RADC-TDR-64-380

77p.

EXPERIMENTAL RESULTS
OF
CIRCULAR POLARIZATION AND SCATTERING MATRIX
MEASUREMENTS

TECHNICAL DOCUMENTARY REPORT NO. RADC-TDR-64-380
June 1964

Space Surveillance and Instrumentation Branch
Rome Air Development Center
Research and Technology Division
Air Force Systems Command
Griffiss Air Force Base, New York

Project No. 6503

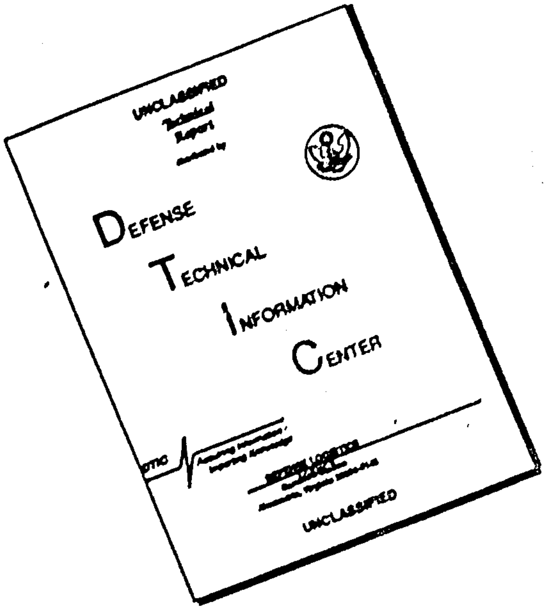
(Prepared by General Dynamics/Fort Worth,
A Division of General Dynamics Corporation
Under Contract No. AF30(602)-2831)

NOTICES

Copies available at Office of Technical Services.

Qualified requesters may obtain copies from Defense Documentation Center.

Do not return this copy. Retain or destroy.



UNCLASSIFIED

Technical

Report

DEFENSE

TECHNICAL

INFORMATION

CENTER

DTIC

UNCLASSIFIED

CLEARINGHOUSE FOR FEDERAL SCIENTIFIC AND TECHNICAL INFORMATION CFSTI
DOCUMENT MANAGEMENT BRANCH 410.11

LIMITATIONS IN REPRODUCTION QUALITY

ACCESSION # AD 605520

☒ 1. WE REGRET THAT LEGIBILITY OF THIS DOCUMENT IS IN PART UNSATISFACTORY. REPRODUCTION HAS BEEN MADE FROM BEST AVAILABLE COPY.

☒ 2. A PORTION OF THE ORIGINAL DOCUMENT CONTAINS FINE DETAIL WHICH MAY MAKE READING OF PHOTOCOPY DIFFICULT.

☐ 3. THE ORIGINAL DOCUMENT CONTAINS COLOR, BUT DISTRIBUTION COPIES ARE AVAILABLE IN BLACK-AND-WHITE REPRODUCTION ONLY.

☐ 4. THE INITIAL DISTRIBUTION COPIES CONTAIN COLOR WHICH WILL BE SHOWN IN BLACK-AND-WHITE WHEN IT IS NECESSARY TO REPRINT.

☐ 5. LIMITED SUPPLY ON HAND: WHEN EXHAUSTED, DOCUMENT WILL BE AVAILABLE IN MICROFICHE ONLY.

☐ 6. LIMITED SUPPLY ON HAND: WHEN EXHAUSTED DOCUMENT WILL NOT BE AVAILABLE.

☐ 7. DOCUMENT IS AVAILABLE IN MICROFICHE ONLY.

☐ 8. DOCUMENT AVAILABLE ON LOAN FROM CFSTI (TT DOCUMENTS ONLY).

☐ 9.

PROCESSOR:

TSL-107-10 64

RADC-TDR-64-380
June 1964

FOREWORD

In order to meet the need for a National Radar Reflectivity Range, Rome Air Development Center (RADC) awarded a development contract on 29 June 1962 to General Dynamics/Fort Worth (GD/FW) to design, fabricate, and develop the Radar Target Scatter Site (Project RAT SCAT) on the Alkali Flats, Holloman AFB, New Mexico. The operational RAT SCAT Site was delivered to the Air Force on 30 June 1964.

The RAT SCAT facility was developed for full-scale radar cross section measurements. In the pursuit of this development, an R&D Program was undertaken to provide for the specific needs of Project RAT SCAT as requirements appeared in the implementation of the function of the Site. A significant portion of this work was subcontracted. Emphasis was placed on those areas thought to be most promising in achieving measurement objectives. The presentation of the results of the R&D Program is covered in eight reports which were prepared as RADC Technical Documentary Reports.

This report (General Dynamics/Fort Worth Report No. FZE-222-2) is No. 2 in the series and was prepared by Mr. B. A. Benn and Dr. C. C. Freeny. The contents and abstract are unclassified.

ABSTRACT

This report contains a description of the results of experiments performed at the RAT SCAT Site, a ground plane radar cross section range, to examine the operational feasibility of measuring arbitrary targets with circular polarization and, in addition, measuring linear scattering matrices.

A calibration procedure compatible with the RAT SCAT facility is presented. Elliptical polarization was used to facilitate the establishment of circular polarization at the target point. Experimental data is presented on the magnitude of polarization degradation as a function of target size and time.

Relative phase measurements, along with the necessary amplitude measurements, were used to determine the linear scattering matrix of a complex target. Finally, two annotated schemes compatible with present RAT SCAT equipment for obtaining the linear scattering matrix are described. This is the second of eight reports prepared under the RAT SCAT R&D Program.

PUBLICATION REVIEW

This report has been reviewed and is approved. For further technical information on this project, contact

John J. Fogarty

Approved: DONALD M. MONTANA
Program Directors' Office
Space Surveillance & Instrumentation Branch

Approved: JOSEPH FALLIK
Chief, Space Surveillance and
Instrumentation Branch
Surveillance & Control Division

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

SECTION 1

INTRODUCTION

A major objective set for the RAT SCAT R&D effort was the investigation of the capability of the RAT SCAT facility relative to circular polarizations and scattering matrix measurements Theoretical investigations pertaining to these two subjects are reported in References 1 and 2. Test programs designed for and conducted at the RAT SCAT Site for the purpose of investigating the facility capability relative to these two subjects are described in this report.

All of the test series reported herein were conducted at 2955 megacycles. This frequency was chosen so that conclusions related to equipment stability and ground plane effects might be reasonably extended to allow similar conclusions to be drawn concerning Bands 4 through 7 (1 through 10 gigacycles). The target-to-antenna range was 1158 feet, and the antenna heights were adjusted to obtain a target center at a point 8 feet above ground level.

Modifications of existing equipment, as well as special test devices, were necessary in performing this experiment. In particular, a vernier-scaled phase shifter and variable attenuators were substituted for the existing phase shifters and 1-db step attenuators. The existing polarization boxes normally located outside of the transmitter room were moved into the transmitter room for the experiment. This modification was made in the interest of convenience for the operator rather than necessity. Special testing equipment consisted of (1) a rotating horn designed to propagate linearly polarized electromagnetic waves from the target region and (2) helix antennas to determine the sense of circular polarizations.

SECTION 2

CIRCULAR POLARIZATION

General

The capability for measurements at circular polarization at the RAT SCAT Site was examined through the execution of a test program. The primary objectives set for the program were (1) the design of a calibration procedure for obtaining circular polarization which would be compatible with the RAT SCAT equipment, (2) the collection of information for use in defining potentially severe limitations which might be imposed (by the antennas and ground plane) on the size of targets that could be measured by employing circular polarization (Reference 1), and (3) the collection of information related to the influence of frequency stability on the maintainability of circular polarization for extended periods of time.

The ground plane effects must be considered whenever a ground plane range is calibrated for measurements made at arbitrary polarizations (particularly those other than vertical and horizontal). However, antenna effects also must be considered in any calibration procedure established for measurements at arbitrary polarizations on a ground plane or a free space range.

Since in fact, the two are actually combined in a single perturbation in the ground plane case, it is seen that the ground plane effects do not compound calibration problems. The only difference is that resulting polarizations must be examined after the ground plane has had its perturbing effect, i.e., a change in resulting polarization will generally accompany a change in location of the target point. However, this phenomenon is germane to the control problem within a target region - not at a target point.

In measuring arbitrary targets, the actual problem is more closely related to controlling polarization within a target region. Practically, this type of control can only be effected by controlling polarizations at a central point (target point) and simply accepting the over-all degradation.

Dual feed antennas are used at the RAT SCAT facility to control the polarization at the target region. Each antenna feed network consists of a variable attenuator (normally 1-db step attenuators are present, but continuously variable types were used for the experiments discussed in this report) and a phase shifter in each of the two orthogonal channels (horizontal, H, and vertical, V). This arrangement is used as a first-order compensation network in that such effects as antenna isolation are not taken into account. However, as shown later, additional sophistication of the compensation network would not be beneficial since overall system limitations were caused primarily by differences in the horizontal and vertical antenna patterns - a problem not readily amenable to solution by use of a compensation network. The compensation network is illustrated schematically in Figure 2-1.

Proper adjustments in the H and V channels of either the transmitter or receiver compensation network will produce a transfer function of the compensation network which equals the inverse of the transfer function of the antenna and the ground plane (Reference 1). Therefore, the transmission of circular polarization will result in circular polarization at the target point.

In the test program, a precision sphere was used for a probe to demonstrate the "purity" of the circular polarization throughout the target region. A sphere was used because it exhibits far field scattering characteristics that simply reverse the sense of the polarization; consequently, the cross section associated with the transmission of right circular (TRC) polarization and the reception of right circular (RRC) polarization is zero. However, the cross section associated with transmitting a polarization other than circular and receiving its orthogonal counterpart is also zero; hence it is also necessary to observe that, once calibrated at the target point, the transmitter and receiver chains track one another as a function of target position since they are essentially identical. Therefore, since the orientation of general elliptical polarizations differs from that of their orthogonal counterparts, a cross section of zero indicates circular polarization.

The frequency stability of the system was examined by repeating sphere probe after probing the target region of interest.

Calibration Procedure

To calibrate the system, a rotating horn, fed by a signal generator, was mounted so that linear polarizations could be emanated from the target point to form a linear time-dependent angle with the horizontal. This procedure represented a modification of a technique suggested in Reference 1. By adjusting the compensation network in each of the transmitter and receiver chains independently (by reciprocity the transmitter was calibrated as a receiver), the system was calibrated to measure with circular

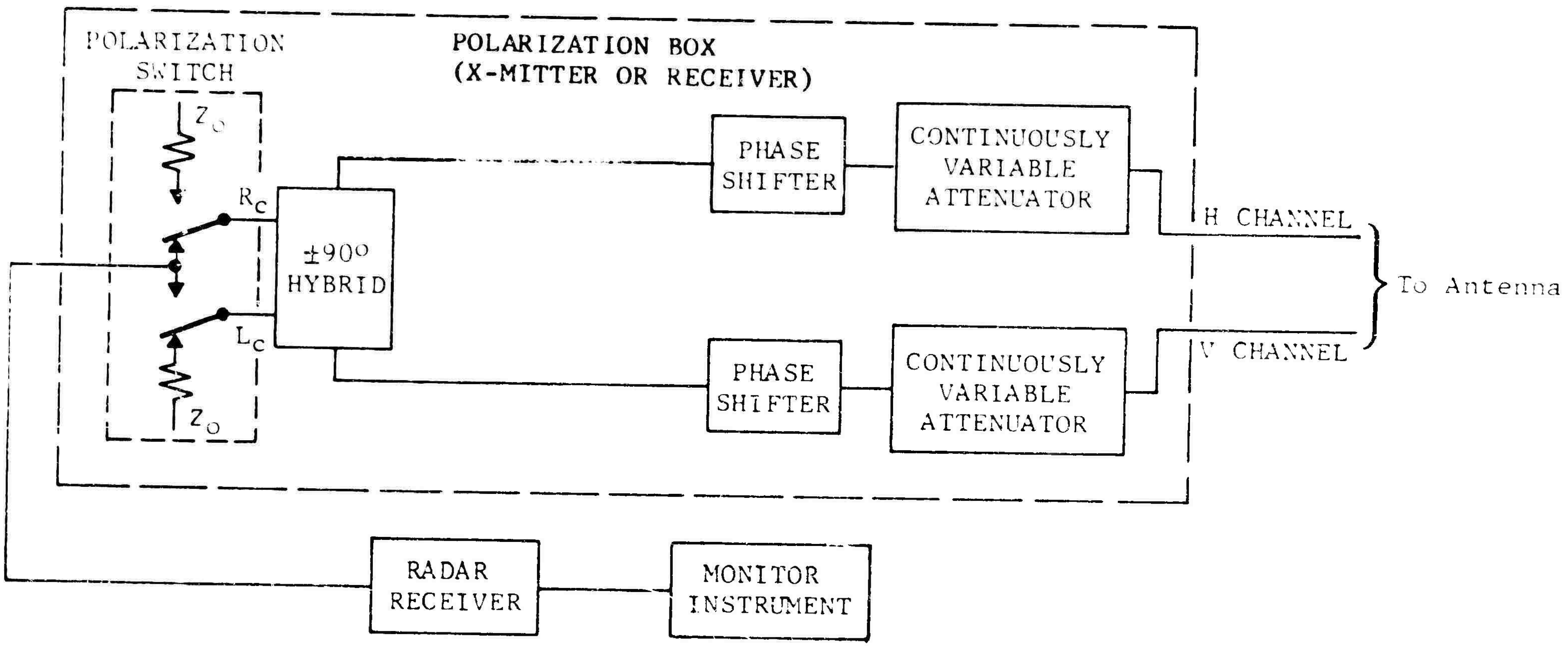


Fig. 2-1 CIRCULAR POLARIZATION COMPENSATION NETWORK

polarization. The exact calibration procedure consisted of the following eight steps:

1. The transmitter antenna (rotating horn) located at the target region is geometrically boresighted. The signal generator is set to the frequency of operation. The transmitter is then energized and the antenna is set to rotating.

2. The local oscillator is then manually tuned to the frequency of the pit-located transmitter frequency plus or minus 60 megacycles.

3. The transmitter compensation network attenuators and phase shifters are then adjusted to achieve minimum variation of the received signal and the dial settings of phase shifters and attenuators are recorded. The transmitter network is then calibrated to produce circular polarization at the target. To demonstrate the adequacy of this procedure, the relationship describing the power, P, received from the pit can be examined as a function of the rotating speed γ:

$$P = A(\mathrm{Sin}^2 \gamma T + \mathrm{Sin}^2\beta \ \mathrm{Cos}^2 \gamma T + 2 \ \mathrm{Sin}\,\beta \ \mathrm{Cos}\,\delta \ \mathrm{Sin}\,\gamma T) \tag{1}$$

   where Sin β represents the ratio of the H and V channel gains and δ is the phase difference between the two channels. It follows from Equation 1 that minimum variation in P occurs only when $\beta = \pm \pi/2$ and $\delta = \pm \pi/2$, in other words, the conditions necessary and sufficient for circular polarization. Typical minimum variations achieved during the demonstration are indicated in Figures 2-2 and 2-3.

4. The 90-degree hybrid switch is energized to reverse the polarization sense. Components and record dial settings are adjusted as necessary in conformance with Step 3.

5. Steps 3 and 4 are repeated for the receiver network.

6. The rotating horn is replaced with the calibration sphere. The transmitter is then manually tuned to the local oscillator plus or minus 60 megacycles depending on the calibration frequency. Use of this procedure results in the

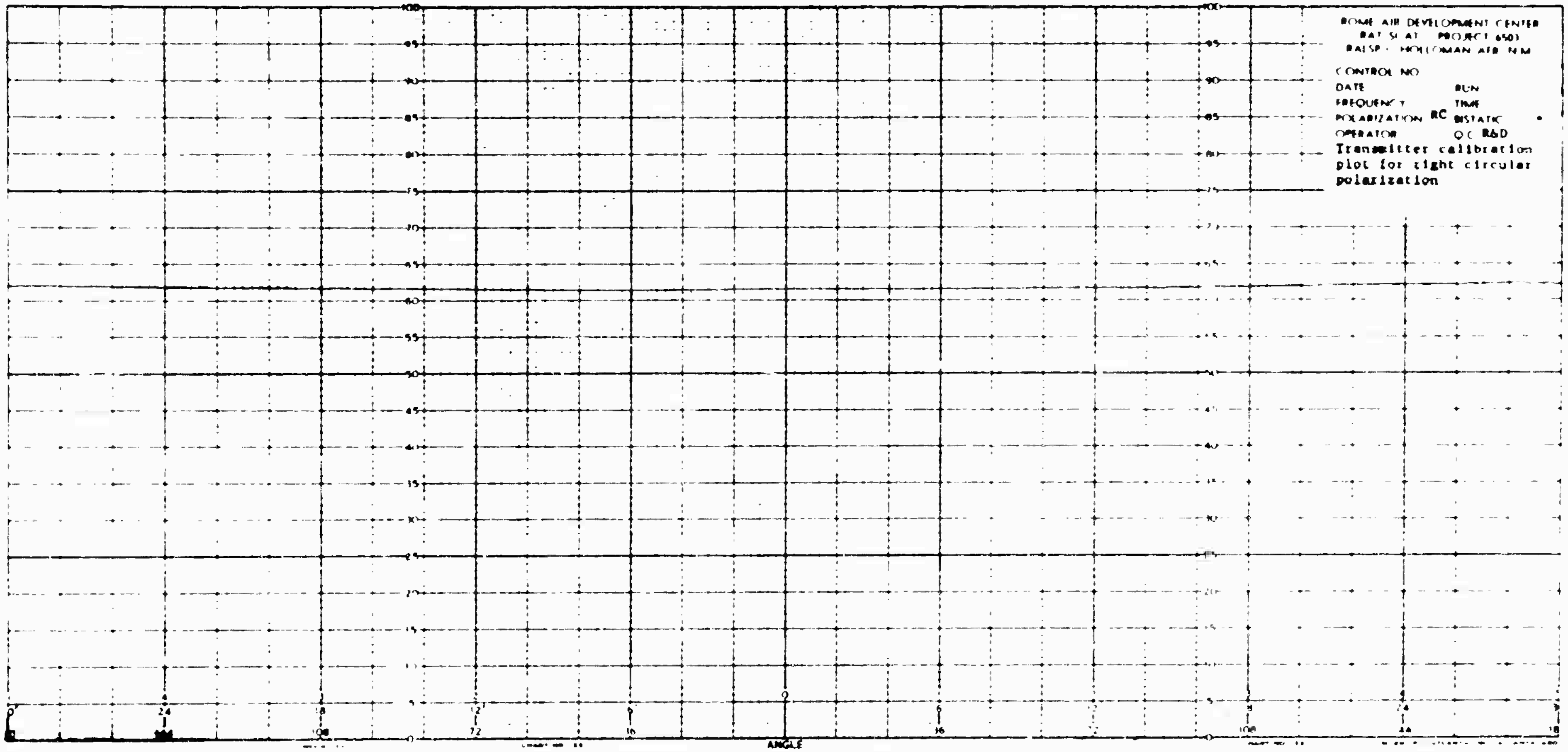


Fig 2-2 TRANSMITTER CALIBRATION (RIGHT CIRCULAR POLARIZATION)

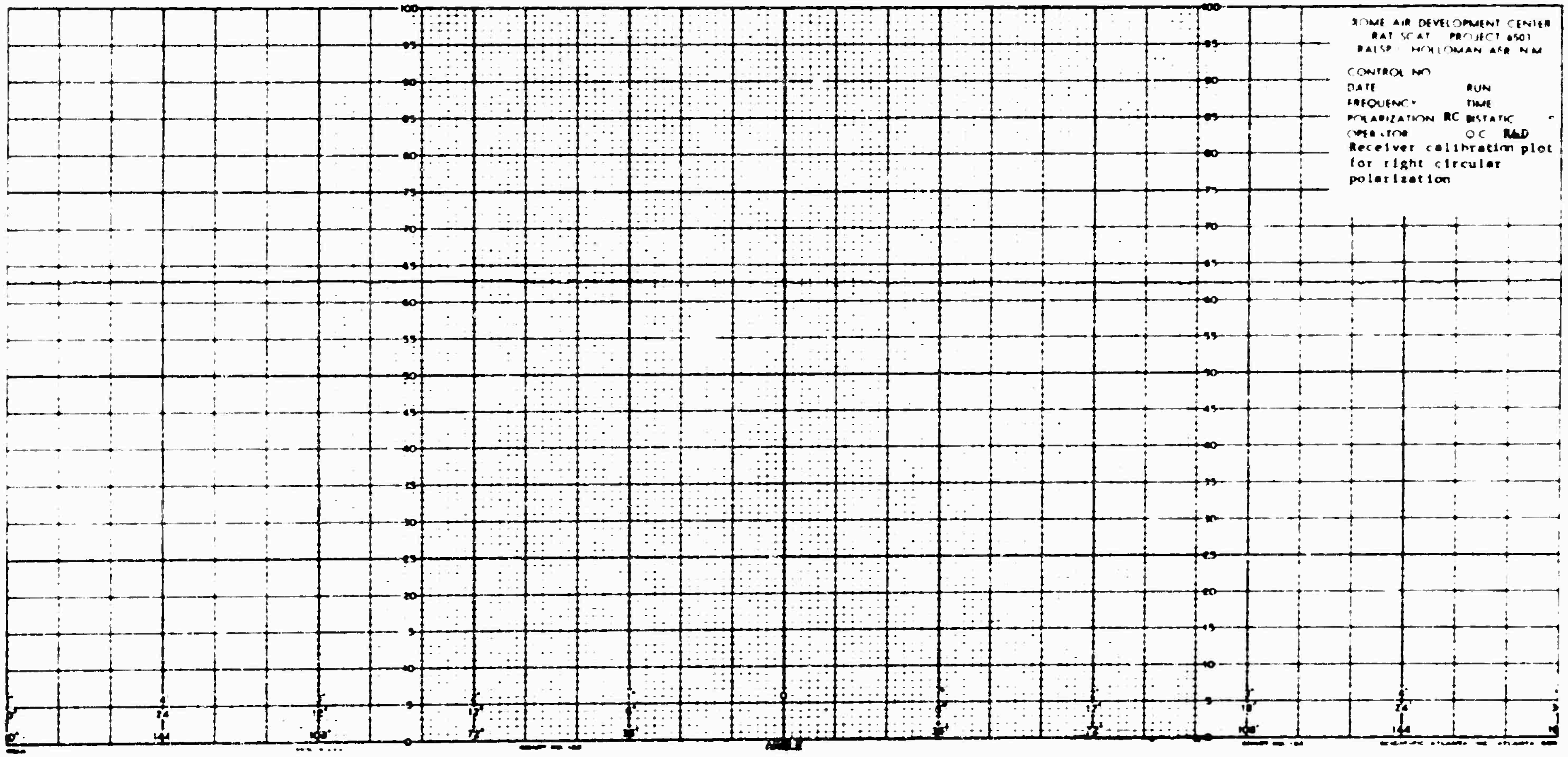


Fig. 2-3 RECEIVER CALIBRATION (RIGHT CIRCULAR POLARIZATION)

transfer of the calibration frequency to the operating frequency with minimum error.

7. The calibration sphere is measured for the condition (TRC, RLC) (maximum return) and (TRC, RRC) (minimum return). The difference between these two measurements is indicative of the "purity" of the circular polarization. Any minor frequency changes that occurred in the transfer described in Step 6 can be compensated by operating TRC, RRC and adjusting the phase shifters to obtain a null. Although the use of this process may produce a polarization slightly different from circular, it will provide an orthogonal set of polarization base vectors.

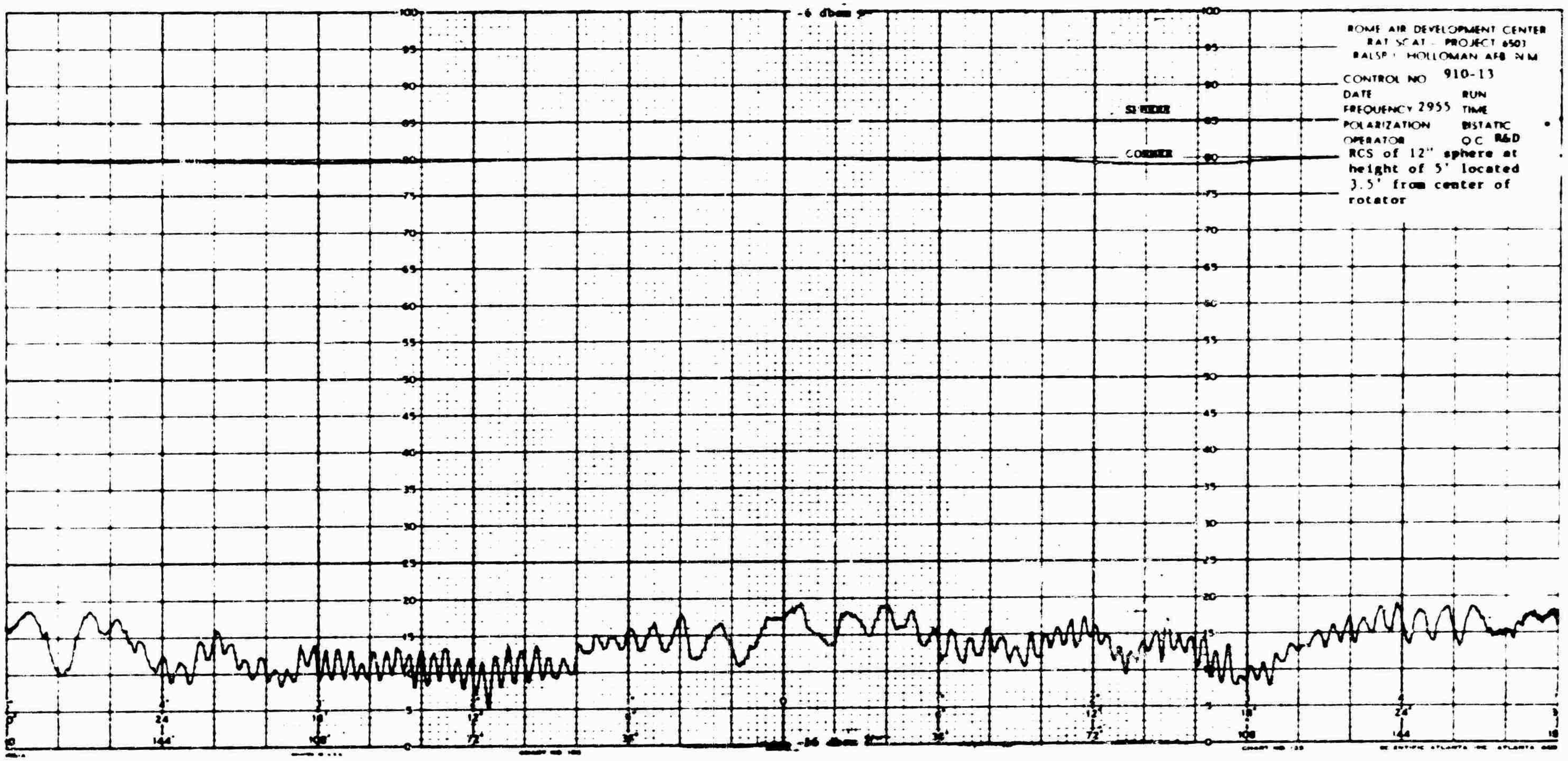
8. Helix antennas are then used to correlate the sense of the transmitter polarization with respect to the polarization switch position (i.e., in Step 7 TRC may well have been TLC and conversely for the receiver). During the actual test, the transmitter was calibrated for TRC and the receiver for both RRC and RLC.

Field Probe Procedure

As mentioned previously, the success of this test series is dependent on the purity of the circular polarization obtained throughout the target region. To determine this, a sphere was placed on a Styrofoam column offset 1.5 feet from the center of the rotator platform at a height of 5 feet. The sphere cross section was recorded under both conditions (RRC and RLC) through 360 degrees of rotation. It was then moved in one-foot vertical increments and measured under conditions (TRC, RRC) and (TRC, RLC), i.e., the above procedure was then repeated for sphere heights of 7, 8, 9, and 10 feet. The column was then offset 3.5 feet, and the above steps were repeated. Finally, a measurement with the sphere at the center of the rotator with height 8.0 feet above ground was made for the purpose of examining system stability.

Measured Data

The plots in Figures 2-4 through 2-6 represent measurements of (TRC, RLC) and(TRC, RRC) for 360 degrees of rotation of a 12-inch sphere for selected probe positions. The probe positions selected are those taken at the extreme positions of the target region, along with the center region probe. Examination of the figures indicates that, even in the regions of least separation, the difference in the sphere returns for the two conditions is



ROME AIR DEVELOPMENT CENTER
RAT SCAT - PROJECT 6503
RALSP - HOLLOMAN AFB N M

CONTROL NO 910-13
DATE
RUN
FREQUENCY 2955
TIME
POLARIZATION
BISTATIC
OPERATOR
O C R&D

RCS of 12" sphere at height of 5' located 3.5' from center of rotator

Fig. 2-4 FIELD PROBE FOR TARGET HEIGHT OF 5 FEET OFFSET FROM CENTER OF ROTATOR 3.5 FEET

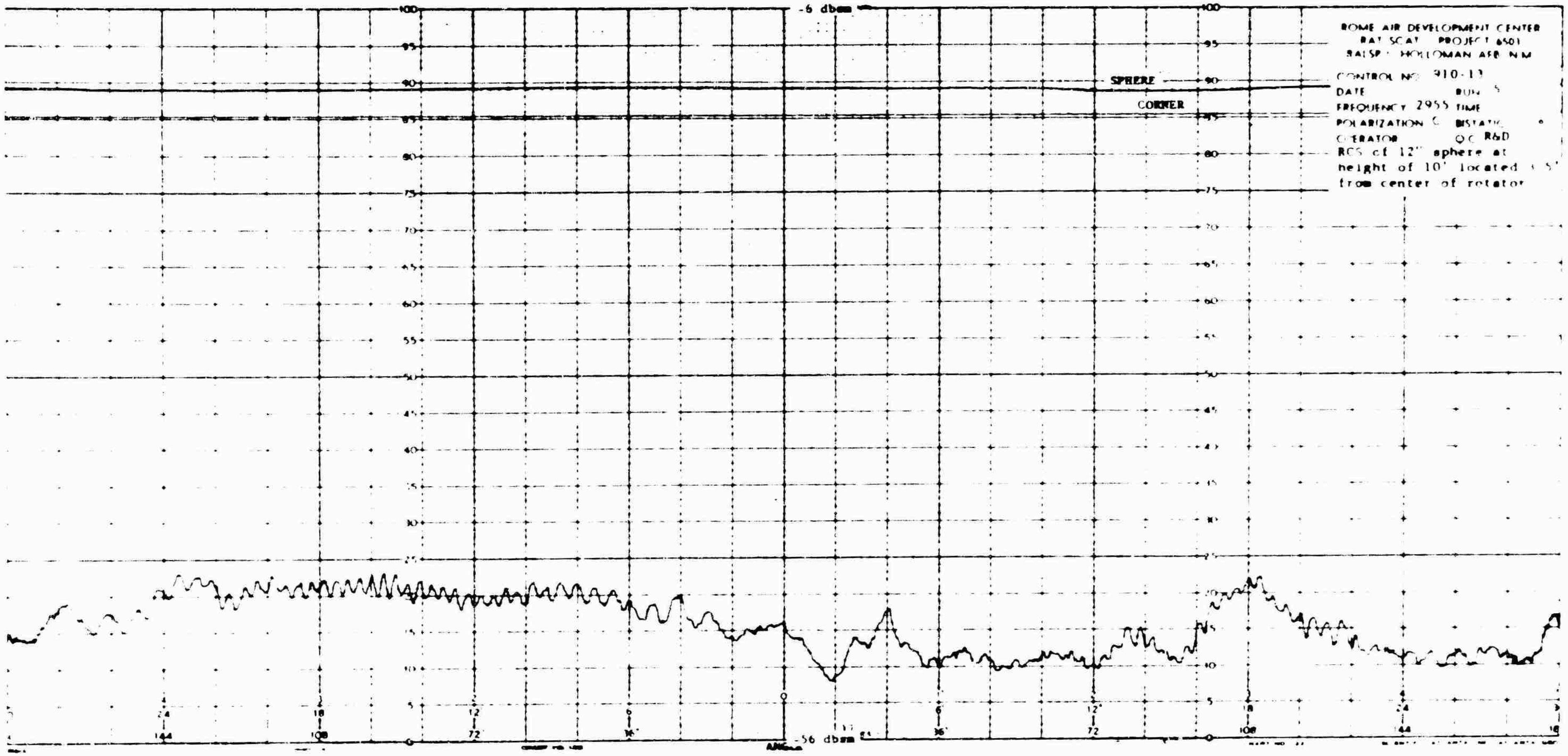
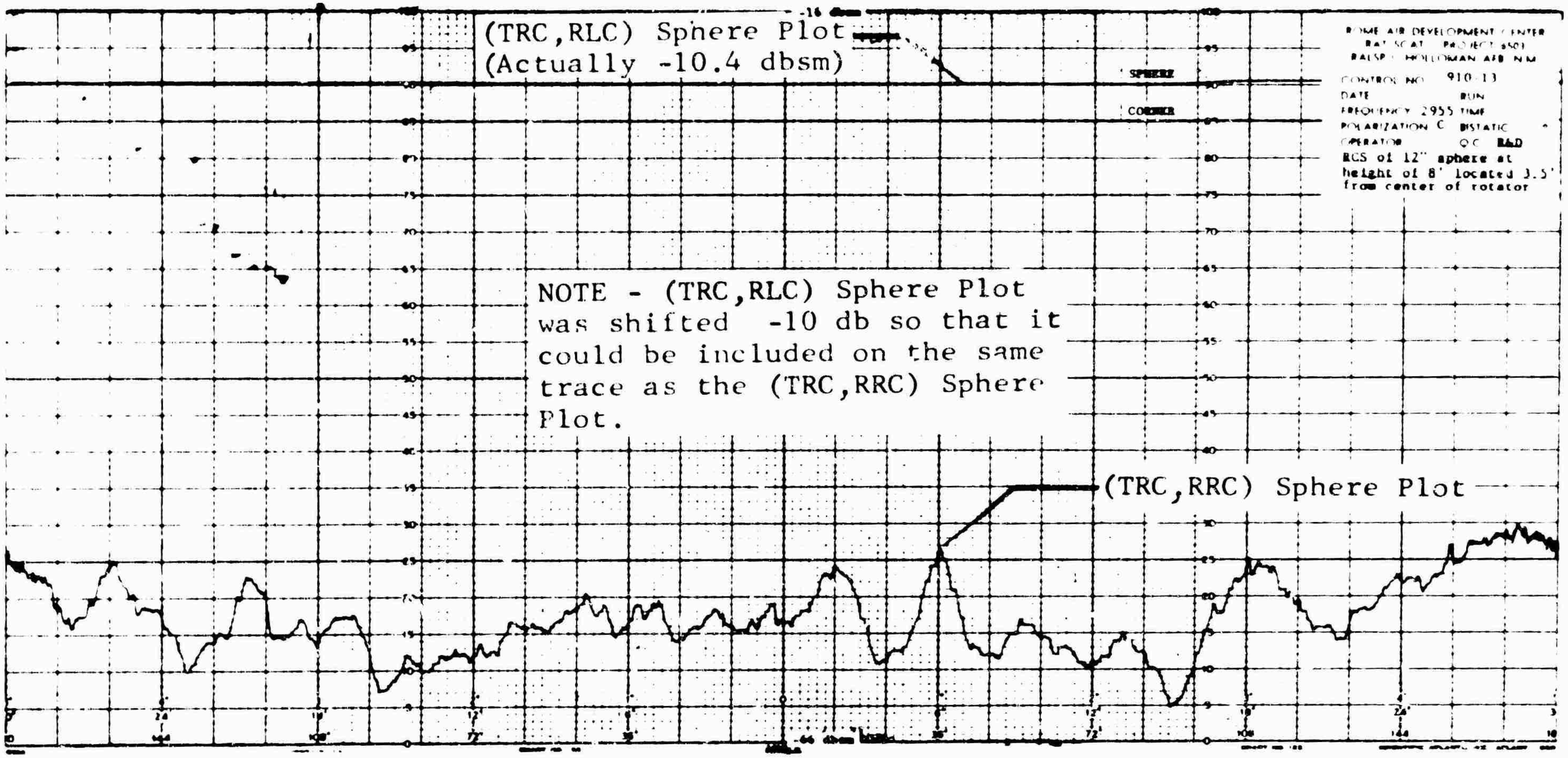


Fig. 2-5 FIELD PROBE FOR TARGET HEIGHT OF 10 FEET OFFSET FROM CENTER OF ROTATOR 3.5 FEET



(TRC,RLC) Sphere Plot
(Actually -10.4 dbsm)

NOTE - (TRC,RLC) Sphere Plot was shifted -10 db so that it could be included on the same trace as the (TRC,RRC) Sphere Plot.

(TRC,RRC) Sphere Plot

Fig. 2-6 FIELD PROBE FOR TARGET HEIGHT OF 8 FEET OFFSET FROM CENTER OF ROTATOR 3.5 FEET

greater than 30 db. Exclusive of the regions where anomalies occur, the ratio is nominally 35 db. Since these plots are those taken with the probe at the extremities of the target region as well as extremities in time the data indicates an extremely high degree of circular polarization purity can be achieved by using the equipment modifications indicated earlier.

The 1-db step attenuators originally prescribed, instead of the variable attenuators employed for this test, were used and it was found that sensitivity was reduced by about 15 db. It was therefore concluded that variable attenuators were not only desirable for compensation networks but, at least with respect to 1-db step attenuators, necessary to obtain reasonable orthogonality.

Analysis of Field Probe Data

In this section the measured data is used to compute two parameters indicative of the amount of circular polarization degradation across the target region.

The ability to achieve circular polarization throughout a given size of target region may be limited by a combination of two types of changes: (1) relative changes between horizontal and vertical amplitudes and (2) relative changes between horizontal and vertical phase patterns. In order to describe the sizes of errors involved, degradations will first be considered to be caused entirely by changes in phase and then entirely by changes in relative amplitudes.

Errors in Phase

If ϕ_T and ϕ_R represent the phases between the H and V channels of the transmitter and receiver chains, then $\phi_T = \phi_R$ since it is assumed that the two systems are reciprocals of one another. If $\Delta\phi = \pi/2 - \phi_T$, it is easy to show that the one-way phase change, $\Delta\phi$, is related to the measured cross sections by

$$\Delta\phi = \frac{1}{2}\cos^{-1}(2P-1) \qquad (2)$$

where P equals the ratio of average cross sections recorded for (TRC, RRC) and (TRC, RLC) as a function of position.

Equation 2 can be used to form a grid by associating a phase error, $\Delta\phi$, with each of the grid points covering the target region probed (cf. Measured Data Subsection). Notice from Figure 2-7 which illustrates this grid that three degrees represents maximum phase error existing throughout the target region probed.

Errors in Relative Amplitude

A convenient method of displaying possible sizes of errors in relative amplitudes is to employ axial ratios, i.e., the ratio of the minor axis of a polarization ellipse to the major axis. A relationship involving the measured cross sections as a function of position can be used to generate yet another grid by associating one-way axial field ratio errors, A_E, in db with a target region grid. The relationship used for this analysis is given in Equation 3:

$$A_E = 5 \text{ Log } [1-2(10^{P/20})] \qquad (3)$$

where P = ratio of average sphere return recorded for (TRC, RRC) and (TRC, RLC).

The errors in axial ratios are less than 0.4 db throughout the target region. Except for a small region, the error was less than 0.1 db, as can be seen by examining the grid shown in Figure 2-8. It is noted that only in the vertical plane does the circular polarization noticeably deteriorate. This deterioration is in accordance with that predicted for a ground plane model in which the reflection coefficients for vertical and horizontal polarization are different (Reference 1). However, the measurement error which results from the demonstrated amount of deterioration should be small compared to the normal-amplitude, near-field error in the vertical plane (Reference 3).

Stability

The circular polarization experiment performed at the RAT SCAT Site was designed to obtain information concerning the time stability of system parameters - notably, the frequency parameter. A small change in frequency activates a change in the electric path length in both channels, and unless H and V channel path lengths are identical, there is a resultant change in relative phase difference between the channels. Also, the sensitivity of the RF network components to small frequency changes may produce the same effect. The change in relative phase, $\Delta\delta$, as a function of path length difference, ΔR, and frequency shift, Δf, is given by

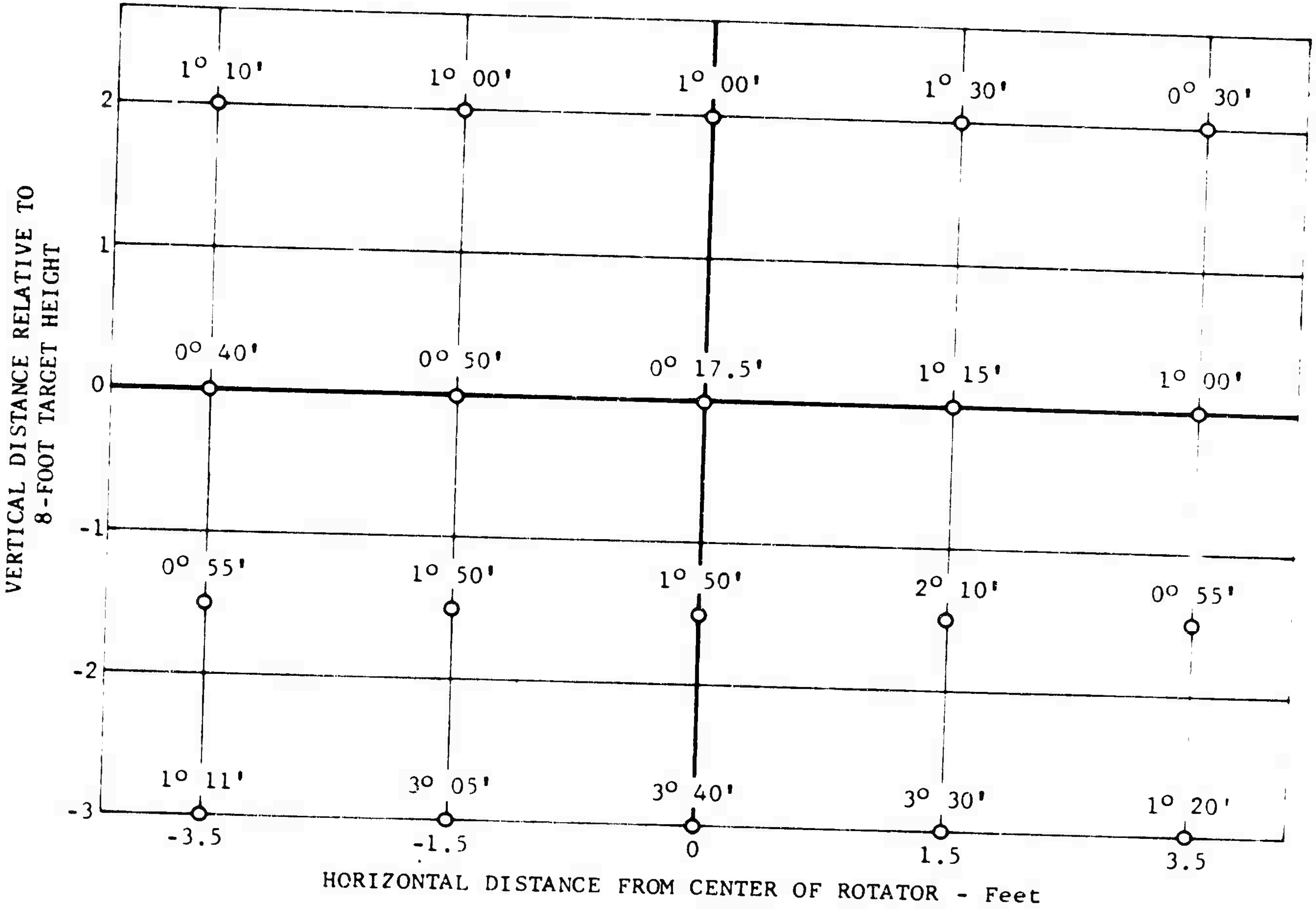


Fig. 2-7 MAXIMUM PHASE DEVIATION COMPUTED BY USING CIRCULAR FIELD PROBE DATA

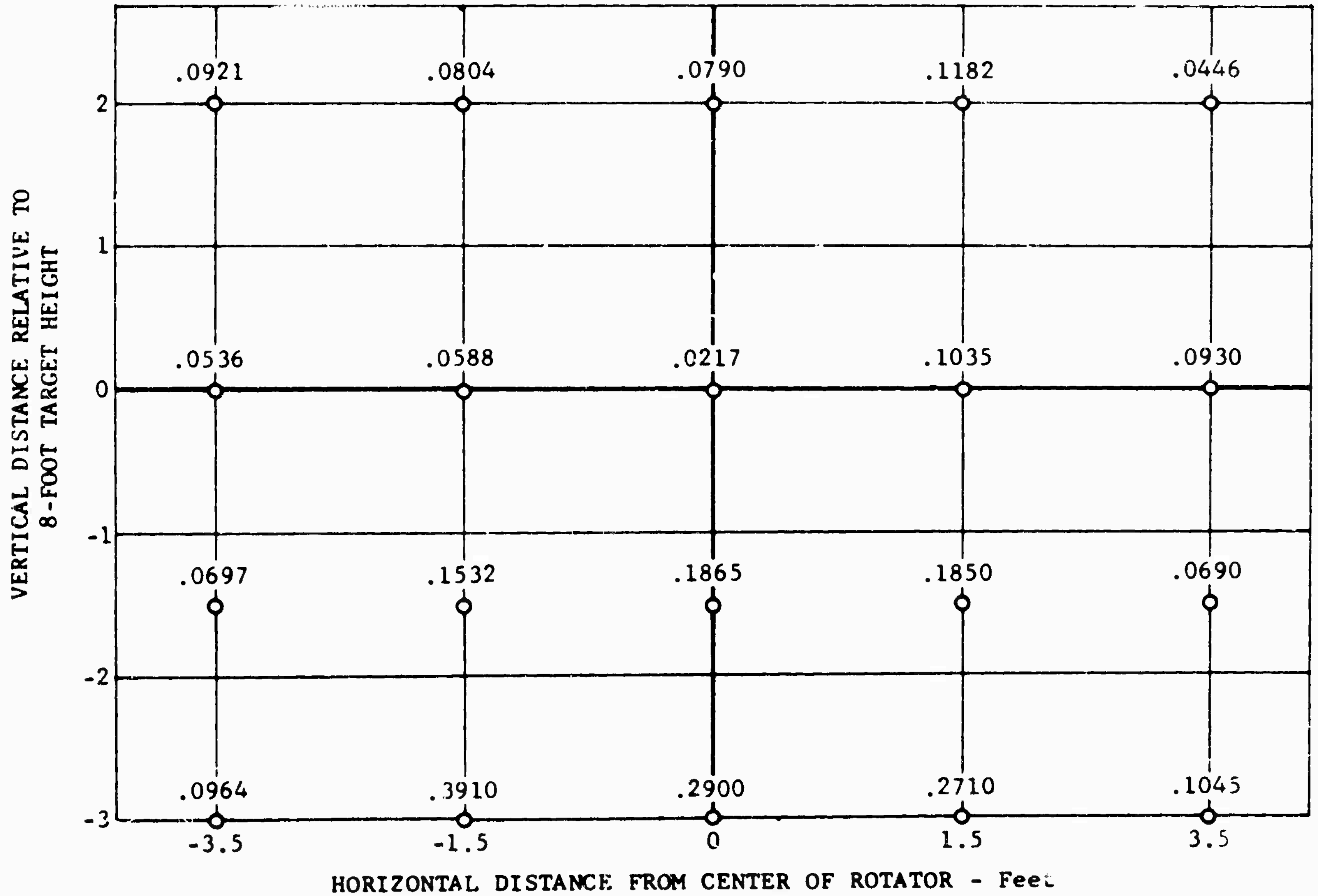


Fig. 2-8 ERROR IN ONE WAY AXIAL FIELDS RATIO, AS FUNCTION OF TARGET POSITION

$$\Delta\delta = \frac{\Delta f \ \Delta R \ (2\pi)}{C} \qquad (4)$$

At 2955 megacycles, for example, with a 10-foot difference in path lengths, the frequency must be stable to 1/6 part in a thousand in order to limit relative phase changes to less than 2 degrees. It can be seen from this example that care must be taken to control the physical path lengths of the antenna cables of both channels unless ultrastable signal generators are used. Measurements of cable lengths indicated that the path length difference in the test setup was less than 5 feet.

The time required to complete the field probe for this test series was considered sufficient to provide an indication of potential frequency stability problems. The last measurement, made with the sphere 8 feet above ground level in the center of the rotator, indicated a phase shift of less than one degree. This measurement was made approximately two hours after the system was calibrated. In addition to the prescribed measurements, the next morning the equipment was turned on and allowed to warm up. The return from the sphere was then measured without changing the equipment settings from those used the previous night. Under these test conditions, the difference between measurements for (TRC, RRC) and (TRC, RLC) indicated that less than a two-degree phase shift occurred between the vertical and horizontal channels. It can be seen from Equation 4 that, for an assumed 5-foot path length difference, the corresponding frequency shift was approximately 1/3 part in 1000. This degree of frequency stability is within the limits of RAT SCAT equipment frequency variation.

Summary

The results of the circular polarization experiment were in general the same as those theoretically predicted by considering an ideal ground plane model (References 1 and 2). The size of the useful target region is approximately the same when circular polarization is as that obtained when linear polarization is used, that is, the amplitude curvature in the vertical plane appears to be the limiting factor in both cases (Reference 3). The calibration procedure designed for the RAT SCAT facility proved to be quite satisfactory. Because of the frequency (approximately 3 gigacycles) used in the demonstration, conclusions regarding equipment stability and ground plane model should be reasonably valid for range operation at Bands 4 through 7 (1 through 10 gigacycles). The only modification of the existing RAT SCAT equipment which appears mandatory to achieve results similar to those presented in this report is the addition of a continuously variable attenuator in series with or in lieu of the step attenuators presently in the polarization boxes (actually only one channel, either V or H, need be modified).

SECTION 3

LINEAR SCATTERING MATRIX MEASUREMENTS

General

Unlike circular polarization, phase and intensity curvature is not the primary factor in the measurement of linear scattering matrices. Here isolation between channels is the acme of the problem since scattering matrix cross terms of many targets are down 10 to 20 db or more from main diagonal elements and, if the isolation is not significantly lower, much of the measured cross term signal will simply be an attenuated main diagonal return.

Another problem peculiar to measuring scattering matrices is that the phase, at least the relative phase, between elements of the matrix must be obtained. Various operational means of measuring phase continuously for 360 degrees of azimuthal rotation are delineated in a following subsection; but for the test program reported herein, such equipment was not available. Instead a calibrated RF phase shifter was used. This setup permitted no more than point-by-point phase measurements; consequently, a sample of only eight azimuth angles was taken for demonstration purposes.

A four-inch diameter, 14-inch long cylinder constructed of chicken wire was mounted on a Styrofoam column for use as a target (see Figure 3-1). At zero degree azimuth it was canted forward approximately 45 degrees. Chicken wire was utilized because its depolarization properties resulted in scattering matrix cross terms of appreciable size. Three amplitude and two relative phase measurements were made on this target to obtain the information necessary to determine the scattering matrix. Since vertical and horizontal linear polarizations were used as basic elements, the following amplitude measurements were required: (TH, RH); (TV, RV); and (TH, RV); (TV, RH). The two required relative phases are $\phi_{VV} - \phi_{VH}$ and $\phi_{HA} - \phi_{HV}$. Both (TH, RV) and (TV, RH) are necessary for calibration purposes.

In order to demonstrate the magnitudes of the measurement errors (T $\pi/4$, R $\pi/4$), measurements were taken and compared against values calculated via the scattering matrix.

Calibration Procedure

Equipment modifications were necessary in order to make

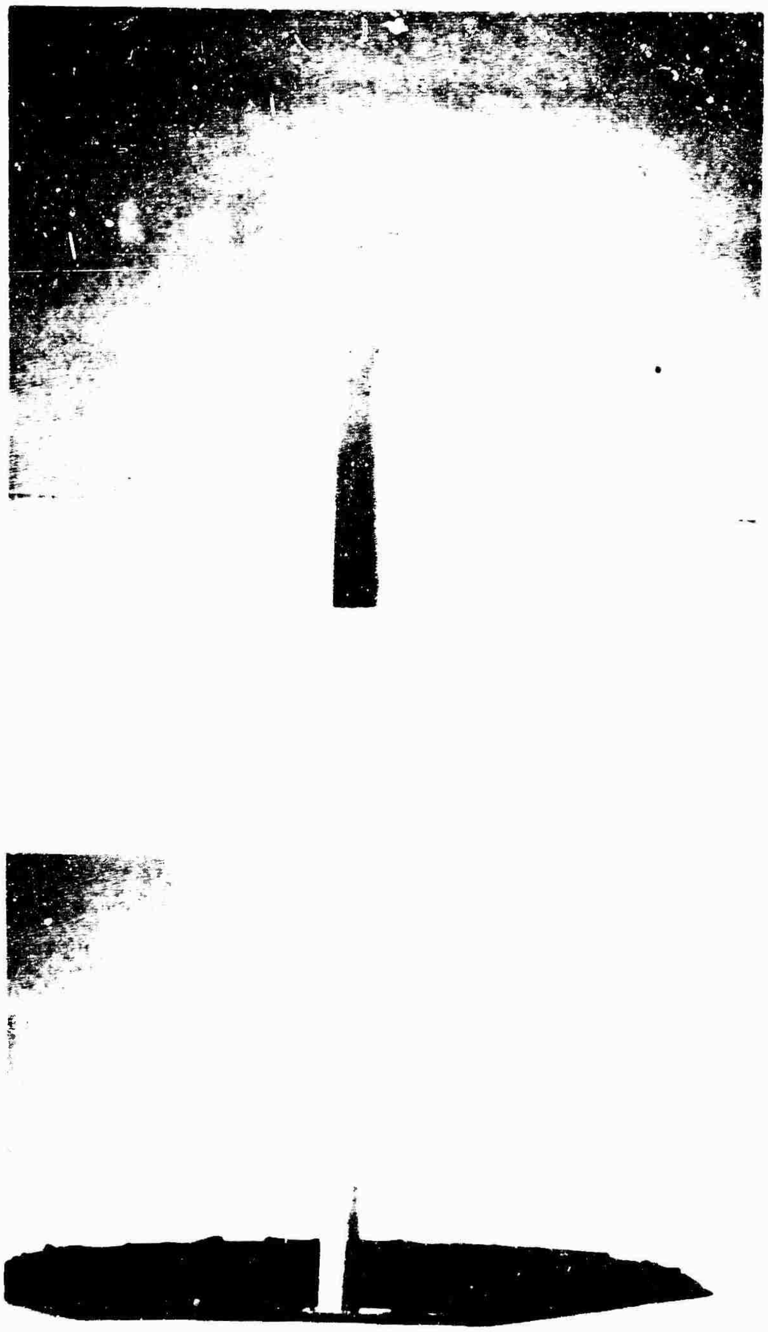


Fig. 3-1 TARGET USED FOR SCATTERING MATRIX EXPERIMENT

relative phase measurements with acceptable accuracy.

The modifications included replacing an existing R.F. uncalibrated phase shifter with an R.F. phase shifter having a calibrated vernier scale. In addition, continuously variable attenuators were used instead of the step attenuators normally employed. The phase measuring network is depicted in Figure 3-2.

Calibration

Calibration was similar to that performed in setting up circular polarization. The rotating horn, fed by a signal generator and pulsed by the transmitter sync pulse, was mounted so that linear polarizations emanated from the target point. This time, however, only four fixed rotational positions of the horn were used. These positions, determined with an inclinometer were H, V, $\pi/4$, and $-\pi/4$. After proper adjustment of the variable attenuators and/or phase shifters in each network, the transmitter and receiver chains were compensated to transmit or receive each of the above polarizations. The following procedure was used in establishing the calibration:

1. The fixed positions of the rotating horn are determined with an inclinometer. Thus H, V, $\pi/4$, and $-\pi/4$ linear polarizations can be transmitted from the target point upon demand.

2. The local oscillator of the receiver is manually tuned to the R.F. signal of the pit-located signal generator, plus or minus 60 megacycles.

3. While H and then V are received as transmitted from the pit, the attenuators in compensating networks are adjusted to obtain equal signal levels through the H and V legs of the compensating networks. Both positions of the polarization switch are then checked to see if the ± 90-degree hybrid influences the attenuator settings. If such influence is present, different attenuator settings are required as a function of the polarization switch.

4. The horn is then set to transmit $-\pi/4$ linear polarization, and phase shifters in compensating networks are adjusted to obtain a null signal. Use of this procedure results in the adjustment of the transmitter and receiver to transmit or receive $\pi/4$ linear polarization. The dial settings of the phase shifters are then recorded.

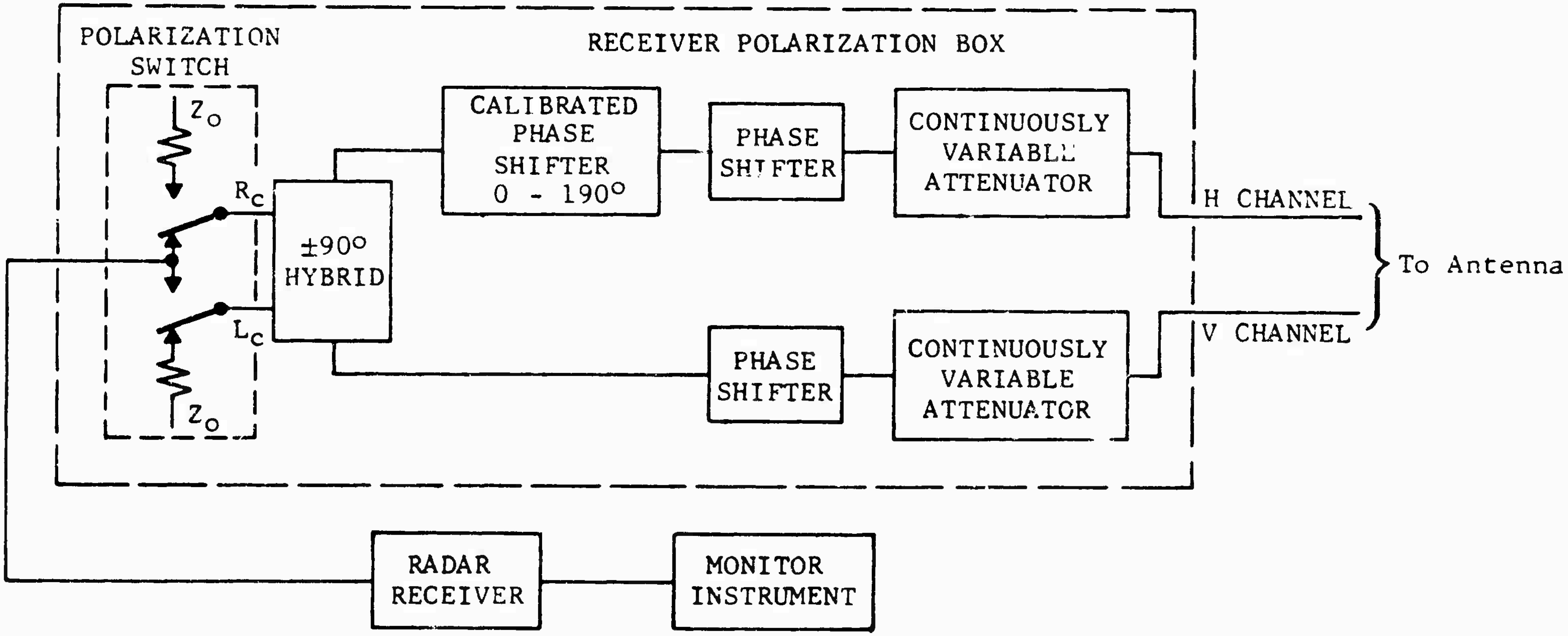


Fig. 3-2 POLARIZATION BOX IMPLEMENTED TO MEASURE RELATIVE PHASE

5. The horn is then set to transmit $\pi/4$ linear polarization, and phase shifters are adjusted to obtain a null with the polarization switch set opposite to the position used in Step 4. Use of this procedure results in the adjustment of the transmitter and receiver to transmit or receive $-\pi/4$ linear polarization. (Note that the attenuator settings found in Step 3 for the distinct positions of the polarization switch should be used.)

6. The signal generator is removed from the pit and replaced with a calibration sphere. The transmitter is then connected to the transmitter compensation network. The transmitter frequency is manually tuned to the local oscillator, plus or minus 60 megacycles, depending on the setting used during calibration. Use of this procedure results in the transfer of the calibration transmitter frequency to the operating transmitter.

7. (T $\pi/4$, R $\pi/4$) and (T $\pi/4$, R $-\pi/4$) are recorded. If it is assumed that the frequency of operation is the same as that used in calibration, these two plots should differ considerably; the amount of difference will depend on the isolation. To account for small frequency changes, the phase shifters in the two networks may need adjusting to achieve a sharper null for the condition (T $\pi/4$, R $-\pi/4$). However, the attenuators should not be changed since nulls can be attained at any two orthogonal linear polarizations.

8. Step 7 is then repeated for the conditions (T $-\pi/r$, R $-\pi/4$) and (T $-\pi/4$, R $\pi/4$) by using the polarization switches. This step is necessary since the calibrated phase shifter used in the relative phase measurements only covers a 190-degree range. Hence the shift of the $\pm$ 90-degree hybrid is used to extend the range.

9. The system is calibrated by measuring the sphere for (T $\pi/4$, R $\pi/4$).

10. The target is mounted and the cross section recorded for (T $\pi/4$, R $\pi/4$).

11. Relative phases ($\phi_{HH} - \phi_{HV}$) and ($\phi_{VV} - \phi_{VH}$) are determined for 0, 24, 48, 72, 96, 132, 156, and 180 degree azimuth angles.

(This task is accomplished by transmitting H (or V) and receiving $\sqrt{\sigma_{HH}}$ and $\sqrt{\sigma_{HV}}$ (or $\sqrt{\sigma_{VV}}$ and $\sqrt{\sigma_{VH}}$ in the orthogonal receiving channels, where $\sqrt{\sigma\alpha\rho}$ is cross section return under condition ($T\alpha$, $R\beta$). Then, the phase shift necessary to minimize the sum of the two received signals is recorded (see Figure 3-1). The following relation can be used to show sufficiency of this technique:

$$\left|\sqrt{\sigma_{HH}}+\sqrt{\sigma_{HV}}\right|^2 = \sigma_{HH}+\sigma_{HV}+2\sqrt{\sigma_{HH}\,\sigma_{HV}}\ \cos(\phi_{HH}-\phi_{HV}) \qquad (5)$$

for the case corresponding to transmit H. Thus, the amount of phase shift necessary to minimize the sum of the received signals is the amount needed for ϕHH to equal $\phi HV + \pi$, and is $\phi HH - \phi HV + \pi$. Increased accuracy in phase measurements is made possible by attenuating $\sqrt{\sigma HH}$ (or $\sqrt{\sigma VV}$) to equal $\sqrt{\sigma HV}$ and thereby balancing the right side of Equation 5 so that $\sqrt{\sigma_{HH}}+\sqrt{\sigma_{HV}}$ goes to zero as $\phi_{HH}-\phi_{HV}$ (or $\phi_{VV}-\phi_{VH}$) approaches π. Thus a very sharp null is always available for setting the phase shifter vernier. The amount of phase shift introduced by the attenuators was checked and found to be negligible. (Nominally less than 3 degrees over a 10-db dynamic range.)

12. The phase measuring network is then removed, and target cross sections σ_{VV}, σ_{VH}, σ_{HH} and σ_{HV} are recorded. (Calibration of the plots of σ_{VH} and σ_{HV} is covered in Reference 1.)

Measured Data

Table 3-1 contains a list of the type of amplitude measurement versus figure number. Table 3-2 contains a list of (1) measured values for both types of phase taken at each of the eight azimuth points chosen and (2) corresponding amplitudes for each transmitter-receiver configuration.

Table 3-1 SCATTERING MATRIX AMPLITUDE MEASUREMENTS

Transmit	Receive	Figure No.
H	H	3-3
V	V	3-4
H	V	3-5
V	H	3-6
$\pi/4$	$\pi/4$	3-7

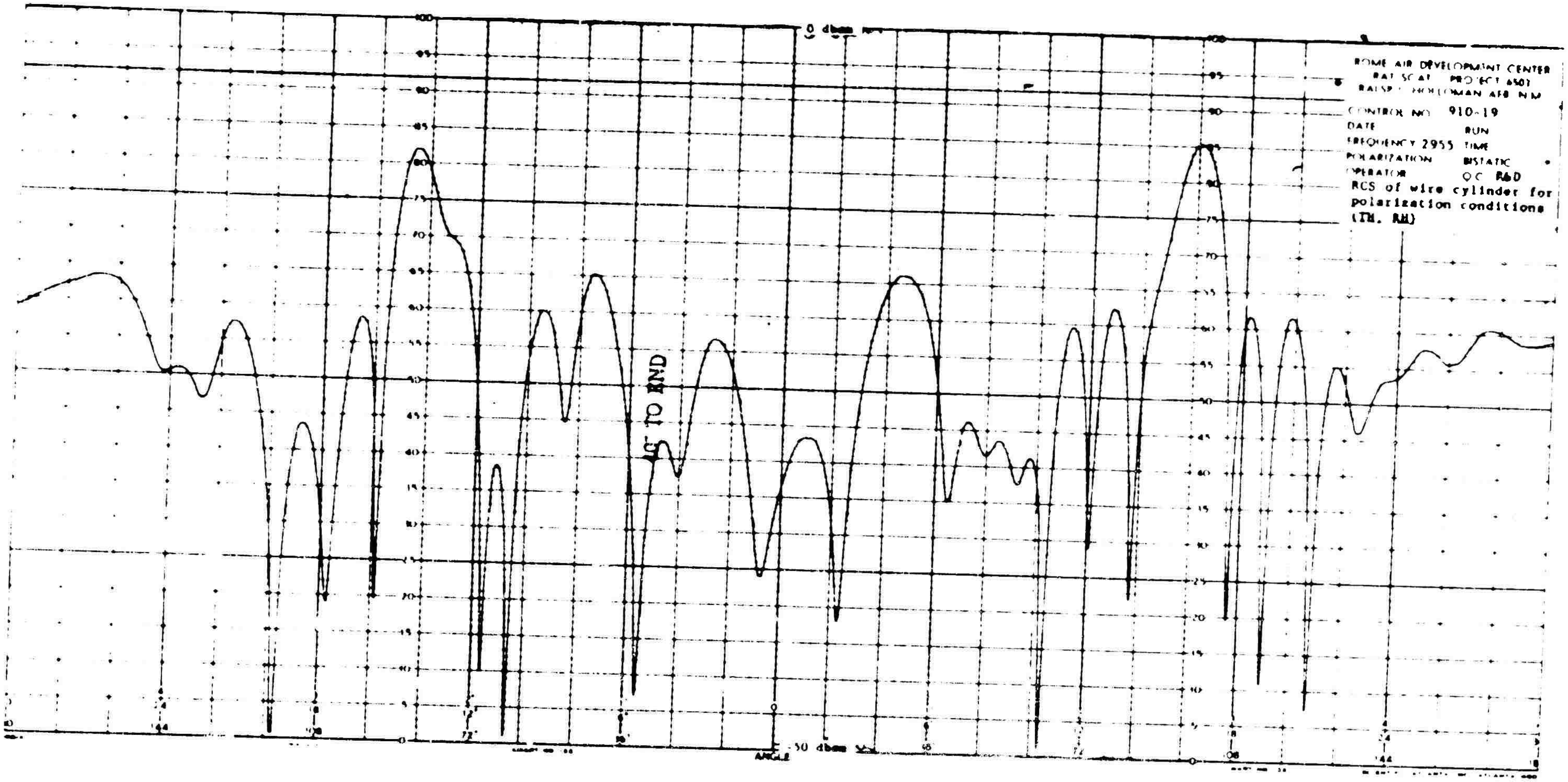


Fig. 3-3 CROSS SECTION FOR (TH ,RH)

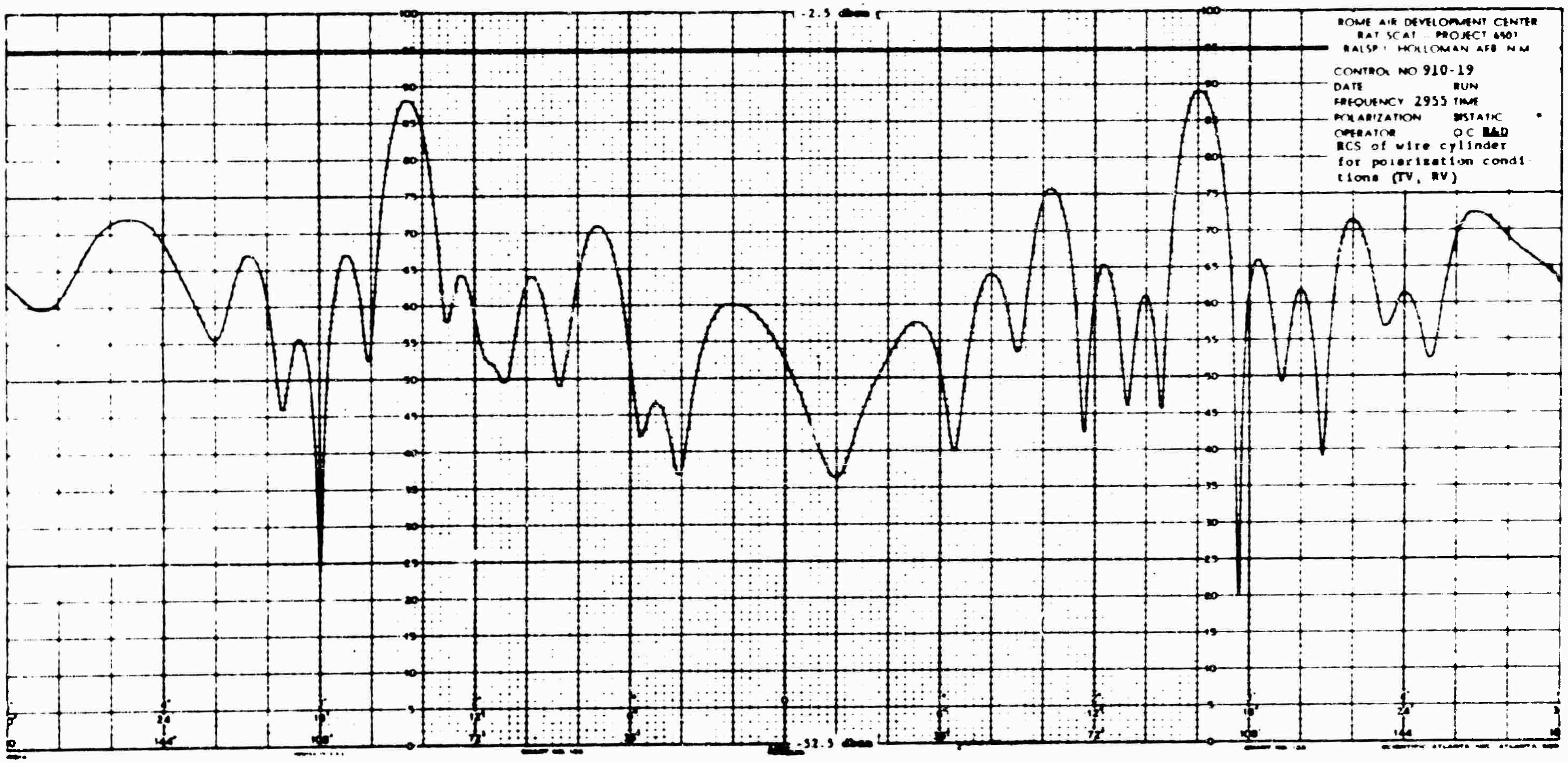


Fig. 3-4 CROSS SECTION FOR (TV,RV)

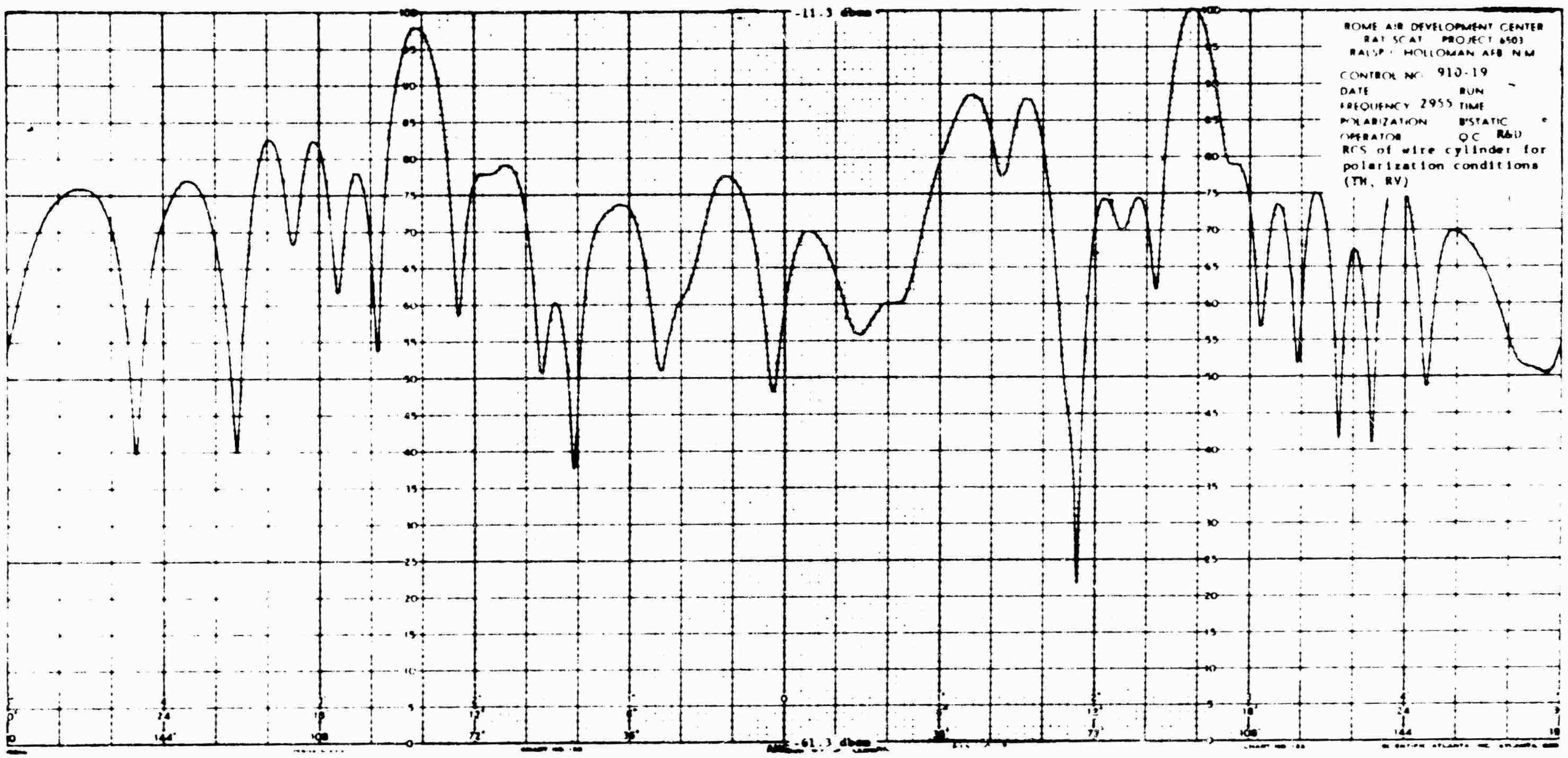


Fig. 3-5 CROSS SECTION FOR (TH ,RV)

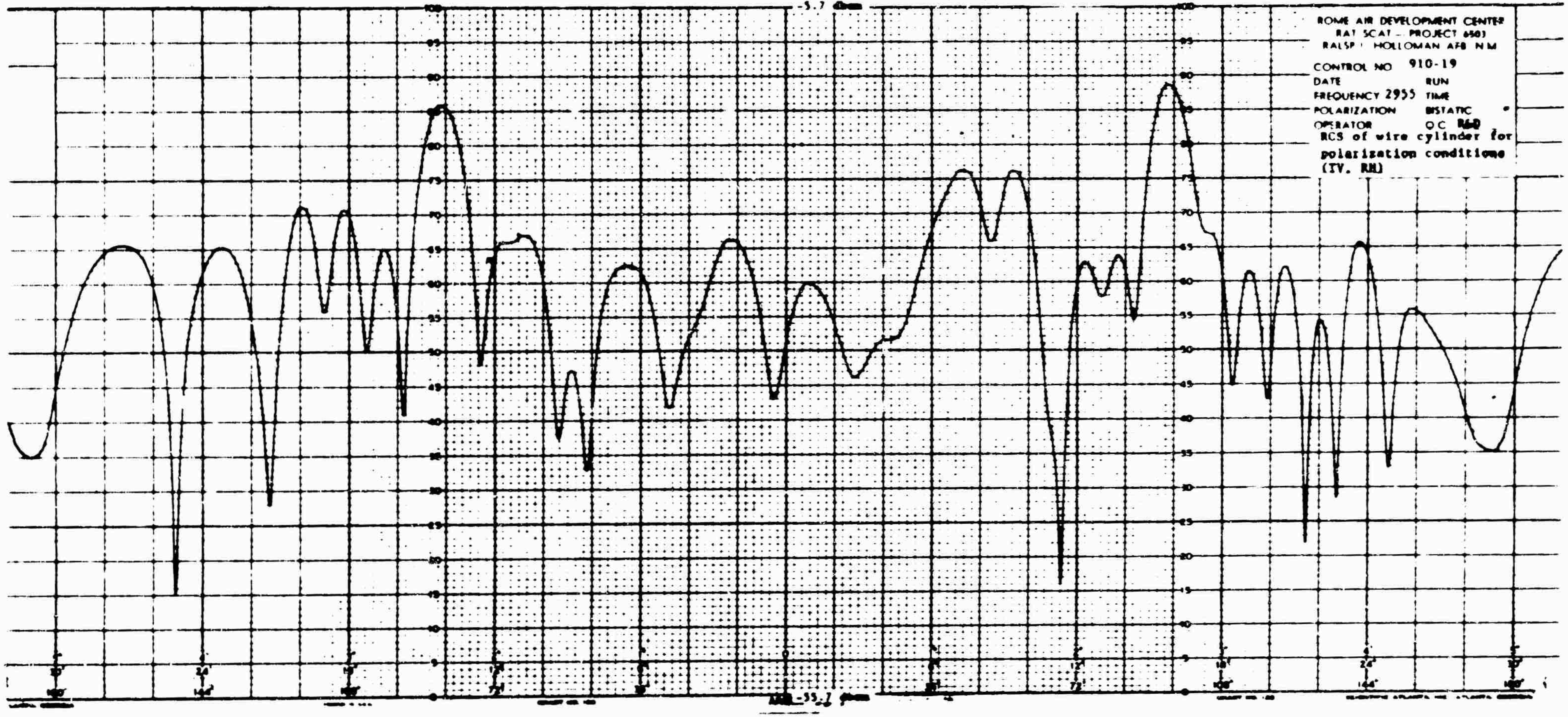


Fig. 3-6 CROSS SECTION FOR (TV,RH)

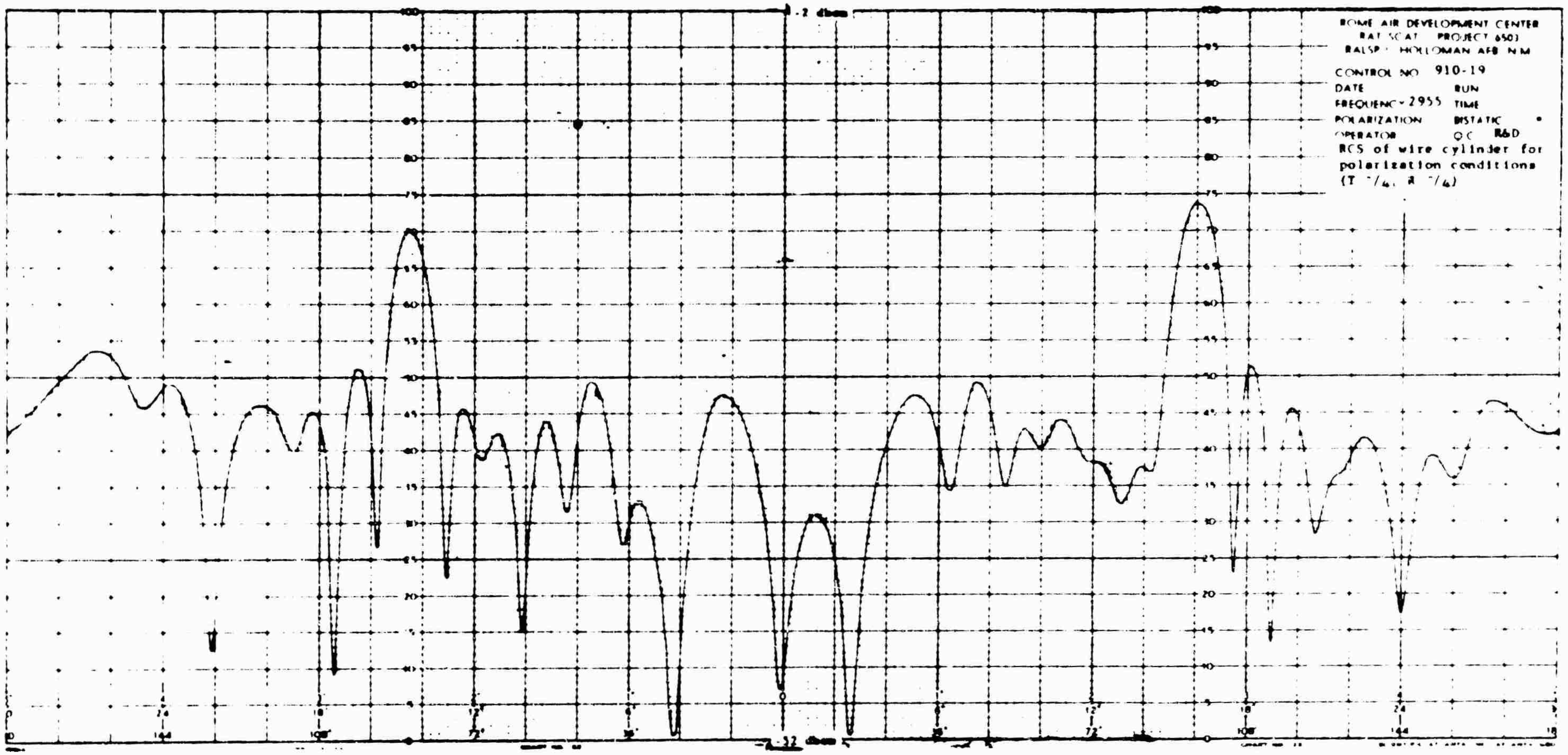


Fig. 3-7 CROSS SECTION FOR (T $\pi/4$, R $\pi/4$)

Table 3-2 SCATTERING MATRIX PHASE AND AMPLITUDE MEASURED VALUES

Azimuth	$\phi_{HH}-\phi_{HV}$	$\phi_{VV}-\phi_{VH}$	σ_{VV}	σ_{HH}	σ_{VH}	$\sigma_{\pi/4,\ \pi/4}$
	(degrees)				(dbsm)	
0	54	175.5	-29.4	-31.7	-30.9	-37.8
24	-69.5	-112	-29.3	-17.9	-30.6	-21.4
48	114	85	-23.7	-29.2	-19.9	-19.2
72	133.5	61.5	-25.1	-32.8	-25.9	-22.8
96	39.5	78.5	-11.2	- 7.3	-11.5	- 5.2
132	44	-86	-20.0	-23.8	-29.7	-22.5
156	192.5	201	-21.0	-22.1	-26.8	-24.0
180	-108	-110	-24.0	-20.5	-33.5	-20.8

Comparison of Measured Data With Theoretical Data

Comparison of Figures 3-5 and 3-6, which correspond to (TH, RV) and (TV, RH), give a clear indication of the accuracies obtained in measuring cross term amplitudes. Since (TV, RV) and (TH, RH) plots differ radically, there is no doubt as to the authenticity of the cross term plots, i.e., they are not attenuated main diagonal returns, which agree simply because the main diagonal terms agree. The data in Figures 3-5 and 3-6 indicate that errors in measuring the cross terms are nearly everywhere less than 1/2 db. The size of these errors, along with nominal 10-db separation between cross terms and main diagonal returns, indicates better than 30-db isolation. The amount of isolation possible is, of course, dependent on several factors. The fundamental limitations stem from the antenna and feed designs and their combination along with the depolarization properties of the ground plane. Aside from these factors, the space orientation of the transmitter and receiver antennas, and terminating impedances for unused feeds, are primary isolation parameters. The isolation achieved in the circular polarization experiment indicates that, with proper spacial orientation and terminating impedances, the antenna system operating at the frequency used during the experiment is capable of close to 40 db of isolation.

Although the problem of measuring cross term amplitudes was surmounted during this test series, there remain relative phase measurement errors which must be considered. An estimate of phase measurement accuracies will result from comparing the data shown in Figure 3-7 with calculated values. Table 3-3 contains a list of measured values, calculated values, and the total measurement error for each of the eight azimuth points. The calculated values corresponding to (T $\pi/4$, R $\pi/4$) were obtained by use of the relation presented in Reference 2:

$$\sigma_{\pi/4,\pi/4} = \frac{\sigma_{VV}+\sigma_{HH}}{4} + \sigma_{VH} + \sqrt{\sigma_{VV}\sigma_{VH}}\cos(\phi_{VV}-\phi_{VH})$$

$$+ \sqrt{\sigma_{HH}\sigma_{HV}}\cos(\phi_{HH}-\phi_{HV}) + \frac{1}{2}\sqrt{\sigma_{VV}\sigma_{HV}}\cos(\phi_{VV}-\phi_{HH}) \qquad (6)$$

In order to estimate phase measurement accuracies, suppose the error in $\phi_{HH} - \phi_{HV}$ is identical to the error in $\phi_{VV} - \phi_{VH}$ and that amplitudes were measured without errors. It then follows that the magnitude of the error in phase $\Delta\phi$ is given by

$$|\Delta\phi| = \left| \frac{\sigma_{\pi/4\ \pi/4}\,(\Delta - 1)}{\sqrt{\sigma_{HH}\sigma_{HV}}\,\mathrm{Sin}(\phi_{HH}-\phi_{HV}) + \sqrt{\sigma_{VV}\sigma_{VH}}\,\mathrm{Sin}(\phi_{VV}-\phi_{VH})} \right| \qquad (7)$$

where Δ is the error listed in Table 3.3. It is seen in Table 3-4 that the phase errors $\Delta\phi$ are generally less than 10 degrees.

Table 3-3 CALCULATED VERSUS MEASURED CROSS SECTION

Azimuth (degrees)	Measured* $\sigma_{\pi/4,\pi/4}$ (dbsm)	Calculated $\sigma_{\pi/4,\pi/4}$ (dbsm)	Measurement Error Δ (db)
0	-37.8	-35.7	+2.1
24	-21.4	-20.6	+0.8
48	-19.2	-18.6	+0.6
72	-22.8	-22.4	+0.4
96	- 5.2	- 4.8	+0.4
132	-22.5	-22.1	+0.4
156	-24.0	-24.2	-0.2
180	-20.8	-21.1	-0.3

* cf. Table 3-2

Table 3-4 PHASE MEASUREMENT ERROR

Azimuth (degrees)	Phase Error $\Delta\phi$
0	10
24	16.8
48	8.1
72	6.1
96	8.7
132	8.9
156	1.3
180	8.6

Comparison of Tables 3.4 and 3.3, sizes of phase error $\Delta\phi$, and magnitudes of the total measurement error Δ, indicates that scattering matrix measurements are feasible at RAT SCAT by using the relative phase technique. However, the procedure outlined in this report is time consuming and is not recommended as an operational procedure.

Automated Scattering Matrix Measurements

Although the method for obtaining the scattering matrix as previously outlined in this section may be used in each of Bands 1 through 7 with only slight modifications of existing equipment, the procedure is extremely time consuming. Two automated measurement procedures could be used in conjunction with RAT SCAT equipment. The techniques will be referred to as the absolute phase and relative phase techniques. An absolute phase measuring system is presently available in Band 4 (1 to 2 gigacycles).

Automated Relative Phase Measurements

The relative phase technique can be implemented in the form of an automated system with which the relative phase angles $\phi_{HH} - \phi_{HV}$, $\phi_{VV} - \phi_{VH}$ and $\phi_{HH} - \phi_{VV}$ (in case $\sigma_{VH} = 0$) can be recorded continuously in azimuth. The system presented in this report was proposed to RADC in 1963 by General Dynamics/Fort Worth. A block diagram of the relative phase measuring system is presented in Figure 3-8. In the proposed scheme, phase measuring is accomplished at the IF level instead of at the RF level, as in the experimental measurements discussed earlier. This approach allows a single calibrated phase shifter to be used independently of the R.F. frequency of operation. In the measurement scheme, the relative phase of the two orthogonal signals from the target is compared with the relative phase produced by a 60-megacycle reference signal fed into the orthogonal channels. Any difference between the two relative phases produces an error signal which is used to drive a reference phase shifter (ϕ shaft in Figure 3-8) to produce a relative phase between the two reference channels which is in phase with the relative phase between the two signals from the target. The shaft of the reference phase shifter is then used to derive an analog voltage proportional to the relative phase between the two signals from the target. In one leg of the reference phase system, a phase shifter is included to adjust the reference phase between the two channels for calibration purposes. Note that in the system indicated in Figure 3-8 the relative magnitudes between the two target signals is equalized by AGC in each channel. This technique is used to replace the R.F. attenuators used for this purpose in the experimental demonstration. One of the primary advantages of the proposed relative phase technique is that the target signal phase and reference signal phase are both operated on by the same circuitry; consequently, measurement errors due to system drift and nonlinearity are reduced. Also, use of the relative phase technique results in relaxing the requirements for the frequency stability necessary in all absolute phase measurement systems. The cross section of the target return in each channel can be recorded in the normal procedure used at RAT SCAT by using the signals available from the sigma servo shafts (noted by σ_1, shaft and σ_2 shaft in Figure 3-8). By using the system described above, the scattering matrix of a target can be obtained with a maximum of only three azimuth rotations and a minimum of one rotation. Three recorders are necessary, in general, two for recording cross section and one for recording relative phase. For the case where the target does not depolarize, only one rotation is necessary, and the necessary measurement is accomplished by setting the transmitter for $\pi/4$ polarization.

Automated Absolute Phase Measurements

The absolute phase technique can be implemented in the form of an automated system with which the absolute phase angles ϕ_{HH}, ϕ_{VV}, and ϕ_{VH} can be determined within a constant. The important difference between the absolute phase measuring system and relative phase measuring system is that the R.F. phase reference in the absolute phase measuring system is located twice the distance to the target from the phases to be measured. Hence radial target movement and R.F. frequency stability become important error factors not present in the relative phase measurement system. A block diagram of the absolute phase measuring system installed at RAT SCAT by General Dynamics/Fort Worth is

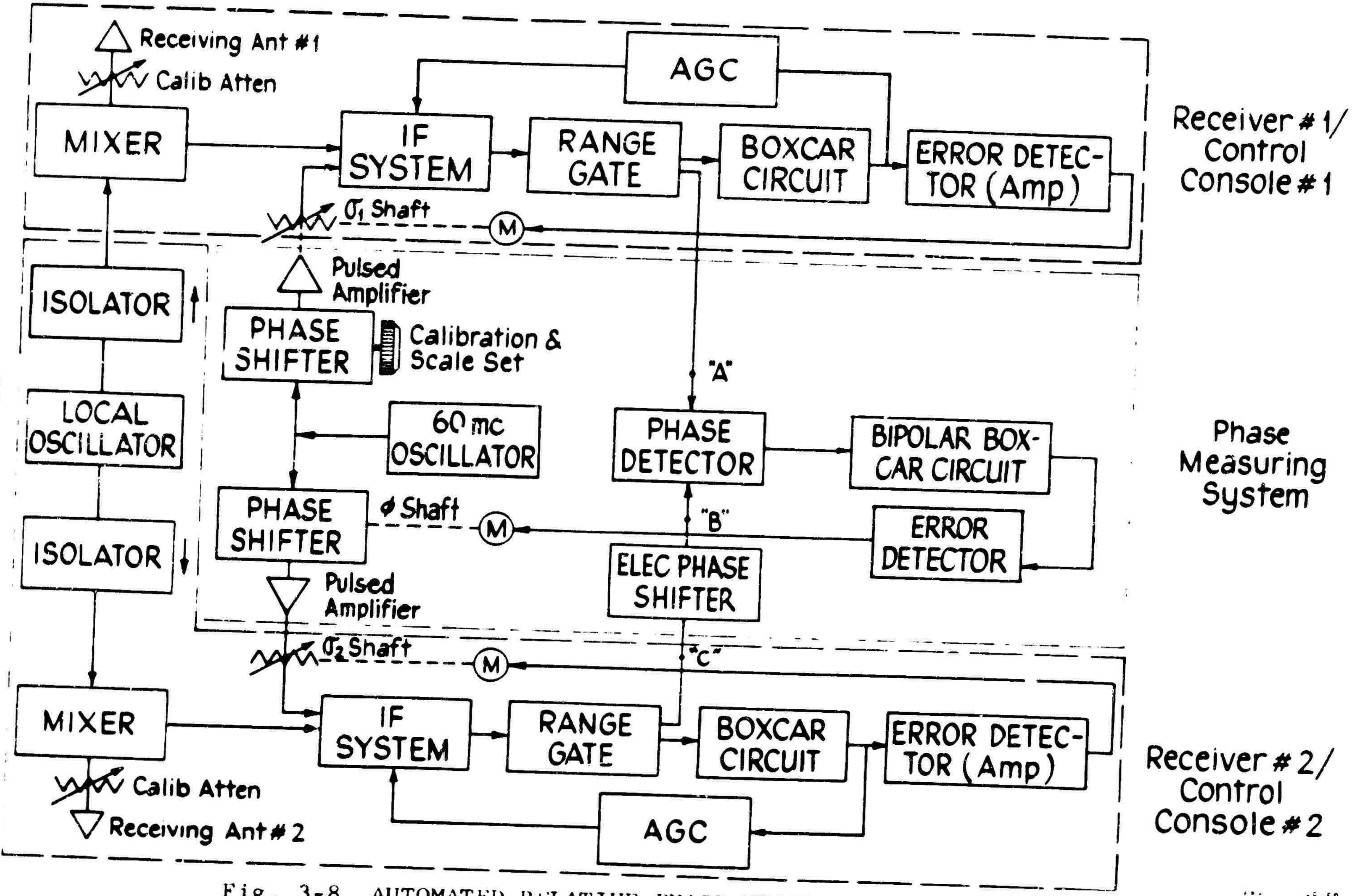


Fig. 3-8 AUTOMATED RELATIVE PHASE MEASURING SCHEME

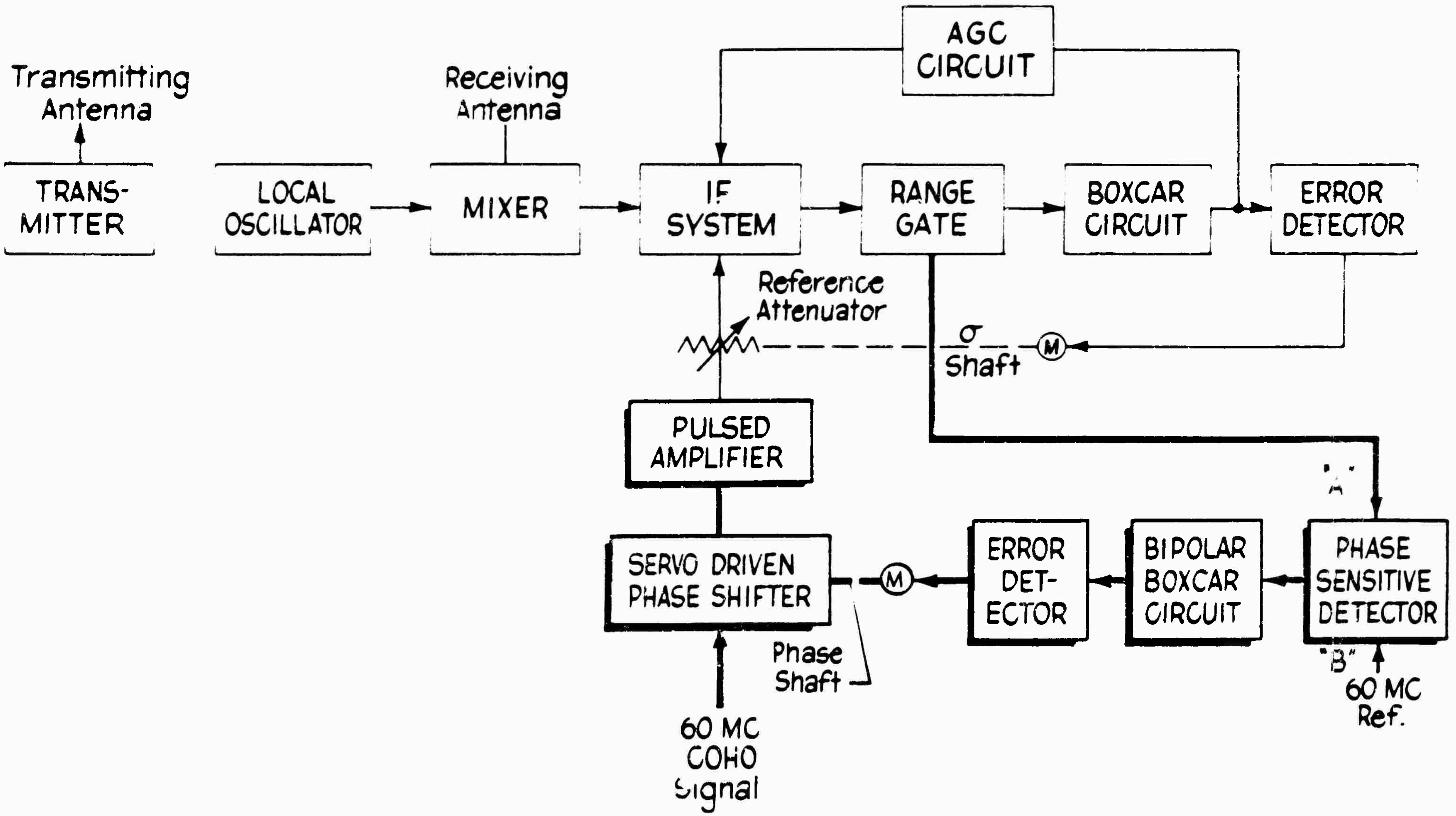


Fig. 3-9 AUTOMATED ABSOLUTE PHASE MEASURING SCHEME

presented in Figure 3-9. It can be seen that the primary difference between the system represented in Figure 3-8 and that represented in Figure 3-9 is the frequency stabilization units necessary in the absolute phase measuring system. The phase measurement is still accomplished at the IF level in the manner described under Automated Relative Phase Measurements. When the absolute phase technique is used, the information required for the linear scattering matrix can be gathered with a maximum of three target rotations. However, the minimum of two is usually required. Two recorders, one for phase and one for cross section are required for each target rotation.

The primary advantage of the absolute phase technique is in the elimination of the time-consuming calibration procedure necessary with the relative phase technique. At the time this report was written, absolute phase measurements could be made at the RAT SCAT Site in Band 4 only. However, as evidenced by the block diagrams in Figures 3-8 and 3-9, the main components of the phase measurement system are common to all bands because the phase is actually compared to the reference phase at the IF level. Hence only a small amount of additional equipment is necessary to extend the phase measuring capability to other bands.

Summary

The results of the scattering matrix experiment indicate that the calibration procedure designed to calibrate a dual-channel antenna system is satisfactory. The process used for measuring the relative phases between elements of the scattering matrix gives satisfactory accuracy but would be unduly time consuming from an operational standpoint. Also, the procedure used would require modifications to the existing equipment in the form of calibrated phase shifters and continuously variable attenuators.

From an operational point of view, the absolute phase measuring system would be the most convenient. However, this technique is inherently the more inaccurate of the two techniques discussed. At the higher frequencies (Bands 6 and 7), the absolute phase technique would probably become unacceptable because of inaccuracies in phase measurements.

The isolation between the orthogonal polarizations (H and V) appears to be satisfactory in Band 5 for measuring cross terms at least 10 db lower than the main diagonal returns with less than a one-db error. These conditions indicate isolation on the order of 30 db, which is better than the design specifications. (The circular polarization experiment indicated $\approx$ 40-db isolation is possible at this frequency with proper alignment.) However, the isolation should be checked at each operating frequency before scattering matrix measurements are attempted. To improve the orthogonalty for H, V base system measurements, it is suggested that the antennas or feeds be rotated to provide the maximum separation in the returns, σ_{HH}, σ_{HV} (or σ_{VV}, σ_{VH}), from a sphere.

REFERENCES

1. An Analysis of the Polarization Capabilities of a Ground Plane Range. Technical Documentary Report No. RADC-TDR-63-484.

2. An Analysis of the Scattering Matrix Measurement Capabilities of A Ground Plane Radar Cross Section Range. Technical Documentary Report No. RADC-TDR-64-317.

3. Investigation of Measurement Errors of the RAT SCAT Cross Section Facility. Technical Documentary Report No. RADC-TDR-64-397.

UNCLASSIFIED
Security Classification

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1 ORIGINATING ACTIVITY (Corporate author)
General Dynamics/Fort Worth
P. O. Box 748
Fort Worth, Texas 76101

2a REPORT SECURITY CLASSIFICATION
UNCLASSIFIED

2b GROUP

3 REPORT TITLE
EXPERIMENTAL RESULTS OF CIRCULAR POLARIZATION AND SCATTERING MATRIX MEASUREMENTS

4 DESCRIPTIVE NOTES (Type of report and inclusive dates)
FINAL

5 AUTHOR(S) (Last name, first name, initial)
Benn, Benjamin A.
Freeny, Charles C.

6 REPORT DATE	7a TOTAL NO OF PAGES	7b NO OF REFS
June 1964	44	3

8a CONTRACT OR GRANT NO
AF30(602)-2831

b PROJECT NO
6503

c

d

9a ORIGINATOR'S REPORT NUMBER(S)
RADC-TDR-64-380

9b OTHER REPORT NO(S) (Any other numbers that may be assigned this report)
GD/FW FZE-222-2

10 AVAILABILITY LIMITATION NOTICES
Qualified requesters may obtain copies of this report from DDC.

11 SUPPLEMENTARY NOTES
None

12 SPONSORING MILITARY ACTIVITY
RADC (EMASP)
Griffiss AFB NY 13442

13 ABSTRACT

This report contains a description of the results of experiments performed at the RAT SCAT Site, a ground plane radar cross section range, to examine the operational feasibility of measuring arbitrary targets with circular polarization and, in addition, measuring linear scattering matrices.

A calibration procedure compatible with the RAT SCAT facility is presented. Elliptical polarization was used to facilitate the establishment of circular polarization at the target point. Experimental data is presented on the magnitude of polarization degradation as a function of target size and time.

Relative phase measurements along with the necessary amplitude measurements, were used to determine the linear scattering matrix of a complex target. Finally, two annotated schemes compatible with present RAT SCAT equipment for obtaining the linear scattering matrix are described. This is the second of eight reports prepared under the RAT SCAT R&D Program.

DD FORM 1473

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Circular Polarization						
Scattering Matrix						

INSTRUCTIONS

1. ORIGINATING ACTIVITY: Enter the name and address of the contractor, subcontractor, grantee, Department of Defense activity or other organization (*corporate author*) issuing the report.

2a. REPORT SECURITY CLASSIFICATION: Enter the overall security classification of the report. Indicate whether "Restricted Data" is included. Marking is to be in accordance with appropriate security regulations.

2b. GROUP: Automatic downgrading is specified in DoD Directive 5200.10 and Armed Forces Industrial Manual. Enter the group number. Also, when applicable, show that optional markings have been used for Group 3 and Group 4 as authorized.

3. REPORT TITLE: Enter the complete report title in all capital letters. Titles in all cases should be unclassified. If a meaningful title cannot be selected without classification, show title classification in all capitals in parenthesis immediately following the title.

4. DESCRIPTIVE NOTES: If appropriate, enter the type of report, e.g., interim, progress, summary, annual, or final. Give the inclusive dates when a specific reporting period is covered.

5. AUTHOR(S): Enter the name(s) of author(s) as shown on or in the report. Enter last name, first name, middle initial. If military, show rank and branch of service. The name of the principal author is an absolute minimum requirement.

6. REPORT DATE: Enter the date of the report as day, month, year, or month, year. If more than one date appears on the report, use date of publication.

7a. TOTAL NUMBER OF PAGES: The total page count should follow normal pagination procedures, i.e., enter the number of pages containing information.

7b. NUMBER OF REFERENCES: Enter the total number of references cited in the report.

8a. CONTRACT OR GRANT NUMBER: If appropriate, enter the applicable number of the contract or grant under which the report was written.

8b, 8c, & 8d. PROJECT NUMBER: Enter the appropriate military department identification, such as project number, subproject number, system numbers, task number, etc.

9a. ORIGINATOR'S REPORT NUMBER(S): Enter the official report number by which the document will be identified and controlled by the originating activity. This number must be unique to this report.

9b. OTHER REPORT NUMBER(S): If the report has been assigned any other report numbers (*either by the originator or by the sponsor*), also enter this number(s).

10. AVAILABILITY LIMITATION NOTICES: Enter any limitations on further dissemination of the report, other than those imposed by security classification, using standard statements such as:

(1) "Qualified requesters may obtain copies of this report from DDC."

(2) "Foreign announcement and dissemination of this report by DDC is not authorized."

(3) "U. S. Government agencies may obtain copies of this report directly from DDC. Other qualified DDC users shall request through

________________________________."

(4) "U. S. military agencies may obtain copies of this report directly from DDC. Other qualified users shall request through

________________________________."

(5) "All distribution of this report is controlled. Qualified DDC users shall request through

________________________________."

If the report has been furnished to the Office of Technical Services, Department of Commerce, for sale to the public, indicate this fact and enter the price, if known.

11. SUPPLEMENTARY NOTES: Use for additional explanatory notes.

12. SPONSORING MILITARY ACTIVITY: Enter the name of the departmental project office or laboratory sponsoring (*paying for*) the research and development. Include address.

13. ABSTRACT: Enter an abstract giving a brief and factual summary of the document indicative of the report, even though it may also appear elsewhere in the body of the technical report. If additional space is required, a continuation sheet shall be attached.

It is highly desirable that the abstract of classified reports be unclassified. Each paragraph of the abstract shall end with an indication of the military security classification of the information in the paragraph, represented as (TS), (S), (C), or (U).

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

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