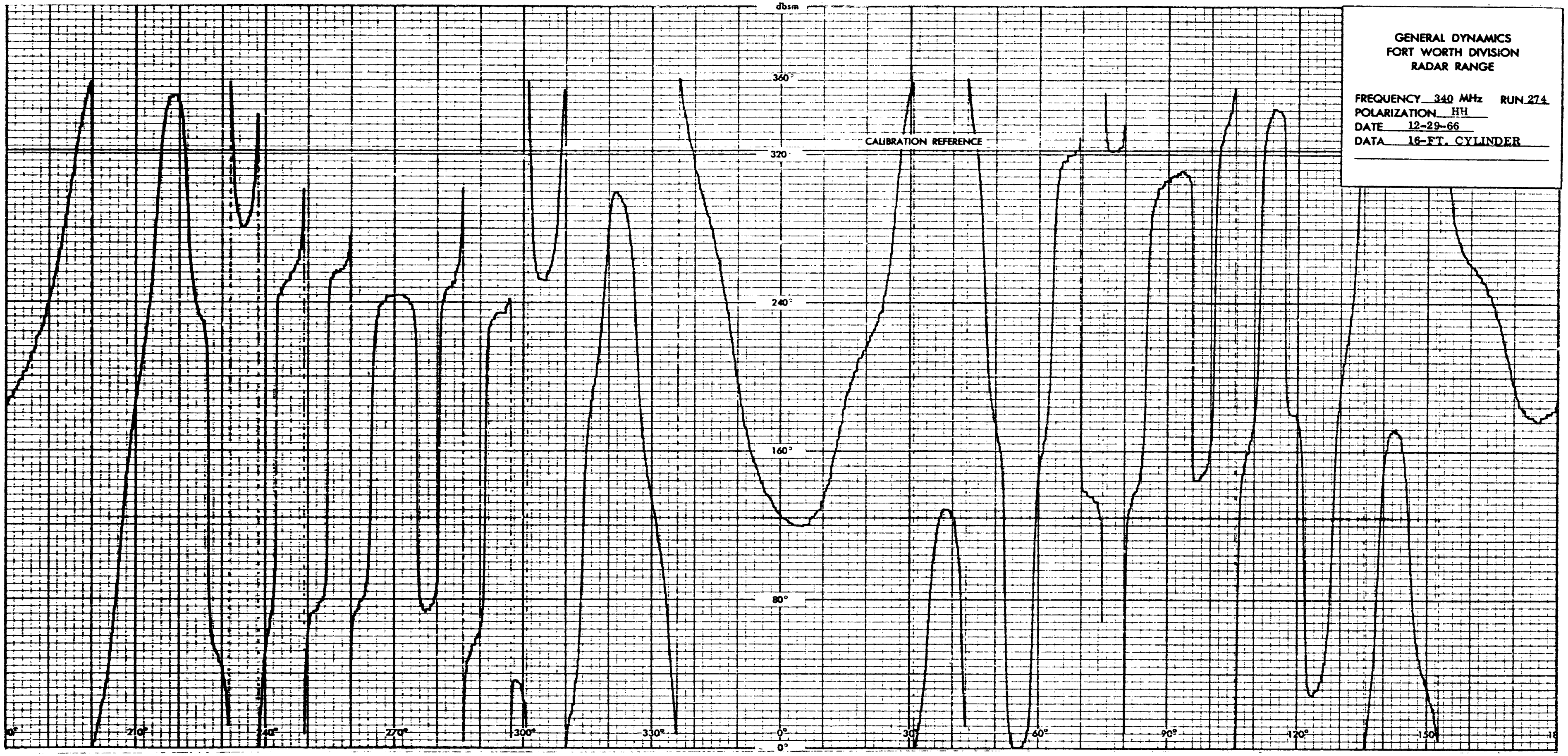


Fig. 5 MEASURED PHASE FOR 16-FOOT CYLINDER - HH POLARIZATION

A plot of the phase, $\psi(\theta)$, which would be measured if $R = 0$ can be obtained by use of the following equation:

$$\psi(\theta) = \psi_m(\theta) + 2kR\cos(\rho - \theta)$$

where $\psi_m(\theta)$ is the phase measured when the cylinder is offset by a distance R at an angle ρ. Application of this equation to the measured phase plotted in Figure 3 would produce a plot which would be symmetrical about the axis of the cylinder.

Interpretation of the horizontal phase data associated with the same target and frequency is extremely difficult as a result of the many points of discontinuous phase. These data may be observed in Figure 5. The horizontal phase is observed to virtually track the vertical phase over the aspect intervals ±40 degrees on each side of the end-on aspects. Further than 40 degrees from end-on the determination of the exact location of the phase center from the measured data is ambiguous. The interpretable portions of horizontal phase are shown in Figure 3.

In addition to the direct use of phase data as an aid in identifying the predominant sources of scattering on a target, numerous examples may be given in which phase data is utilized. For example, the use of phase in conjunction with the polarization scattering matrix as a means of computing the response to an arbitrary polarization has been well demonstrated.

(References 5 and 6). Discriminants based on the use of the polarization scattering matrix which includes relative phase terms have been used to describe the polarization characteristics of a variety of targets (Reference 7). An inverse scattering technique which is based on the use of measured phase has been demonstrated successfully as a means of locating the predominant scattering centers on arbitrary targets. (Reference 7). This technique was found to be of much greater value when vertical polarization phase was utilized. Reference 7 also contains an analysis of practical uses of scattering phase.

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ABSTRACT

A program under which selected radar cross section measurement ranges were evaluated is described. Some details are given on the test models involved and on the test procedures used. Test results are summarized and the ranges are assigned ratings according to their performance in an evaluation that includes many points of comparison. Problem areas in radar cross section measurements are outlined and some recommended solutions are given. Some suggestions for the optimum utilization of radar cross section ranges are given for the benefit of the potential range user.

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