Activity Supply Officer, USAECOM
Building 2504, Charles Wood Area
Fort Monmouth, New Jersey

MARKED FOR: Electromagnetic Environment Division
ATTN: Contracting Officer's Designated Representative
Inspect at Destination
FR No. 28-043-M6-22074(E)

FOR: Accountable Property Officer


Gentlemen:

A research program to investigate electromagnetic measurement methods for use in shielded enclosures in accordance with Electronics Command Technical Requirement No. SCL-2895A was initiated 1 June 1966.

Thus far, five sub-tasks have been initiated under this program. A series of antenna coupling measurements over the frequency range from 500 KHz to 50 MHz is being performed both in the open-field and in a shielded enclosure. The objective of these measurements is to determine the effect of the shielded enclosure on measurements at frequencies well below the lowest resonant frequency of the enclosure.

A theoretical study program to investigate the near-field of a radiating source is being performed. The polarization, phase, and magnitude characteristics of the principle and secondary fields in the near region of the source are being examined in some detail. It is planned that the results from the low-frequency measurement program will be utilized to substantiate the theoretical results, and on the other hand, the theoretical results will be utilized to explain some of the measurement results.

A conical log-helix antenna to cover the range from 1 to 12 GHz has been designed and fabricated. VSWR measurements have been performed on this antenna over the frequency range from 1 to 9 GHz and the results are very encouraging. The average VSWR over this range was found to be 2.2,
the maximum 3.9, and the minimum 1.1. Gain and pattern measurements are presently being performed on this antenna.

A conical log-helix antenna to cover the frequency range from 200 to 1500 MHz is being designed. It is anticipated that fabrication of this antenna will begin within one week.

A study to develop technically valid measurement procedures for performing case radiation and susceptibility measurements in shielded enclosures has been initiated. To date, the measurement procedures from 19 specifications and standards have been compiled and are presently being analyzed. With the results from this analysis and results from various measurement programs, it is expected that decisions can be made on questions such as (1) is a ground plane required for these measurements, and if so, what are the optimum parameters and orientation for the ground plane?, (2) what is the optimum approach to standardizing power line impedance?, (3) routing, length, and orientation for power and signal cables, (4) optimum test configuration and location in shielded enclosure, and (5) optimum data format.

Respectfully submitted:

William R. Free
Project Director

Approved:

D. W. Robertson, Head
Communications Branch
Activity Supply Officer, USAECOM
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Fort Monmouth, New Jersey

MARKED FOR: Electromagnetic Environment Division
ATTN: Contracting Officer's Designated Representative
Inspect at Destination
FR No. 28-043-M6-22074(E)

FOR: Accountable Property Officer

to 1 August 1966, Contract DA 28-043 AMC-02381(E), "Electromagnetic Interference Measurement Methods - Shielded Enclosure."

Gentlemen:

A research program to investigate electromagnetic measurement methods
for use in shielded enclosures, as described in the last monthly report,
has continued during this reporting period.

A hooded, conical log-helix antenna to cover the frequency range from
1 to 12 GHz has been designed and fabricated. Antenna pattern measurements
have been performed on this antenna over the frequency range from 1 to 12
GHz. Gain and VSWR measurements have been completed over the frequency
range from 1-10 GHz. Gain and VSWR measurements are presently being con-
ducted in the range from 10 to 12 GHz. It is anticipated that the gain
and VSWR measurements as well as polarization measurements will be completed
on this antenna during the coming month.

A conical log-helix antenna to cover the frequency range from 200 to
1500 MHz has been designed and fabricated. VSWR measurements have been
completed on this antenna, and it is anticipated that gain, antenna pattern
and polarization measurements will be performed during the coming month.

A theoretical study program to investigate the near-field of a radiating
source and a study to develop technically valid measurement procedures for
performing case radiation and susceptibility measurements in shielded
enclosures have continued during this period.

Respectfully submitted:

William R. Free
Project Director

Approved:

D. W. Robertson, Head
Communications Branch
Gentlemen:

A research program to investigate electromagnetic measurement methods for use in shielded enclosures, as described in the previous reports, has continued during this reporting period.

The evaluation of a hooded, conical log-helix antenna to cover the frequency range from 1 to 12 GHz has been completed and is reported in detail in Quarterly Report No. 2. A series injection calibration network has been integrated into this hooded antenna configuration and measurements are presently being performed to determine the effects of the addition of this network on the characteristics of the hooded antenna.

The evaluation of a conical log-helix probe antenna to cover the frequency range from 200 to 1500 MHz has continued during this report period and it is estimated that this task is 80 percent complete. The fabrication of a hood for use with this probe antenna has been in progress during this period. The hood is being constructed from an aluminum cylinder which is four feet long and two feet in diameter. The cylinder is mounted on a cart with wheels so that the final hooded antenna will be readily movable for orientation purposes. The cylinder is being lined with the Ecocore NZ-1 ferrite absorbing material. It is estimated that the fabrication of the hood is 50 percent complete.
The theoretical and experimental studies to investigate the near-fields of radiating sources at low frequencies and a study to develop technically valid measurement procedures for performing case radiation and susceptibility measurements in shielded enclosures have continued during this period.

Respectfully submitted:

William R. Free
Project Director

Approved:  

D. W. Robertson, Head
Communications Branch
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Building 2504, Charles Wood Area
Fort Monmouth, New Jersey

MARKED FOR: Electromagnetic Environment Division
ATTN: Contracting Officer's Designated Representative
Inspect at Destination
FR No. 28-043-M6-22074(B)

FOR: Accountable Property Officer


Gentlemen:

A research program to investigate electromagnetic measurement methods for use in shielded enclosures, as described in the previous reports, has continued during this reporting period.

The evaluation of a microwave hooded probe antenna, incorporating a series injection calibration network, has continued during this period. This probe antenna is intended to cover the frequency range from 1 to 12 GHz. The purpose of the current evaluation is to determine the effects of the series calibration network on the characteristics of the hooded antenna. At the conclusion of the present evaluation, a program will be initiated to calibrate the probe antenna in terms of field intensity incident on the antenna versus calibrate power at the calibrate port of the antenna. It is planned that the calibration will be accomplished by establishing standard field intensities by means of standard gain horns.

The fabrication of a cylindrical hood, four feet long and two feet in diameter, for use with a UHF probe antenna over the frequency range from 200 to 1500 MHz was completed during this period. The probe antenna is presently being mounted in the hood, and the evaluation of the complete hooded configuration will be initiated in the near future.

Theoretical and experimental studies to investigate the near-fields of radiating sources at low frequencies in shielded enclosures have continued during this period. Previous measurements have demonstrated the low-frequency field distribution on the axis of a shielded enclosure with one
end wall covered with absorbing material. The objectives of the present measurements are to show the effects of (1) removing the absorbing material from the end wall, (2) changing the location of the radiating source within the shielded enclosure, and (3) changing the length of the shielded enclosure.

Respectfully submitted:

William R. Free
Project Director

Approved:  

D. W. Robertson, Head
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ATTN: Contracting Officer's Designated Representative
Inspect at Destination
FR No. 28-043-M6-22074(E)

FOR: Accountable Property Officer


Gentlemen:

A research program to investigate electromagnetic measurement methods for use in shielded enclosures, as described in the previous reports, has continued during this reporting period.

The development and evaluation of a microwave hooded probe antenna to cover the frequency range from 1 to 12 GHz and a UHF hooded probe antenna to cover the frequency range from 200 to 1500 MHz are continuing.

Measurements to evaluate the characteristics of the UHF hooded probe antenna are being conducted. Techniques and procedures have been developed for calibrating the microwave hooded antenna to obtain antenna correction factors over the operating range of the probe antenna. The antenna correction factors will make it possible to convert signal power levels at the antenna terminal to field intensity levels at the aperture of the antenna.

Theoretical and experimental studies to investigate the near-fields of radiating sources at low frequencies in shielded enclosures have continued during this period.

On-axis and off-axis antenna coupling measurements, previously performed in a 8 x 8 x 20 foot shielded enclosure, are being repeated in a 8 x 8 x 12 foot enclosure to determine if the results and conclusions based on the measurements in the 8 x 8 x 20 foot enclosure are applicable to shielded enclosures having different dimensions.
Efforts have continued to develop a mathematical model describing the field distribution within shielded enclosures as a function of frequency. Due to the complexity of the calculations required for this development, the problem is being programmed for the Burroughs 5500 Computer. Several of the required program blocks have been completed during this reporting period.

Respectfully submitted:

William R. Free
Project Director

Approved:

D. W. Robertson, Head
Communications Branch
1 February 1967

Activity Supply Officer, USAECOM
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Fort Monmouth, New Jersey

MARKED FOR: Electromagnetic Environment Division
ATTN: Contracting Officer's Designated Representative
Inspect at Destination
FR No. 28-043-M6-22074(E)

FOR: Accountable Property Officer

SUBJ: Monthly Report No. 6, 5 February 1967, Report Period 1
January 1967 to 1 February 1967, Contract DA 28-043
AMC-02381(E), "Electromagnetic Interference Measurement
Methods - Shielded Enclosure."

Gentlemen:

Measurements to evaluate the UHF hooded probe antenna to cover the
frequency range from 200 to 1500 MHz were completed during this report
period. The data from these measurements are being analyzed and prepared
for presentation in the next quarterly report.

Measurements to evaluate the microwave hooded probe antenna after the
modification to add a series injection calibration network were also
completed during this period. The data obtained from these measurements
will be presented in the next quarterly report.

Experimental coupling measurements in a 8 x 8 x 12 foot shielded
enclosure over the frequency range from 1 to 100 MHz were completed during
this period. A comparison of the results obtained from these measurements
with results obtained in a 8 x 8 x 20 foot enclosure will be included in
the next quarterly report.

A computer program for simulating reflection conditions in a shielded
enclosure has been completed. The current version of this program sums
the electric fields from the direct transmission path and six reflected
transmission paths when "short" dipoles are used as radiating and
receiving elements.
Runs have been made for 12 different frequencies, with antenna element separation being varied from 12 inches to 100 inches for each run. Six of the runs show reasonable good correlation with data obtained from experimental measurements made in a shielded enclosure.

Respectfully submitted:

William R. Free
Project Director

Approved:

D. W. Robertson, Head
Communications Branch
GEORGIA INSTITUTE OF TECHNOLOGY
ENGINEERING EXPERIMENT STATION
ATLANTA, GEORGIA 30332

1 April 1967

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Fort Monmouth, New Jersey

MARKED FOR: Electromagnetic Environment Division
ATTN: Contracting Officer's Designated Representative
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FR No. 28-043-M6-22074(E)

FOR: Accountable Property Officer

to 1 April 1967, Contract DA 28-043 AMC-02381(E), "Electromagnetic
Interference Measurement Methods - Shielded Enclosure."

Gentlemen:

During this reporting period a series injection calibration network was
installed in the UHF hooded antenna. Some re-evaluation of this antenna
is being performed to determine the effects of the calibration network on
the antenna characteristics. At the conclusion of this re-evaluation, the
microwave and UHF hooded antennas will be field-intensity calibrated.

An AEL cavity-backed spiral antenna (Model ASN 118A) is being eva-
ualted as a possible probe antenna for the hooded technique. Since this
antenna is a planar structure, it offers the possible advantages of allow-
ing a shorter hood to be used and provides a fixed phase-center for the
probe antenna within the hood. Antenna patterns for the cavity-backed spiral
antenna, both hooded and unhooded, have been obtained over the frequency
range from 2 to 11 GHz. Gain measurements for this antenna over the 2 to
11 GHz frequency range are presently being conducted.

A number of runs of the computer program simulating reflection condi-
tions in a shielded enclosure is currently in progress. The purpose of
these runs is to simulate different locations for the radiating element in
the enclosure and different enclosure dimensions.

Respectfully submitted,

William R. Free
Project Director

Approved:  

D. W. Robertson, Head
Communications Branch

REVIEW

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Fort Monmouth, New Jersey

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ATTN: Contracting Officer's Designated Representative
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FR No. 28-043-M6-22074(E)

FOR: Accountable Property Officer

SUBJ: Monthly Report No. 8, 5 May 1967, Report Period 1 April 1967
to 1 May 1967, Contract DA 28-043 ANC-02381(E), "Electromagnetic Interference Measurement Methods - Shielded Enclosure".

Gentlemen:

The evaluation of the AEL cavity-backed spiral antenna (Model ASN 118A), hooded and unhooded, was completed during this reporting period. The data from this evaluation is being processed and will be presented in the final report.

The field-intensity calibration of the microwave hooded antenna is currently being performed. It is anticipated that the field-intensity calibrations of both the microwave and UHF hooded antennas will be completed during the month of May.

Case emission measurements are being performed on a small mobile transmitter in the frequency range from 1 to 30 MHz. The measurements are being performed in the open-field and in a shielded enclosure to show the correlation between the measurements over this frequency range. The results from these measurements will be presented in the final report.

A computer program for simulating the transmission conditions in a shielded enclosure where the radiating element is a "long" dipole was completed during this period. Some preliminary runs of this program are currently in progress.

Respectfully submitted,

William R. Free
Project Director

Approved: 

D. W. Robertson, Head
Communications Branch
TECHNICAL REPORT ECOM-02381-1

ELECTROMAGNETIC INTERFERENCE MEASUREMENT METHODS-SHIELDED ENCLOSURE

QUARTERLY REPORT 1

By

W. R. FREE, C. H. BONHAM, R. E. GIBSON
J. H. GUTZKE and B. M. JENKINS

JANUARY 1967

ECOM
UNITED STATES ARMY ELECTRONICS COMMAND • FORT MONMOUTH, N.J.

Contract DA 28-043 AMC-02381(E)
Engineering Experiment Station
GEORGIA INSTITUTE OF TECHNOLOGY
Atlanta, Georgia
NOTICES

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Disposition

Destroy this report when it is no longer needed. Do not return it to the originator.
ELECTROMAGNETIC INTERFERENCE MEASUREMENT
METHODS-SHIELDED ENCLOSURE

QUARTERLY REPORT NO. 1
1 JUNE 1966 TO 31 AUGUST 1966
Report No. 33

CONTRACT NO. DA 28-043 AMC-02381(E)
DA TASK NO. 1E6 205010D 149 01

Prepared By
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ATLANTA, GEORGIA

For

U. S. ARMY ELECTRONICS COMMAND
FORT MONMOUTH, N. J.
ABSTRACT

During the period covered by this report, investigations have been conducted to develop test techniques and procedures for making radiated measurements in shielded enclosures which can be correlated with open-field measurements. The primary objective of this program is to develop a capability for determining the case radiation and susceptibility characteristics of U. S. Army communication equipments in the controlled environment of a shielded enclosure.

A microwave hooded probe antenna was designed, fabricated and evaluated during this period. The evaluation has demonstrated the capability of this probe antenna in performing radiated measurements in a shielded enclosure over the frequency range from 1 to 12 GHz which have very good correlation with measurements made in the open-field.

A UHF hooded probe antenna, for use over the frequency range from 200 to 1500 MHz, has been designed and fabricated. This antenna is presently being evaluated.

A theoretical and experimental investigation to determine the field distribution within a shielded enclosure at low frequencies is being conducted. The present status of these programs is discussed.

A study to develop technically valid procedures and test setups for use in making measurements in shielded enclosures is also being conducted. A description of the study program is presented.
FOREWORD

This report was prepared at the Georgia Tech Engineering Experiment Station on Contract No. DA 28-043 AMC-02361(E). The work covered by this report was performed within the Communications Branch under the general supervision of Mr. D. W. Robertson, Head of the Communications Branch. The report covers the activities and results of the first quarter's effort on a project to determine methods for measuring the interference characteristics of U. S. Army communication equipments in shielded enclosures.

The authors are pleased to acknowledge the efforts of J. W. Cofer, J. D. Doster and W. S. Giddens in a number of the fabrication and measurement phases of the program.
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I. FACTUAL DATA

A. Introduction

1. Purpose and Objectives of the Program

This report covers the work performed under contract DA 28-045 AMC-02381(B), "Electromagnetic Interference Measurement Methods - Shielded Enclosure," for the period from 1 June 1966 to 31 August 1966.

The purpose of this program is to conduct a theoretical and experimental investigation to determine the test setups, accessories and procedures best suited to measurement, in shielded enclosures, of the electromagnetic emission and susceptibility characteristics of military communication-electronic equipment.

The program is divided into three primary tasks. These tasks are:

(a) The development of hooded probe antennas to cover, as a minimum, the frequency range 200 MHz to 12 GHz.

(b) A theoretical and experimental study of the problems associated with near-field measurements in shielded enclosures below 50 MHz.

(c) The development of measurement procedures for making emission and susceptibility measurements in shielded enclosures. These procedures will utilize the results from (a) and (b) above and will include specific test setups and necessary accessories.

2. Background

Present techniques for case and cable emission and susceptibility measurements are seriously inadequate, and need to be improved to assure repeatability and correlation between measurement data taken at different times and/or different locations. If these measurements are made in the "open-field", strong man-made and atmospheric background interference make measurements difficult and often impossible. If the measurements are made in a shielded enclosure to avoid the environmental interference, standing waves and enclosure resonances make the measurements highly susceptible to minor variations in equipment placement, enclosure dimensions, and personnel location.
A considerable amount of effort was devoted to this problem during the last six quarters of a previous program at Georgia Tech under contract DA 36-039 AMC-02296(2).1,6

Under this program a number of the basic problems associated with making emission and susceptibility measurements in shielded enclosures were investigated.

A typical measurement setup in a shielded enclosure is shown in Figure 1. The diagram shows some of the multiple signal paths which exist with this measurement configuration. An extensive measurement program was conducted as a part of the earlier program to determine the magnitude of the effects of the shielded enclosure on the measurements. Measurements were made to determine the effects of a shielded enclosure on the coupling between two antennas (a) at a fixed separation as a function of frequency, (b) at a fixed frequency as a function of separation and (c) as a function of the location of the test setup within the shielded enclosure.

A curve showing the coupling between two antennas spaced 1 meter apart in a 8 x 8 x 8 foot shielded enclosure over the frequency range from 40 MHz to 2 GHz is shown in Figure 2. This curve has been normalized with respect to an open-field coupling curve to remove the coupling variations due to the antenna characteristics, and hence, all coupling variations shown in the normalized coupling curve result from the presence of the shielded enclosure walls. The results indicate that coupling variations in the order of ±40 db are possible as a function of frequency of operation. Similar results were obtained as a function of separation between the two antennas and as a function of location of the test setup within the shielded enclosure. It is obvious that measurements made under these conditions are of little value and the possibility of correlating these measurements with measurements made in the open-field is small.

A number of techniques for reducing the multipath reflections within shielded enclosures were investigated during this prior program. These investigations included the evaluation of several types of absorbing materials, the evaluation of various shapes and placements of absorbing materials within shielded enclosures, and the evaluation of shielded enclosures in a variety of shapes, including enclosures in the form of paraboloidal and ellipsoidal sections. While some of these techniques appeared to satisfactorily reduce the multipath reflections over a significant part of the frequency range of interest, the implementation of these techniques is expensive, involves complex fabrication techniques to obtain the required shapes and requires considerable space to accommodate the required shapes and absorbing materials.

The continuing search for a technique which would reduce the multipath reflections in shielded enclosures, but which would not have the
Figure 1. Diagram of a Conventional Measurement Setup in a Shielded Enclosure Showing Multiple Signal Paths.

Figure 2. Coupling Between Antennas in a Shielded Enclosure as a Function of Frequency at a Spacing of 1 Meter.
cost, fabrication and space limitations mentioned above, led to a concept of shielding the probe antenna in all directions except the desired signal path. From this concept, a hooded antenna measurement technique was developed and evaluated. A diagram showing a typical hooded antenna measurement setup in a shielded enclosure is shown in Figure 3. A number of possible signal paths are shown in the shielded enclosure, but as illustrated, only that signal traveling the desired path reaches the shielded probe antenna.

The antenna hood consists of a metal shield or box, open on one end, the walls of which are lined on the inside with absorbing material. Additional absorbing material is required on the shielded enclosure wall opposite the open end of the hood to prevent multiple reflections from reaching the antenna.

The concept of the hooded antenna differs little from the concept of the conventional RF absorbing material lined enclosure. The five absorber lined walls of the hood, together with the partially lined enclosure wall look essentially the same to the receiving antenna as the six absorber lined walls of the conventional enclosure. The principle difference is that the hooded antenna concept requires considerably less absorbing material.

![Diagram of a Hooded Antenna Measurement Setup in a Shielded Enclosure.](image-url)
Results from initial evaluations of the hooded antenna technique over the frequency range from 200 MHz to 10 GHz indicate that this technique is capable of reducing the multi-path reflections in shielded enclosures to a level comparable with the reflections normally encountered in open-field measurements. Antenna patterns of an eighteen-inch dish with a log-periodic feed at a frequency of 2 GHz are shown in Figure 4. These patterns were made in the open-field and in a shielded enclosure both with a conventional unshielded probe antenna and a hooded probe antenna. It is apparent that there is good correlation between the two open-field patterns and the pattern made in the shielded enclosure with the hooded probe antenna. However, severe distortion is apparent in the pattern made in the shielded enclosure with the unshielded probe antenna. These patterns demonstrate the ability of the hooded antenna to reduce the multi-path reflections in a shielded enclosure.

Several broadband, circularly-polarized, balanced antenna configurations were tested in order to select optimum probe antenna types for use in the evaluation of the hooded antenna technique. The results of this initial evaluation indicated that the conical log-helix antenna was probably the best configuration from which to develop test antennas for use with the hood.

Experimental hooded antennas covering the frequency range from 200 MHz to 10 GHz have been fabricated. These antennas were developed to prove the feasibility of the approach but the designs were not refined beyond the point of meeting the requirements of the preliminary evaluation. Consequently, a need exists to improve the design of these hooded antennas to the point that operational hooded antennas can be fabricated.

B. Development of Hooded Antennas

1. General

A primary objective of the present program is to develop hooded antennas to cover, as a minimum, the frequency range from 200 MHz to 12 GHz. An initial goal is to cover this frequency range with two antennas, a VHF/UHF hooded antenna and a microwave hooded antenna.

As mentioned previously, several broadband, circularly-polarized, balanced antenna configurations were evaluated on the previous program under contract DA-36-039 AMC-02294(B) to determine the optimum probe antenna types for use in the hooded antennas. Of all the antenna configurations considered, the balanced conical log-helix antenna appeared most likely to satisfy all of the requirements for the test antenna. The bandwidth obtainable with this antenna configuration is almost entirely at the discretion of the designer. Antennas with bandwidths of higher than
Figure 4. Antenna Patterns of an Eighteen Inch Dish with a Log-Periodic Feed at a Frequency of 2 GHz.
40 to 1 have been constructed. A balanced antenna may be obtained by winding two identical spiral arms on a conical surface. As long as physical symmetry is maintained by using identical spirals maintained at 180 degrees on the conical surface, a balanced, essentially constant impedance is obtained at the apex of the antenna over the design bandwidth. Circular-polarization is obtained with this antenna configuration. A maximum on-axis voltage axial ratio of 1.2 is typical over the bandwidth of the antenna. The field is circularly-polarized well off-axis, and a voltage axial ratio of less than 2.0 is typical out to 45 degrees off-axis. In addition to satisfying the broadband, balanced, circular-polarization requirements for a test antenna, the conical log-helix antenna offers a number of other desirable characteristics. The field pattern of the conical antenna is confined to one hemisphere, i.e., it is unidirectional, with the main lobe occurring on the longitudinal axis off the apex of the cone. For small cone angles, 20 degrees or less, a rotationally symmetrical main lobe with a half-power beamwidth of 50 to 70 degrees is obtained. Under these conditions a front-to-back ratio of 15 dB or greater is obtained. These unidirectional characteristics are desirable in a test antenna to be used in a shielded enclosure since they significantly reduce the susceptibility of the test antenna to multi-path reflections from the enclosure walls. The directional characteristics of the antenna improve the threshold sensitivity of the instrumentation system, and the rotational symmetry of the main lobe masks the beam rotation with frequency, which is inherent in the log-helix antenna. In addition, the configuration of the conical log-helix antenna is particularly compatible with a number of broadband balun techniques.\textsuperscript{7,8,9}

The geometry of a balanced conical log-helix antenna is shown in Figure 5. The diameter of the truncated apex, $d$, defines the upper frequency limit of the antenna and is defined by

$$d = \frac{\lambda_H}{2}$$

(1)

where: $\lambda_H =$ wavelength of the highest useable frequency. The diameter of the base, $D$, determines the lower frequency limit of the antenna and is defined by

$$D = \frac{\lambda_L}{2}$$

(2)

where: $\lambda_L =$ wavelength of the lowest useable frequency. The helical arms are shown as solid diagonal lines on the surface of the cone.
Figure 5. Diagram of Balanced Conical Log-Helix Antenna.
The second line is the second arm of the balanced structure and is rotated 180 degrees on the cone surface relative to the first arm. The arms alternate and the spacing between the arms increases in a logarithmic fashion in moving from the apex to the base. The arms maintain a constant angle, \( \alpha \), with the radius vector of the cone. The pattern beamwidth, front-to-back ratio, axial ratio and VSWR characteristics all appear to be related to the rate of spiral and hence are dependent on the angle \( \alpha \) and the cone angle \( \theta_0 \). Thus, after the bandwidth has been determined by selecting values for the truncation diameters, \( D \) and \( d \), it is necessary to select values for \( \alpha \) and \( \theta_0 \) which will provide the desired pattern and impedance characteristics over the operating bandwidth. Reference \( (10) \) contains monographs relating parameters to the operating characteristics.

The helical arms are defined on the surface of the cone by

\[
\rho = \rho_o e^{\frac{\tan \alpha}{\tan \theta_0}} \psi , \tag{3}
\]

where: \( \theta_0 = \frac{1}{2} \) cone angle,
\( \alpha = \) spiral angle,
\( \psi = \) angle of progression of the spiral around the cone starting at \( \rho = \rho_o \),
\( \rho_o = \frac{d}{2 \sin \theta_0} \), and
\( \rho_{\text{max}} = \frac{D}{2 \sin \theta_0} \). \tag{4}

The length of the antenna, \( h \), is a function of the diameters of the truncations and the cone angle and is given by

\[
h = \frac{D}{2 \tan \theta_0} - \frac{d}{2 \tan \theta_0} , \text{ or} \tag{5}
\]

\[
h = \frac{D - d}{2 \tan \theta_0} .
\]
2. Development of a Microwave Hooded Antenna

The design of a microwave hooded antenna to cover the frequency range from 1 GHz to 12 GHz was initiated at the start of this program. The following design parameters were selected for the conical log-helix probe antenna for this hooded configuration:

\[
\theta_0 = 15^\circ, \\
\alpha = 80^\circ, \\
d = \frac{\lambda_h}{4} = \frac{1}{4}'' = 0.25'', \\
D = \frac{\lambda_L}{3} = \frac{15''}{3} = 5'', \\
h = \frac{D - d}{2 \tan \theta_0} = \frac{5 - 0.25}{2(0.2679)} = 8.86, \text{ and}
\]

Frequency Range = 1 to 12 GHz.

These parameters were compromised to some extent in an attempt to obtain the best possible probe antenna characteristics under restricted dimensional limitations. A smaller cone angle, 20 degrees or less, is highly desirable in this type probe antenna since this provides a rotationally symmetrical main lobe and improved directivity characteristics. Since the length of the antenna increases inversely as the tangent of 1/2 the cone angle, increasing the cone angle from 20 degrees to 30 degrees reduces the length of the probe antenna by approximately 1/3. Thus, a cone angle of 30 degrees was selected to obtain a short probe antenna which could be operated in an eighteen-inch long hood. Also, previous evaluations of hooded antennas had indicated that the main lobe structure and directivity characteristics of the hooded configuration were determined, to a large extent, by the hood, and that a slight degradation in the basic probe characteristics had very little effect on the characteristics of the complete hooded antenna.

The microwave conical log-helix antenna was constructed on a solid epoxy resin conical core. Spiral slots were cut in the core to provide rigid support for the arms of the antenna. The arms were wound with solid-shield semi-rigid, 0.036 inch diameter coaxial cable (Precision Tube Co. Part No. PT 196). Coaxial cable was used for the arms because
it was planned that one arm would be used as the feed line for the antenna and act as an "infinite balun". It was also planned that the second arm would be utilized for the injection of the calibrating signal. The small diameter coaxial cable was necessary to meet the spacing requirements near the apex of the antenna structure.

Two photographs of the completed microwave probe antenna are shown in Figure 6. The upper photograph shows the antenna mounted on an expanded polyethylene and wood stand as it was operated to measure the characteristics of the probe antenna unhooded. The lower photograph shows the antenna mounted on the end plate of the antenna hood ready to be inserted into the hood.

The measured gain of the unhooded probe antenna relative to a \( \lambda/2 \) dipole and the VSWR referred to 50 ohms over the design bandwidth are shown in Figure 7. The upper curve in this figure shows the measured gain of the probe antenna compared to the gain of a horizontal dipole (actually a horizontally-polarized standard gain horn was used as the standard antenna and correction factors were applied to convert to \( \lambda/2 \) dipole gain) while utilizing a horizontal dipole as a radiating source. The curve shows only the frequency range from 1 to 10 GHz due to the frequency limitations of the Empire Devices MF-112 receiver. However, gain data at 11 and 12 GHz have subsequently been obtained. At 11 GHz the measured gain was -5.1 dB relative to a \( \lambda/2 \) dipole and at 12 GHz was -5.7 dB. The second curve shows the gain of the probe antenna compared with the gain of a vertical dipole (again a standard horn was used and corrected to a \( \lambda/2 \) dipole) utilizing a vertical dipole as a radiating source. The measured gain at 11 GHz was -7.7 dB and at 12 GHz was -9.0 dB. The average gain of the probe antenna over the design bandwidth is approximately -3 dB relative to a \( \lambda/2 \) dipole. The VSWR of the probe antenna over the design bandwidth is shown in the bottom curve. The average VSWR appears to be approximately 2.2 with some deterioration becoming apparent at the upper frequency limit.

Antenna patterns of the unhooded microwave probe antenna over the frequency range from 0.9 to 12 GHz are shown in Figures 8-11. The patterns obtained at 0.9 and 0.95 GHz, Figure 8, are included to show the pattern characteristics when the antenna is operated below the design bandwidth. The distorted pattern appears to be due to the active region of the antenna being located at the base truncation at this frequency. This results in no stop region being left to give a back-fire unidirectional pattern. In addition, the absence of a stop region causes the conditions for the "infinite balun" to be violated; the balanced feed conditions are no longer obtained, and a severely distorted dipole pattern is obtained. The pattern obtained at 0.95 GHz indicates that this frequency too is below the operating bandwidth of the probe antenna since a front-to-back ratio of 1:1 is obtained. It appears that sufficient stop region to give a back-fire unidirectional pattern is not available, but since an essentially undistorted
Figure 6. Two Views of Microwave Conical Log-Helix Antenna.
Figure 7. Gain and VSWR Curves of the Microwave Conical Log-Helix Antenna.
Figure 8. E Antenna Patterns of Microwave Conical Log-Helix Antenna at 0.9, 0.95, 1 and 1.5 GHz.
Figure 9. EΦ Antenna Patterns of Microwave Conical Log-Helix Antenna at 2, 2.5, 3 and 4 GHz.
Figure 10. E\$ Antenna Patterns of Microwave Conical Log-Helix Antenna at 5, 6, 7 and 8 GHz.
Figure 11. *E*θ Antenna Patterns of Microwave Conical Log-Helix Antenna at 9, 10, 11 and 12 GHz.
dipole pattern is obtained, sufficient stop region is apparently available at this frequency to allow the "infinite balun" to operate properly. The pattern obtained at 1 GHz indicates that this frequency is above the lower frequency limit of the probe antenna since a well-formed pattern with a 4 db front-to-back ratio is obtained. There is no explanation at the present time for the poor pattern obtained at 1.5 GHz. However, a good pattern was obtained with the hood indicating a possibility that the poor pattern obtained with the unhooded probe was due to reflections on the measurement range and/or external interference. Satisfactory patterns were obtained over the frequency range from 2 to 7 GHz. Within this range well-formed unidirectional patterns were obtained with half-power beamwidths in the range from 60 to 110 degrees. Maximum sidelobes and backlobes are down 4 to 10 db from the main lobe and the main lobes are well aligned with the mechanical bore sight. In the frequency range from 8 to 12 GHz, the main lobes are skewed off bore sight, and at some frequencies, are beginning to break up. It was anticipated that the hood would eliminate some of these undesirable characteristics at the upper frequency limit of the antenna.

On-axis polarization patterns of the unhooded microwave probe antenna at 1, 5 and 12 GHz are shown in Figure 12. These patterns indicate that the circular-polarization characteristics of this antenna are quite good over the entire operating range.

A comparison of the polarization patterns with the gain curves in Figure 7 reveals an inconsistency between the two sets of measurements. The patterns indicate that the gain of the probe antenna for a horizontally polarized signal is approximately equal to the gain for a vertically polarized signal. The gain curves indicate that the vertical gain is approximately 3 db less than the horizontal gain. The discrepancy is believed to reflect the accuracy limitation in calibrating the probe antenna relative to a half-wave dipole.

A small circular hood lined with ferrite absorbing material (Emerson and Cuming Eccosorb NZ-1) was used with the microwave probe antenna to obtain the desired hooded configuration. The top photograph in Figure 13 shows the hood, the microwave probe antenna and the hood end-plate just prior to assembly. The lower photograph in Figure 13 shows an open-end view of the hooded microwave antenna after assembly. The hood is 8 inches in diameter and 19 1/2 inches long. The inside diameter (clearance inside the ferrite absorbing material) is 6 1/4 inches. The complete microwave hooded antenna weighs 47 pounds.

After the microwave probe antenna was mounted in the hood, the gain and antenna pattern measurements were repeated. The horizontal and vertical gain curves for the microwave hooded antenna over the frequency range from 1 to 10 GHz are shown in Figure 14. Comparing the gain curves of Figure 14 with the curves of Figure 7 reveals that the addition of the hood reduced the gain of the antenna from 2 to 12 GHz by an average of approximately 4 db. However, the addition of the hood reduced the
Figure 12. Polarization Patterns of Microwave Conical Log-Helix Antenna at 1, 6, and 12 GHz.
Figure 13. Two Views of Hood for the Microwave Conical Log-Helix Antenna.
Figure 14. Gain Curves of Hooded Microwave Conical Log-Helix Antenna.
gain of the antenna by 25 db at 1 GHz. Again, the gain at 11 and 12 GHz was measured after the curves in Figure 14 had been completed. The measured gain of the hooded antenna for a horizontally-polarized field at 11 GHz was -6.8 db relative to a λ/2 dipole and at 12 GHz was -8.9 db. For a vertically-polarized field, at 11 GHz the measured gain was -11.9 db and at 12 GHz was -13.6 db.

The antenna patterns obtained with the microwave hooded antenna over the frequency range from 0.9 to 12 GHz are shown in Figures 15-18. Comparing the patterns of the hooded antenna in Figures 15-18 with the patterns of the unhooded basic probe antenna in Figures 8-11 reveals the significant improvements in the antenna patterns obtained by the addition of the hood. This comparison reveals that the hood reduces the half-power beamwidths of the main lobes by a factor of approximately one-half and reduces the maximum sidelobes and backlobes from 6 db at the lowest and highest frequencies to 25 db at the intermediate frequencies. This comparison also reveals how well the hood screens the skewing and beam splitting at the higher frequencies.

The patterns obtained with the microwave hooded antenna are considered satisfactory for a test antenna to make case radiation and susceptibility measurements in a shielded enclosure. Thus, to complete the development of the 1 to 12 GHz operational prototype of the hooded antenna, the only tasks remaining are the integration of a series injection calibration network into the microwave hooded antenna and the establishment of a complete field intensity calibration of the hooded antenna.

3. Development of a UHF Hooded Antenna

The design of a UHF hooded antenna to cover the frequency range from 200 to 1500 MHz was initiated during the month of August. The following design parameters were selected for the conical log-helix probe antenna for this hooded configuration:

$$\theta_0 = 30^\circ,$$
$$\alpha = 80^\circ,$$
$$d = \frac{\lambda_H}{4} = \frac{7.88}{4} \approx 2\text{"},$$
$$D = \frac{\lambda_L}{3} = \frac{60}{3} = 20\text{"}, \text{ and}$$
$$h = \frac{D - d}{2 \tan \theta_0} = 16.2\text{"}.$$
Figure 15. Eθ Antenna Patterns of Hooded Microwave Conical Log-Helix Antenna at 0.9, 0.95, 1 and 1.5 GHz.
Figure 16. E\(\Phi\) Antenna Patterns of Hooded Microwave Conical Log-Helix Antenna at 2, 2.5, 3 and 4 GHz.
Figure 17. E\$ Antenna Patterns of Hooded Microwave Conical Log-Helix Antenna at 5, 6, 7 and 8 GHz.
Figure 18. E$\Phi$ Antenna Patterns of Hooded Microwave Conical Log-Helix Antenna at 9, 10, 11 and 12 GHz.
The 60-degree cone angle was selected to keep the length of the antenna and the length of the associated hood within reasonable limits. This large cone angle will yield poorer pattern characteristics, but it was anticipated that the beam shaping of the hood would be sufficient to provide satisfactory patterns over the bandwidth of the hooded antenna.

The UHF probe antenna was formed on an expanded polyethylene conical form with plastic strips imbedded for additional support. The arms were wound with solid-shield, semi-rigid, 0.141 inch diameter coaxial cable (Precision Tube Co., Part No. 1163T 1413-19). Coaxial cable was used for the spirals because it was planned that one arm would be utilized as the feed line for the antenna and the second arm would be used for the injection of the calibrating signal.

The fabrication of the UHF probe antenna has been completed and VSWR measurements over the frequency range from 300 to 1500 MHz have been made. The measured VSWR curve over this range is shown in Figure 19. This curve indicates that the impedance of the probe antenna is reasonably well behaved over this frequency range.

It is anticipated that the evaluation of the UHF probe antenna, the fabrication of a hood for use with the UHF probe antenna, and the evaluation of the UHF hooded antenna will be completed during the next quarter.

![VSWR Curve of UHF Conical Log-Helix Antenna Over the Frequency Range from 300 to 1500 GHz.](image)
C. Study of Near-Field Measurement Problems

1. Background

At higher frequencies, where the shielded enclosure dimensions and spacings between the probe antennas and the equipment under test are large relative to the wave lengths involved, the variations in coupling between the equipment under test and the probe antenna within a shielded enclosure can be explained by the reflection of linearly polarized waves from plane surfaces with the resultant out-of-phase cancellations and in-phase additions. Results from previous investigations have indicated that these undesirable coupling variations can be eliminated by the use of hooded probe antennas and proper measurement procedures. However, at lower frequencies, where the shielded enclosure dimensions and probe antenna spacings are small relative to the wave lengths involved, the coupling between the equipment under test and the probe antenna becomes much more complicated and includes additional components of the more complex near-field. The behavior of these near-field components in the shielded enclosure is not well understood, and there is a very limited amount of information on this subject in the literature. In order to determine the measurement problems to be anticipated in this frequency range, it was considered necessary to conduct a theoretical study of the near-fields of radiators and to conduct an experimental measurement program in the near-fields of radiators. While it is quite possible that an experimental measurement program would reveal any measurement problems which might exist in this frequency range, the theoretical study was considered necessary as a background to adequately explain the results obtained and to determine techniques for eliminating the problems which exist.

2. Theoretical Study

Due to the complexity of the near-field, it was decided to start the theoretical study with an analysis of a simple short-dipole antenna operating in free-space. Future efforts will consider such an antenna operating in a shielded enclosure and an attempt will be made to correlate the theory with measured results obtained with dipole antennas. If this task is successful, the theory will be extended to more complex radiating configurations.

The total E/M (electromagnetic) field surrounding a short dipole antenna can be expressed by the following equations:  

\[ E = \frac{I}{2\pi} \cdot \frac{e^{-jkr}}{r} \]  

\[ H = \frac{I}{2\pi} \cdot \frac{e^{-jkr}}{r^2} \]
\[ E_\theta = \frac{I_o \ell e^{j(\omega t - \beta r)}}{4\pi \epsilon_o} \sin \theta \left[ \frac{j \omega}{c r} + \frac{1}{cr^2} + \frac{1}{j\omega r^2} \right], \quad (6) \]

\[ E_\rho = \frac{2 I_o \ell e^{j(\omega t - \beta r)} \cos \theta}{4\pi \epsilon_o} \left[ \frac{1}{cr^2} + \frac{1}{j\omega r^2} \right], \quad (7) \]

\[ H_z = \frac{I_o \ell e^{j(\omega t - \beta r)} \sin \theta}{4\pi} \left[ \frac{j \omega}{cr} + \frac{1}{r^2} \right], \quad (8) \]

where

- \( I_o \) = peak value of current (amperes),
- \( \ell \) = length of dipole (meters),
- \( \omega \) = radian frequency, \( 2\pi f \) (radian/sec),
- \( \beta \) = phase constant, \( 2\pi/\lambda \) (radian/meter),
- \( \epsilon_o \) = permittivity of free space (8.85 \times 10^{-12} \text{ farad/meter}),
- \( c \) = velocity of light (3 \times 10^8 \text{ meter/sec}),
- \( j \) = complex operator \( (\sqrt{-1}) \), and
- \( r \) = distance from center of dipole to point \( \rho \) (meters).

The coordinate system used for the E/M field components of a short dipole antenna is shown in Figure 20.

In the electric field equations (6) and (7), let \( c = f \lambda = \omega \lambda/2\pi \).

Then

\[ E_\theta = \frac{I_o \ell e^{j(\omega t - \beta r)}}{4\pi \epsilon_o \omega} \sin \theta \left[ j \left( \frac{2\pi}{\lambda^2} \right)^2 + \frac{2\pi}{\lambda r^2} - \frac{j}{r^3} \right], \quad (9) \]

and

\[ E_\rho = \frac{2 I_o \ell e^{j(\omega t - \beta r)} \cos \theta}{4\pi \epsilon_o \omega} \left[ \frac{2\pi}{\lambda r^2} - \frac{j}{r^3} \right]. \quad (10) \]
In equations (9) and (10), let 

$$K = \frac{I_o J \cdot e^{j(\omega t - \beta r)}}{4\pi \varepsilon_o \omega \lambda^3}.$$ 

Then

$$E_\theta = K \sin \theta \left[ \frac{j(2\pi)^2}{r/\lambda} + \frac{2\pi}{(r/\lambda)^2} - \frac{j}{(r/\lambda)^3} \right], \quad (11)$$

and

$$E_\rho = 2K \cos \theta \left[ \frac{2\pi}{(r/\lambda)^2} - \frac{j}{(r/\lambda)^3} \right]. \quad (12)$$

The distance term, \( r \), can be normalized in terms of the wavelength \( \lambda \). In equations (11) and (12), let \( R_n = r/\lambda \).

$$E_\theta = K \sin \theta \left[ \frac{j(2\pi)^2}{R_n} + \frac{2\pi}{R_n^2} - \frac{j}{R_n^3} \right], \quad (13)$$

30
and

\[ E_\rho = 2k \cos \theta \left( \frac{2n^2}{R_n^2} - \frac{j}{R_n^3} \right). \]  \hspace{1cm} (14)

The separate terms of each field component vary in magnitude as powers of \(1/R_n\). The term \(1/R_n\) is known as the radiation or far-field term, \(1/R_n^2\) is called the induction term, and \(1/R_n^3\) is the static term. Note that the \(E_\rho\) component is insignificant in the far-field. Figure 21 shows the relative magnitude of each term in equations (13) and (14) as a function of \(r/\lambda\) or \(R_n\). Solid lines indicate terms from equation (13); dashed lines indicate terms from equation (14).

Equations of the \(E\) field components at \(\theta = 0^\circ\) (end-fire) and \(\theta = 90^\circ\) (bore-sight) are of interest, and follow.

![Figure 21. Relative Magnitude of Terms of the Electric Field Components in the Near-Field of a Short Dipole.](image-url)
For $\theta = 0^\circ$,

$$E_\theta = 0,$$  \hspace{1cm} (15)

and

$$E_\rho = 2K \left[ \frac{2\pi}{R_n^2} - \frac{j}{R_n^3} \right].$$  \hspace{1cm} (16)

For $\theta = 90^\circ$,

$$E_\theta = K \left[ j \frac{(2\pi)^2}{R_n} + \frac{2\pi}{R_n^2} - \frac{j}{R_n^3} \right],$$  \hspace{1cm} (17)

and

$$E_\rho = 0.$$  \hspace{1cm} (18)

The relative magnitude of equations (16) and (17) as a function of normalized distance $R_n$ is shown in Figure 22. The $E_\theta$ curve has a slope

![Figure 22. Relative Magnitude of Electric Field Components in the Near-Field of a Short Dipole.](image-url)
of 18 db/octave \((1/R_n^3)\) variation at \(R_n\) less than 0.05; changes to a 12 db/octave slope \((1/R_n^2)\) variation at \(R_n = 1/2\pi\); and finally changes to a 6 db/octave slope \((1/R_n)\) variation at \(R_n = 0.5\). Open-field measurements on bore-sight of a short-dipole antenna have closely approached this \(E_y\) curve.\(^2,6\) The \(E_y\) curve has a slope of 18 db/octave at \(R_n\) less than 0.05, and a 12 db/octave slope at \(R_n\) greater than 0.5, with an intermediate slope of 15 db/octave at \(R_n = 1/2\pi\). Open-field measurements on a short dipole antenna should resemble this \(E_y\) curve at \(\theta = 0^\circ\).

Consider a short dipole antenna operating in an open-field configuration. Assume an observation point at some \(R_n\) between 0.05 and 0.5, and at any angle \(\theta\) other than \(0^\circ\) or \(90^\circ\). The electric field equations are given by (13) and (14). These equations each represent a linear wave polarization with respect to time, but their vector sum in the general case represents an elliptical wave polarization. The ellipse is different for each location of \(R_n\) and \(\theta\).

Figure 22 also shows that the magnitude of \(E_y\) and \(E_\rho\) is different at each value of \(R_n\) except at one cross-over point. The phase of \(E_y\) and \(E_\rho\) is also different at each \(R_n\) as shown by Figure 23(a), which was derived from the bracketed terms of equations (13) and (14). Figure 23(b) includes the \(e^{-j\beta_r}\) term contained in \(K\), and shows the cumulative phase shift of \(E_y\) and \(E_\rho\). Figure 23(c) shows the difference phase angle, \(\delta\), by which \(E_y\) leads \(E_\rho\) in time. The angle \(\delta\), derived from equations (13) and (14) is given by

\[
\delta = \arctan \left( \frac{(2\pi R_n)^2}{2\pi R_n} \right) - \arctan \left( \frac{1}{2\pi R_n} \right). \tag{19}
\]

Near the antenna, where \(R_n\) is less than 0.05, the two \(E\) components are almost in phase, and at \(R_n = 1\), they are almost \(90^\circ\) out of phase. The phase angle \(\delta\) is independent of \(\theta\).

Equations (6) and (7) can now be expressed as

\[
E_\rho = E_y \cos \theta \sin \omega t', \tag{20}
\]
Figure 23. Phase Characteristics in the Near-Field of $\phi_{10}$ Short Dipole (a) $1/R^n$ terms, (b) $1/R$ and $e^{j\phi}$ terms, and (c) Phase Angle $\delta$. 
and

\[ E_0 = E_2 \sin \theta \sin (\omega t' + \delta). \]  \hspace{1cm} (21)

Where

\[ E_1 = 2K' \left| \left[ \frac{2n}{R_n} - \frac{j}{R_n^3} \right] \right|, \]  \hspace{1cm} (22)

\[ E_2 = K' \left| \left( \frac{(2n)^2}{R_n^2} + \frac{2n}{R_n} - \frac{j}{R_n^3} \right) \right|, \]  \hspace{1cm} (23)

\[ K' = \frac{l}{4\pi \varepsilon_0 \omega^2}, \text{ and} \]  \hspace{1cm} (24)

\[ \omega t' = (\omega t - \beta r). \]  \hspace{1cm} (25)

The instantaneous value of the total \( \overline{B} \) field from the two linearly polarized waves, equations (20) and (21) is

\[ \overline{E} = \overline{\sigma} \rho \rho + \overline{\sigma} \varphi \rho' \]  \hspace{1cm} (26)

where \( \overline{\sigma}_\varphi \) and \( \overline{\sigma}_\rho \) are unit vectors in the \( \rho \) and \( \theta \) directions respectively, or

\[ \overline{E} = \overline{\rho} \rho \cos \theta \sin (\omega t' + \delta) + \overline{\rho} \varphi \rho' \sin \theta \sin (\omega t' + \delta). \]  \hspace{1cm} (27)

Evaluating equation (27) as a time function at a fixed \( R_n \) and \( \theta \) produces a rotating electric vector field, whose locus in the \( \rho-\theta \) plane is an ellipse. The axis of this polarization ellipse does not, in general coincide with the \( \rho \)-axis. The tilt angle, \( \tau \), is the orientation of the polarization ellipse axis from the \( \rho \)-axis in a clockwise direction. It may be found from the following equation, \(^{13}\)
\[ \tau = \frac{1}{2} \arctan \left[ \frac{2 \cos \delta}{\frac{E_1 \cos \theta}{E_2 \sin \theta} - \frac{E_2 \sin \theta}{E_1 \cos \theta}} \right] \quad (28) \]

where \( E_1, E_2, \) and \( \delta \) are functions of \( R_n \). Figure 24 is a family of curves showing \( \tau \) as a function of \( R_n \) for five different values of \( \theta \). For values of \( R_n \) less than 0.05, the tilt angle is approximately constant for a given \( \theta \). For small \( R_n \), \( \theta \) and \( \tau \) approach 0° and 90° together.

The major axis of the polarization ellipse lies \( \tau \) degrees clockwise from the \( \rho \)-axis. The magnitude of the semi-major or semi-minor axis depends on the time variation of the generating vectors, \( E_\rho \) and \( E_\theta \), and can be found by squaring equation (27), eliminating the cross-product terms, and differentiating with respect to \( \omega t' \):

\[
2E \frac{\partial E}{\partial \omega t'} = 2(E_1 \cos \theta)^2 \sin \omega t' \cos \omega t' + 2(E_2 \sin \theta)^2 \sin(\omega t' + \delta) \cos(\omega t' + \delta). \quad (29)
\]

Figure 24. Tilt Angles in the Near-Field of a Short Dipole.
Setting equation (29) equal to zero determines the \( \omega t' \) angle that will maximize or minimize \( \mathbf{E} \):

\[
\omega t' = \frac{1}{2} \arctan \left[ -\frac{(E_2 \sin \theta)^2 \sin 2\delta}{(E_1 \cos \theta)^2 + (E_2 \sin \theta)^2 \cos 2\delta} \right]
\]  

(30)

Substituting these values of \( \omega t' \) into equations (20) and (21) gives the magnitude of \( E_\rho \) and \( E_\theta \) at a point \( R_n \). The magnitude of the \( \mathbf{E} \) vector along the major or minor axis is found from

\[
|\mathbf{E}| = \sqrt{E_\rho^2 + E_\theta^2}.
\]  

(31)

At \( \omega t' = 0^\circ \), equations (20) and (21) become

\[
E_\rho = 0,
\]  

(32)

and

\[
E_\theta = E_2 \sin \theta \sin \delta.
\]  

(33)

Equation (33) is the magnitude of the ellipse vector along the \( E_\theta \) axis. At \( \omega t' + \delta = 180^\circ \), these equations give:

\[
E_\rho = E_1 \cos \theta \sin (180^\circ - \delta),
\]  

(34)

and

\[
E_\theta = 0.
\]  

(35)

Equation (34) is the magnitude of the ellipse vector along the \( E_\rho \) axis.

From equations (31), (33), and (34), eight points of the polarization ellipse can be located and the resulting figure sketched. Figure 25 shows a typical ellipse located at \( r = \lambda/2\pi \) and \( \theta = 60 \) degrees. In a similar manner, the polarization ellipse for any value of \( r \) and \( \theta \) around a short dipole antenna can be determined.
Figure 25. A Typical Polarization Ellipse in the Near-Field of a Short Dipole.

Figure 26 shows the changing tilt-angles, \( \tau \), in the \( \rho-\theta \) plane as a function of distance along fixed angles \( \theta \). Figure 27 shows polarization ellipses at various values of \( R_n \) and \( \theta \) in the \( \rho-\theta \) plane. Relative magnitudes of the major and minor axes are given for each ellipse sketched.

This study has described the total electric field vectors surrounding a short dipole antenna operating in a free-space environment. Linearly polarized waves are found very near the antenna and in the "far-field" region; however, elliptically polarized waves exist in the intermediate or "near-field" region. Future work will use similar analyses to describe the electric field generated when such an antenna operates in a reflective (shielded enclosure) environment.

3. Experimental Measurement Program

In order to investigate the problems associated with making radiated measurements in a shielded enclosure at low frequencies, a series of measurements of the coupling between two antennas as a function of spacing was conducted. The measurements were made in the open-field and repeated in a 8 x 8 x 20 foot shielded enclosure in which one end wall was covered with 6-foot thick Ecocorb HPY-72 absorbing material. Data were collected over the frequency range of 0.5 MHz to 150 MHz.
Figure 26. Tilt Angle of Polarization Ellipses in $\rho$-$\theta$ Plane.
Figure 27. Typical Ellipses in the φ-θ Plane.
The test setups used to make these measurements are shown in Figures 26 and 29. The photograph of Figure 28 shows the test setup in the open-field. The antennas consisted of two "identical" bow-tie antennas, 30-inches long, with a 45-degree flare angle. The source or radiating antenna was mounted on a positioner and the receiving antenna was mounted on a movable cart which was located on a calibrated track. The receiving antenna was moved from a spacing of 12 inches to a spacing of 100 inches in 1 inch increments. The antenna coupling at each increment over this spacing range was recorded. The diagram in Figure 29 depicts the measurement setup shown in Figure 28 located in the shielded enclosure and shows the orientation of the measurements setup with respect to the enclosure walls and the absorbing material. It should be noted that the centers of the bow-tie antennas were located on the axis of the shielded enclosure so that they were equal distance from the four 8-foot walls. The results from the spacing measurements, both in the open-field and in the shielded enclosure, are shown in Figures 30-41.

The coupling curves show that the correlation between the open-field and shielded enclosure measurements is quite good at all test frequencies for small spacings between the antennas. For example, at a spacing of 12 inches, the open-field and shielded enclosure coupling measurements agree within approximately 1 db at all test frequencies except 1 and 100 MHz. At these two frequencies, the measurements are within approximately 3 db.

At the lower frequencies, the agreement between open-field and shielded enclosure coupling curves remains quite good over an appreciable spacing range. For example, at 0.5 MHz the open-field and shielded enclosure coupling values gradually diverge from a 1 db difference at a 12-inch spacing to a 3 db difference at a 45-inch spacing, and at 10 MHz they gradually diverge from a 1 db difference at a 12-inch spacing to a 3 db difference at a 40-inch spacing.

At the high frequencies the difference between the open-field and shielded enclosure coupling values can vary quite rapidly with spacing. For example, at 37.5 MHz the coupling curves diverge from 1 db difference at a 12-inch spacing to a 28 db difference at a 42.5-inch spacing and at 150 MHz the difference increases from 1 db at 12 inches to 30 db at 25 inches.

At frequencies above 10 MHz a distinct null or point of maximum difference between the coupling curves becomes apparent in the 12-inch to 100-inch spacing range. As the spacing is increased beyond this null the difference between the open-field and shielded enclosure coupling curves tends to decrease. As the frequency increases the location of this null tends to shift to shorter spacings, and at the highest test frequency of 150 MHz, two nulls are apparent within the spacing range.
Figure 28. Measurement Setup.

Figure 29. Diagram of Measurement Setup in a Shielded Enclosure.
Figure 30. Coupling Between Antennas as a Function of Spacing, in a Shielded Enclosure and in the Open-Field, at 0.5 MHz.

Figure 31. Coupling Between Antennas as a Function of Spacing, in a Shielded Enclosure and in the Open-Field, at 1.0 MHz.
Figure 32. Coupling Between Antennas as a Function of Spacing, in a Shielded Enclosure and in the Open-Field, at 5 MHz.

Figure 33. Coupling Between Antennas as a Function of Spacing, in a Shielded Enclosure and in the Open-Field, at 10 MHz.
Figure 34. Coupling Between Antennas as a Function of Spacing, in a Shielded Enclosure and in the Open-Field, at 15 MHz.

Figure 35. Coupling Between Antennas as a Function of Spacing, in a Shielded Enclosure and in the Open-Field, at 20 MHz.
Figure 36. Coupling Between Antennas as a Function of Spacing, in a Shielded Enclosure and in the Open-Field, at 25 MHz.

Figure 37. Coupling Between Antennas as a Function of Spacing, in a Shielded Enclosure and in the Open-Field, at 30 MHz.
Figure 38. Coupling Between Antennas as a Function of Spacing, in a Shielded Enclosure and in the Open-Field, at 37.5 MHz.

Figure 39. Coupling Between Antennas as a Function of Spacing, in a Shielded Enclosure and in the Open-Field, at 50 MHz.
Figure 40. Coupling Between Antennas as a Function of Spacing, in a Shielded Enclosure and in the Open-Field, at 100 MHz.

Figure 41. Coupling Between Antennas as a Function of Spacing, in a Shielded Enclosure and in the Open-Field, at 150 MHz.
Up to the present time, it has not been possible to satisfactorily explain the coupling variations and null locations within the shielded enclosure at low frequencies. Some preliminary attempts to explain the measured results in terms of multi-path reflections and path length differences have not been successful. The significant phase shifts and elliptical polarizations associated with the very near-fields of antennas, discussed in the previous section, indicate that a theoretical analysis of multi-path reflections at low frequencies in a shielded enclosure is a much more complex problem than at high frequencies, requiring the consideration of several additional variables. In order to obtain a valid theoretical explanation for the coupling variations and the location of the coupling nulls at low frequencies, it appears it will be necessary to expand the near-field theoretical study.

In order to obtain a more complete evaluation of the effects of the coupling variations within the shielded enclosure on measurements made in the enclosure, antenna pattern measurements were made at the same test frequencies over the frequency range from 0.5 MHz to 150 MHz at a fixed spacing of 40 inches between antennas. The measured antenna patterns are shown in Figures 42-53. It is apparent that there is good correlation between the antenna patterns measured in the open-field and the patterns measured in the shielded enclosure over the frequency ranges from 0.5 MHz to 10 MHz and from 50 MHz to 150 MHz. However, the enclosure patterns for the test frequencies in the 15 to 37.5 MHz range show various degrees of distortion when compared to the patterns obtained in the open-field.

A comparison between the antenna patterns with the antenna coupling curves of Figures 30-41 revealed that the shielded enclosure antenna patterns were distorted at those frequencies where the 40-inch spacing placed the probe antenna in or near the null shown in the coupling curves. At those frequencies where the probe antenna position was well removed from the null and located on a peak or a relatively flat portion of the coupling curve, no significant distortion was apparent. In addition, it appears that the degree of distortion appears to be determined by the depth of the null at the probe antenna location. For example, of all the test frequencies shown in Figures 42-53, the 40-inch probe spacing places the probe antenna nearest the coupling null at 37.5 MHz (Figure 58 shows the null bottom to be at approximately 42.5 inches) and a check of the patterns reveals that the maximum distortion was obtained in the pattern made in the enclosure at 37.5 MHz. At 30 MHz the probe antenna at 40 inches is still well within the skirts of the null and some distortion is still apparent in the enclosure pattern. At 50 MHz, however, the 40-inch spacing places the probe antenna well past the coupling null on a reasonably flat portion of the coupling curve and no significant distortion is apparent in the pattern obtained at this frequency.
Figure 42. Open-Field and Shielded Enclosure Antenna Patterns, at a Spacing of 40 Inches, of a Horizontal Bow-Tie at 0.5 MHz.

Figure 43. Open-Field and Shielded Enclosure Antenna Patterns, at a Spacing of 40 Inches, of a Horizontal Bow-Tie at 1 MHz.
Figure 44. Open-Field and Shielded Enclosure Antenna Patterns, at a Spacing of 40 Inches, of a Horizontal Bow-Tie at 5 MHz.

Figure 45. Open-Field and Shielded Enclosure Antenna Patterns, at a Spacing of 40 Inches, of a Horizontal Bow-Tie at 10 MHz.
Figure 46. Open-Field and Shielded Enclosure Antenna Patterns, at a Spacing of 40 Inches, of a Horizontal Bow-Tie at 15 MHz.

Figure 47. Open-Field and Shielded Enclosure Antenna Patterns, at a Spacing of 40 Inches, of a Horizontal Bow-Tie at 20 MHz.
Figure 48. Open-Field and Shielded Enclosure Antenna Patterns, at a Spacing of 40 Inches, of a Horizontal Bow-Tie at 25 MHz.

Figure 49. Open-Field and Shielded Enclosure Antenna Patterns, at a Spacing of 40 Inches, of a Horizontal Bow-Tie at 30 MHz.
Figure 50. Open-Field and Shielded Enclosure Antenna Patterns, at a Spacing of 40 Inches, of a Horizontal Bow-Tie at 37.5 MHz.

Figure 51. Open-Field and Shielded Enclosure Antenna Patterns, at a Spacing of 40 Inches, of a Horizontal Bow-Tie at 50 MHz.
Figure 52. Open-Field and Shielded Enclosure Antenna Patterns, at a Spacing of 40 Inches, of a Horizontal Bow-Tie at 100 MHz.

Figure 53. Open-Field and Shielded Enclosure Antenna Patterns, at a Spacing of 40 Inches, of a Horizontal Bow-Tie at 150 MHz.
To substantiate the hypothesis that distortion is obtained when the probe antenna is located in the null region of the coupling curve and no distortion is obtained when the probe antenna is located in a flat region of the coupling curve, spacings for maximum and minimum distortion were predicted from the enclosure coupling curves for each of the test frequencies from 5 MHz to 150 MHz. Antenna patterns were made at the predicted spacings for maximum and minimum distortion at each of these test frequencies and are shown in Figures 54-63. At 5 and 10 MHz, since no nulls occur within the 12 to 100 inch spacing range, the maximum spacing of 100 inches was selected as the predicted maximum distortion points since this is the point nearest to the nulls which occur at greater spacings at these frequencies. At all other test frequencies the spacing at which the null bottom occurred was selected as the predicted maximum distortion point. At 20 MHz and above, a point on the flat portion of the coupling curve following the null was selected as the predicted minimum distortion point. The patterns in Figures 54-63 show that locating the probe antenna at a spacing where a null occurred in the coupling curve resulted in a severely distorted antenna pattern, and locating the probe antenna at a spacing where a flat region of the coupling curve occurred resulted in an essentially undistorted antenna pattern being obtained. At 5 and 10 MHz, where nulls were not present within the spacing range, some distortion was apparent when the probe antenna was placed at a maximum spacing of 100 inches, however, this distortion was considerably less than that obtained at null spacings.

The results from this measurement program indicate a definite possibility of making radiated measurements at low frequencies in shielded enclosures which can be correlated with open-field measurements. The correlation of the enclosure measurements with open-field measurements will possibly necessitate a calibration of the shielded enclosure to obtain a "coupling correction factor" and/or some attention to the spacing between the equipment under test and the probe antenna.

It is noted that all enclosure data discussed in this section were obtained in one 8 x 8 x 20 foot enclosure with HPY-72 absorbing material covering one end wall. It is planned that these measurements will be repeated in the 8 x 8 x 20 foot enclosure with the absorbing material removed, and in a 8 x 8 x 12 foot shielded enclosure without absorbing material. An analysis of the data from these measurements should make it possible to develop conclusions in terms of more general shielded enclosures.
Figure 54. Shielded Enclosure Antenna Patterns, at Spacings of 40 Inches and 100 Inches, of a Horizontal Bow-Tie at 5 MHz.

Figure 55. Shielded Enclosure Antenna Patterns, at Spacings of 40 Inches and 100 Inches, of a Horizontal Bow-Tie at 10 MHz.
Figure 56. Shielded Enclosure Antenna Patterns, at Spacings of 40 Inches and 94 Inches, of a Horizontal Bow-Tie at 15 MHz.

Figure 57. Shielded Enclosure Antenna Patterns, at Spacings of 78 Inches and 98 Inches, of a Horizontal Bow-Tie at 20 MHz.
Figure 58. Shielded Enclosure Antenna Patterns, at Spacings of 65 Inches and 85 Inches, of a Horizontal Bow-Tie at 25 MHz.

Figure 59. Shielded Enclosure Antenna Patterns, at Spacings of 55 Inches and 78 Inches, of a Horizontal Bow-Tie at 30 MHz.
Figure 60. Shielded Enclosure Antenna Patterns, at Spacings of 40 Inches and 66 Inches, of a Horizontal Bow-Tie at 37.5 MHz.

Figure 61. Shielded Enclosure Antenna Patterns, at Spacings of 25 Inches and 40 Inches, of a Horizontal Bow-Tie at 50 MHz.
Figure 62. Shielded Enclosure Antenna Patterns, at Spacings of 25 Inches and 72 Inches, of a Horizontal Bow-Tie at 100 MHz.

Figure 63. Shielded Enclosure Antenna Patterns, at Spacings of 25 Inches and 40 Inches, of a Horizontal Bow-Tie at 150 MHz.
D. Development of Measurement Procedures

A study to develop technically valid measurement procedures for performing radiated measurements in shielded enclosures is being conducted. Since the accuracy and validity of the measured data obtained by means of a measurement procedure are generally limited by the weakest link in the measurement procedure, it is vitally important that every aspect of the measurement procedure be given ample consideration to assure the required accuracy and validity for the overall measurement procedure.

In spite of attempts to facilitate and standardize the determination of the electromagnetic interference characteristics of electronic equipments, there are currently over 20 industry and government specifications stipulating the tests to be performed and the test procedures and techniques to be utilized. The specifications still are, in general, inadequate and the technical foundation for the various procedures and techniques specified is seldom known. There are a number of reasons why this situation exists. In some cases, procedures and techniques, adequate for very limited and specific types of equipment, were developed and successfully applied. Later, these procedures and techniques were applied to broad types of equipment without knowledge of their original narrow and specific intent. The result is an inadequate specification. In other cases, tentative procedures and requirements were generated which were recognized initially as less than adequate, but gradually these procedures and requirements found their way into final specifications and, through rigid and blind compliance demands, their original tentative status was forgotten. The resulting specifications were obviously deficient. In still other cases, valid procedures and requirements have been developed and applied successfully to broad types of equipments, but these procedures and requirements have not subsequently been updated to reflect the advances in equipment state-of-the-art, and again, the result has been deficient test procedures.

With this current situation in mind, it is obvious that any effort which proposes to determine adequate methods for measuring the radiation characteristics of equipment must include a thorough analysis of existing test procedures and techniques. A primary objective of this study should be to obtain a thorough knowledge of the basis for and the intent of the existing procedures and techniques. With this knowledge, applicable and adequate portions of these procedures can be identified and utilized. Where inadequate, existing procedures can be updated and/or modified as necessary to render them applicable to the desired measurement requirements.

Consequently, considerable effort is being devoted to the analysis of existing measurement procedures. The measurement procedures from 19 specifications and standards have been compiled and are being analyzed.
Some of the parameters and requirements of the test procedures and techniques receiving consideration for radiated measurements are the following:

(a) Positioning of the test specimen.
   (1) Location of the test specimen in enclosure.
   (2) Orientation of specimen relative to probe antenna.
   (3) Number of orientations necessary to adequately describe specimen.
   (4) Is rotating positioner necessary or desirable?

(b) Ground plane considerations.
   (1) Is a ground plane necessary?
   (2) Optimum configuration for the ground plane.
   (3) Optimum orientation of the ground plane.

(c) Test specimen arrangement during tests.
   (1) Length of interconnecting, test and power cables.
   (2) Conductor-to-ground plane spacing for cables.
   (3) Conductor-to-conductor spacing for cables.

(d) Test equipment arrangement during tests.
   (1) Test equipment required for tests.
   (2) Location of test equipment relative to specimen.
   (3) Orientation and spacing of test equipment cables.

(e) Optimum data format.
   (1) Data required.
   (2) Analog or digital data.
   (3) Number of measurements necessary to adequately describe interference characteristics.

In the process of studying the above measurement procedure requirements, the analysis is being guided by the following additional factors:

(a) Requirements imposed by the planned use of a hooded antenna probe.

(b) The necessity for thorough technical justifications for all recommendations.

(c) A desire to be consistent, where possible, with existing procedures and specifications.

(d) A desire for convenient and efficient performance of the individual tests.
A considerable amount of the analysis of these parameters and requirements have been accomplished and some preliminary conclusions and recommendations have been developed. However, due to the still preliminary status of this study, it is considered desirable to postpone detailed discussions of this study until later in the program.
II. CONCLUSIONS AND RECOMMENDATIONS

The results from the evaluation of the microwave hooded antenna developed on this program indicate that the performance of this probe antenna is satisfactory for making radiated measurements in shielded enclosures over the frequency range from 1 to 12 GHz. Although there was some deterioration in the pattern characteristics of the basic conical log-helix probe antenna at the low and high frequency limits of the frequency range, the improvement obtained in the pattern characteristics by the addition of the hood was sufficient to make the complete hooded configuration satisfactory over the entire range.

The only tasks remaining in the development of the microwave hooded antenna for use as an operational probe antenna are the addition of a series injection calibration network and a calibration of the complete hooded antenna, in terms of field intensity, over the complete frequency range.

A UHF conical log-helix probe antenna to cover the frequency range from 200 to 1500 MHz has been developed and is presently being evaluated. A hood for use with this probe antenna is being fabricated. It is planned that the complete UHF hooded antenna will be evaluated during the next quarter.

The results from an experimental measurement program indicate that there is a possibility that radiated measurements can be made in shielded enclosures at relatively low frequencies which can be correlated with open-field measurements. It is planned that additional measurements will be made in different size enclosures and with the measurement setup in different locations within the enclosures to further evaluate the effect of the shielded enclosure at low frequencies.

A study to develop technically valid measurement procedures for performing radiated measurements in shielded enclosures is being conducted. To date, the measurement procedures from 19 specifications and standards have been compiled and are being analyzed. With the results from this analysis and results from various measurement programs, it is expected that decisions can be made on questions such as (1) is a ground plane required for these measurements, and if so, what are the optimum parameters and orientation for the ground plane?, (2) what is the optimum approach to standardizing power line impedance?, (3) routing, length, and orientation for power and signal cables, (4) optimum test configuration and location in shielded enclosure, and (5) optimum data format.
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**13. ABSTRACT**
During the period covered by this report, investigations have been conducted to develop test techniques and procedures for making radiated measurements in shielded enclosures which can be correlated with open-field measurements. The primary objective of this program is to develop a capability for determining the case radiation and susceptibility characteristics of U. S. Army communication equipments in the controlled environment of a shielded enclosure.

A microwave hooded probe antenna was designed, fabricated and evaluated during this period. The evaluation has demonstrated the capability of this probe antenna in performing radiated measurements in a shielded enclosure over the frequency range from 1 to 12 GHz which have very good correlation with measurements made in the open-field.

A UHF hooded probe antenna, for use over the frequency range from 200 to 1500 MHz, has been designed and fabricated. This antenna is presently being evaluated.

A theoretical and experimental investigation to determine the field distribution within a shielded enclosure at low frequencies is being conducted. The present status of these programs is discussed.

A study to develop technically valid procedures and test setups for use in making measurements in shielded enclosures is also being conducted. A description of the study program is presented.
Electromagnetic Interference
Measurement Methods
Conical Log-Helix Antenna
Hooded Antenna
Shielded Enclosure
Absorbing Material
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TECHNICAL REPORT ECOM-02381-2

ELECTROMAGNETIC INTERFERENCE
MEASUREMENT METHODS—SHIELDED
ENCLOSURE

QUARTERLY REPORT

By
W. R. FREE, C. H. BONHAM,
R. E. GIBSON, J. H. GUTZKE
and B. M. JENKINS

APRIL 1967

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ELECTROMAGNETIC INTERFERENCE MEASUREMENT
METHODS-SHIELDED ENCLOSURE

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For

U. S. ARMY ELECTRONICS COMMAND
FORT MONMOUTH, N. J.
ABSTRACT

During the period covered by this report, investigations of techniques and procedures for making radiation measurements in shielded enclosures which can be correlated with open-field measurements have continued. The primary objective of this program is to develop a capability for determining the case radiation and susceptibility characteristics of U. S. Army communication equipments in the controlled environments of shielded enclosures.

A microwave hooded antenna capable of making the desired measurements in a shielded enclosure over the frequency range from 1 to 12 GHz has been developed and evaluated. Techniques for calibrating this probe antenna have been investigated during this period and are described in detail.

A UHF hooded antenna, for use over the frequency range from 200 to 1500 MHz, has also been developed. The evaluation of this probe antenna has continued during this period and the results obtained to date are presented.

Theoretical and experimental investigations of the field distribution within a shielded enclosure at low frequencies are discussed.
FOREWORD

This report was prepared at the Georgia Tech Engineering Experiment Station on Contract No. DA 28-043 AMC-G2381(E). The work covered by this report was performed within the Communications Branch under the general supervision of Mr. D. W. Robertson, Head of the Communications Branch. The report covers the activities and results of the second quarter's effort on a project to determine methods for measuring the interference characteristics of U. S. Army communication equipments in shielded enclosures.

The authors are pleased to acknowledge the efforts of J. D. Doster and W. S. Giddens in a number of the fabrication and measurement phases of the program.
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I. FACTUAL DATA

A. Introduction

This report covers the work performed under Contract DA 28-043 AMC-02381(E), "Electromagnetic Interference Measurement Methods-Shielded Enclosure," for the period from 1 September 1966 to 30 November 1966.

The purpose of the program is to conduct a theoretical and experimental investigation to determine the test setups, accessories and procedures best suited to measurement, in shielded enclosures, of the electromagnetic emission and susceptibility characteristics of military communication-electronic equipment.

The three primary objectives of the program are (1) the development of hooded probe antennas to cover the frequency range from 200 MHz to 12 GHz, (2) a theoretical and experimental study of the problems associated with near-field measurements in shielded enclosures at frequencies below 200 MHz and (3) the development of measurement procedures for making emission and susceptibility measurements in shielded enclosures.

During this report period, the majority of the effort has been directed toward the development and evaluation of hooded probe antennas and the theoretical and experimental study of low-frequency measurement problems in shielded enclosures.

Consideration was also given to possible techniques for calibrating the hooded probe antennas so that the field intensity incident on the antennas can be accurately determined. Techniques for injecting calibrating signals at the terminals of the hooded antennas were included in the investigation.

B. Development of Hooded Antennas

1. General

A number of techniques for reducing the effect of multipath reflections on measurements made within shielded enclosures were investigated during a prior program under contract DA 36-039 AMC-02294(E). The results from these investigations indicated that shielding the measurement probe antenna in all directions except the desired signal path by means of a metal shield or hood, lined with absorbing material, provided a satisfactory and economical means for reducing multipath reflections. The antenna-hood configuration is called a hooded antenna.
Probe antennas for measurements in shielded enclosures should be broadband, and balanced. The broad bandwidth is desirable so that the large frequency range of interest can be covered with a minimum number of probe antennas. Balanced antennas are desirable to eliminate the effects of signal pickup on the transmission cable. Circular-polarization is also desirable so that the antennas will be responsive to all signals, with the one exception of an opposite-sense circular polarization.

Results from investigations on the previous program led to the selection of a conical log-helix antenna as the probe configuration most likely to satisfy all of the requirements for the probe antennas. The design and fabrication of a microwave probe antenna, to cover the frequency range from 1 to 12 GHz, and a UHF probe antenna, to cover the range from 200 to 1500 MHz, were described in the previous quarterly report. The results from a preliminary evaluation of the microwave probe antenna, both unhooded and hooded, with respect to gain, VSWR, polarization and antenna patterns were also presented in the previous report. The results from a similar preliminary evaluation of the unhooded UHF probe antenna are presented in a later section of this report.

Another important consideration with respect to probe antennas for radiated electromagnetic interference measurements is calibration. In order to assure the validity of the resulting data, it is necessary to be able to convert the signal level at the receiver (or at the signal generator in the case of susceptibility measurements) into field intensity at the surface of the antenna.

In view of the importance of calibration in probe antennas, several calibrating techniques have been investigated during this reporting period and are discussed in some detail in the next section.

2. Microwave Hooded Antenna

The design, fabrication and preliminary evaluation of a microwave hooded antenna to cover the frequency range from 1 to 12 GHz were discussed in the previous quarterly report. The primary emphasis in the development of the microwave hooded antenna during this reporting period has been devoted to an investigation of techniques for calibrating the probe in terms of field intensity at the surface of the antenna, and modifying the antenna structure to be compatible with the calibration techniques to be used.

The determination of an accurate conversion factor which may be used to convert signal power at the terminal of an antenna to a field intensity level at the surface of the antenna with a high degree of confidence is a very difficult task. If the gain of the probe antenna
is known, the conversion can be calculated from

\[ \text{FI} = \frac{4\pi P_r}{G_o \lambda^2}, \quad (1) \]

where:

- \( \text{FI} \) = Field intensity at the aperture of the antenna.
- \( G_o \) = Free-space gain of the antenna relative to an isotropic source.
- \( P_r \) = Signal power at the antenna terminal.
- \( \lambda \) = Wavelength.

The calculated conversion is quite accurate if the gain data is sufficiently accurate. However, except in the case of standard gain antennas, a lack of confidence is normally associated with the resulting calculation. In general, the determination of a sufficiently accurate gain calibration would be more tedious and difficult than the standard field calibration techniques discussed below.

A more direct approach is to immerse the antenna to be calibrated in a standard field whose field intensity at the surface of the antenna is accurately known and to measure the signal level at the terminal of the antenna. The difficulty with this technique is in establishing the standard field with sufficient accuracy.

There are two approaches which may be taken to establishing a standard field. One approach is to use an antenna with a very accurately calibrated gain as a radiating source for the standard field. The field intensity at a specified distance from such a radiating source may be calculated by

\[ \text{FI} = G_o \left[ \frac{P_t}{4\pi R^2} \right], \quad (2) \]

where:

- \( G_o \) = Free-space gain of radiating antenna relative to an isotropic source.
- \( P_t \) = Power at the terminal of the radiating antenna.
\[ R = \text{Distance from the radiating antenna to the reference point.} \]

The accuracy of this calculation is dependent on (1) the accuracy to which the gain of the radiating antenna is known, (2) the accuracy to which the power into the antenna can be determined, (3) the accuracy to which the distance \( R \) can be determined, and (4) the degree to which reflections and interference can be eliminated from the measurement range.

This is an accepted method of establishing a standard field, it is frequently used and, with sufficient care, good accuracy is possible. The technique does however, require precision measurement and close control of a number of parameters and some lack of confidence in the results exists due to the fact that the standard field is not measured at the point it is to be used.

An alternate method of establishing a standard field is to radiate a field with a more or less arbitrary antenna and measure the field intensity at the point of interest by means of a very accurate gain-calibrated substitution antenna. The substitution antenna is replaced by the antenna to be calibrated and hence the unknown antenna is immersed in a calibrated standard field. By measuring the signal level at the terminal of the antenna to be calibrated, the desired conversion factor is obtained.

The substitution antenna method of establishing a standard field has a number of advantages over the calibrated source method previously discussed. The substitution antenna method does not require the determination of the distance from the radiating source to the reference point nor knowledge of the power level at the terminal of the radiating antenna. In addition, reflections and interference are not as great a problem since the spurious signals are incident on both the substitution antenna and the antenna being calibrated and hence, they become a part of the calibrated standard field.

The substitution antenna method requires the calculation of an antenna conversion factor, and at first glance, it would appear that this technique would suffer from the same gain measurement and lack of confidence difficulties as the calculated antenna conversion factor technique discussed previously. However, this is not necessarily the case, since the substitution antenna technique allows complete freedom in the selection of the antenna type to be used for the substitution antenna, and if standard gain horns or other standard gain antennas are selected as the substitution antennas, the gain and antenna conversion factors are sufficiently well known and validated that no problems should be encountered in the validation of the calibration of the substitution antenna.
Very accurately calibrated standard gain pyramidal horn antennas covering the frequency range from 1 to 12 GHz are readily available and are particularly well suited for use as substitution antennas. Their gains and radiation patterns are very accurately known and their low side and back lobe levels significantly reduce the possibility of reflection problems.

The present plans are that the microwave hooded antenna will be calibrated in an anechoic chamber utilizing the substitution antenna technique to establish a standard field. A set of standard gain pyramidal horns will be used as substitution antennas.

The calibration of a field intensity measurement system is normally made at the terminal of the receiver. However, if this approach is taken, calibration factors for the transmission line and all associated components must be included along with the antenna conversion factor. A much more desirable approach is to perform the calibration at the terminal of the probe antenna by injecting a substitute signal at the terminal while the probe antenna, transmission line, all associated components and receiver remain connected in their normal operating configuration. Since under these conditions the transmission line, components and receiver are not in the calibration path, they are eliminated from the calibration.

A simplified schematic diagram of a series injection calibration technique which will permit this type of calibration to be made is shown in Figure 1. The calibration signal is injected in series with the transmission line at the probe antenna terminal. Since this technique requires that the calibration network be connected during normal operation, a 10:1 divider network is provided to reduce the loading of the calibrator. It is apparent from Figure 1 that this technique makes it possible to calibrate the system with all connections in their normal operating configuration.

A series injection calibration network was integrated into the microwave conical log-helix antenna as shown in Figure 2. The second coaxial arm of the antenna was used as the calibration feed line. This arm also exhibits an "infinite balun" effect which should be very nearly identical with the "infinite balun" action obtained in the normal feed arm. The center conductor of the second arm was connected to the center conductor of the feed arm through a 45 ohm metal film microwave resistor (Filmore MW125 series). The center conductor of the feed arm was connected to the shield of the second arm through a 5 ohm microwave resistor. This configuration gives the coaxial equivalent of Figure 1.

After the installation of the series injection calibration network at the apex of the antenna was completed, a 1/4" coating of epoxy was cast over the entire structure to provide rigid support for the antenna arms and the calibration network. A photograph of the microwave conical
Figure 1. Diagram of a Series Injection Calibration Technique.
Figure 2. Conical Log-Helix Antenna with Integrated Series Injection Calibration Network.

The log-helix antenna after the installation of the calibration network and the final epoxy coating is shown in Figure 3.

Measurements are presently being made to evaluate the characteristics of the microwave hooded antenna after the above modifications. If the results from these measurements indicate that the characteristics of the hooded antenna are satisfactory, calibration measurements will be initiated in the anechoic chamber, utilizing the substitution antenna method for establishing standard fields, to determine antenna conversion factors for the microwave hooded antenna.

3. UHF Hooded Antenna

The design and fabrication of a UHF hooded antenna to cover the frequency range from 200 to 1500 MHz was discussed in the previous quarterly report. Photographs of the completed antenna are shown in Figures 4 and 5. Figure 4 shows the antenna mounted on the end plate of the antenna hood ready to be inserted in the hood. Figure 5 shows the antenna mounted in the hood.

The hood was constructed from an aluminum cylinder two feet in diameter and four feet long; the wall thickness is 1/8 inch. An end plate was machined from 1/2 inch sheet aluminum. The cylinder and end plate were lined with ferrite absorbing material (Emerson and Cuming
Figure 3. Microwave Log-Helix Antenna with Series Injection Network Installed and Final Epoxy Coating Completed.

Figure 4. UHF Conical Log-Helix Probe Antenna.
Ecosorb NZ-1). To facilitate handling, the hood was mounted on a cart with casters. The height of the cart was chosen so that the center of the hooded antenna is 4 feet above floor level. This maintains the antenna in the center of the vertical dimension of the screen room.

The measured gain of the unhooded probe antenna relative to a λ/2 dipole is shown in Figure 6. The upper curve in this figure shows the measured gain of the probe antenna compared to the gain of a horizontal dipole while utilizing a horizontal dipole as a radiating source. The second curve shows the gain of the probe antenna compared with the gain of a vertical dipole while utilizing a vertical dipole as a radiating source. The average gain of the probe antenna over the design bandwidth is approximately -3.0 dB relative to a λ/2 dipole.

Selected antenna patterns of the unhooded antenna over the frequency range from 200 to 1600 MHz are shown in Figures 7 and 8. Both $E_\theta$ and $E_\phi$ patterns were made every 100 MHz over the operating band. The patterns are very similar at all frequencies and for both polarizations. The patterns illustrated were selected to show the characteristics in the middle of the operating range and at either end. The patterns at 1500 MHz and 1600 MHz illustrate what occurs at the high end of the operating band. The active region of the antenna is located at the truncated tip and this stops the normal scaling of the antenna with frequency change. As the frequency is increased, the region just
Figure 6. Gain of UHF Probe Antenna.
Figure 7. E$\hat{\phi}$ Antenna Patterns of UHF Conical Log-Helix Antenna at 200, 400, 700 and 900 MHz.
Figure 8. E\*
Antenna Patterns of UHF Conical Log-Helix Antenna
at 1100, 1400, 1500 and 1600 MHz.
behind the tip continues to act as the active region but becomes larger in terms of wavelengths. This causes the antenna to scan away from backfire and the front-to-back ratio to approach unity. As can be seen in the patterns in Figures 7 and 8, the front-to-back ratio of this antenna is relatively low and is a result of the large cone angle used in constructing the antenna. However, as was explained in the previous report, the beam shaping provided by the hood should compensate for these large back lobes.

On-axis polarization patterns of the unhooded UHF probe antenna at 200, 600, 1000, and 1500 MHz are shown in Figure 9. These patterns indicate that the circular-polarization characteristics of this antenna are quite good, especially considering the large cone angle.

Measurements to evaluate the characteristics of the hooded UHF probe antenna are presently in progress and it is anticipated that the evaluation of the hooded configuration will be completed during the next reporting period. If the characteristics of the UHF hooded antenna appear satisfactory, and if the series injection calibration technique proves successful with the microwave hooded antenna, a series injection calibration network will be integrated into the UHF hooded antenna configuration and the field intensity calibration of the probe antenna will be initiated.

C. Study of Near-Field Measurement Problems

1. General

At low frequencies, where the shielded enclosure dimensions and probe antenna spacings are small relative to the wave lengths involved, the coupling between the equipment under test and the probe antenna becomes much more complicated because of the additional components of the more complex near-field. In order to determine the measurement problems to be anticipated in this frequency range, it was considered desirable to conduct a theoretical study of the near-fields of radiators and to perform a series of experimental measurements in the near-fields of radiators, both in shielded enclosures and in the open-field.

Preliminary results from these efforts were presented in the previous quarterly report. A theoretical analysis of the near-field of a simple short-dipole antenna operating in free-space was described. The results from a series of measurements of the coupling between two antennas as a function of spacing were presented. The measurements were made in the open-field and repeated in a 8 x 8 x 20 foot shielded enclosure in which one end wall was covered with Ecosorb HPY-72
Figure 9. Polarization Patterns of UHF Conical Log-Helix Antenna at 200, 600, 1000 and 1500 MHz.
absorbing material. These measurements were made over the frequency range of 0.5 to 150 MHz.

2. Theoretical Study

As part of the continuing study of the theoretical aspects of field distributions in shielded enclosures, the composite electric field vector at several points within such an enclosure was calculated for a simplified case. For measurements made along the longitudinal centerline of the test rectangular shielded enclosure, one direct path and six first-order reflection paths exist. Figure 10, a side-view of the 8' x 8' x 20' shielded enclosure, shows the direct path (A) and four of the first-order reflections paths (2B, 2B, C, and D). When short, horizontal dipoles are considered as the source radiator and sampling probe, the electromagnetic propagation along the five paths shown in this figure may be characterized by linearly polarized electric vectors and independence of antenna departure or arrival angle. This is because each path lies in the antennae planes of symmetry, i.e., all transmissions are along boresite paths. The two sidewall reflections (not shown in Figure 10) involve non-boresite paths and thus, elliptically polarized electric vectors exist. These contributions were not considered in the following analysis.

Figure 10. Shielded Enclosure-Sideview Showing Reflection Paths.
Each transmission path length may be expressed in terms of \( A \), the antenna element separation in inches, as follows:

\[
C \text{ path (left end wall reflection)} \ C = 186 + A \\
D \text{ path (right end wall reflection)} \ D = 294 - A \\
2B \text{ paths (floor and ceiling reflections)} \ 2B = \sqrt{(96)^2 + A^2}
\]

The factors \( C \), \( D \), and \( 2B \) were calculated for ten values of \( A \), ranging from 12 inches to 100 inches. All factors were then normalized in terms of wavelength for three frequencies; 35, 37, and 59 MHz. These data are presented in Figure 11.

In the previous quarterly report, Figures 22 and 23(b) show the relative magnitude and phase angle of \( E_b \), the electric field component on antenna boresite, as functions of antenna separation normalized to wavelength. These curves were used in combination with Figure 11 to calculate the composite electric vector expected at the receiving antenna for the various element separations (\( A \) factors). Figure 12 shows the relative power level, due to this total electric vector, as a function of element separation, with points taken every ten inches, for a frequency of 37 MHz. A shallow null, about 4 dB in depth, occurs at \( A = 80 \) inches.

The nearest comparable experimental data are shown in Figure 13, which shows the normalized coupling between horizontal bow-tie antennas operating at 37.5 MHz in a shielded enclosure. The coupling curve is for a transmitter-to-backwall spacing of 93 inches and shows a pronounced null, about 50 dB in depth, at an element separation of 43 inches.

The non-conformity of Figure 12 with experimental measurement data challenges the initial simplifying assumption that an acceptable mathematical model can ignore contributions of the elliptically polarized sidewall reflection components to the total received electric vector.

It appears a more detailed analysis considering the summation of all first-order reflection paths will be necessary to substantiate the experimental measurement data. This leads to the use of image transmitting antennas and the expression of their electric vector components in a common coordinate system originating at the receive antenna. Due to the numerous calculations involved, a decision was made to write computer programs for the various segments of the analysis. Extended ALGOL programming language as applied to the Burroughs B500 Information Processing System was used. At present, program blocks have been written and successfully run for four factors involved in the analysis.
Figure 11. Reflection Paths—Normalized Distance Factors.

Figure 12. Total Power Coupling Along Paths A, 2B, 2B, C and D.
Figure 13. Measured Coupling Between Antennas as a Function of Separation in a Shielded Enclosure at 37.5 MHz.

Future work will include writing of computer program blocks for direction cosine calculations, vector resolutions, and final resultant vector combinations.

3. Experimental Measurement Program

The experimental measurement program concerned with making radiation measurements in shielded enclosures at low frequencies was continued during this reporting period. The measurements were made in the 8 x 8 x 20 foot shielded enclosure described in the previous quarterly report but with the 6-foot thick Ecosorb HPY-72 absorbing material removed from the end wall. Data were collected, over the frequency range of 1 MHz to 150 MHz, both on and off the axis of the shielded enclosure for different source antenna locations. The test setups used in making these measurements are shown in Figures 14 and 15. The antennas consisted of two "identical" bow-tie antennas, 30-inches long, with a 45-degree flare angle. The source antenna was stationary while the test antenna was mounted on a movable cart. The coupling between the antennas was recorded over the entire spacing range. The diagram of Figure 14 shows the location of the antennas relative to the shielded enclosure boundaries (i.e., equal distances from the side walls, ceiling, and floor) for the on-axis setup. The off-axis setup, Figure 15, differs from the on-axis setup in that both antennas were located two feet off-axis toward a side wall.
Figure 14. Measurement Setup On the Axis of a Shielded Enclosure.

Figure 15. Measurement Setup Off the Axis of a Shielded Enclosure.
On-axis measurements were taken with the source antenna positioned at four different locations; 93, 45, 22 1/2 and 12 inches as measured from the end wall. These measurements were taken to determine the difference in coupling with and without the absorbing material on the end wall and to observe the coupling variations due to source antenna locations relative to the reflectivity boundary at the end wall. The results from these measurements are shown in Figures 16-23. Results from open-field measurements are included for comparison.

These coupling curves show that very good correlation exist between the measurements taken with and without the absorbing material on the end wall for all test frequencies up to and including 100 MHz. At these frequencies the locations of the observed nulls, with and without absorbing material, agreed within 2 inches, while the coupling magnitude for all points outside of the null areas agrees within 2 dB. At the test frequency of 150 MHz very little correlation between the curves exists and the null locations are approximately 27 inches apart.

The coupling curves, obtained with different locations of the source antenna, show a definite pattern with regard to null movement and coupling magnitude for test frequencies up to and including 50 MHz. As the source antenna was placed nearer to the end wall, the nulls were observed to occur at greater separations between the source and test antennas. The magnitude of the coupling curves show close correlation for antenna separations from 12 inches out to the point where the effect of the nulls become apparent. As the antenna spacing is increased beyond the null areas the curves maintain the same shapes, however, the coupling magnitudes are less in these areas as the source antenna is moved closer to the end wall. This effect is readily apparent in Figure 18. At 100 and 150 MHz, very little correlation is apparent between any of the resulting coupling curves.

Off-axis measurements were made with the source antenna positioned at three different locations; 93, 45 and 12 inches from the end wall. These measurements were made to determine the effects of moving the antenna off the geometric center line of the shielded enclosure. The results from the off-axis measurements are compared with their on-axis counterparts in Figures 24-31.

At the test frequencies of 1 MHz and 10 MHz, the off-axis measurements indicated that no nulls exist and these curves tend to follow the open-field curves more closely than the on-axis curves. However, at 15 and 25 MHz, with the off-axis source antenna located 12 inches from the end wall, minimums were observed and were located at antenna separations greater than those existing at the same frequency for the on-axis setup. No minimums were observed when the source antenna was located 93 inches and 45 inches from the end wall. Results from the 30 MHz off-axis measurements show minimums appearing for all source antenna locations. These minimums are again located at greater antenna spacings.
Figure 16. Coupling Between Antennas as a Function of Spacing and Source Location, On-Axis, in a Shielded Enclosure at 1 MHz.

Figure 17. Coupling Between Antennas as a Function of Spacing and Source Location, On-Axis, in a Shielded Enclosure at 10 MHz.
Figure 18. Coupling Between Antennas as a Function of Spacing and Source Location, On-Axis, in a Shielded Enclosure at 15 MHz.

Figure 19. Coupling Between Antennas as a Function of Spacing and Source Location, On-Axis, in a Shielded Enclosure at 25 MHz.
Figure 20. Coupling Between Antennas as a Function of Spacing and Source Location, On-Axis, in a Shielded Enclosure at 30 MHz.

Figure 21. Coupling Between Antennas as a Function of Spacing and Source Location, On-Axis, in a Shielded Enclosure at 50 MHz.
Figure 22. Coupling Between Antennas as a Function of Spacing and Source Location, On-Axis, in a Shielded Enclosure at 100 MHz.

Figure 23. Coupling Between Antennas as a Function of Spacing and Source Location, On-Axis, in a Shielded Enclosure at 150 MHz.
Figure 24. Coupling Between Antennas as a Function of Spacing and Source Location, On-Axis and Off-Axis, in a Shielded Enclosure at 1 MHz.

Figure 25. Coupling Between Antennas as a Function of Spacing and Source Location, On-Axis and Off-Axis, in a Shielded Enclosure at 10 MHz.
Figure 26. Coupling Between Antennas as a Function of Spacing and Source Location, On-Axis and Off-Axis, in a Shielded Enclosure at 15 MHz.

Figure 27. Coupling Between Antennas as a Function of Spacing and Source Location, On-Axis and Off-Axis, in a Shielded Enclosure at 25 MHz.
Figure 28. Coupling Between Antennas as a Function of Spacing and Source Location, On-Axis and Off-Axis, in a Shielded Enclosure at 30 MHz.

Figure 29. Coupling Between Antennas as a Function of Spacing and Source Location, On-Axis and Off-Axis, in a Shielded Enclosure at 50 MHz.
Figure 30. Coupling Between Antennas as a Function of Spacing and Source Location, On-Axis and Off-Axis, in a Shielded Enclosure at 100 MHz.

Figure 31. Coupling Between Antennas as a Function of Spacing and Source Location, On-Axis and Off-Axis, in a Shielded Enclosure at 150 MHz.
than those obtained with the on-axis measurements. At 50 MHz, minimums were obtained at all three off-axis source locations, but they occur at antenna spacings less than those of the on-axis measurements. The off-axis coupling curves resulting from the upper test frequencies of 100 and 150 MHz show little or no correlation with the on-axis curves.

The results from these measurements indicate that over the frequency range from 1 to 30 MHz it may be possible to make radiation measurements in an 8 x 8 x 20 foot shielded enclosure which are essentially independent of the location of the test setup in the enclosure. In order to realize this independence of location over this frequency range, however, it is necessary that the spacing between the probe antenna and the source of the radiation be no greater than approximately one meter (see Figure 20). If this spacing limitation is met, the coupling curves also indicate that good agreement exists between the results obtained in the shielded enclosure and the results obtained from the same measurements in the open-field.

Similar measurements are planned for an 8 x 8 x 12 foot shielded enclosure to determine if these results and conclusions can be applied to the more general case of shielded enclosures having different dimensions.
II. SUMMARY

A series injection calibration network was integrated into the microwave hooded antenna configuration. A 1/4 inch coating of epoxy was cast over the cone structure to provide rigid support for the antenna arms and the calibration network. Measurements are presently in progress to determine the effects of these modifications on the probe antenna characteristics. If the characteristics prove to be satisfactory, a field intensity calibration of the microwave hooded antenna over the frequency range from 1 to 12 GHz will be initiated.

Measurements to evaluate the characteristics of the UHF hooded antenna are being conducted. It is anticipated that the evaluation will be completed during the next reporting period. If the characteristics of the UHF hooded antenna appear satisfactory, and if the series injection calibration technique proves successful with the microwave hooded antenna, a series injection calibration network will be integrated into the UHF hooded antenna configuration and the field intensity calibration of the probe antenna will be initiated.

In an attempt to theoretically describe the field distribution within a shielded enclosure, the composite electric field vector at several points within such an enclosure was calculated for a simplified case. To simplify the calculations required for this analysis, an assumption was made that the contributions of the elliptically-polarized sidewall reflection components to the total electric vector could be neglected. However, the lack of agreement between the calculated results and results from experimental measurements indicates that this assumption was probably invalid, and that a more detailed analysis considering the summation of all first-order reflections will be necessary to substantiate the experimental measurement data.

Due to the numerous calculations required for the more detailed analysis, a decision was made to write computer programs for the various segments of the analysis. Program blocks have been written and successfully run for four factors involved in the analysis. Future work will include writing program blocks for the remaining factors and writing a program for combining the factors to obtain the composite results.

Results from experimental measurements made in a shielded enclosure and in the open-field indicate that over the frequency range from 1 to 30 MHz it is possible to make radiation measurements in an 8 x 8 x 20 foot shielded enclosure which are essentially independent of the location of the test setup in the enclosure. In order to realize this independence of location over this frequency range, however, it is necessary that the spacing between the probe antenna and the source of the radiation be no greater than approximately one meter. If this spacing
limitation is met, the coupling curves also indicate that good agreement exists between the results obtained in the shielded enclosure and results obtained from the same measurements in the open-field.

Similar measurements are planned for an 8 x 8 x 12 foot shielded enclosure to determine if these results and conclusions can be applied to the more general case of shielded enclosures having different dimensions.
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ELECTROMAGNETIC INTERFERENCE MEASUREMENT METHODS-SHIELDED ENCLOSURE

Quarterly Report No. 2, 1 September 1966 to 30 November 1966

Free, William R., Bonham, Charlton H., Gibson, Robert E., Gutzke, John H., and Jenkins, Bernard M.

April 1967

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Radio Frequency Interference
Communications

U. S. Army Electronics Command
Port Monmouth, New Jersey AMSEL-RD-GF

During the period covered by this report, investigations of techniques and procedures for making radiation measurements in shielded enclosures which can be correlated with open-field measurements have continued. The primary objective of this program is to develop a capability for determining the ease of radiation and susceptibility characteristics of U. S. Army communication equipments in the controlled environments of shielded enclosures.

A microwave hooded antenna capable of making the desired measurements in a shielded enclosure over the frequency range from 1 to 12 GHz has been developed and evaluated. Techniques for calibrating this probe antenna have been investigated during this period and are described in detail.

A UHF hooded antenna, for use over the frequency range from 200 to 1500 MHz, has also been developed. The evaluation of this probe antenna has continued during this period and the results obtained to date are presented.

Theoretical and experimental investigations of the field distribution within a shielded enclosure at low frequencies are discussed.
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ELECTROMAGNETIC INTERFERENCE
MEASUREMENT METHODS—SHIELDED ENCLOSURE

QUARTERLY REPORT

By
W. R. FREE, C. H. BONHAM,
R. E. GIBSON,
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AUGUST 1967

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METHODS-SHIELDED ENCLOSURE

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ABSTRACT

Investigation of techniques and procedures for making radiated measurements in shielded enclosures, which can be correlated with measurements made in the open-field, have continued during this reporting period. The primary objective of this program is to develop a capability for determining the ease radiation and susceptibility characteristics of U.S. Army communications equipments in the controlled environments of shielded enclosures.

A microwave hooded antenna for use over the 1 to 12 GHz frequency range was evaluated after a modification to integrate a series injection calibration network into the antenna structure. The results of this evaluation indicate that the characteristics of the probe antenna are acceptable.

An evaluation of a UHF hooded antenna for use over the 200 to 1500 MHz region was completed. The results of this evaluation indicate that the characteristics of the hooded probe antenna are acceptable.

A series of antenna coupling measurements were performed in an 8 x 8 x 12 foot shielded enclosure over the frequency range from 1 to 100 MHz. The results from these measurements were compared with results obtained in an 8 x 8 x 20 foot enclosure to determine the effects of enclosure dimensions on measurements in this frequency range. An analysis of these measurements indicates that satisfactory measurements can be made at low frequencies in shielded enclosures, and that the results are essentially independent of both the location of the test setup and the dimensions of the enclosure.

A computer program for simulating reflection conditions in a shielded enclosure was completed during this period. The development of the computer program and a discussion of preliminary results obtained with the program are presented.
FOREWORD

This report was prepared at the Georgia Tech Engineering Experiment Station on Contract No. DA 28-043 AMC-02381(E). The work covered by this report was performed within the Electronics Division under the supervision of Mr. D. W. Robertson, Head of the Communications Branch. The report covers the activities and results of the third quarter's effort on a project to determine methods for measuring the interference characteristics of U. S. Army communication equipments in shielded enclosures.
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I. FACTUAL DATA

A. Introduction

This report covers the work performed under Contract DA 26-043 AMC-02581(E), "Electromagnetic Interference Measurement Methods-Shielded Enclosure," for the period 1 December 1966 to 28 February 1967.

The purpose of the program is to conduct a theoretical and experimental investigation to determine the test setups, accessories and procedures best suited to measurement, in shielded enclosures, of the electromagnetic emission and susceptibility characteristics of military communication-electronic equipment.

The three primary objectives of the program are (1) the development of hooded probe antennas to cover the frequency range from 200 MHz to 12 GHz, (2) a theoretical and experimental study of the problems associated with near-field measurements in shielded enclosures at frequencies below 200 MHz, and (3) the development of measurement procedures for making emission and susceptibility measurements in shielded enclosures.

During this report period a significant amount of effort was allotted to each of the three primary tasks. An extensive series of measurements were made to evaluate the performance of a microwave hooded antenna over the frequency range from 1 to 12 GHz and the performance of a UHF hooded antenna over the frequency range from 200 to 1500 MHz.

A theoretical study of the field distributions in shielded enclosures at low frequencies was continued during this period. A computer program for simulating reflection conditions in a shielded enclosure was completed. The current version of this program sums the electric fields from the direct transmission path and from six reflected transmission paths. The program is based on the use of "short" dipoles as radiating and receiving elements.

Computer runs have been made for ten different frequencies, with antenna element separations of 12 to 100 inches for each run. Five of the runs show reasonably good correlation with existing data obtained from experimental measurements made in a shielded enclosure.

The experimental data, however, was taken using 30 inch bow-tie antennas rather than dipoles. Thus the measurement data can be considered only as approximate validation of the model. The experimental antenna coupling measurements using bow-tie antennas were made in a
8 x 8 x 12 foot shielded enclosure over the frequency range from 1 to 100 MHz. A comparison of the results obtained from these measurements with results obtained in an 8 x 8 x 20 foot enclosure is included.

B. Development of Hooded Antennas

1. General

Results from previous work indicated that shielding the measurement probe antenna in all directions except the desired signal path by means of a metal shield or hood, lined with absorbing material, provided a satisfactory and economical means for reducing the multi-path reflections encountered in making measurements in shielded enclosures. It has been determined that this technique works quite well over the frequency range from 200 MHz to 12 GHz. Thus a primary objective of this program is the development of hooded probe antennas to cover this frequency range.

2. Microwave Hooded Antenna

The design, fabrication and preliminary evaluation of a microwave hooded antenna to cover the frequency range from 1 to 12 GHz were discussed in the previous quarterly reports. During the last reporting period this antenna was modified to include a series injection calibration network. A series of measurements were performed during this reporting period to evaluate the characteristics of the microwave hooded antenna after this modification.

The measured gain of the modified microwave hooded antenna relative to a 1/2 dipole and the VSWR referred to 50 ohms over the design bandwidth are shown in Figure 1. A comparison of these gain curves with gain curves obtained before the modification (Figure 14, Quarterly Report No. 1) reveals that the modification changed the gain characteristics of the hooded antenna to some extent. The most significant effects resulting from the addition of the calibration network are a flattening of the gain characteristics in the range from 2.5 to 10.5 GHz and a sharp decrease in gain in the 10.5 to 12 GHz region.

A comparison of the VSWR curve in Figure 1 with the VSWR for the unhooded probe antenna before the modification (Figure 7, Quarterly Report No. 1) reveals that the addition of the calibration network significantly improved the VSWR characteristics in the 1 to 10 GHz range (with the exception of a single spike in the 3.0 to 3.5 GHz region). The addition of the network significantly degraded the VSWR characteristics above 11.5 GHz. The low gains and high values of VSWR
Figure 1. Gain and VSWR Curves of the Microwave Hooded Antenna.
obtained above 10.5 GHz after the modification indicate that the performance of the microwave resistors used in the calibration network degenerated above this frequency.

Antenna patterns obtained with the modified microwave hooded antenna are shown in Figures 2-4. Both EΦ and Eθ patterns were made at 1 GHz increments over the design band width of the antenna. The EΦ and Eθ patterns were quite similar, and for brevity, only EΦ patterns at ten selected frequencies are shown to demonstrate the operation of the antenna.

A comparison of these antenna patterns with those obtained before the modification (Figures 15-18, Quarterly Report No. 1) indicates that the addition of the calibration network had no significant effect on the antenna patterns in the 1 to 6 GHz region, although some reduction in the main lobe beamwidths was noted. At 1 GHz, the half-power beamwidth was reduced from 36 degrees to 24 degrees and at 6 GHz the 3 dB beamwidth was reduced from 30 degrees to 15 degrees. In the 7 to 12 GHz region, beam-splitting was much more apparent after the modification. While beam-splitting is undesirable, it is apparent from the patterns that the beam shape and symmetry of the main lobe on boresight are satisfactory at 10 and 11 GHz after the modification. This is due to the fact that, although beam-splitting is more severe after the modification, the splitting does not occur as near boresight.

The on-axis polarization patterns of the microwave hooded antenna at 1, 6 and 10 GHz are shown in Figure 5. A comparison of these patterns with patterns obtained with the unhooded probe antenna (Figure 12, Quarterly Report No. 1) indicates that the addition of the hood and the calibration network has degraded the circular-polarization characteristics to some extent.

The characteristics of the microwave hooded antenna are considered acceptable for a prototype probe antenna even though the gain is less than desirable in the 1 to 2 GHz and 11 to 12 GHz regions and there is some undesirable beam-splitting in the frequency range above 6 GHz. These problems can probably be resolved by a more extensive development effort of the antenna configuration.

During the next reporting period, the microwave hooded antenna will be field-intensity calibrated in accordance with the standard field calibration technique described in the last quarterly report.
Figure 2. $\vec{E}$ Antenna Patterns of Microwave Hooded Antenna at 1, 2, 3, and 4 GHz.
Figure 3. Eφ Antenna Patterns of Microwave Hooded Antenna at 5, 6, 7, and 8 GHz.
3. UHF Hooded Antenna

The design, fabrication, and preliminary evaluation of a UHF hooded antenna to cover the frequency range from 200 MHz to 1.5 GHz were discussed in the previous quarterly reports. The primary emphasis during this reporting period has been the evaluation of the hooded characteristics.

The measured gain of the hooded probe antenna relative to a $\lambda/2$ dipole and the VSWR referred to 50 ohms over the design bandwidth are shown in Figure 6. The upper curve shows the measured gain of the probe antenna compared to the gain of a horizontal dipole while utilizing a horizontal dipole as a radiating source. The second curve shows the gain of the probe antenna compared with a vertical dipole while utilizing a vertical dipole as a source. The average gain of the probe antenna over a $\lambda/2$ dipole is approximately -10 dB. Comparing this with the measured gain of the unhooded antenna, published in the last quarterly report, shows that the gain has been reduced approximately 2 dB at the high end of the band and 22 dB at the low end. On the average the gain has been reduced by 7 dB. The VSWR of the probe antenna is shown in the bottom curve. The average VSWR is approximately 2.5.

Selected antenna patterns of the hooded antenna over the design bandwidth are shown in Figures 7 and 8. Both $E_\theta$ and $E_\phi$ patterns were made every 100 MHz over the operating band. The patterns are very similar at all frequencies and for both polarizations. The patterns
Figure 5. Polarization Patterns of Microwave Hooded Antenna at 1, 6, and 10 GHz.
Figure 6. Gain and VSWR Curves of the UHF Hooded Antenna.
Figure 7. Eφ Antenna Patterns of UHF Hooded Antenna at 200, 400, 700, and 900 MHz.
Figure 8. $\Sigma\phi$ Antenna Patterns of UHF Hooded Antenna at 1100, 1400, 1500, and 1600 MHz.
shown were selected to show the characteristics in the middle of the operating range and at either end. Comparison of these patterns with those published in the last report shows how the hood narrows the main lobe and decreases the level of the side and back lobes. At the lower end of the band the beam shaping and side lobe suppression effects of the hood are at a minimum as can be seen from the 200 MHz pattern. At this frequency, the front-to-back ratio is only 6 dB and the 3 dB beamwidth is 60 degrees. This, however, is still an improvement over the 1 dB front-to-back ratio and 100 degree beamwidth obtained at 200 MHz without the hood. The improvement at higher frequencies was more pronounced. For example, at 700 MHz the hood increased the front-to-back ratio by 16 dB and decreased the beamwidth by 60 degrees.

On-axis polarization patterns of the hooded UHF probe antenna at 200, 600, 1000, and 1500 GHz are shown in Figure 9. These patterns indicate, when compared with those for the unhooded antenna in the last report, that the addition of the hood results in a slight improvement in the circular-polarization characteristics of the probe antenna.

The characteristics of the UHF hooded antenna are considered acceptable for a prototype probe antenna even though the gain is less than desirable at the low end of the design frequency range.

During the next reporting period, a series injection calibration network will be integrated into the UHF hooded antenna. After some evaluation to determine the effects of the addition of the calibration network, the hooded antenna will be field-intensity calibrated.

C. Study of Near-Field Measurement Problems

1. General

Results from previous work have indicated that at low frequencies, where the shielded enclosure dimensions and probe antenna spacings are small relative to the wave lengths involved, the coupling between the equipment under test and the probe antenna does not exhibit the erratic variations as a function of spacing and/or frequency which are present at higher frequencies. The observation of this phenomenon led to the hypothesis that below some low frequency limit it may be possible to make measurements in shielded enclosures, with conventional probes, which can be correlated within several dB with measurements made in the open-field. In order to determine the feasibility of this hypothesis and to establish the critical or upper limit frequency for this low frequency range, theoretical and experimental studies were initiated to investigate the field distributions within shielded enclosures at low frequencies.
Figure 9. Polarization Patterns of UHF Hooded Antenna at 200, 600, 1000, and 1500 MHz.
2. Theoretical Study

Work has been completed on a computer program which simulates the multipath transmission conditions in a shielded enclosure when the source and probe antennas are assumed to be short dipoles. The primary program restriction requires that both dipoles be boresighted along a centerline of the shielded enclosure.

An analysis similar to that contained in Quarterly Report No. 1 was used to derive electric vector magnitudes and phase angles. The more important steps in the analysis are given below, beginning with expressions for $E_p$ and $E_\theta$, the orthogonal vectors of interest:

$$E_p = E_l \cos \theta \sin \omega t', \quad (1)$$

$$E_\theta = E_2 \sin \theta \sin (\omega t' + \delta), \quad (2)$$

where:

$$E_l = 2K' \left| \frac{2\pi}{R_n^2} - \frac{j}{R_n^3} \right|, \quad (3)$$

$$E_2 = K' \left| \frac{2\pi}{R_n^2} + j \frac{4\pi^2}{R_n^2} - \frac{j}{R_n^3} \right|, \quad (4)$$

$$\omega t' = \omega t - \beta r, \quad (5)$$

$$R_n = R/\lambda \text{ (normalized antenna separation)}, \quad (6)$$

$$K' = \frac{I_o \ell}{4\pi \varepsilon_o \omega \lambda^2}, \quad (7)$$

$I_o = \text{peak value of current (amperes)}, \quad (8)$

$\ell = \text{length of dipole (meters)}, \quad (9)$

$\omega = \text{radian frequency, } 2\pi f \text{ (radian/sec)}, \quad (10)$

$\beta = 2\pi/\lambda \text{ (phase constant)}, \quad (11)$
\[ \delta = \arctan \left( \frac{(2\pi R)^2 - 1}{2\pi R} \right) = \arctan \left( -\frac{1}{2\pi R} \right). \] (12)

Theta (θ) is the angle between the antenna axis and the transmission path; thus for end fire transmissions θ = 0° or 180°, and for boresite transmissions θ = 90°. Figure 10 shows the θ angles for the two side wall reflection paths.

The program simulates one direct and six reflected transmission paths between antennas boresighted along the longitudinal centerline of an 8' x 8' x 20' shielded enclosure. The source antenna was fixed at 93 inches from the left-hand end wall, and the spacing between source and probe antennas was varied from 12 inches to 100 inches by one inch increments. Program runs were made for each of ten different frequencies, ranging from 1 to 100 MHz.

Four of the six reflection paths are boresite paths with respect to both the source and probe antennas; the two end wall paths and the floor and ceiling paths. The electric vectors on boresite in the near-field of a short dipole lie parallel to the dipole. Thus, for these four paths, the electric vectors are tangential to their respective reflective surfaces and undergo a 180 degree spatial phase shift upon reflection. Arriving at the probe antenna the vectors are again parallel to the dipole, but have a sense opposite to that of the direct path vector.

The two side wall reflection paths, detailed in Figure 10, are not boresite paths. This figure shows the breakdown of \( E_\rho \) and \( E_\theta \) into components tangential and normal to the reflection surfaces. Observing the usual rules for reflections from an assumed perfectly conducting surface, Figure 10 shows that the two side wall reflection components combine at the probe antenna to give resultant vectors which are parallel to the receiver dipole. Although elliptically-polarized electric vectors exist along the two side wall reflection paths, it can be seen by inspection of Figure 10 that, at the receive probe, all electric vectors are parallel to the dipole and may be combined arithmetically. This results from the symmetry of the centerline transmission path and the sense reversal of \( E_\rho \) as angle θ passes through 90 degrees.

Expressions (1) and (2) show that, for a given value of theta, the vectors \( E_\rho \) and \( E_\theta \) are phase-shifted sine functions of \( \omega t \). For computation purposes trigonometric identities were used to convert (1) and (2) to the form shown below:
Figure 10. Shielded Enclosure - Top View Showing Side Wall Reflection Paths.
\[ E_\rho = \text{ERSC} \sin \omega t + \text{ERCC} \cos \omega t, \]  
\[ E_\theta = \text{ETSC} \sin \omega t + \text{ETCC} \cos \omega t, \]  
where: \[ \text{ERSC} = E_\rho \text{ sine coefficient}, \]  
\[ \text{ERCC} = E_\rho \text{ cosine coefficient}, \]  
\[ \text{ETSC} = E_\theta \text{ sine coefficient}, \]  
\[ \text{ETCC} = E_\theta \text{ cosine coefficient}. \]  

For every value of element separation, the four coefficients named above were computed for each of seven transmission paths. It is evident from (1) that the \( E_\rho \) coefficients must be zero for the direct path and the four boresite paths, since \( \theta \) is 90° for these paths. The non-zero values of the \( E_\rho \) coefficients are associated with the side wall reflection paths. The sine and cosine coefficients were assigned appropriate signs and separately summed by the program. The final result, the magnitude of the resultant total E-field vector, was calculated as the root-sum-square of the two coefficient sums. This factor, converted to dB, represents the magnitude of coupling between antennas for the particular frequency and element spacing used.

Figures 11-20 show the computed antenna coupling in a shielded enclosure as a function of dipole element spacing for ten different frequencies. Two sets of measured coupling data, using 30 inch bow-tie antennas in a shielded enclosure and in the open-field, are also plotted. It should be noted that at each frequency, all three curves were normalized to 120 dB at the minimum element spacing, thus the curve-to-curve correspondence is relative.

The computer-generated curves show coupling nulls at five of the ten frequencies considered: 20 MHz, 25 MHz, 30 MHz, 37.5 MHz, and 50 MHz (Figures 15 - 19). The null depth relative to open-field bow-tie antenna measurement data varies greatly for the computer-generated data and ranges from 5 dB at 20 MHz (Figure 15) to 35 dB at 37.5 MHz (Figure 18). At 37.5 MHz, the computed coupling curve shows a discontinuity at the null.

As can be seen, the shielded enclosure data show nulls at several frequencies. Although differences exist between the two sets of data
Figure 11. Coupling Between Antennas as a Function of Spacing at 1 MHz.

Figure 12. Coupling Between Antennas as a Function of Spacing at 5 MHz.
Figure 13. Coupling Between Antennas as a Function of Spacing at 10 MHz.

Figure 14. Coupling Between Antennas as a Function of Spacing at 15 MHz.
Figure 15. Coupling Between Antennas as a Function of Spacing at 20 MHz.

Figure 16. Coupling Between Antennas as a Function of Spacing at 25 MHz.
Figure 17. Coupling Between Antennas as a Function of Spacing at 30 MHz.

Figure 18. Coupling Between Antennas as a Function of Spacing at 37.5 MHz.
Figure 19. Coupling Between Antennas as a Function of Spacing at 50 MHz.

Figure 20. Coupling Between Antennas as a Function of Spacing at 100 MHz.
with regard to null shapes and null locations, this was to be expected, because the physical measurement setup was only a partial analogue of the mathematical model. However, the degree of correlation with measured data observed in Figures 11-20 tends to support the validity of both the measured data and the mathematical model.

3. Experimental Measurement Program

A series of measurements of the coupling between two antennas as a function of spacing, over the frequency range from 1 to 150 MHz, were performed in an 8 x 8 x 20 foot shielded enclosure. The results from these measurements were presented in Quarterly Reports Nos. 1 and 2. The results indicated that over the frequency range from 1 to 30 MHz, it may be possible to make radiation measurements in an 8 x 8 x 20 foot shielded enclosure which are essentially independent of the location of the test setup in the enclosure.

During this reporting period, this series of measurements have been repeated in an 8 x 8 x 12 foot shielded enclosure to determine if the results and conclusions obtained from the 20 foot enclosure measurements can be applied to the more general case of shielded enclosures having different dimensions.

Antenna coupling data were obtained over the frequency range of 1 to 100 MHz with the test configurations shown in Figures 21 and 22. Data were obtained under the following conditions:

(a) Both antennas located on the centerline of the long dimension of the enclosure (on-axis) and with the source antenna positioned 45 inches from the enclosure end wall.

(b) Both antennas located on the centerline of the long dimension of the enclosure (on-axis) and with the source antenna positioned 12 inches from the enclosure end wall.

(c) Both antennas located 2 feet off center of the long dimension of the enclosure (off-axis) and with the source antenna positioned 45 inches from the enclosure end wall.

(d) Both antennas located 2 feet off center of the long dimension of the enclosure (off-axis) and with the source antenna positioned 12 inches from the enclosure end wall.

The two antennas were bow-tie antennas, 30 inches long with a 45-degree flare angle. The antennas were maintained on the vertical center (i.e., equal distances from the ceiling and floor) for all measurements. The source antenna position was stationary during each
Figure 21. Measurement Setup On the Axis of a Shielded Enclosure.

Figure 22. Measurement Setup Off the Axis of a Shielded Enclosure.
run while the test antenna position was varied by means of a movable cart. Coupling data were obtained over the entire spacing range of the two antennas.

On-axis measurements were made to determine the extent of correlation between antenna coupling data obtained in two different size shielded enclosures. Data resulting from the on-axis measurements are shown in Figures 23-27. Results from previous measurements made in an 8 x 8 x 20 foot enclosure and in the open-field are included in these figures for comparison.

The coupling curves show satisfactory correlation between measurements made in the two enclosures over a frequency range of 1 to 50 MHz. The curves obtained in the two enclosures under equivalent measurement conditions (corresponding source antenna locations) show that the locations of the nulls agree within one inch. Coupling magnitudes agree within 2 dB, except at null points and at separation distances which placed the test antenna, in the 12 foot enclosure, within 30 inches of the end wall. Under these conditions the effect of the wall on the test antenna in the 12 foot enclosure caused a divergence between the results obtained in the two enclosures. The end wall distortion was not apparent in the 20 foot enclosure measurements at these separation distances because of the additional enclosure length. As shown in Figure 27, no correlation existed between the coupling data obtained in the two enclosures at a test frequency of 100 MHz.

As an additional means of evaluating correlation between coupling measurements in different size enclosures, on-axis antenna patterns of the source antenna were recorded in both the 8 x 8 x 12 and 8 x 8 x 20 foot enclosures. The source antenna was 45 inches from the end wall and the spacing between antennas was maintained at 40 inches in both enclosures. Test frequencies corresponded to those used for the above coupling measurements. The resulting antenna patterns are shown in Figures 28-32.

Analysis of the figures shows that satisfactory correlation existed between the patterns in the two enclosures at frequencies of 1, 10, and 37.5 MHz. The patterns recorded at 37.5 MHz revealed some distortion. This distortion can be attributed to the fact that the 40 inch separation distance placed the test antenna in a null area as shown by Figure 25. The fact that distortion occurs when the probe antenna is located in or near a null was established in Quarterly Report No. 1. At 50 MHz, marginal correlation existed at the pattern peaks and no correlation was evident in the pattern nulls. Referring to the 50 MHz coupling curve (Figure 26), it can be seen that the 40 inch separation distance placed the test antenna near a null on the coupling curve, and, some distortion is to be expected. At 100 MHz, the antenna patterns showed that no correlation between field patterns in the two enclosures existed. Reference to the 100 MHz coupling curves
Figure 23. Coupling Between Antennas as a Function of Spacing in a 12 and 20 Foot Enclosure at 1 MHz.

Figure 24. Coupling Between Antennas as a Function of Spacing in a 12 and 20 Foot Enclosure at 10 MHz.
Figure 25. Coupling Between Antennas as a Function of Spacing in a 12 and 20 Foot Enclosure at 37.5 MHz.

Figure 26. Coupling Between Antennas as a Function of Spacing in a 12 and 20 Foot Enclosure at 50 MHz.
Figure 27. Coupling Between Antennas as a Function of Spacing in a 12 and 20 Foot Enclosure at 100 MHz.

(Figure 27) shows that the 40 inch separation distance caused the test antenna in the 8 x 8 x 12 foot enclosure to be located where the field coupling was relatively constant with spacing; conversely, this separation distance in the 8 x 8 x 20 foot enclosure caused the test antenna to be located directly in a coupling null. Under these conditions, correlation between the field patterns would not be expected.

Off-axis coupling measurements were made in the 8 x 8 x 12 foot enclosure to determine the effect of moving the antennas off the geometric centerline of the enclosure. As with the on-axis measurements, these were made with separation distances between the source antenna and end wall of 45 and 12 inches. Results of these measurements are shown in Figures 33-37. Results of the on-axis and open-field measurements are also shown in these figures for comparison.

At test frequencies of 1 and 10 MHz, correlation between the coupling data obtained on- and off-axis was satisfactory. In fact, the off-axis coupling curve tended to follow the open-field curve more closely than the on-axis curve. For test frequencies of 37.5 and 50 MHz, the resulting on- and off-axis coupling curves show correlation only to the extent that the curve shapes are similar. Location of the off-axis nulls was shifted such that they occurred at shorter separation distances than the on-axis nulls. At 100 MHz, no correlation between on- and off-axis coupling existed.
Figure 28. Antenna Patterns Made in a 12 and 20 Foot Shielded Enclosure at 1 MHz.

Figure 29. Antenna Patterns Made in a 12 and 20 Foot Shielded Enclosure at 10 MHz.
Figure 30. Antenna Patterns Made in a 12 and 20 Foot Shielded Enclosure at 37.5 MHz.

Figure 31. Antenna Patterns Made in a 12 and 20 Foot Shielded Enclosure at 50 MHz.
Figure 32. Antenna Patterns Made in a 12 and 20 Foot Shielded Enclosure at 100 MHz.

Based on the results of the above coupling data and field patterns, it appears that satisfactory correlation exists between measurements made in different size shielded enclosures (for equivalent source antenna locations) over the frequency range of 1 to 37.5 MHz. Marginal correlation exists between the same measurements at 50 MHz, and no correlation exists at 100 MHz.

It was shown in Quarterly Report No. 2 that good correlation was obtained between measurements made in the open-field and measurements made in the shielded enclosure (independent of the location of the test setup within the enclosure) over a frequency range of 1 to 30 MHz and over a spacing range of 12 to 40 inches. Since it has been shown in this report that good correlation is obtained between measurements made in different size enclosures over this frequency and spacing range, it appears that measurements can be made in conventional shielded enclosures (not exceeding $8 \times 8 \times 20$ feet) which are essentially independent of the location of the test setup within the enclosure and/or the dimensions of the enclosure. Under worst case conditions, the maximum error between shielded enclosure and open-field measurements will be approximately 10 dB.
Figure 33. Coupling Between Antennas as a function of Spacing, On-Axis and Off-Axis, in a 12 Foot Shielded Enclosure at 1 MHz.

Figure 34. Coupling Between Antennas as a Function of Spacing, On-Axis and Off-Axis, in a 12 Foot Shielded Enclosure at 10 MHz.
Figure 35. Coupling Between Antennas as a Function of Spacing, On-Axis and Off-Axis, in a 12 Foot Shielded Enclosure at 37.5 MHz.

Figure 36. Coupling Between Antennas as a Function of Spacing, On-Axis and Off-Axis, in a 12 Foot Shielded Enclosure at 50 MHz.
Figure 37. Coupling Between Antennas as a Function of Spacing, On-Axis and Off-Axis, in a 12 Foot Shielded Enclosure at 100 MHz.
II. SUMMARY

The microwave hooded antenna has been modified to include a series injection calibration network. Measurements to determine the effects of this modification indicate that the addition of the calibration network degraded the gain and VSWR characteristics above 10.5 GHz, decreased the main lobe beamwidth above 4 GHz, and caused more severe beam-splitting above 7 GHz.

The characteristics of the microwave hooded antenna are considered acceptable for a prototype probe antenna even though the gain is less than desirable at the upper and lower ends of the frequency range and there is some undesirable beam-splitting above 6 GHz. Future work will include a complete field-intensity calibration of the microwave hooded antenna.

Measurements to evaluate the characteristics of the UHF hooded antenna were completed during this reporting period. The results indicate that the characteristics of the UHF hooded antenna are acceptable for a prototype probe antenna even though the gain is less than desirable at the low end of the design frequency range.

During the next reporting period, a series injection calibration network will be integrated into the UHF hooded antenna. Following the evaluation of the calibration network, the UHF hooded probe antenna will also be field-intensity calibrated.

A computer program to simulate the multipath transmission conditions between short dipoles in a shielded enclosure at lower frequencies was completed during this period. Measured data taken in a similar shielded enclosure, but using different antennas, was presented for comparison. Sufficient correlation was obtained to support the validity of both the measured data and the mathematical model.

A series of antenna coupling measurements were performed in an 8 x 8 x 12 foot enclosure. On the basis of an analysis of the results of these measurements and the results from the same measurements made in an 8 x 8 x 20 foot enclosure, it appears that radiated measurements can be made in conventional shielded enclosures over the frequency range from 1 to 30 MHz, with conventional probe antennas, which are essentially independent of the location of the test setups within the enclosure and the dimensions of the enclosure.
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ELECTROMAGNETIC INTERFERENCE MEASUREMENT METHODS-SHIELDED ENCLOSURE

Quarterly Report No. 3, 1 December 1966 to 28 February 1967

Free, William R., Bonham, Charlton H., Gibson, Robert E., and Jenkins, Bernard M.

August 1967

Radio Frequency Interference Communications

U. S. Army Electronics Command
Fort Monmouth, New Jersey

Investigation of techniques and procedures for making radiated measurements in shielded enclosures, which can be correlated with measurements made in the open-field, have continued during this reporting period. The primary objective of this program is to develop a capability for determining the case radiation and susceptibility characteristics of U. S. Army communications equipments in the controlled environments of shielded enclosures.

A microwave hooded antenna for use over the 1 to 12 GHz frequency range was evaluated after a modification to integrate a series injection calibration network into the antenna structure. The results of this evaluation indicate that the characteristics of the probe antenna are acceptable.

An evaluation of a UHF hooded antenna for use over the 200 to 1500 MHz region was completed. The results of this evaluation indicate that the characteristics of the hooded probe antenna are acceptable.

A series of antenna coupling measurements were performed in an 8 x 8 x 12 foot shielded enclosure over the frequency range from 1 to 100 MHz. The results from these measurements were compared with results obtained in an 8 x 8 x 20 foot enclosure to determine the effects of enclosure dimensions on measurements in this frequency range.

A computer program for simulating reflection conditions in a shielded enclosure was completed during this period. The development of the computer program and a discussion of preliminary results obtained with the program are presented.
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ELECTROMAGNETIC INTERFERENCE
MEASUREMENT METHODS—SHIELDED ENCLOSURE

FINAL REPORT

By
W. R. FREE, R. E. GIBSON,
B. M. JENKINS, C. W. STUCKEY
AND J. C. TOLER

DECEMBER 1967

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METHODS-SHIELDED ENCLOSURE

FINAL REPORT
1 JUNE 1966 TO 31 JULY 1967

Report No. 36

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DA TASK NO. 186 20501D 449 01

Prepared By
W. R. FREE, R. E. GIBSON, B. M. JENKINS,
C. W. STUCKEY AND J. C. TOLER

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ATLANTA, GEORGIA

For

U. S. ARMY ELECTRONICS COMMAND
FORT MONMOUTH, N. J.

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ABSTRACT

This report summarizes the accomplishments on a program to develop test techniques and procedures for making radiated measurements in shielded enclosures which can be correlated with open-field measurements.

A technique of shielding the probe antenna in all directions except that of the desired signal path by means of a metal hood lined with absorbing material was developed. An evaluation indicated that, over the frequency range from 200 MHz to 12 GHz, the technique is capable of reducing the multipath reflections in shielded enclosures to a level comparable with the reflections normally encountered in open-field measurements.

The development, fabrication and evaluation of two hooded probe antennas covering the frequency range from 200 MHz to 12 GHz are described. The field-intensity calibration of the two hooded probe antennas is also described.

At lower frequencies where the shielded enclosure dimensions and probe antenna spacings are small relative to the wave lengths involved, tests which correlate with open-field measurements can be made. In order to establish the critical or upper limit frequency for this low frequency range, theoretical and experimental studies were conducted to investigate the field distributions within shielded enclosures at low frequencies. These studies established that satisfactory measurements can be made with conventional probe antennas in the frequency range from 1 to 30 MHz.

It is concluded that reliable radiated measurements can be made in shielded enclosures over the frequency ranges from 1 to 30 MHz and from 200 MHz to 12 GHz.
FOREWORD

This report was prepared at the Georgia Tech Engineering Experiment Station on Contract No. DA 28-043 AMC-02381(E). The work covered by this report was performed within the Electronics Division under the supervision of Mr. D. W. Robertson, Head of the Communications Branch. The report covers the results of a one year effort directed to the determination of the techniques best suited to measurement, in shielded enclosures, of the interference characteristics of U. S. Army communications-electronic equipments.
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I. FACTUAL DATA

A. Introduction

1. Purpose and Objectives of the Program

This report covers the work performed under contract DA 28-043 AMC-02381(E) for the period from 1 June 1966 to 31 July 1967.

The purpose of the program was to conduct a theoretical and experimental investigation to determine the test setups, accessories and procedures best suited to measurement, in shielded enclosures, of the electromagnetic emission and susceptibility characteristics of military communication-electronic equipment.

The three primary objectives of the program were (1) the development of hooded probe antennas to cover the frequency range from 200 MHz to 12 GHz, (2) a theoretical and experimental study of the problems associated with measurements in shielded enclosures at frequencies below 200 MHz and (3) the development of measurement procedures for making reliable and repeatable emission and susceptibility measurements in shielded enclosures.

2. Background

Present techniques for case and cable emission and susceptibility measurements are seriously inadequate, and need to be improved to assure repeatability and correlation between measurement data taken at different times and/or different locations. If these measurements are made in the "open-field", strong man-made and atmospheric background interference make measurements difficult and often impossible. If the measurements are made in a shielded enclosure to avoid the environmental interference, standing waves and enclosure resonances make the measurements highly susceptible to minor variations in equipment placement, enclosure dimensions, and personnel location.

A typical measurement setup in a shielded enclosure is shown in Figure 1. The diagram shows some of the multiple signal paths which exist with this measurement configuration. An extensive measurement program was conducted to determine the magnitude of the effects of the shielded enclosure on the measurements. Measurements were made to determine the effects of a shielded enclosure on the coupling between two antennas (a) at a fixed separation as a function of frequency, (b) at a fixed frequency as a function of separation and (c) as a function of the location of the test setup within the shielded enclosure.
Figure 1. Diagram of a Conventional Measurement Setup in a Shielded Enclosure Showing Multiple Signal Paths.

A curve showing the coupling between two antennas spaced 1 meter apart in an 8 x 8 x 20 foot shielded enclosure over the frequency range from 1 MHz to 1 GHz is shown in Figure 2. This curve has been normalized with respect to an open-field coupling curve to remove the coupling variations due to the antenna characteristics, and hence, all coupling variations shown in the normalized coupling curve result from the presence of the shielded enclosure walls. The results indicate that coupling variations in the order of ± 40 dB are possible as a function of frequency of operation. Similar results were obtained as a function of separation between the two antennas and as a function of location of the test setup within the shielded enclosure. It is obvious that measurements made under these conditions are of little value and the possibility of correlating these measurements with measurements made in the open-field is small.

3. Approaches

A number of techniques for reducing the multipath reflections within shielded enclosures were investigated on a previous program under Contract No. DA 36-039 AMC-02894(E). These investigations included the evaluation of several types of absorbing materials, the evaluation of various shapes and placements of absorbing materials within shielded enclosures, and the evaluation of shielded enclosures
Figure 2. Coupling Between Antennas in a Shielded Enclosure as a Function of Frequency at a Spacing of 1 Meter.

in a variety of shapes, including enclosures in the form of paraboloidal and ellipsoidal sections. While some of these techniques appeared to satisfactorily reduce the multipath reflections over a significant part of the frequency range of interest, the implementation of these techniques is expensive, involves complex fabrication techniques to obtain the required shapes and requires considerable space to accommodate the required shapes and absorbing materials.

The continuing search for a technique which would reduce the multipath reflections in shielded enclosures, but which would not have the cost, fabrication and space limitations mentioned above, led to a concept of shielding the probe antenna in all directions except the desired signal path. From this concept, a hooded antenna measurement technique was developed and evaluated. A diagram showing a typical hooded antenna measurement setup in a shielded enclosure is shown in Figure 3. A number of possible signal paths are shown in the shielded enclosure, but as illustrated, only that signal traveling the desired path reaches the shielded probe antenna.
The antenna hood consists of a metal shield or box, open on one end, the walls of which are lined on the inside with absorbing material. Additional absorbing material is required on the shielded enclosure wall opposite the open end of the hood to prevent multiple reflections from reaching the antenna.

The concept of the hooded antenna differs little from the concept of the conventional RF absorbing material lined enclosure. The five absorber-lined walls of the hood, together with the partially lined enclosure wall look essentially the same to the receiving antenna as the six absorber-lined walls of the conventional enclosure. The principle difference is that the hooded antenna concept requires considerably less absorbing material.

Results from initial evaluations of the hooded antenna technique over the frequency range from 200 MHz to 10 GHz indicate that this technique is capable of reducing the multipath reflections in shielded enclosures to a level comparable with the reflections normally encountered in open-field measurements. Antenna patterns of an eighteen-inch dish with a log-periodic feed at a frequency of 2 GHz are shown in Figure 4. These patterns were made in the open-field and in a
Figure 4. Antenna Patterns of an Eighteen-inch Dish at 2 GHz.
shielded enclosure both with a conventional unshielded probe antenna and a hooded probe antenna. It is apparent that there is good correlation between the two open-field patterns and the pattern made in the shielded enclosure with the hooded probe antenna. However, severe distortion is apparent in the pattern made in the shielded enclosure with the unshielded probe antenna. These patterns demonstrate the ability of the hooded antenna to reduce the effects of the multipath reflections in a shielded enclosure.

Consideration was also given to techniques for calibrating the hooded probe antennas so that the field intensity incident on the antennas can be accurately determined. Techniques for injecting calibrating signals at the terminals of the hooded antennas were included in the investigation.

B. Development of Hooded Antennas

1. General

A primary objective of the program was to develop hooded antennas to cover, as a minimum, the frequency range from 200 MHz to 12 GHz.

In addition to being hooded, it was deemed desirable that the probe antennas for measurements in shielded enclosures should be broadband, balanced and circularly-polarized. A broad bandwidth is desirable so that the large frequency range of interest can be covered with a minimum number of probe antennas. Balanced antennas are desirable to eliminate the effects of signal pickup on the transmission cable. Circular-polarization is desirable so that the antennas will be equally responsive to all linearly polarized signals.

Several broadband, circularly-polarized, balanced antenna configurations were evaluated to determine the optimum probe antenna types for use in the hooded antennas. Of all the antenna configurations considered in this evaluation, the balanced conical log-helix antenna appeared most likely to satisfy all of the requirements for the test antennas. The bandwidth obtainable with this antenna configuration is almost entirely at the discretion of the designer. Antennas with bandwidths of greater than 40 to 1 have been constructed. A balanced antenna may be obtained by winding two identical spiral arms on a conical surface. As long as physical symmetry is maintained by using identical spirals maintained at 180 degrees on the conical surface, a balanced, essentially constant impedance is obtained at the apex of the antenna over the design bandwidth. Circular-polarization is obtained with this antenna configuration. A maximum on-axis voltage axial ratio of 1.2 is typical over the bandwidth of the antenna. The field is circularly-polarized well off-axis, and a voltage axial ratio of less that 2.0 is typical out to
45 degrees off-axis. In addition to satisfying the broadband, balanced, circular-polarization requirements for a test antenna, the conical log-helix antenna offers a number of other desirable characteristics. The field pattern of the conical antenna is confined to one hemisphere, i.e., it is unidirectional, with the main lobe occurring on the longitudinal axis off the apex of the cone. For small cone angles, 20 degrees or less, a rotationally symmetrical main lobe with a half-power beam-width of 50 to 60 degrees is obtained. Under these conditions a front-to-back ratio of 15 dB or greater is obtained. These unidirectional characteristics are desirable in a test antenna to be used in a shielded enclosure since they significantly reduce the susceptibility of the test antenna to multipath reflections from the enclosure walls. The directional characteristics of the antenna improve the threshold sensitivity of the instrumentation system, and the rotational symmetry of the main lobe masks the beam rotation with frequency, which is inherent in the log-helix antenna. In addition, the configuration of the conical log-helix antenna is particularly compatible with a number of broadband balun techniques.1,2,3

The geometry of a balanced conical log-helix antenna is shown in Figure 5. The diameter of the truncated apex, \( d \), defines the upper frequency limit of the antenna and is defined by

\[
d = \frac{\lambda_H}{4}
\]

where: \( \lambda_H \) = wavelength of the highest useable frequency. The diameter of the base, \( D \), determines the lower frequency limit of the antenna and is defined by

\[
D = \frac{\lambda_L}{3}
\]

where: \( \lambda_L \) = wavelength of the lowest useable frequency. The helical arms are shown as solid diagonal lines on the surface of the cone in Figure 5. The second line is the second arm of the balanced structure and is rotated 180 degrees on the cone surface relative to the first arm. The arms alternate and the spacing between the arms increases in a logarithmic fashion in moving from the apex to the base. The arms maintain a constant angle, \( \alpha \), with the radius vector of the cone. The pattern beamwidth, front-to-back ratio, axial ratio and VSWR characteristics all are related to the rate of spiral and hence are dependent on the angle \( \alpha \) and the cone angle \( 2\theta_c \). Thus, after the bandwidth has been determined by selecting values for the truncation diameter, \( D \) and \( d \), it is necessary to select values for characteristics over the operating bandwidth. Reference (4) contains monographs relating
Figure 5. Diagram of Balanced Conical Log-Helix Antenna.
parameters to the operating characteristics.

The helical arms are defined on the surface of the cone by

\[ \rho = \rho_o e^{\left[ \frac{\sin \theta_o}{\tan \alpha} \right] \psi}, \]

where: \( \theta_o = 1/2 \) cone angle,

\( \alpha = \) spiral angle,

\( \psi = \) angle of progression of the spiral around the cone starting at \( \rho = \rho_o \),

\[ \rho_o = \frac{d}{2 \sin \theta_o}, \]

and

\[ \rho_{\text{max}} = \frac{D}{2 \sin \theta_o}. \]  \hspace{1cm} (4)

The length of the antenna, \( h \), is a function of the diameters of the truncations and the cone angle and is given by

\[ h = \frac{D}{2 \tan \theta_o} - \frac{d}{2 \tan \theta_o}, \] or

\[ h = \frac{D - d}{2 \tan \theta_o}. \] \hspace{1cm} (5)

When the probe antenna is placed in a hood, the radiation-field pattern of the hooded configuration is considerably different from the pattern of the basic unhooded probe antenna. The addition of the absorber-lined hood produces a field that closely approximates the field that would be obtained from the basic probe antenna radiating through a circular aperture in an infinite absorbing screen. Thus the pattern of the hooded antenna is essentially the diffracted field that would result from the aperture of the hood.

The diffracted fields or secondary patterns resulting from the transmission of electromagnetic energy through apertures are discussed quite extensively in the literature.\(^5,6,7\) The normalized radiation-
field pattern of a uniformly illuminated circular aperture in a perfectly absorbing screen of infinite extent is given by

\[ F = (1 + \cos \theta) \frac{J_1(\pi D/\lambda \sin \theta)}{\pi D/\lambda \sin \theta} \]  

(6)

where

\[ D = \text{diameter of aperture}, \]
\[ \lambda = \text{free-space wavelength}, \]
\[ \theta = \text{angle with respect to the normal to the aperture}, \]
\[ J_1 = \text{first-order Bessel function}. \]

The patterns for an aperture diameter of 22.25 inches at 400, 700 and 1500 MHz were calculated by means of (6). These patterns are shown with measured patterns obtained with a 22.25 inch diameter hooded antenna in Figures 6, 7 and 8. The correlation between the calculated and measured patterns is sufficient to demonstrate that the pattern of the hooded antenna is primarily determined by the aperture of the hood.

Patterns were calculated for a 6.25 inch diameter aperture at 2, 5 and 10 GHz and are shown with measured patterns for a 6.25 inch diameter hooded antenna in Figure 9, 10 and 11. Good correlation between the calculated and measured patterns is again apparent.

These results indicate that hooded antennas can be designed to provide beamwidth and sidelobe characteristics on the basis of aperture calculations, or that the pattern characteristics of a given hooded antenna configuration can be predicted with good accuracy over a given frequency range.

2. UHF Hooded Antenna

A UHF hooded antenna was designed to cover the frequency range from 200 to 1500 MHz. The following design parameters were selected for the conical log-helix probe antenna for this hooded configuration:

\[ \theta = 30^\circ, \]
\[ \alpha = 80^\circ, \]
\[ d = \frac{\lambda_H}{4} = \frac{7.88}{4} \approx 2'' , \]
Figure 6. Measured and Calculated Patterns for a Hooded Antenna at 400 MHz.

Figure 7. Measured and Calculated Patterns for a Hooded Antenna at 700 MHz.
Figure 8. Measured and Calculated Patterns for a Hooded Antenna at 1500 MHz.

Figure 9. Measured and Calculated Patterns for a Hooded Antenna at 2 GHz.
Figure 10. Measured and Calculated Patterns for a Hooded Antenna at 5 GHz.

Figure 11. Measured and Calculated Patterns for a Hooded Antenna at 10 GHz.
\[ D = \frac{\lambda L}{3} = \frac{60}{3} = 20" \quad \text{and} \]

\[ h = \frac{D - d}{2 \tan \theta} = 16.2" \]

The 60-degree cone angle was selected to keep the length of the antenna and the length of the associated hood within reasonable limits. This large cone angle will yield poorer pattern characteristics, but it was anticipated that the beam shaping of the hood would be sufficient to provide satisfactory patterns over the bandwidth of the hooded antenna.

The UHF probe antenna was formed on an expanded polyethylene conical form with plastic strips imbeded for additional support. The arms were wound with solid-shield, semi-rigid, 0.141 inch diameter coaxial cable (Precision Tube Co. Part No. 1163T 1413-19). Coaxial cable was used for the spirals because it was planned that one arm would be utilized as the feed line for the antenna and the second arm would be used for the injection of the calibrating signal. A photograph of the completed probe antenna is shown in Figure 12.

The hood was constructed from an aluminum cylinder two feet in diameter and four feet long; the wall thickness is 1/8 inch. An end plate was machined from 1/2 inch sheet aluminum. The cylinder and end plate were lined with ferrite absorbing material (Emerson and Cuming Ecocorb NZ-1). To facilitate handling, the hood was mounted on a cart with casters. The height of the cart was chosen so that the center of the hooded antenna is 4 feet above floor level. This maintains the antenna in the center of the vertical dimension of the screen room. A photograph of the completed UHF hooded antenna is shown in Figure 13.

The measured gain of the hooded probe antenna relative to a \( \lambda/2 \) dipole and the VSWR referred to 50 ohms over the design bandwidth are shown in Figure 14. The upper curve shows the measured gain of the hooded probe antenna relative to a horizontal dipole radiating source. The second curve shows the gain of the hooded probe antenna relative to a vertical dipole for a vertical dipole source. The average gain of the hooded antenna relative to a \( \lambda/2 \) dipole is approximately -10 dB. The gain curves of the unhooded probe antenna are shown for reference. The VSWR of the hooded antenna is shown in the bottom curve. The average VSWR is approximately 2.5.

Selected antenna patterns of the hooded antenna over the design bandwidth are shown in Figures 15 and 16. Both \( E_\phi \) and \( E_\theta \) patterns were made every 100 MHz over the operating band. The patterns are very similar at all frequencies and for both polarizations. The patterns shown were selected to show the characteristics in the middle of the operating range and at either end. At the lower end of the band the beam shaping and side lobe suppression effects of the hood are at a
minimum as can be seen from the 200 MHz pattern. At this frequency, the front-to-back ratio is only 6 dB and the 3 dB beamwidth is 60 degrees. This, however, is still an improvement over the 1 dB front-to-back ratio and 100 degree beamwidth obtained at 200 MHz without the hood. The improvement at higher frequencies was more pronounced. For example, at 700 MHz the hood increased the front-to-back ratio by 16 dB and decreased the beamwidth by 60 degrees. On-axis polarization patterns of the hooded UHF probe antenna at 200, 600, 1000, and 1500 MHz are shown in Figure 17.

3. Microwave Hooded Antenna

A microwave hooded antenna was designed to cover the frequency range from 1 to 12 GHz. The following design parameters were selected for the conical log-helix probe antenna for this hooded configuration:

\[
\begin{align*}
\theta_0 &= 15^\circ , \\
\alpha &= 30^\circ , \\
d &= \frac{\lambda_H}{4} = \frac{1''}{4} = 0.25'' , \\
D &= \frac{\lambda_L}{3} = \frac{15''}{3} = 5'' , \text{ and} \\
h &= \frac{D - d}{2 \tan \theta_0} = \frac{5 - 0.25}{2(0.2679)} = 8.86
\end{align*}
\]
Figure 13. UHF Hooded Antenna.
Figure 14. Gain and VSWR Curves of the UHF Hooded Antenna.
Figure 15. E$\phi$ Antenna Patterns of UHF Hooded Antenna at 200, 400, 700, and 900 MHz.
Figure 16. Eφ Antenna Patterns of UHF Hooded Antenna at 1100, 1400, 1500, and 1600 MHz.
Figure 17. Polarization Patterns of UHF Hooded Antenna at 200, 600, 1000, and 1500 MHz.
These parameters were compromised to some extent in an attempt to obtain the best possible probe antenna characteristics under restricted dimensional limitations. A smaller cone angle, 20 degrees or less, is highly desirable in this type probe antenna since this provides a rotationally symmetrical main lobe and improved directivity characteristics. Since the length of the antenna increases inversely as the tangent of 1/2 the cone angle, increasing the cone angle from 20 degrees to 30 degrees reduces the length of the probe antenna by approximately 1/3. Thus, a cone angle of 30 degrees was selected to obtain a short probe antenna which could be operated in an eighteen-inch long hood. Also, previous evaluations of hooded antennas had indicated that the main lobe structure and directivity characteristics of the hooded configuration were determined, to a large extent, by the hood, and that slight degradation in the basic probe characteristics had very little effect on the characteristics of the complete hooded antenna.

The microwave conical log-helix antenna was constructed on a solid epoxy resin conical core. Spiral slots were cut in the core to provide rigid support for the arms of the antenna. The arms were wound with solid-shield, semi-rigid, 0.056 inch diameter coaxial cable (Precision Tube Co. Part No. PT 196). Coaxial cable was used for the arms because it was planned that one arm would be used as the feed line for the antenna and act as an "infinite balun". It was also planned that the second arm would be utilized for the injection of the calibrating signal. The small diameter coaxial cable was necessary to meet the spacing requirements near the apex of the antenna structure. A photograph of the completed probe antenna is shown in Figure 18.

A small circular hood lined with ferrite absorbing material (Emerson and Cuming Eccosorb NZ-1) was used with the microwave probe antenna to obtain the desired hooded configuration. The top photograph in Figure 19 shows the hood, the microwave probe antenna and the hood end-plate just prior to assembly. The lower photograph in Figure 19 shows an open-end view of the hooded microwave antenna after assembly. The hood is 8 inches in diameter and 19 1/2 inches long. The inside diameter (clearance inside the ferrite absorbing material) is 6 1/4 inches. The measured gain of the microwave hooded antenna relative to a half wave dipole and the VSWR referred to 50 ohms over the frequency range from 1 to 10 GHz are shown in Figure 20.

Antenna patterns for the microwave hooded antenna are shown in Figure 21-23. Both E and B patterns were made at 1 GHz increments over the design bandwidth of the antenna. The E and B patterns were quite similar, and for brevity, only E patterns at ten selected frequencies are shown to demonstrate the operation of the antenna. On-axis polarization patterns at 1, 6, and 10 GHz are shown in Figure 24.
4. Series Injection Calibration Technique

The calibration of measurement systems is an extremely important consideration since the accuracy of the data obtained with the system can be no better than the accuracy of the calibration. The calibration of a field intensity measurement system is particularly difficult since there is normally an appreciable length of transmission line between the test antenna and the receiver. This transmission line may include several components (filters, rejection networks, attenuators, etc.) all of which have frequency sensitive insertion losses and VSWR's. In addition, the impedance of the test antenna is frequency sensitive to some extent, and thus, the match between the test antenna and the transmission line is frequency sensitive. Ideally, the calibration technique would take all of these factors into account.

A series injection calibration technique appears to be the best presently available method for including all of these factors in the calibration since this technique allows the test antenna, transmission line, all transmission line components and the receiver to remain connected in their normal operating configuration during calibration.

A simplified schematic diagram of a series injection calibration technique which will permit this type of calibration to be made is shown
Figure 19. Two Views of Microwave Hooded Antenna.
Figure 20. Gain and VSWR Curves of the Microwave Hooded Antenna.
Figure 21. E\theta Antenna Patterns of Microwave Hooded Antenna at 1, 2, 3, and 4 GHz.
Figure 22. \( \mathbf{E}_\theta \) Antenna Patterns of Microwave Hooded Antenna at 5, 6, 7, and 8 GHz.
in Figure 25. The calibration signal is injected in series with the transmission line at the probe antenna terminal. Since this technique requires that the calibration network be connected during normal operation, a 10:1 divider network is provided to reduce the loading of the calibrator. It is apparent from Figure 25 that this technique makes it possible to calibrate the system with all connections in their normal operating configuration.

Series injection calibration networks were integrated into the conical log-helix antennas as shown in Figure 26. The second coaxial arms of the antennas were used as the calibration feed lines. These arms also exhibit an "infinite balun" effect which should be very nearly identical with the "infinite balun" action obtained in the normal feed arms. The center conductor of the second arm was connected to the center conductor of the feed arm through a 45 ohm metal film microwave resistor (Film ohm MR125 series). The center conductor of the feed arm was connected to the shield of the second arm through a 5 ohm microwave resistor. This configuration gives the coaxial equivalent of Figure 25.

The antenna pattern and gain measurements of the conical log-helix antennas were repeated after the calibration networks were added, and compared with measurements made before the networks were added. The results indicated that the effects of the calibration networks on these parameters of the antenna were negligible.
Figure 24. Polarization Patterns of Microwave Hooded Antenna at 1, 6, and 10 GHz.
Figure 25. Diagram of a Series Injection Calibration Technique.
5. Field-Intensity Calibration

The end objective of case emission and susceptibility measurements is to establish the field intensity levels at the aperture of the probe antenna. Thus, the determination of an accurate conversion factor which may be used to convert signal power at the terminal of a probe antenna to a field intensity level at the aperture of the probe antenna is an important part of the development of probe antennas for use in these measurements.

The use of the series injection calibration technique and the integration of series injection calibration networks into the antenna structure tends to make the calibration of the probe antennas independent of the characteristics of the transmission lines, receivers, signal generators and accessory components which may be used with the antennas, and hence, make it possible to accurately field-intensity calibrate the probe antennas independent from the rest of the measurement system.

If the gain of the probe antenna is known, the conversion can be calculated by

$$P_I = \frac{4\pi P_r}{c_0 \lambda^2} \; ,$$

(7)
where:

\[ \text{FI} = \text{Field intensity at the aperture of the antenna.} \]

\[ G_o = \text{Free-space gain of the antenna relative to an isotropic source.} \]

\[ P_t = \text{Signal power at the antenna terminal.} \]

\[ \lambda = \text{Wavelength.} \]

The calculated conversion is quite accurate if the gain data is sufficiently accurate. However, except in the case of standard gain antennas, a lack of confidence is normally associated with the resulting calculation. In general, the determination of a sufficiently accurate gain calibration would be more tedious and difficult than the standard field calibration techniques discussed below.

A more direct approach is to immerse the antenna to be calibrated in a standard field whose field intensity at the surface of the antenna is accurately known and to measure the signal level at the terminal of the antenna. The difficulty with this technique is in establishing the standard field with sufficient accuracy.

There are two approaches which may be taken to establishing a standard field. One approach is to use an antenna with a very accurately calibrated gain as a radiating source for the standard field. The field intensity at a specified distance from such a radiating source may be calculated by

\[ \text{FI} = G_o \frac{P_t}{4\pi R^2} \]

where:

\[ G_o = \text{Free-space gain of radiating antenna relative to an isotropic source.} \]

\[ P_t = \text{Power at the terminal of the radiating antenna.} \]

\[ R = \text{Distance from the radiating antenna to the reference point.} \]

The accuracy of this calculation is dependent on (1) the accuracy to which the gain of the radiating antenna is known, (2) the
accuracy to which the power into the antenna can be determined, (3) the accuracy to which the distance \((R)\) can be determined, and (4) the degree to which reflections and interference can be eliminated from the measurement range.

This is an accepted method of establishing a standard field, it is frequently used and, with sufficient care, good accuracy is possible. The technique does however require precision measurement and close control of a number of parameters and some lack of confidence in the results exists due to the fact that the standard field is not measured at the point it is to be used.

An alternate method of establishing a standard field is to radiate a field with a more or less arbitrary antenna and measure the field intensity at the point of interest by means of a very accurate gain-calibrated substitution antenna. The substitution antenna is replaced by the antenna to be calibrated and hence the unknown antenna is immersed in a calibrated standard field. By measuring the signal level at the terminal of the antenna to be calibrated, the desired conversion factor is obtained.

The substitution antenna method of establishing a standard field has a number of advantages over the calibrated source method previously discussed. The substitution antenna method does not require the determination of the distance from the radiating source to the reference point nor knowledge of the power level at the terminal of the radiating antenna. In addition, reflections and interference are not as great a problem since the spurious signals are incident on both the substitution antenna and the antenna being calibrated and hence, they become a part of the calibrated standard field.

The substitution antenna method requires the calculation of an antenna conversion factor, and at first glance, it would appear that this technique would suffer from the same gain measurement and lack of confidence difficulties as the calculated antenna conversion factor technique discussed previously. However, this is not necessarily the case, since the substitution antenna technique allows complete freedom in the selection of the antenna type to be used for the substitution antenna, and if standard gain horns or other standard gain antennas are selected as the substitution antennas, the gain and antenna conversion factors are sufficiently well known and validated that no problems should be encountered in the validation of the calibration of the substitution antenna.

Very accurately calibrated standard gain pyramidal horn antennas covering the frequency range from 1 to 12 GHz are readily available and are particularly well suited for use as substitution antennas. Their gains and radiation patterns are very accurately known and their low side and back lobe levels significantly reduce the possibility of reflection problems.
The measurement setups used to field-intensity calibrate the microwave hooded antenna by means of the substitution antenna method are shown in Figure 27. The upper photograph shows a radiating antenna (1-12 GHz log-periodic antenna) and a standard gain horn setup in an anechoic chamber to establish a standard field intensity at the aperture of the horn. The bottom photograph shows the microwave hooded antenna substituted for the horn in the standard field intensity for calibration.

The same calibration technique was utilized for the calibration of the UHF hooded antenna over the 1 to 1.5 GHz frequency region. Below 1 GHz, standard gain horns become quite large and unwieldy, and their use in this frequency range becomes considerable less attractive. A standard gain dipole antenna was used as a substitution antenna to establish a standard field intensity to calibrate the UHF hooded antenna over the frequency range from 350 to 600 MHz. A photograph of the standard gain dipole antenna is shown in Figure 28. The standard gain dipole has adjustable dipole elements and an adjustable balun with engraved calibration marks at 20 MHz intervals. When the dipole elements and balun are adjusted properly, the gain of the standard gain dipole is equal to the gain of an ideal \( \lambda/2 \) Dipole (2.15 dB relative to an isotropic source) within a fraction of a decibel.

A field-intensity calibration curve for the UHF hooded antenna is shown in Figure 29. Only one standard gain dipole antenna, covering the frequency range from 350 to 600 MHz, was procured for this calibration since it was felt that this was sufficient to demonstrate the feasibility of the calibration technique. The range from 1150 to 1500 MHz was calibrated with a standard gain horn.

The calibration curve was obtained by establishing a -30 dBm/m² field intensity at each test frequency. The -30 dBm/m² standard field intensity was established by locating a standard gain antenna (dipole or horn) one meter from the radiating source antenna and adjusting the output of the signal generator feeding the radiating antenna until the output of the standard gain antenna was equal to the value calculated for a -30 dBm/m² field intensity. The standard gain antenna was then removed and the aperture of the UHF hooded antenna was placed in the same location. The RF attenuator and gain control of a field intensity meter, connected to the antenna port of the hooded antenna, were adjusted to obtain a convenient reference level on the output meter. The radiating signal generator was turned off at this point and the output of a calibrating signal generator, connected to the calibrate port of the hooded antenna, was adjusted to obtain the same reference reading on the field intensity meter. The calibration curve shows the amount of calibration power required at the calibration port to duplicate the
Figure 27. Measurement Setups for Field-Intensity Calibrating the Microwave Hooded Antenna.
signal conditions at the hooded antenna port with a -30 dBm/m$^2$ field intensity at the aperture of the antenna. This procedure was repeated at 25 MHz intervals over the calibration ranges.

To describe how the calibration curve is used to determine the field intensity at the aperture of the hooded antenna, a complete measurement procedure will be described. The hooded antenna is positioned so that it is boresighted on the radiating source and the aperture of the hood is one meter from the radiating source. A field-intensity receiver is connected to the antenna port and a signal generator is connected to the calibrate port of the hooded antenna. The field-intensity receiver is tuned until a signal level of interest is obtained. The receiver tuning is optimized and the RF attenuator and gain control of the receiver are adjusted to obtain a well defined reference level on the output meter. The radiating source is turned off. The signal generator connected to the calibrate port is tuned to the same frequency as the receiver and the output level is adjusted to give the same reference level on the receiver output meter. The calibration power required to duplicate the reference reading is obtained from the signal generator output attenuator dial and recorded as $P_{cm}$. The calibration power required to duplicate a -30 dBm/m$^2$ field intensity at the same frequency is obtained from the calibration curve and recorded as $P_{cc}$. The field intensity at the
Figure 29. Field Intensity Calibration Curve for UHF Hooded Antenna.
aperture of the hooded antenna is obtained by

$$FL = -30 + (P_{cm} - P_{cc}) \frac{dBm}{m^2}$$  \hspace{1cm} (9)

where:

$FL = $ Field intensity.

$P_{cm} = $ Calibration power required for measurement (dBm).

$P_{cc} = $ Calibration power from calibration curve (dBm).

A number of field intensity measurements were made using both the hooded antenna and standard gain antennas. These measurements were made over the calibration frequency ranges and at arbitrary field intensities. The results from these measurements are shown in Table I. The table also shows the difference between the two sets of measurement results. It is seen that the results obtained with the UHF hooded antenna and the calibration curve agree well within 1 dB with the results obtained with the standard gain antennas. The average difference between the measurements was 0.25 dB.

A field intensity calibration curve for the microwave hooded antenna is shown in Figure 30. The microwave hooded antenna was calibrated in an anechoic chamber. In all other respects, the calibration procedure for the microwave hooded antenna was identical with the procedure used for the UHF hooded antenna over the 1150 to 1500 MHz range. The calibration curve for the microwave hooded antenna is complete over the operating range of the antenna except for three small gaps, the 1.0 to 1.15 GHz and 1.7 to 2.6 GHz ranges where standard gain horns were not available, and the 11.7 to 12 GHz range where sufficient system gain to calibrate the antenna was not available.

A series of field intensity measurements of arbitrary field intensities were made using both the microwave hooded antenna and the standard gain horns. The results from these measurements and the difference between the two sets are shown in Table II. It is seen from this table that the two sets of measurements agreed well within 1 dB except at 8.0 GHz, where the difference was 1.1 dB. The average difference between the two sets of measurements was 0.37 dB.

These results demonstrate the feasibility of field-intensity calibrating hooded probe antennas, which in this case was accomplished for a given linear polarization.
<table>
<thead>
<tr>
<th>FREQ. (MHz)</th>
<th>Field Intensity Measured with Hooded UHF Antenna (dBm/m^2)</th>
<th>Field Intensity Measured with Standard Gain Horn/Dipole (dBm/m^2)</th>
<th>DIFFERENCE (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>350</td>
<td>-38.7</td>
<td>-38.8</td>
<td>.1</td>
</tr>
<tr>
<td>375</td>
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<td>-30.4</td>
<td>.1</td>
</tr>
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<td>.2</td>
</tr>
<tr>
<td>1500</td>
<td>-41.3</td>
<td>-41.4</td>
<td>.1</td>
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</table>

TABLE I. Field Intensity Measurements with UHF Hooded Antenna.
Figure 30. Field Intensity Calibration Curve for Microwave Hooded Antenna.
<table>
<thead>
<tr>
<th>FREQ (GHz)</th>
<th>FIELD INTENSITY Measured with Hooded Microwave Antenna</th>
<th>FIELD INTENSITY Measured with Standard Gain Horn</th>
<th>DIFFERENCE (dB)</th>
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<td>.4</td>
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<td>-18.9</td>
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<td>.4</td>
</tr>
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<td>-29.7</td>
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<td>.3</td>
</tr>
<tr>
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<td>-22.6</td>
<td>-23.7</td>
<td>1.1</td>
</tr>
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<td>-10.7</td>
<td>.7</td>
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<tr>
<td>10.0</td>
<td>-4.9</td>
<td>-4.8</td>
<td>.1</td>
</tr>
<tr>
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<td>- .5</td>
<td>0</td>
<td>.5</td>
</tr>
<tr>
<td>10.6</td>
<td>- .2</td>
<td>+ .3</td>
<td>.5</td>
</tr>
<tr>
<td>11.0</td>
<td>- 7.2</td>
<td>- 8.0</td>
<td>.8</td>
</tr>
<tr>
<td>11.4</td>
<td>- 1.0</td>
<td>- .8</td>
<td>.2</td>
</tr>
</tbody>
</table>

TABLE II. Field Intensity Measurements with Microwave Hooded Antenna.
6. Evaluation of Cavity-Backed Spiral Antenna

There have been significant improvements in the state-of-the-art of cavity-backed spiral antennas since initiation of the evaluation program to select a probe antenna configuration for hooded antennas. A number of cavity-backed spiral antennas having bandwidths from 4:1 to 10:1 have become commercially available. These antennas appear to have all of the desirable characteristics of the conical log-helix antennas, i.e. broad bandwidth, circular-polarization, unidirectional pattern and balanced operation. In addition, the cavity-backed spirals are planar structures so that the phase-center remains fixed over the operating bandwidth and the antenna can be flush mounted on the end plate of the antenna hood.

In view of the advancements in the design and fabrication of cavity-backed spiral antennas and the increasing variety of these antennas becoming available as off-the-shelf units, it was deemed desirable to evaluate the cavity-backed spiral antenna as a possible probe antenna for hooded antenna configurations.

An AEL cavity-backed spiral antenna (Model ASN 118A) was procured for the evaluation program. A photograph of this antenna is shown in Figure 31. The diameter of the spiral is 2 1/4 inches, the diameter of the mounting flange is 3 inches, and the total length (including type N connector) is 2 3/16 inches. According to the manufacturer, typical specifications for this antenna are:

Frequency Range: 2 to 11 GHz
Gain: 7 to 8 dB
VSWR: 1.5
Beamwidth (3dB): 75°
Front-to-back ratio: 15 dB
Axial ratio: 1.0 dB

The antenna was evaluated both unhooded and mounted in the microwave hood as shown in Figure 32.

The measured gain of the cavity-backed spiral antenna relative to a half-wavelength tuned dipole is shown in Figure 33. The top curves show the gain of the cavity-backed spiral antenna, both hooded and unhooded, relative to a horizontal half-wavelength dipole in a horizontally polarized field. The bottom curves show the gain
Figure 31. Cavity-backed Spiral Antenna.

Figure 32. Cavity-backed Spiral Antenna Mounted in Microwave Hood.
Figure 33. Gain Curves of the Cavity-backed Spiral Antenna, Hooded and Unhooded.
relative to a vertical half-wavelength dipole in a vertically polarized field. These curves indicate that the addition of the hood reduced the gain at 2 GHz by approximately 12 dB and increased the gain at 10 GHz by approximately 7 dB. The addition of the hood had very little effect on the gain over the frequency range from 3 to 8 GHz.

The average gain of the unhooded cavity-backed spiral antenna relative to a half-wavelength tuned dipole was determined to be 2.6 dB. This is equivalent to an average gain of 7.75 dB relative to a circular-polarized isotropic antenna which agrees with the manufacturer's quoted typical gain.

The measured VSWR of the unhooded cavity-backed spiral varied from 1.15 at 2 GHz to 2.75 at 10.5 GHz. The average VSWR over the 2 to 11 GHz range was determined to be approximately 1.73 which is somewhat worse than the manufacturer's quoted typical value of 1.5.

The measured axial ratio of the unhooded cavity-backed spiral varied from 2.139 at 2 GHz to 1.15 at 10 GHz. The average axial ratio over the 2 to 10 GHz range was determined to be 1.54 or 3.75 dB, which is considerably worse than the manufacturer's quoted typical value of 1 dB.

Antenna patterns for the cavity-backed spiral, both unhooded and hooded are shown in Figures 34-37. The patterns indicate that the unhooded spiral exceeds the manufacturer's quoted front-to-back ratio of 15 dB. Over the range from 3 to 7 GHz the 3 dB beamwidths remain in the 60 to 75 degree range. At 2, 8 and 10 GHz the 3 dB beamwidths exceed 100 degrees.

A comparison of the unhooded and hooded patterns indicate that the addition of the hood significantly reduces the side lobes, reduces the main lobe beamwidths and improves the shape of the main lobes.

C. Low Frequency Experimental Measurements

At low frequencies, where the shielded enclosure dimensions and probe antenna spacings are small relative to the wave lengths involved, the coupling between the equipment under test and the probe antenna becomes much more complicated and includes additional components of the more complex near-field. The behavior of these near-field components in the shielded enclosure is not well understood, and there is a very limited amount of information on this subject in the literature. In order to determine the measurement problems to be anticipated in this frequency range, a series of experimental measurements were made. The measurements were made in the 8 x 8 x 20 foot shielded enclosure. Data were collected, over the frequency range of 1 MHz to 150 MHz, both on and off the axis of the
Figure 34. E4 Antenna Patterns of Cavity-backed Spiral Antenna, Hooded and Unhooded, at 2 and 3 GHz.
Figure 35. B4 Antenna Patterns of Cavity-backed Spiral Antenna, Hooded and Unhooded, at 4 and 5 GHz.
Figure 36. E\^\Phi Antenna Patterns of Cavity-backed Spiral Antenna, Hooded and Unhooded, at 6 and 7 GHz.
Figure 37. *E*Φ Antenna Patterns of Cavity-backed Spiral Antenna, Hooded and Unhooded, at 8 and 10 GHz.
shielded enclosure for different source antenna locations. The test setups used in making these measurements are shown in Figures 38 and 39. The antennas consisted of two "identical" bow-tie antennas, 30 inches long, with a 45-degree flare angle. The source antenna was stationary while the test antenna was mounted on a movable cart. The coupling between the antennas was recorded over a spacing range from 12 to 180 inches. The diagram of Figure 38 shows the location of the antennas relative to the shielded enclosure boundaries (i.e., equal distances from the side walls, ceiling, and floor) for the on-axis setup. The off-axis setup, Figure 39, differs from the on-axis setup in that both antennas were located two feet off-axis toward a side wall.

Both on-axis and off-axis measurements were made with the source antenna positioned at three locations; 93, 45 and 12 inches from the end wall. The results from these measurements are shown in Figures 40-47. Results from open-field measurements are included for comparison.

The coupling curves, obtained with different locations of the source antenna, show a definite pattern with regard to null movement and coupling magnitude for test frequencies up to and including 50 MHz. As the source antenna was placed nearer to the end wall, the nulls were observed to occur at greater separations between the source and test antennas. The magnitude of the coupling curves show close correlation for antenna separations from 12 inches out to the point where the effect of the nulls become apparent. As the antenna spacing is increased beyond the null areas the curves maintain the same shapes, however, the coupling magnitudes are less in these areas as the source antenna is moved closer to the end wall. At 100 and 150 MHz, very little correlation is apparent between any of the resulting coupling curves.

At the test frequencies of 1 MHz and 10 MHz, the off-axis measurements indicated that no nulls exist and these curves tend to follow the open-field curves more closely than the on-axis curves. At 15 and 25 MHz, with the off-axis source antenna located 12 inches from the end wall, minimums were observed and were located at antenna separations greater than those existing at the same frequency for the on-axis setup. No minimums were observed when the source antenna was located 93 inches and 45 inches from the end wall. Results from the 30 MHz off-axis measurements show minimums appearing for all source antenna locations. These minimums are again located at greater antenna spacings than those obtained with the on-axis measurements. At 50 MHz, minimums were obtained at all three off-axis source locations, but they occur at antenna spacings less than those of the on-axis measurements. The off-axis coupling curves resulting from the upper test frequencies of 100 and 150 MHz show little or no correlation with the on-axis curves.
Figure 38. Measurement Setup On the Axis of a Shielded Enclosure.

Figure 39. Measurement Setup Off the Axis of a Shielded Enclosure.
Figure 40. Coupling Between Antennas as a Function of Spacing and Source Location, On-Axis and Off-Axis, in a Shielded Enclosure at 1 MHz.

Figure 41. Coupling Between Antennas as a Function of Spacing and Source Location, On-Axis and Off-Axis, in a Shielded Enclosure at 10 MHz.
Figure 42. Coupling Between Antennas as a Function of Spacing and Source Location, On-Axis and Off-Axis, in a Shielded Enclosure at 15 MHz.

Figure 43. Coupling Between Antennas as a Function of Spacing and Source Location, On-Axis and Off-Axis, in a Shielded Enclosure at 25 MHz.
Figure 44. Coupling Between Antennas as a Function of Spacing and Source Location, On-Axis and Off-Axis, in a Shielded Enclosure at 30 MHz.

Figure 45. Coupling Between Antennas as a Function of Spacing and Source Location, On-Axis and Off-Axis, in a Shielded Enclosure at 50 MHz.
Figure 46. Coupling Between Antennas as a Function of Spacing and Source Location, On-Axis and Off-Axis, in a Shielded Enclosure at 100 MHz.

Figure 47. Coupling Between Antennas as a Function of Spacing and Source Location, On-Axis and Off-Axis, in a Shielded Enclosure at 150 MHz.
The results from these measurements indicate that over the frequency range from 1 to 30 MHz it may be possible to make radiation measurements in an 8 x 8 x 20 foot shielded enclosure which are essentially independent of the location of the test setup in the enclosure. In order to realize this independence of location over this frequency range, however, it is necessary that the spacing between the probe antenna and the source of the radiation be no greater than approximately one meter. If this spacing limitation is met, the coupling curves also indicate that good agreement exists between the results obtained in the shielded enclosure and the results obtained from the same measurements in the open-field.

This series of measurements was repeated in an 8 x 8 x 12 foot shielded enclosure to determine if the results obtained from the 20 foot enclosure measurements could be applied to the more general case of shielded enclosures having different dimensions.

A comparison of the coupling curves obtained in the two enclosures showed good correlation over the frequency range from 1 to 50 MHz. The curves obtained in the two enclosures under equivalent measurement conditions (corresponding source antenna locations) show that the locations of the nulls agree within one inch. Coupling magnitudes agree within 2 dB, except at null points and at separation distances which placed the test antenna, in the 12 foot enclosure, within 30 inches of the end wall. Under these conditions, the effect of the wall on the test antenna in the 12 foot enclosure caused a divergence between the results obtained in the two enclosures. The end wall distortion was not apparent in the 20 foot enclosure measurements at these separation distances because of the additional enclosure length. Above 50 MHz there was no apparent correlation between the coupling data obtained in the two enclosures.

On the basis of the results from these measurements, it appears that over the frequency range from 1 MHz to 30 MHz measurements can be made in conventional shielded enclosures (not exceeding 8 x 8 x 20 feet) which are essentially independent of the location of the test setup within the enclosure and/or the dimensions of the enclosure. Under worst case conditions, the maximum error between shielded enclosure and open-field measurements will be approximately 10 dB.

D. Theoretical Study of Shielded Enclosure Measurement Problems

Early in the experimental measurement program, data were taken showing the coupling between two thirty-inch bow-tie antennas mounted on a movable platform inside a shielded enclosure over
the frequency range from 1 to 150 MHz. At eight different frequencies ranging from 15 MHz to 150 MHz, one or more distinct coupling nulls were observed for certain antenna separations.

At the lower frequencies, the transmission path lengths within the shielded enclosure, both direct and reflected, are small fractions of the wavelengths. The observed nulls are thus difficult to explain on the basis of simple cancellation and addition of waves reflected from plane surfaces. For these lower frequencies, the coupling measurements were made in the antennas' near-field regions.

Since little information was found in the literature on the near-field behavior of antennas operating in a shielded enclosure, it was decided to conduct a theoretical study of this problem. An analysis was first made of the total electric field surrounding a short dipole transmitting element operating in free space. This analysis, contained in detail in Quarterly Report No. 1, showed that the near-field region of a short dipole antenna contains elliptically polarized electric vectors when the transmission path is other than boresight or endfire. Regions very near the antenna (less than 0.05 wavelength) and regions well removed from the antenna (greater than 2 wavelengths) contain essentially linearly polarized electric vectors, as do all regions along boresight or endfire paths.

Several auxiliary factors relating to the elliptical polarization region were derived. These included the relative magnitude of the space-orthogonal vectors, the time-phase angle between these vectors, the ellipticity ratio, and the major-axis tilt angle relative to the transmission path. The auxiliary factors were plotted as functions of the transmission path-length, and a method was presented for sketching typical polarization ellipses.

The early experimental measurements were made with both transmit and receive antennas positioned horizontally and boresighted along the longitudinal centerline of a rectangular shielded enclosure. For such a configuration the electric field vectors of all reflection paths except the side wall paths are equivalent to boresight paths with respect to both transmit and receive antenna elements.

Using only the direct path and the equivalent boresight reflection paths (floor, ceiling, and both end wall paths) the antenna coupling between short dipoles operating in a shielded enclosure was calculated for 37 MHz. A comparison was made with experimental coupling data taken under similar geometric conditions but using thirty-inch bow-tie antennas as transmit and receive elements. A lack of close correlation indicated the need for a more detailed analysis which would include all first order reflection paths within the shielded enclosure. At this point a decision was made to write computer programs for further analyses.
Expressions developed in Quarterly Report No. 1 for the space-orthogonal components of the near-field electric vectors were programmed for all reflection paths as functions of the antenna element separation. It was noted that for antennas placed along the enclosure centerline, elliptically polarized side wall reflections combined at the receive element to produce a linearly polarized resultant vector. Computer runs were made for ten different frequencies from 1.0 MHz to 150 MHz to determine the total antenna coupling as a function of antenna separation. The computer-generated data and measured coupling data from both open-field and shielded enclosure configurations were normalized to a common minimum separation coupling value and plotted. The measured data was taken using thirty-inch bow-tie antennas for both transmit and receive elements while the computed data assumed short dipole elements. The ten curves are shown in Figures 48-57. The computer-generated curves show coupling nulls for five of the ten frequency runs. Null positions and null depths are not consistent with those observed in the measured coupling data. However, exact correlation was not expected, since the short dipole used in the computer program did not duplicate the bow-tie antennas used in the experimental measurements program.

It was decided to devote further work to a mathematical model which would better represent the experimental antenna setup. A major portion of the fourth quarter theoretical study effort was concerned with the writing and use of a computer program to simulate transmission conditions in a shielded enclosure with a long dipole as the transmit element and a point source isotropic antenna as the receive element. The program was based on the expression:

\[
E_z = -j30 I_m \left[ \frac{e^{-jR_1}}{R_1} + \frac{e^{-jR_2}}{R_2} - 2 \cos \beta L \frac{e^{-jR_0}}{R_0} \right]
\]

where:

- \(E_z\) = electric field component parallel to transmit element,
- \(I_m\) = peak current in transmit element (amperes),
- \(\beta\) = phase constant, \(2\pi/\lambda\) (radians/meter),
- \(L\) = half-length of dipole (meters),
- \(R_0\) = distance, center of dipole to receive point (meters), and
- \(R_1, R_2\) = distances, ends of dipole to receive point (meters).
Figure 48. Coupling Between Antennas as a Function of Spacing at 1 MHz.

Figure 49. Coupling Between Antennas as a Function of Spacing at 5 MHz.
Figure 50. Coupling Between Antennas as a Function of Spacing at 10 MHz.

Figure 51. Coupling Between Antennas as a Function of Spacing at 15 MHz.
Figure 52. Coupling Between Antennas as a Function of Spacing at 20 MHz.

Figure 53. Coupling Between Antennas as a Function of Spacing at 25 MHz.
Figure 54. Coupling Between Antennas as a Function of Spacing at 30 MHz.

Figure 55. Coupling Between Antennas as a Function of Spacing at 37.5 MHz.
Figure 56. Coupling Between Antennas as a Function of Spacing at 50 MHz.

Figure 57. Coupling Between Antennas as a Function of Spacing at 100 MHz.
Since $e^{jk} = \cos k + jsin k$, (10) may be expanded, and real and imaginary terms collected:

$$\frac{E_z}{3CL_m} = \left[\frac{2 \cos \beta L \sin \beta R O}{RO} - \frac{\sin \beta R_1}{R_1} - \frac{\sin \beta R_2}{R_2}\right]$$

$$+ j\left[\frac{2 \cos \beta L \cos \beta R O}{RO} - \frac{\cos \beta R_1}{R_1} - \frac{\cos \beta R_2}{R_2}\right]. \quad (11)$$

Both transmit and receive elements are assumed to be located on the longitudinal centerline of a rectangular shielded enclosure. The transmit element is replaced by an equivalent three point-source transmitter. Thus for any given element separation, twenty-one transmission paths exist. Figures 58, 59, 60, and 61 show details of the path-length calculations. In each figure, $M$ represents an initially unknown coordinate of the reflection point, and $A$ represents the element separation.

In Figures 58a, b, and c, origins are established at the dipole center for calculating the sidewall reflection path lengths. Since the angle of incidence equals the angle of reflection, the path illustrated in Figure 58a ($R_2$ path) may be characterized by:

$$\tan \phi = \tan \theta, \quad (12)$$

$$\frac{H - L}{M} = \frac{H}{A - M}, \quad (13)$$

$$M = \frac{A(H - L)}{(2H - L)}, \quad (14)$$

$$R_2 = \sqrt{(H - L)^2 + M^2} + \sqrt{(A - M)^2 + H^2}. \quad (15)$$

$H$, the halfwidth of the shielded enclosure, was 48 inches, and $L$, the halflength of the dipole, was 15 inches throughout the program.

Figure 58b shows the dipole center-to-receive point path length where, by inspection,

$$R_0 = \sqrt{(2H)^2 + A^2}. \quad (16)$$
Figure 58. Side Wall Reflections, Details of Three Paths.
Figure 59. Floor or Ceiling Reflection, Detail of Element-End-Path.

Figure 60. End Wall Reflection, Detail of Element-End Path.
In Figure 58c, the R1 path is shown:

\[
\frac{H + L}{M} = \frac{H}{A - M},
\]

(17)

\[
M = \frac{A(H + L)}{2H + L}, \text{ and}
\]

(18)

\[
R1 = \sqrt{(H + L)^2 + M^2} + \sqrt{(A - M)^2 + H^2}.
\]

(19)

In Figure 59 an origin at the dipole end is used to calculate the floor or ceiling reflection path-length:

\[
\frac{H}{M} = \frac{H}{\sqrt{A^2 + L^2} - M},
\]

(20)

\[
M = \frac{1}{2} \sqrt{A^2 + L^2},
\]

(21)

\[
2M = \sqrt{A^2 + L^2},
\]

(22)
\[ R_1 = R_2 = \sqrt{M^2 + H^2} + \sqrt{(M^2 + L^2 - M)^2 + H^2}, \quad (23) \]

\[ R_1 = R_2 = \sqrt{M^2 + H^2} + \sqrt{M^2 + H^2}, \quad \text{and} \]

\[ R_1 = R_2 = 2\sqrt{M^2 + H^2}. \quad (25) \]

By inspection, the RO path (not drawn in Figure 59) is

\[ R_O = \sqrt{(2H)^2 + A^2}. \quad (26) \]

In Figure 60, an origin at the center back wall is used to calculate the back wall reflection path lengths where S is the transmitter-to-back wall spacing:

\[ \frac{S}{L - M} = \frac{S + A}{M} \quad , \quad (27) \]

\[ M = \frac{L(S + A)}{(2S + A)}, \quad \text{and} \quad (28) \]

\[ R_1 = R_2 = \sqrt{S^2 + (L - M)^2} + \sqrt{(S + A)^2 + M^2}. \quad (29) \]

By inspection, the centerline RO path (not drawn in Figure 60) is

\[ R_O = 2S + A. \quad (30) \]

In Figure 61, a similar origin is used to calculate the front wall reflection path lengths where T is transmitter-to-front wall spacing:

\[ \frac{T}{L - M} = \frac{T - A}{M} \quad , \quad (31) \]

\[ M = \frac{L(T - A)}{(2T - A)}, \quad \text{and} \quad (32) \]

\[ R_1 = R_2 = \sqrt{T^2 + (L - M)^2} + \sqrt{(T - A)^2 + M^2}. \quad (33) \]

By inspection, the centerline RO path (not drawn in Figure 61) is

\[ R_O = 2T - A. \quad (34) \]
The long dipole program used expression (11) to evaluate the electric field components due to transmissions along the paths given by expressions (15), (16), (19), (25), (26), (29), (30), (33), and (34) for a variable antenna separation (factor A). A modification factor allowed an attenuation of the reflected components by any desired percentage. The various electric field components at the receive point were combined by the program and the resultant relative antenna coupling was plotted as a function of antenna element spacing. An ALGOL language compilation for the program is included in Appendix A.

A test run was made for the single frequency 37.5 MHz, using five different reflection attenuation factors: -5%, -10%, -15%, -20% and -25%. Little difference was noted in the antenna coupling versus element separation curves as the reflection attenuation factor was varied. As the separation was increased from twelve inches to forty inches a rapid coupling fall-off of about 32 dB was noted, followed by a very slow decrease in coupling totaling about 80 dB as the separation was further increased from forty inches to 180 inches. However, for four of the five reflection factors, very shallow, broad nulls occurred at element spacings between 42 inches and 48 inches. These nulls showed only a 1 dB depth relative to the rising portion of the curve which followed, and their width, measured at the -1 dB level, ranged from five inches to fourteen inches.

A reflection factor of -20% was selected for further study, since this factor produced the five inch minimum null width in the 37.5 MHz frequency analysis. Ten computer runs were made for frequencies ranging from 0.5 MHz to 50 MHz. For the first four frequency runs, 0.5, 1.0, 5.0 and 10 MHz, the coupling plots were characterized by sharp nulls at element spacings ranging from 160 inches down to 143 inches, as the frequency was increased. These nulls were all more than 60 dB below the maximum (12 inch element separation) coupling value and their shape suggested function discontinuity. Frequency runs at 15, 20, 25, 30 and 37.5 MHz showed broad shallow nulls at element spacings ranging from 69 inches down to 45 inches. The depth of these nulls ranged from 66 dB at 15 MHz to 32 dB at 37.5 MHz, referred to the maximum coupling value. The remaining frequency run, 50 MHz, showed a very broad, shallow null at an element spacing of 110 inches.

The long dipole simulation program failed to show improved correlation with the measured coupling data. Deep nulls observed in the computed data at the four lowest frequencies are in contrast to the complete absence of nulls at these frequencies in the measured data. Broad shallow nulls observed in the computed data at the six highest frequencies contrast with deep nulls in the measured data. The null location did occur at decreasing element separation values as the frequency was increased, as was the case with the measured data.
A single exception to this pattern occurred in the computer generated data for 50 MHz.

The theoretical study of shielded enclosure measurement problems included an analysis of the electric field polarizations near a short dipole transmitter, calculation of the expected coupling between short dipoles operating at a single frequency in a shielded enclosure, and the use of two computer programs for more extensive multi-frequency antenna coupling calculations. Although close correlation with measured coupling data was not evident, short dipole computer analysis did show a reasonable degree of correlation with measured data for the middle range of frequencies.

The bow-tie shape of the experimental measurement antennas was not duplicated in either of the mathematical models; the models instead assumed thin dipole elements. Perfect reflectivity was assumed for the enclosure walls in the short dipole analysis, while several values of wall reflectivity were used in the long dipole analysis.

Although nulls were observed in computer generated coupling data, it must be concluded that the mathematical models developed are not sufficiently detailed to accurately predict the coupling conditions in shielded enclosures at low frequencies.

E. Transmitter Case Emission Measurements

The measurement results reported in Section C indicated that, provided a probe-to-source distance of no greater than one meter was maintained, good agreement exists between results obtained in a shielded enclosure and results obtained from the same measurements in the open-field at frequencies below 30 MHz. In order to further examine the extent of this previously observed agreement, it was decided that a comparison of the actual case emission patterns from a transmitter, located first in the open-field and then in an 8 x 8 x 20 foot shielded enclosure, should be made.

To augment this experiment, the platform shown in Figure 62 was constructed. On one end of the platform an antenna positioner was mounted. The test transmitter and associated power supply were mounted on the positioner turntable. Also mounted on the turntable were the transmitter dummy load and a 1 kHz modulation source. At the other end of the platform a 30 inch bowtie probe antenna having a 45-degree flare angle was mounted. The probe antenna, antenna positioner, transmitter, power supply and other equipment was rigidly mounted such that the center of the transmitter was located opposite the center of the probe antenna. The transmitter to probe antenna separation distance was fixed at 40 inches. Because of the rigid mounting, the only relative motion possible between the transmitter and probe antenna was the desired azimuth rotation of the transmitter with respect to the probe antenna.
Figure 62. Two Views of Low Frequency Transmitter Case Emission Measurement Setup.
From the first measurements of the azimuth case emission patterns of the transmitter, it was apparent that the patterns recorded were very sensitive to small changes in the test conditions. One critical test condition was the placement of the power cord leading to the transmitter. To minimize the effects of the power cord placement on the measured results, this cord was routed through the center of the positioner pedestal.

It was determined that any change in the grid or plate current of the final output tube of the transmitter also produced a change in the pattern of the case emissions. A similar effect was noted if the loading capacitance was changed. The sensitivity of the case emissions to small changes in these test conditions was found to be more pronounced at harmonics of the tuned frequency than at the fundamental.

Corresponding azimuth patterns of case emission were made in the open-field and shielded enclosure at frequencies of 3.9, 14.3, 21.5 and 29.5 MHz. Under each test condition (open field or shielded enclosure) two sets of patterns were recorded at each test frequency. One set was made at a fixed location and reflects the repeatability of transmitter tuning. To obtain this set of patterns at each test frequency the transmitter was completely retuned at least four times, with no less than two hours of elapsed time between successive tunings. The other set of patterns reflects the effects of siting on pattern repeatability. To obtain this set of patterns at each test frequency, the transmitter (and measurement platform) was relocated to at least four measurement sites in the open-field and shielded enclosure. The sites were randomly chosen in the open-field. In the shielded enclosure, all sites were located along the center-line of the enclosure, so that even though the distance from the transmitter to the enclosure end walls was varied, the corresponding distances to the side walls, floor, and ceiling remained constant.

The results of all tests are shown in Figures 63 through 66. As shown in Figure 63, the open-field and shielded enclosure patterns agree closely at a frequency of 3.9 MHz. The good repeatability of the patterns at various locations in the open-field and in the shielded enclosure is a further indication that the effect of multipath reflection is minimal at this frequency. While there is little doubt that reflections do exist, particularly in the shielded enclosure, the path length differences as a fraction of the wavelength are small, thereby affecting the pattern only slightly. As would be expected, principle differences between the open-field and shielded enclosure patterns are the depths of the nulls and the detailed null pattern characteristic shapes. Since it is unlikely that either of these considerations will prove critical in case emission measurements and subsequent EMC evaluations, it would seem more appropriate to judge the extent of agreement between open-field and shielded enclosure patterns on the basis of agreement at peak levels. On this basis the agreement at 3.9 MHz is excellent.
Figure 63. Transmitter Case Emission Patterns at 3.9 MHz.
Figure 64. Transmitter Case Emission Patterns at 14.3 MHz.
Figure 65. Transmitter Case Emission Patterns at 21.5 MHz.
Figure 66. Transmitter Case Emission Patterns at 29.5 MHz.
As the wavelength decreases, the effect of multipath reflections becomes more pronounced as shown in Figures 64, 65 and 66. It should be noted that the multipath effect increases in the open-field as well as in the shielded enclosure. Agreement between the open-field and shielded enclosure patterns at the nulls is almost casual in the 14 to 30 MHz frequency range. However, agreement at the peak responses continues quite good in this frequency range. The approximate 3 dB less coupling between the transmitter and probe antenna in the enclosure at 29.5 MHz (Figure 66) is in conformance with the results obtained from the low frequency coupling measurements reported in Section C. This effect could be calibrated out of the results in an applied case emission measurement program.

From these results, as well as those previously reported, it appears that good agreement exists between case emission peak responses measured in the open-field and corresponding peak responses measured in the shielded enclosure at frequencies below 30 MHz, provided a probe-to-source distance of no greater than one meter is maintained.

Transmitter case emission measurements were also performed at 464 MHz to evaluate the hooded antenna technique in actual case emission measurements. These tests consisted of recording case emission from an actual transceiver case, first in an 8 x 8 x 20 foot shielded enclosure and then in the open-field.

In both test locations, the test configuration shown in Figure 67 was used. The equipment case was a Vocaline Model JRC 400 transceiver modified so that it was in the transmit mode throughout the test. A 1 kHz source was mounted on top of the transceiver and provided a modulation signal. The output of the transceiver was a signal at a frequency of 464 MHz amplitude modulated at 1 kHz. As during the lower frequency measurements, the transceiver and modulator were rigidly mounted to each other and then to an antenna positioner which provided the azimuth rotation needed for pattern plotting. Rigid mounting of all the equipment prevented physical changes in the test configuration which could have resulted in non-repeatable data. The probe antenna was the UHF hooded antenna described in Section B.2.

Two sets of data were obtained in each of the two test locations and are shown in Figure 68. In the shielded enclosure, the case emission patterns were first obtained with maximum transceiver output as the position of the test configuration was varied along the long dimension of the shielded enclosure. This data was then repeated with minimum transceiver output. In the open-field, patterns were recorded at four different test locations with maximum transceiver output. The output was then adjusted to minimum, and patterns were again recorded.
Figure 67. Two Views of the Hooded Antenna Measurement Setup for Transmitter Case Emission Measurements in a Shielded Enclosure.
Figure 68. Transmitter Case Emission Patterns at 464 MHz.
Analysis of the data obtained in both locations reveals that pattern peaks are readily repeatable with ± 2 dB while the pattern null locations and depths vary significantly. However, as was stated previously, the parameters of interest in case emission measurements are the peak levels and the null structures are of little interest in determining the correlation between measurements made in shielded enclosures and in the open-field.

F. Summary

The results of the low frequency experimental measurement program, presented in Section C, and of the evaluation of the hooded antenna measurement technique, presented in Section B, indicate that reliable radiated measurements can be made in 8' x 8' shielded enclosures over the frequency ranges from 1 to 30 MHz and from 200 MHz to 12 GHz.

To substantiate these results, the coupling between two antennas was measured for a spacing of one meter in an 8 x 8 x 20 foot shielded enclosure over the frequency range of 1 MHz to 10 GHz. Hooded probe antennas were used as the receiving antennas over the range from 200 MHz to 10 GHz, and unhooded probe antennas for the 1 MHz to 200 MHz range.

![Graph](image)

Figure 69. Coupling Between Antennas at 1 Meter Separation, Normalized to Open-Field Coupling, over the Frequency Range 1 MHz to 10 GHz.
The results of these measurements are shown in Figure 69. The shielded enclosure coupling curve shown in the figure has been normalized with respect to the coupling curve obtained in the open-field. The curve shows that the measurement results obtained in the enclosure over the frequency range from 1 to 30 MHz are approximately 2 to 3 dB lower than the results obtained in the open-field. In the range from 30 MHz to 200 MHz, the curve indicates that the enclosure results deviate as much as ±40 dB from the open-field results. From 200 MHz to 10 GHz, using the hooded antenna technique, it is seen that the enclosure results remain within 2 to 3 dB of the open-field results.

From the results shown in Figure 69, it is concluded that reliable radiated measurements can be made in 8' x 8' shielded enclosures over the frequency range from 1 MHz to 10 GHz with the exception of the 30 to 200 MHz range.

All of the low frequency experimental data were obtained in shielded enclosures which were 8 feet high and 8 feet wide. Different length enclosures (12 feet and 20 feet) were utilized in these measurements and the results indicate that the length of the enclosure has no significant effect on the measurement results. However, the height and width dimensions determine the location of the coupling nulls within the enclosure, and, hence, determine the upper frequency limit at which reliable measurements can be made with unhooded probe antennas.

The measurement results indicate that for an 8' x 8' enclosure and a probe spacing of one meter this upper frequency limit is approximately 30 MHz. These results may be scaled to establish the upper frequency limits of other size enclosures. For example, for a 8' x 12' or 12' x 12' enclosure, the upper frequency limit would be 20 MHz, and for an 8' x 16', 12' x 16' or 16' x 16' enclosure, the upper limit would be 15 MHz.
II. CONCLUSIONS AND RECOMMENDATIONS

The results from the experimental measurement program indicate that reliable radiated measurements, which can be correlated with open-field measurements, can be made in conventional 8' x 8' shielded enclosures over the frequency range from 1 to 30 MHz. The upper frequency limits for other size enclosures may be established by scaling the results from the 8' x 8' enclosure measurements.

The results from the evaluation of the two hooded probe antennas indicate that reliable radiated measurements, which can be correlated with open-field measurements, can be made in shielded enclosures over the frequency range from 200 MHz to 12 GHz.

The hooded antenna technique is independent of the dimensions of the shielded enclosure as long as the aperture illumination of the hooded antenna is restricted to a back wall covered with absorbing material; hence, equivalent measurement results should be obtained in enclosures of any size or shape.

It is recommended that additional investigations be performed in the frequency ranges of 14 kHz to 1 MHz and 30 MHz to 200 MHz to develop satisfactory measurement techniques for these ranges.

It is also recommended that additional investigation be performed to develop a satisfactory *balanced* probe antenna for use in the 14 kHz to 30 MHz frequency range.

The development of detailed measurement procedures, utilizing the results of this program is also recommended.
III. LITERATURE CITED


APPENDIX A. COMPUTER PROGRAM

For Shielded Enclosure Reflection Analysis

GEORGIA TECH RECC B=5500 ALWDL COMPILER TUESDAY 5/9/67 10:03 PM

BEGIN

COMMENT TX TO BACKWALL SPACING IS 45 INCHES
% B58X20 ENCLOSE
REAL h,m,x,t,s,F,R,n,M,S,UEMZ,K,SUMEZ,K,P,BETA
REAL R,
INTEGER I,J,P,J
SAVE REAL ARRAY E2R,E2I,E20,E2O,E2D0,E2D80
FILE OUT PNT (2,15)
PROCEDURE PRINTIME BEGIN FORMAT FMTT("PROCESSOR TIME",F9.3,X10,
"ID TIME",F9.3)) LIST LSTT(TIME(2)/60.0,TIME(3)/60.0))

WRITE(PRT, FMTT,LSTT) END PRINTIME

FORMAT FMT2(15F8.2)

LIST LST2(FOR I+12 STEP 1 UNTIL 180 DO FOR J+0 STEP 1 UNTIL 14 DO PATH(J+1))
"SUMEZ",X7,"E2D8")

FORMAT FMT4(X2,F5.0,3E10,2,3,F6.2)

LIST LST3(A,SUMEZR,SUMEIZ,SUMEZ,E2D8(A))
% PRINTER PLOTTER PROCEDURE
% EXPLANATION OF CALL
% PLOT (P="M",DOC[I],MAX-MIN,FALSE,TRUE ) ) %
% PLOT (P="M",DOC[I],MAX-MIN,FALSE,TRUE ) ) %
% PLOT (P="M",DOC[I],MAX-MIN,FALSE,TRUE ) ) %
% PLOT (P="M",DOC[I],MAX-MIN,FALSE,TRUE ) ) %
% PLOT (P="M",DOC[I],MAX-MIN,FALSE,TRUE ) ) %
% THE FIRST CALL BLANKS THE LINE AND INSERTS AN "M" IN POSITION
% THE SECOND CALL INSERTS A "M" IN POSITION
% THE THIRD CALL INSERTS AN "M" IN POSITION
% THE FOURTH CALL INSERTS AN "M" IN POSITION AND PRINTS THE LINE
SAVE ARRAY Z0M,Z0E (0114) %
PROCEDURE PLOT (FIL,CHAR,NBR,MAX-MIN,PRINT,CLEAR) %
VALUE CHAR,NBR,MAX-MIN,PRINT,CLEAR %
REAL NBR,MAX-MIN %
INTEGER CHAR %
FILE FIL %

(Continued)
Appendix A. Computer Program (Continued)

boolean

begin %
integer i; j

begin %
real r; j

stream procedure p (m; c; x; z; cl) j %
value w; c; x; cl j %

begin %
di + z j %
clos + 8 lit " j %
si + z j %
ds + 14 wds j %
di + z j %
si + loc ch j %
si + si+7 j %
w(di + di+63) j %
di + di+63 j %
di + loc+1 %
di + si+1 %
di + ch plus j %
di + si+7 j %
di + wds j %
di + 20 wds j %
di < max = min < r = 40 = j %
si + loc c j %
si + si+7 j %
di + wds j %
di + loc ch j %
si + si+7 j %
di + si+7 j %
di + wds j %
end p j %

stream procedure e (c; q; z) j %
value c; q j %

begin %
si + loc q j %
si + si+7 j %
di + z j %
di + wds j %
di + 4 wds j %
di + 3 lit " j %
si + z j %
si + wds j %
end e j %

if r + max = min < r = 40 then begin %
e (char; 12; zqe) j %
write (fil; 15; zqe[*]) j %
end else begin %
if l + 120 x (nbr = min) / %
if l = 0 then l + 0 j %
p(i + l div 63; i + l mod 63; char; zqm; clear) j %
end j %
if print then write (fil; 15; zqm[*]) j %
end plot j %

write (printno); %

m = 88; s = 45; t = 195; l = 15;
for a = 12 step 1 until 180 do begin
path(0; a) + a %
path(1; a) + sqrt(a + 2 * l + 2) %
path(2; a) + path(1; a) %
path(3; a) + sqrt((9216 + a + 2)) %
path(4; a) + 2 * sqrt(m + 2 * h + 2) %
path(5; a) + path(4; a) %
end

(Continued)
Appendix A. Computer Program (Continued.)

PATH(6,...) = PATH(3,...) % SIDEWALLS, CENTER
M+A=X(2H)-L/2
PATH(7,...) = SQRT(M^2+H^2)+SQRT(A^2+H^2) % SIDEWALL, END
PATH(8,...) = 2X+2A
PATH(9,...) % BACKWALL, CENTER
M+L=(A+S+M)/2
PATH(10,...) = SQRT(A^2+L^2)+SQRT(A^2+M^2) % BACKWALL, END
PATH(11,...) % FRONTWALL, CENTER
PATH(12,...) = 2X+T
PATH(13,...) = SQRT(T^2+(L-M)^2)+SQRT(T^2+M^2) % FRONTWALL, END
ENDJ WRITE(PRT,PAGE))
WRITE(PRT,FMT3,F))
PI4 = 3.14159
FOR P=0,20,30,40 DO BEGIN
WRITE(PRT,FMT3,F))
WRITE(PRT,FMT3,F))
ENDJ ENDJ
FOR R=1,6 DO BEGIN
FOR A=12 STEP 1 UNTIL 180 DO BEGIN
SUMEZ*EZ(R,A) = R*EZR(A) = 0.5*XZ(R,A) = 0.5*XZ(A)
SUMEZ*EZ1 = 1.0*EZ1 = 0.5*XZ1 = 0.5*XZ1(A)
SUMEZ = SQRT(SUMEZ2+SUMEZ2)
IF A=12 THEN X=6/SUMEZ
EZDB(A) = 8.65896*LN(X/SUMEZ)
ENDJ ENDJ
WRITE(PRT,FMT4,F,LA7)
ENDJ WRITE(PRT,PAGE))
ENDJ WRITE(PRT,PAGE))
ENDJ

CUS IS SEGMENT NUMBER 0010
LIS IS SEGMENT NUMBER 0011
SRT IS SEGMENT NUMBER 0012
OUTPUT IS SEGMENT NUMBER 0013
BLOQ IS SEGMENT NUMBER 0014
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ELECTROMAGNETIC INTERFERENCE MEASUREMENT METHODS-SHIELDED ENCLOSURE

This report summarizes the accomplishments on a program to develop test techniques and procedures for making radiated measurements in shielded enclosures which can be correlated with open-field measurements.

A technique of shielding the probe antenna in all directions except that of the desired signal path by means of a metal hood lined with absorbing material was developed. An evaluation indicated that, over the frequency range from 200 MHz to 12 GHz, the technique is capable of reducing the multipath reflections in shielded enclosures to a level comparable with the reflections normally encountered in open-field measurements.

The development, fabrication and evaluation of two hooded probe antennas covering the frequency range from 200 MHz to 12 GHz are described. The field-intensity calibration of the two hooded probe antennas is also described.

At lower frequencies where the shielded enclosure dimensions and probe antenna spacings are small relative to the wave lengths involved, tests which correlate with open-field measurements can be made. In order to establish the critical or upper limit frequency for this low frequency range, theoretical and experimental studies were conducted to investigate the field distributions within shielded enclosures at low frequencies. These studies established that satisfactory measurements can be made with conventional probe antennas in the frequency range from 1 to 30 MHz.

It is concluded that reliable radiated measurements can be made in shielded enclosures over the frequency ranges from 1 to 30 MHz and from 200 MHz to 12 GHz.
### Key Words

- Electromagnetic Interference
- Measurement Methods
- Cavity-Backed Spiral Antenna
- Conical Log-Helix Antenna
- Shielded Enclosure
- Absorbing Material
- Near-Field Antenna Theory

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