The Measurement

of Radiated Emissions

on Frequencies below 30 MHz

Materials for the ANSI C63 Committee

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The Measurement of Radiated Emissions on Frequencies below 30 MHz Using Loop Antennas

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Preface

Many factors, including the proliferation of RF lighting devices operating on frequencies around 1 MHz, and the continuing need to protect the AM broadcast service from unwarranted interference, prompted the Federal Communications Commission in 1986 to review its methods of measuring radiated emissions on frequencies below 30 MHz. The purpose of the investigation was to develop a measurement procedure for the measurement of radiated emissions on frequencies below 30 MHz using loop antennas.

Considerable progress has been made towards the attainment of this goal. A method has been developed which, if adopted, would allow the measurement of the H component of the radiated field in a typical open-field testing environment, at distances of 3 and 10 meters from the piece of equipment under test (EUT), rather than at the distances of 30, 300 and 1600 meters that are specified in the FCC Rules. This is a significant result since the present FCC Part 15 and Part 18 Rules require the measurement of field strengths as low as 4.9 uV/m at 300 meters to demonstrate compliance. Fields of this magnitude are difficult to measure using typical commercialy available field strength measuring equipment, particularly, in the presence of ambient fields. Consequently, it would benefit industry if a practical and accepted measurement procedure were developed that allowed these fields to be measured for compliance purposes at the close-in distances of 3 or 10 meters, and then extrapolated to the limits for the 30, 300 and 1600 meter distances that are specified in the Rules.

However, the work is presently at an impasse because experimental data show that the extrapolation procedures developed are valid only when the H component of the field being measured is normal to the measuring loop antenna. In making actual measurements of the spurious emissions produced by an EUT, it is not possible to orient the loop antenna beforehand so that its plane is normal to the direction of the maximum emitted radiation, since the pattern of the spurious emissions from the EUT is rarely known in advance. Methods devised for rotating the EUT to ensure that the H component of the radiated field is normal to the measuring loop antenna do not appear to be easily adaptable to a practical industry accepted standard.

The FCC acknowledges and appreciates the past efforts of the ANSI C63 Committee in developing EMI test procedures suitable for incorporation by reference in its rules. The C63 Committee has proven to be an effective forum for developing test procedures that serve both industry and government goals in preserving electromagnetic compatibility while not unduly burdening industry. We submit this report to the C63 Committees with the hope that, by bringing a panel with such wide-ranging expertise as the C63 Committee to bear on this problem, we can develop an adequate test procedure for the measurement of radiated emissions on frequencies below 30 MHz.

The nine parts of this report are arranged in a logical sequence and do not reflect the sequence in which the work was done. However, the work reported here in Parts 3 through 6 is arranged in the order in which it was performed. In these four parts, a loop antenna was used as the source of the radiating field and a second loop antenna was used to measure the field.

In Part 3, our present method of calibrating loop antennas is examined. Parts 4 and 5 contain the theoretical and experimental analysis that was performed to determine if a simple single-turn loop antenna model could be used to accurately model a loop antenna's response. The measurements reported in these two parts were made at loop antennna separations of 1.48, 1.87 and 3.20 meters. The work performed in Part 6 extended these measurements to an open-field test site with various antenna separations from 1.7 to 21.8 meters. The work done in these four parts supported the use of the single-turn loop antenna model in the interpretation of many of these measurements.

Because there was a desire to rapidly develop a measurement procedure in light of the recent major rewrite of Part 15, a Draft Measurement Procedure, (Part 9 of this report), was being assembled at the same time that the experimental work in Parts 3 through 6 was being done. To proof the measurement procedure, measurements of the spurious emissions from two pieces of electronic equipment were made on an open-field test site. However here it was found that the simple single-turn loop antenna model could not predict the measuring loop antenna's response when the characteristics of the radiating source were not known. Even the falloff of the radiating field with distance could not be predicted. Consequently, the measurement procedure was not acceptable and still remains incomplete. The measurements made with these two radiating sources on an open-field test site are reported in Part 7.

Nevertheless, it was felt that if either the loop antenna or the EUT could be rotated to a position where the maximum level of emissions were to be recorded, then the simple single-turn loop antenna model might prove an acceptable means of extrapolating measurements made at the 30, 300, and 1600 meter distances that are specified in the Rules to the more convenient measuring distances of 3 and 10 meters. The extrapolation formulas that were worked out based upon the falloff with distance of the magnetic field emitted by a magnetic dipole, (which has exactly the same falloff with distance of the electric field emitted by a electric dipole), are presented in Part 8. (These formulas have also been incorporated into the draft measurement procedure.)

A comprehensive summary and overview of the work done in Parts 3 through 9 is contained in Part 2

January 24, 1991

The Measurement of Radiated Emissions
on Frequencies below 30 MHz
Using Loop Antennas

Materials for the ANSI C63 Committee
Part 1: Introduction*

I. Introduction

Radiation emission limits on frequencies down to 9 kHz are specified for devices operating under the Part 15 and Part 18 FCC Rules. (47 CFR 15.209, 47 CFR 18.305(b))[1] In the measurement of radiated emissions, a frequency of 30 MHz is usually chosen as the separation frequency for various types of measurements and for various FCC rule specifications since it represents the lowest frequency at which a tuned dipole can be conveniently used in making radiated measurements. The antennas that are recommended for use on frequencies below 30 MHz are magnetic loop antennas and shortened dipoles.[2,3,4] Shortened dipoles are recommmended for use in the measurement of radiated emissions on frequencies between 20 and 30 MHz. Single-turn loop antennas are generally used for the measuremnt of radiated emissions on frequencies below 20 MHz and are also used on frequencies up to 32 MHz. The present measurement procedures recommended by the Commission for the measurement of radiated emissions on frequencies above 10 kHz are specified in the FCC/OST Bulletin MP-5.[2]

In the present Part 18 rules, line conducted emission limits are specified for RF lighting devices and consumer equipment in the frequency range from 450 kHz to 30 MHz and radiation emission limits for frequencies from 30 to 1000 MHz (47 CFR 18.305(c)).[1] For ultrasonic equipment and induction cooking ranges, line conducted limits are specified down to 10 kHz.(47 CFR 18.307(a),(b))[1]

The measurement of radiated emissions on frequencies below 30 MHz is not a new technique that has yet to be developed and mastered. As was mentioned above, radiation emission limits are already specified in the Rules for frequencies down to 9 kHz as a general requirement for low power communication devices (47 CFR 15.209).[1] In testing these devices for compliance with the emission limits, field intensity measurements down to 9 kHz are routinely performed at the Laboratory. However, it can be be anticipated that questions may be raised as to the adequacy of our measurement procedures for the measurement of

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* Compiled from work done in September 1986 by Joseph Mc Nulty at the FCC Laboratory in Columbia, Maryland

both the line conducted and radiated emissions from some consumer products such as RF lighting devices, particularly on frequencies below 30 MHz. This is because these devices, if they are allowed unrestricted marketing, will be operating in close proximity to communications equipment in a great many communications environments. The potential for interference from these devices is a real concern to all users of those services who feel that they may be in danger of receiving harmful amounts of interference from these devices. As the present generation of RF lighting devices operate on a fundamental frequency of a few MHz, most of the potentially interfering radiation is expected to be confined to the region below 30 MHz. Consequently, a survey of our present measurement procedures in the 9 kHz to 30 MHz frequency range is appropriate at this time.

II. The State of Our Present Measurement Procedures

The measurement procedures* recommended by the Commission for the measurement of radiated and line conducted emissions on frequencies above 10 kHz are specified in the FCC/OST Bulletin MP-5[2]. In FCC/OST Bulletins, MP-3, and MP-4[3,4] the measurement procedures for the measurement of radiated emissions on frequencies above 30 MHz and for the measurement of line conducted emissions from 450 kHz to 30 MHz have been further specified. The measurement procedures which are set down in these three Bulletins are in agreement with the ANSI Standards, ANSI C63.2-1980 and ANSI C63.4-1981[5,6] which cover the measurement of line conducted and radiated emissions in these frequency ranges.

Nevertheless, some industry groups have questioned whether radiated measurements are needed at all on frequencies below 30 MHz and whether line conducted measurements alone are sufficient to determine the interference potential of a device. CBEMA, the Computer and Business Equipment Manufacturers Association, in its 1977 report[7] concluded that

> Having established the range of 0.45 to 1000 MHz as the frequencies with possible interference potential, it was then necessary to determine appropriate frequency limits for radiated and conducted emanations.... The frequency of 30 MHz was identified as a significant breakpoint. Propagation losses were unfavorable to radiation below 30 MHz and very unfavorable to conduction above this frequency; hence the upper limit for conducted emanation potential was set at 30 MHz. ...In summary, there is a high confidence that: EDP/OE [Electronic Data Processing and Office Equipment] conduction emanation limits between 0.45 and 30 MHz and radiated emanation limits between 30 and 1000 MHz will provide

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* The references in this paragraph were made in 1986. All three of the measurement procedures, MP-3, MP-4 and MP-5 are currently being revised by the Commission in conjugation with the ANSI C63 Committee.

adequate protection to communication services.
[CBEMA Report ESC5, May 1977, pages 6-3 through 6-5]*

III. Some Difficulties in making Radiated Measurements below 30 MHz

A frequency of 30 MHz is usually chosen as the separation frequency for various types of measurements and for various Rule specifications since it represents the lowest frequency at which a tuned dipole can be conveniently used in making radiated measurements. At 30 MHz, each ear of a tuned half-wave dipole is already 8 feet long and increases progressively with decreasing frequency. Since tuned half-wave dipoles can no longer be conveniently used below 30 MHz to make radiated measurements (the lowest frequency to which our laboratory dipoles can be tuned is 27.7 MHz), other types of antennas must be used. The antennas that are recommended for use on these frequencies are magnetic loop antennas and shortened dipoles.[2,5,6]

Near Field Effects: But, independent of what antenna is used to make the measurements, at frequencies below 30 MHz near field effects begin to appear and dominate the measurements that are made at 3 and 10 meter sites. These effects do not appear to be well understood for either the shortened dipole or the loop antenna. Consequently, the behavior of neither of these antennas is well understood in a <u>measuring</u> environment where the antenna is both in close proximity to the piece of equipment under test and to ground.

The H Field is Measured with Loop Antennas and not the E Field: Many of our radiated measurements below 30 MHz are made with loop antennas that measure the magnetic field intensity, H, of the radiation. However, this is usually not the quantity of interest because the allowable radiation emission limits in the Part 15 and Part 18 rules are generally specified in terms of the electric field intensity, E. But, there does not appear to be any great difficulty here because these two fields quantities are connected by Maxwell's equations. If one of the two fields has been measured, it would seem to be a simple matter to convert it into the other. However, in order to do this, the exact theoretical specification of the fields must be known or have been experimentally determined.

The Relationship between the E and the H Fields Is Not Known: Unfortunately, the exact relationships between the two fields have not been worked out for either loop antennas or shortened dipoles where either of these antennas is in close proximity to the radiating source and ground. This means, that for electromagnetic measurements made with either of these two antennas, the

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* Although CBEMA has produced an excellent report and has done a great amount of much needed work in this area, their report does not appear to have the adequate depth of analysis needed to support the far-reaching conclusion -- that radiated measurements are not needed below 30 MHz and that equipment compliance with line conducted standards will ensure that operation of the equipment will not cause any harmful interference to other authorized services.

relationship between the electric field vector, E, and the magnetic field vector, H, is not known and furthermore is unlikely to be a constant or even a simple value. For waves propagating in free space and in the far field of the radiating source, the ratio of these two vectors is the constant value of 377 Ohms. However, in actual measurement situations, the relationship can be expected to be far more complicated, and will perhaps depend on the antenna-source separation, the antenna height and the amount of energy reflected from the ground.

Calibration of the Antennas An additional difficulty encountered in attempting to use these antennas for radiated measurements below 30 MHz is that they must first be calibrated. Accurate and reliable calibration sources for these antennas on frequencies below 30 MHz may be difficult to find.

IV. The Present Laboratory Procedures for Making Radiated Measurements below 30 MHz

Shortened Dipole Antennas Dipole antennas, that have been extended to their fullest length (27.7 MHz), are used at the FCC Laboratory for making radiated measurements in the 20 to 30 MHz frequency range. The theoretical antenna factors for this frequency range have been calculated for these antennas by Willmar Roberts, a former Chief of the FCC Laboratory, and are used to convert the field intensity meter readings to E field values. Below 20 MHz, dipole anntennas are not used at the Laboratory in making radiated measurements as the antenna factors for these frequencies have not been worked out.

Loop Antennas Loop antennas are used at the Laboratory to make most of the radiated measurements below 20 MHz. But as it was mentioned above, an adequate theoretical analysis of open site measurements using loop antennas has not yet been carried out and so the Laboratory's radiated measurements from 10 kHz to 20 MHz are made using the following simplifying assumptions:

1. the manufacturer's recommended calibration procedures are used for the calibration of the loop antennas,

2. the magnetic field intensity values, H, are converted to the electric field intensity values, E, by multipling them by the free space impedance value of 377 Ohms, and,

3. the measurements are made at the distance at which the limits are specified in the Rules to the greatest extent possible. However, testing may be done at closer distances than this, especially for equipment for which the emission limits are specified for distances greater than 30 meters, providing that a sufficient number of measurements are made to determine the polar pattern of the radiation and the direction of the major emission lobe. A sufficient number of field strength measurements are then made along a radial in the direction of the major lobe in order to determine the falloff of the field strength with distance. The measured field strength values are plotted and the field strength

> at the distance at which emission limit is specified in the Rules is then extrapolated from the plotted values."* [FCC/OST MP-5, pg 5, Paragraph 2.2.6][2]

However, in contrast to the relative looseness in the procedures for measuring radiated emissions on frequencies below 30 MHz, the procedures for making line conducted measurements in the 10 kHz to 30 MHz frequency range are well defined and both the Commission and industry have agreed upon an acceptable standard for making these measurements.[2,3,4,5,6] Consequently, we do not feel that there is a need at this time to review or reevaluate the line conducted measurement procedures established for the 10 kHz to 30 MHz range.

V. Opinions and Comments of the National Institute of Standards and Technology (NIST)

Effect of the Ground upon the Measurements: Ezra Larsen, a National Institute of Standards and Technology authority on measurements made below 30 MHz using loop antennas, states that from his experience there is no considerable contribution made to the magnetic field intensity due to the reflection of energy from the ground. Hence a ground correction factor is not needed when a loop antenna is used. Furthermore, the measurements do not have to be made over a conducting ground plane.

Effect of the Height upon the Measurements: He also stated that the magnetic field intensity does not vary appreciably with height. Thus, when using a loop antenna, the height of the loop antenna above ground does not have to be varied in seeking the height at which the maximum value of the magnetic field intensity occurs, (a procedure that often has to be followed when using other antennas). He also states that the electric field intensity, if measured at the same frequency, will vary with height. Therefore, there is not a constant conversion factor, such as 377 Ohms, that can be used to convert the magnetic

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* In all tests of equipment for compliance with the emission limits stated in the Rules, the measurements that are made at the FCC Laboratory are carried out according to the laborious procedure delineated above. Nevertheless, the Commission only requires that manufacturer's submit a single measurement made according to the following abbreviated procedure when a piece of equipment is being submitted for certification.

> "The Commission as an alternative shall accept measurements [made] at a closer fixed distance, provided 1/d is used as an attenuation law factor (where d is the distance measured in appropriate units)." [FCC/OST MP-5, pg 5, Paragraph 2.2.6][2]

In the event that there is a conflict between the field strength values that are obtained by these two methods, the field strengths obtained from the more accurate extrapolated radial procedure are the ones that are used by the Laboratory in judging whether the equipment under test passes the compliance test or whether it fails it.

field intensity as measured with a loop antenna into an electric field intensity, the quantity that is usually desired. His conclusion, drawn from his experience with these types of measurements, is that if one wishes to obtain the value of the E field, an antenna or probe must be used that actually measures the E field. It cannot accurately be obtained from the H field.

The NIST Procedure for Calibrating Loop Antennas: Calibration of loop antennas at the National Institute of Standards and Technology is carried out in a known geometry. From a known amount of current flowing in a single turn transmitting antenna, the field at the receiving antenna and the current flowing through it are established. This, however, is not an easy task as it involves a double integration involving both loops, the integration being carried out using the spherical Hankel functions.

REFERENCES for PART 1

1. Code of Federal Regulations, Title 47, Parts 0 thru 19, Revised as of October 1, 1989, U.S. Government Printing Office, Washington: 1989

2. FCC/OST MP-5, FCC Methods of Measurements of Radio Noise Emissions from Industrial, Scientific, and Medical Equipmenmt, February 1986

3. FCC/OST MP-3, FCC Methods of Measurements of Output Signal Level, Output Terminal Conducted Spurious Emissions, Transfer Switch Characteristics, and Radio Noise Emissions from TV Interface Devices, January 1985

4. FCC/OST MP-4, FCC Methods of Measurements of Radio Noise Emissions from Computing Devices, December 1983

5. ANSI C63.2-1980, Specifications for Electromagnetic Noise and Field Strength Instrumentation, 10 kHz to 1 GHz, IEEE, Inc., New York, N.Y., 1980

6. ANSI C63.4-1981, Methods of Measurement of Radio-Noise Emissions from Low-Voltage Electrical and Electronic Equipment in the Range of 10 kHz to 1 GHz, IEEE, Inc., New York, N.Y., 1981

7. CBEMA/ESC5, Limits and Methods of Measurement of Electromagnetic Emanations from Electronic Data Processing and Office Equipment, CBEMA, (Computer and Business Equipment Manufacturers Association), May 1977

The Measurement of Radiated Emissions
on Frequencies below 30 MHz
Using Loop Antennas

Materials for the ANSI C63 Committee
Part 2: A Summary and an Overview*

I. Introduction

In an earlier phase of this project, a draft procedure for the measurement of radiated emissions on frequencies below 30 MHz was prepared.[1] Subsequent measurements on the open field test sites revealed that, although the test procedure could be used to accurately measure the emissions from intentional radiators where the directions of the emissions were known, it did not produce consistent and predictable measurements of fields where the directional characteristics of the field were not known. These latter type fields are produced by unintentional radiators and are encountered when measuring the spurious emissions produced by a piece of electical equipment under test (EUT). The measurement of the fields produced by unintentional radiators is the primary purpose for the development of this measurement procedure.

The Bureau's present objectives for this project (as of September 1988) specify that the draft measurement procedure is to be revised and completed in the coming fiscal year's first quarter. This is to be followed in the second quarter by the preparation of an NPRN that will propose the adoption of the test procedure for the measurement of the emissions from Part 15 devices operating on frequencies below 30 MHz.

In the light of the experimental findings, both of these objectives appear to be premature. There are problems in the use of the draft test procedure and a review of the past experimental work will show where the difficulties lie. This review is undertaken here.

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* Compiled from work done in September 1989 by Joseph Mc Nulty at the FCC Laboratory in Columbia, Maryland

II. Loop Antenna Calibration Procedures

The procedures which we use in the calibration of our loop antennas are based upon the theoretical work of Greene[2] which he developed at the National Bureau of Standards (NBS). Greene's derivation assumes that a magnetic field is produced by a current, I, flowing in a single turn loop antenna of radius, r1. The magnetic field is being measured by a second loop antenna of radius, r2 which is placed parallel to the transmitting loop antenna and is coaxial with it. The two antennas are separated by the distance, D.

After making some simplifying approximations, Greene found that the average value of the normal component of the magnetic field, H(av), over the surface of the measuring loop antenna is

$$H(av) = \frac{r1^2 I}{2 R^3}(1+(\beta R)^2)^{1/2} \quad (1)$$

where

$$R = \sqrt{r1^2 + r2^2 + D^2} \quad (2)$$

β = (2*pi*F(MHz)/300, where F(MHz) is the frequency of the excitation current in megahertz.

Greene's expression for the magnetic field intensity is an average over the surface area of the receiving loop antenna. Consequently, the value of the field, as determined from equation 1, will depend upon the size of the receiving antenna. Taggart and Workman,[3] who were also at NBS, removed a portion of the dependence of the magnetic field intensity on the radius of the receiving antenna by equating the R term under the radical in the numerator of equation 1 to the separation distance between the antennas, D. They did not make this same approximation throughout the equation and so the R term in the denominator of equation 1 still retains its original dependence on r1, r2 and D.

Taggart and Workman's modified form of Greene's equation is

$$H(av) = \frac{r1^2 I}{2 R^3}(1+(\beta D)^2)^{1/2} \quad (3)$$

In an earlier report in this project[4], it was shown that, for frequencies below 30 MHz and antenna separations of less than 3.2 meters, Taggart and Workman's simplification introduces a maximum error 0.2 dB in the calibration of loop antennas up to 35 inches in diameter. Hence, this approximation does not appreciably affect the accuracy of the calibration of our loop antennas. In this same report, it was also shown,[5] that for all frequencies below 25 MHz and for antenna separations from 3 to 22 meters, the R term in the denominator of equations 1 and 3 can be equated to the antenna separation, D, with less than 0.1 dB loss in accuracy. Hence, for these frequencies and antenna separations, Greene's equation reduces to:

$$H(av) = \frac{r1^2 I}{2\ D^3}(1+(\beta D)^2)^{1/2} \qquad (4)$$

Equation 4 also happens to be the equation for the field that is produced by a small single turn loop antenna at any point, D, along the axis that is perpendicular to the antenna surface. This suggests that the simple loop antenna model can be used to predict the far field behavior of the radiation fields on these frequencies, and can provide a basis for establishing criteria for the extrapolation of fields for different measurement distances.

III. The Small Circular Current Loop

The equations for the E and H fields that are set up by a circular loop antenna whose diameter is small compared to the wavelength of the sinusoidal current feeding the loop are given by Jasik[6] as:

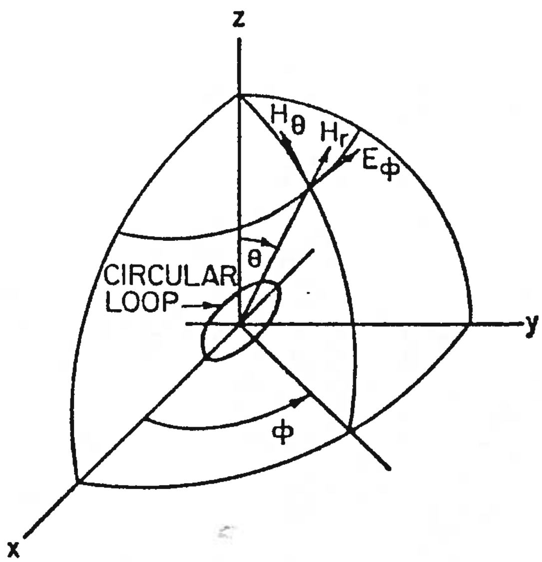
$$E_\phi = 30\beta^3 IA\left[\frac{1}{\beta r} - \frac{j}{(\beta r)^2}\right]\sin\theta\, e^{-j\beta r} \qquad (5)$$

$$H_r = \frac{\beta^3 IA}{2\pi}\left[\frac{j}{(\beta r)^2} + \frac{1}{(\beta r)^3}\right]\cos\theta\, e^{-j\beta r} \qquad (6)$$

$$H_\theta = -\frac{\beta^3 IA}{4\pi}\left[\frac{1}{\beta r} - \frac{j}{(\beta r)^2} - \frac{1}{(\beta r)^3}\right]\sin\theta\, e^{-j\beta r} \qquad (7)$$

The circular loop is located in the x-y plane and is centered about the origin. Its orientation with respect to the spatial coordinate system is shown in Figure 1. The surface area of the loop is A and the magnitude of the loop current is I. The Greek symbol, theta, is the angle between the radial vector, r, and the z axis.

Jasik states that these "expressions are accurate for loop diameters which are considerably less than one-tenth wavelength." As the transmitting loop antenna which is used for our loop antenna calibrations has a radius of 0.133 meters, equations 5 through 7 should characterize the fields which are produced by this antenna for frequencies up to 5 or 10 MHz, providing of course, that any field distortions due to reflection from the ground or other surfaces are negligible, and that any coupling between the transmitting loop antenna and the receiving loop antenna that is being used can be ignored.



$$E_\phi = 30\beta^3\, dm \left[\frac{1}{\beta r} - \frac{j}{(\beta r)^2}\right] \sin\theta\, e^{-j\beta r}$$

$$H_r = \frac{\beta^3}{2\pi}\, dm \left[\frac{j}{(\beta r)^2} + \frac{1}{(\beta r)^3}\right] \cos\theta\, e^{-j\beta r}$$

$$H_\theta = -\frac{\beta^3}{4\pi}\, dm \left[\frac{1}{\beta r} - \frac{j}{(\beta r)^2} - \frac{1}{(\beta r)^3}\right] \sin\theta\, e^{-j\beta r}$$

$$E_r = E_\theta = H_\phi = 0$$

Figure 1

Radiation from a Small Circular Loop Antenna

(The loop is centered at the origin and is located in the X-Y plane.)

IV.The Use of the Simple Single Turn Loop Model in These Investigations

At points along an axis perpendicular to the surface of the loop, the angle theta is equal to zero and equations 6 and 7 become

$$|H_r| = \frac{r_1^2 I}{2D^3}\left(1+(\beta D)^2\right)^{1/2} \tag{8}$$

$$H_\theta = \emptyset \tag{9}$$

Under these conditions, the total field is axial and is identical to that given in equation 4. This gives support to an investigation of the use of this model to characterize the magnetic field of the emissions on frequencies below 30 MHz.

Near Field Analysis
In the near field of the transmitting antenna, the first power term in 1/r in equation 7 can be neglected. For distances and frequencies where this approximation holds, the radial and angular components of the magnetic field reduce to:

$$H_r = \frac{r_1^2 I}{2r^3}(1+j\beta r)\cos\theta\, e^{-j\beta r} \tag{10}$$

$$H_\theta = \frac{r_1^2 I}{4r^3}(1+j\beta r)\sin\theta\, e^{-j\beta r} \tag{11}$$

At zero degrees and at 90 degrees, we have

$$H(0^\circ) = H_r = \frac{r_1^2 I}{2r^3}(1+j\beta r)e^{-j\beta r} \tag{12}$$

$$H(90^\circ) = H_\theta = \frac{r_1^2 I}{4r^3}(1+j\beta r)e^{-j\beta r} \tag{13}$$

If the receiving antenna is placed parallel to the transmitting antenna and is coaxial with it, only the radial component of the H field will be measured; if the receiving antenna is placed parallel to the transmitting antenna and is coplanar with it, only the theta component of the H field will be detected. From equations 10 and 13, it can be seen that these two measurements of the H field should differ by 6 dB if the diameters of the loops are small in comparison to the wavelength of the excitation current, and if the measurements are made in the near field of the transmitting loop. Consequently, these two measurements of the H field can provide a useful test as to the adequacy of using the simple loop antenna model for describing these measurements.

V. A Review of the Measurements

The Measurement of the Calibration Factors

In our present loop calibration procedures, loop antennas are calibrated at distances of 1.48, 1.87 and 3.20 meters from a standard loop antenna with a radius of 0.133 meters. These 3 calibration positions will be referred to here as positions 1, 2 and 3 respectively. Loops with a radius of less than that of the standard loop are normally calibrated at Position 1, those with a radius close to that of the standard loop are calibrated at Position 2 and those with a radius greater than that of the standard loop are calibrated at Position 3. However, calculations show that the calibrations of a loop antenna up to 14 inches in diameter that are made at any one of these three positions should not vary from one another by more than 1% and the calibrations of a 15 inch loop antenna should not vary more than 1.2%.[7]

The following table taken from the December 1986 Internal Technical Note.[8] shows the calibration measurements made for the 11.5 inch diameter Empire LP-105 antenna. The sixth column of the table gives the total spread in the 3 calibration factors that were measured for each frequency.

Table 1

Empire Loop LP-105
11.5 Inch Diameter
150 kHz to 30 MHz

Frequency	Measured Antenna Calibration Factor (dB) Pos. 1	Pos. 2	Pos. 3	Spread (dB)
150 kHz	61.0	61.7	61.0	0.7
500 kHz	54.2	54.0	54.0	0.2
1 MHz	54.0	53.8	53.2	0.8
5 MHz	46.1	46.6	46.5	0.5
10 MHz	41.4	41.6	40.6	1.0
15 MHz	39.8	40.3	39.8	0.5
20 MHz	39.4	39.1	38.4	1.0
25 MHz	39.0	38.4	36.8	2.2

For frequencies below 20 MHz, the calibration factors measured at the three calibration positions are in close agreement with one another. Above 20 MHz, the measured values of the calibration factors begin to show a strong dependence upon the calibrating position. Similar behavior was also observed with the 15 inch Stoddart 92200-3 loop antenna.

From the table it is seen that for frequencies below 20 MHz the calibration factors determined for the Empire LP-105 antenna are independent of the distance separating the transmitting and receiving antennas. In the tight geometry in which the antennas are calibrated, there is a considerable variation in the curvature of the magnetic field over the surface of the receiving antenna as one progresses from one calibration position to the next. Hence it is reasonable to assume that if consistent calibration factors can be measured in regions where the shape of the field is changing rapidly, then these same calibration factors should yield accurate and consistent values of the magnetic field at greater antenna separations where the field over the surface of the antenna is more uniform and the shape of the field varies to a much lesser degree with antenna separation.

Preliminary Confirmation of the Use of the Simple Loop Antenna Model
Additional measurements of the magnetic field were made in the loop calibration building at each of the three calibration positions. At each frequency and loop position two measurements were made, one with the receiving antenna parallel to the transmitting antenna and coaxial with it and one with the receiving antenna parallel to the transmitting antenna and coplanar with it. The first of these two measurements was a measure of an H field in the radial direction that had no theta component and the second was a measure of an H field in the theta direction that had no radial component. It was shown above that in the near antenna field the simple loop antenna model predicts that these two measures of the field will differ by 6 dB.

The measurements were presented in the report of September 30, 1987.[9] Tables 6 and 7 of that report are presented here as Tables 2 and 3. From these measurements, it appears that, for source and antenna separations of 3 meters and frequencies below 10 MHz, there is a possibility that the simple loop antenna model can form an adequate basis for predicting the behavior of the field and for extrapolating measurements made at various distances.

On the basis of the simple loop antenna model, it is expected that the 6 dB ratio between the radial and theta measurements would begin to fail when the term in 1/r raised to the first power begins to become an appreciable fraction of the cubic term in 1/r. When the single power term is four-tenths that of the cubic term, the simple model predicts that the ratio will drop to 3 dB at 10, 8 and 5 MHz for the distances of 1.48, 1.87 and 3.2 meters respectively. This is what is observed.

Measurements Made on the Open Field Test Site: Stage 1
A single turn transmitting loop was used to set up a magnetic field of known intensity on the open field test site. The transmitting antenna was a duplicate of the standard 0.133 meter radius loop used in our antenna calibrations. Measurements were made at different frequencies from 10 kHz to 25 MHz using different receiving antennas positioned from 1.7 meters to 21.8 meters from the transmitting source. For each distance and frequency, measurements were made with the receiving antenna parallel to the transmitting antenna and coaxial with it and with the receiving antenna parallel to the transmitting antenna and coplanar with it. These data were analyzed and presented in the December 1987 and March 1988 reports.[10,11] Tables 4 and 5 from the March 1988 report are reproduced here as Tables 4 and 5. Although measurements were made up to 25 MHz, for purposes of clarity only the measurements up to 1 MHz are shown in these tables.

For frequencies below 1 MHz and antenna separations less than 10 meters, the agreement is good between the measured data and the values of the field predicted by the simple loop antenna model when the two antennas are parallel to one another and coaxial with one another. However, when the two antennas are coplanar with one another, the agreement is good only for frequencies below 100 kHz at antenna separations of 10 meters. Above 1 MHz the agreement between theory and measurements is not good for either case for antenna separations greater than 10 meters.

In these two tables, the measured value of the field components is being compared with the values that are predicted by the simple loop antenna model. Hence, what is being observed here is not an effect that is due to a breakdown in the near field, far field approximation, but rather a breakdown in the applicability of the simple loop antenna model to adequately explain the measurements. Nevertheless, these measurements by themselves would not negate the creation of a test procedure for measurements on frequencies below 1 MHz. However, any measurement procedure that would be produced would perhaps have to be limited to frequencies below 1 Mhz and receiving antenna placements that were not more than 10 meters from the radiating source.

Measurements Made on the Open Field Test Site: Stage 2
Two pieces of electronic equipment were found that emitted radiations on frequencies below 30 MHz; they were

1. a 14 inch Hitachi TV which radiated on the harmonics of its horizontal sweep frequency of 15.7 kHz, and,

2. a breadboard oscillator which radiated on the harmonics of its design frequency of 6.8 MHz.

The radiated emissions from these two sources were measured with loop antennas on the open field test site for different frequencies and different source antenna configurations. At each of the measurement distances, the receiving antenna was held stationary and the source was rotated about a vertical axis until the maximum level of emissions was obtained. No scanning was done in the vertical direction as is normally required in most of our measurement procedures since we do not have an antenna mast sturdy enough to support these relatively heavy and unwieldy loop antennas. Measurements of the emissions from these two devices were made with the sources in an upright position and with the sources turned over on their sides. (The Hitachi TV was turned over on its face.) The measurement data were presented in the December 1988 Internal Technical Note.[12] Table 1 of that report is reproduced here as Table 6.

From these data, it is apparent that the radiations from these two pieces of electrical equipment are highly directional. But since the direction of the radiation is not known, the angle at which the flux is intercepted by the receiving antenna is not known either. In the Stage 1 measurements of this project, a single turn loop antenna was used to establish the field. The direction of this field was known and the receiving antenna could be positioned so that the flux was normal to the surface of the receiving antenna. However for those cases where the direction and characteristics of the radiating emissions are not known in advance, then either the antenna must be moved around the source until a maximum reading is obtained or the source will have to be moved about the antenna to get the maximum reading.

A simple rotation or translation of either the antenna or the piece of equipment under test is not sufficient to ensure that the emitted radiation is normal to the antenna surface. A complete rotation of either the search antenna or the EUT about at least two orthogonal axes is needed to do this. This rules out the normal method which is presently used for detecting radiations with dipole antennas of rotating the source and scanning in the vertical direction with the measuring antenna.

VI. Conclusions

From the work done in this project up to this point, we can at the present time say that:

1. the calibration of our loop antennas appear to be accurate and the antenna factors that are determined in a close in calibration geometry can be used to accurately determine the magnitude of the fields at distances farther away from an emitting source,

2. for intentional radiators, a method of extrapolation has been developed which can be used to convert readings made at 10 meters or less from an emitting source into equivalent readings for the distances of 30 and 300 meters that are specified in the Rules, and,

3. possible means of determining the upper limits on the frequencies and distances at which a measurement procedure can be used have been developed.

On the other hand though, we cannot uniquely measure the unintentional emissions from an ordinary piece of electronic equipment under test with our present testing methods. Because of our limited shop facilities, we are unable to fabricate any of the hardware that would enable us to develop alternative testing methods. In short, we do not have a hardware solution to the data collection problem, nor do we have the resources to develop one. Without this, we are not in a position at this time to develop a practical measurement procedure. A hardware solution to the data collection problem is vital not only to make intelligible and reproducible measurements with loop antennas but also to verify the measurement procedure itself.

Given these observed problems and our resource limitations, the present plans for revising the existing measurement procedure in the next quarter are therefore unrealistic. The existing experimental problems may prove to be soluble, but only time, money and support can accomplish this. Should further investigations be pursued in this project then:

1. further theoretical work should be done to model the off axis response of loop antennas,

2. an antenna mast should be designed that is movable but also sturdy enough so that a vertical scan is possible with a loop antenna, and,

3. a method of tumbling the piece of equipment under test in some type of gimbal support should be developed so that the EUT is able to be rotated about two mutually orthogonal axes while the measuring antenna is kept stationary.

The second of the above three proposals seems to run counter to the analysis presented in this report which shows that scanning in the vertical direction with loop antennas will not produce a unique and determinable measurement of the magnetic field. Nevertheless, if the off axis modelling of the loop response of these antennas proves fruitful, or if our understanding of the nature of the emissions from unintentional radiators is enhanced, then scanning in the vertical direction could be a viable alternative, measurement approach. Although the tumbling device specified in the third proposal is at the present time the more promising of the two measurement systems, work on both the mast and the tumbling device should proceed simultaneously so that adequate experimental planning can be done and both measurement systems are available if and when they are needed

TABLE 2

RANGE MEASUREMENT DATA

Empire LP-105
11.5 inch diam. loop antenna
150 kHz to 30 MHz

Antenna Separation: 1.48 meters						
		Magnetic Field Intensity				
Freq-uency	Antenna Factor	Radial Theor.	Radial Meas.	Radial Diff.	Theta Meas.	6dB - ((R-T) Diff)
///////	dB	dBuA/m	dBuA/m	dB	dBuA/m	dB
50 kHz	61.0	48.5	48.5	0.0	43.5	1.0
00 kHz	54.0	48.5	48.5	0.0	42.5	0.0
1 MHz	53.2	48.5	48.7	-0.2	42.7	0.0
5 MHz	46.5	48.6	50.0	-1.4	44.0	0.0
10 MHz	40.6	48.9	48.6	0.3	41.6	-1.0
15 MHz	39.8	49.4	49.3	0.1	42.3	-1.0
20 MHz	38.4	49.9	49.4	0.5	46.4	3.0
25 MHz	36.8	50.6	49.3	1.3	44.8	1.5

Antenna Separation: 1.87 meters						
		Magnetic Field Intensity				
Freq-uency	Antenna Factor	Radial Theor.	Radial Meas.	Radial Diff.	Theta Meas.	6dB - ((R-T) Diff)
///////	dB	dBuA/m	dBuA/m	dB	dBuA/m	dB
150 kHz	61.0	42.5	42.0	0.5	36.5	0.5
500 kHz	54.0	42.5	42.5	0.0	36.5	0.0
1 MHz	53.2	42.5	42.7	-0.2	36.7	0.0
5 MHz	46.5	42.7	44.0	-1.3	38.5	0.5
10 MHz	40.6	43.1	42.6	0.5	35.6	-1.0
15 MHz	39.8	43.8	44.3	-0.5	36.8	-1.5
20 MHz	38.4	44.6	44.4	0.2	42.9	4.5
25 MHz	36.8	45.4	44.3	1.1	41.3	3.0

TABLE 2 (continued)

RANGE MEASUREMENT DATA

Antenna Separation: 3.20 meters

Freq-uency	Antenna Factor	Radial Theor.	Magnetic Field Intensity Radial Meas.	Radial Diff.	Theta Meas.	6dB - ((R-T) Diff)
///////	dB	dBuA/m	dBuA/m	dB	dBuA/m	dB
150 kHz	61.0	28.6	28.5	0.1	22.5	0.0
500 kHz	54.0	28.6	28.5	0.1	22.5	0.0
1 MHz	53.2	28.6	28.7	-0.1	22.7	0.0
5 MHz	46.5	29.1	30.0	-0.9	25.0	1.0
10 MHz	40.6	30.2	31.1	-0.9	22.1	-3.0
15 MHz	39.8	31.6	33.3	-1.7	31.3	4.0
20 MHz	38.4	33.1	33.9	-0.8	36.9	9.0
25 MHz	36.8	34.4	35.3	-0.9	35.8	6.5

NOTES TO TABLE 2:

1. The H field in microamperes per meter is calculated from the measured FIM value by summing the antenna factor in dB and the FIM value in dBm and then adding 55.5 dB to the
2. The fifth column of the table lists the differences between the measured value of the radial E field and Greene's theoretical value for this field component.
3. The differences listed in the last column of the table are the deviations of the difference of the radial and theta E field values from the 6 dB value that is predicted by the simple loop antenna model.
4. This table is Table 6 in the Internal Technical Note of September 30, 1987.

TABLE 3: RANGE MEASUREMENT DATA

Empire LP-3-105
35 inch diameter loop antenna
150 kHz to 30 MHz

Antenna Separation: 3.20 meters

Freq-uency	Antenna Factor	Magnetic Field Intensity: Radial Theor.	Radial Meas.	Radial Diff.	Theta Meas.	6dB - ((R-T) Diff)
///////	dB	dBuA/m	dBuA/m	dB	dBuA/m	dB
150 kHz	45.9	28.6	28.4	0.2	23.4	1.0
200 kHz	44.1	28.6	27.6	1.0	21.6	0.0
300 kHz	43.0	28.6	27.5	1.1	22.0	0.5
400 kHz	41.0	28.6	28.5	0.1	22.5	0.0
500 kHz	41.2	28.6	27.7	0.9	21.7	0.0
610 kHz	41.5	28.6	27.5	1.1	21.5	0.0
700 kHz	41.1	28.6	27.6	1.0	21.6	0.0
800 kHz	41.0	28.6	27.5	1.1	22.0	0.5
870 kHz	41.0	28.6	27.5	1.1	21.5	0.0
870 kHz	40.8	28.6	28.3	0.3	21.8	-0.5
910 kHz	41.0	28.6	28.5	0.1	22.5	0.0
1 MHz	40.8	28.6	28.3	0.3	22.8	0.5
1.5 MHz	36.0	28.6	28.5	0.1	22.5	0.0
2 MHz	34.1	28.7	28.1	0.6	23.1	1.0
3 MHz	32.3	28.8	28.8	-0.0	23.8	1.0
4 MHz	30.7	28.9	28.2	0.7	21.2	-1.0
5 MHz	31.3	29.1	29.8	-0.7	24.8	1.0
6 MHz	31.6	29.3	31.1	-1.8	26.1	1.0
7 MHz	29.7	29.5	29.2	0.3	24.2	1.0
8 MHz	27.9	29.7	27.9	1.8	22.9	1.0
9 MHz	28.5	30.0	29.0	1.0	23.0	0.0
10 MHz	28.1	30.2	29.6	0.6	23.1	-0.5
11 MHz	29.1	30.5	31.1	-0.6	24.6	-0.5
12 MHz	27.2	30.8	30.2	0.6	25.7	1.5
12.7 MHz	30.3	31.0	33.8	-2.8	29.8	2.0

NOTES TO TABLE 3:

1. The H field in microamperes per meter is calculated from the measured FIM value by summing the antenna factor in dB and the value in dBm and then adding 55.5 dB to this sum.
2. The fifth column of the table lists the differences between the measured value of the radial E field and Greene's theoretical value for this field component.
3. The differences listed in the last column of the table are the deviations of the difference of the radial and theta H field values from the 6 dB value that is predicted by the simple loop model.

TABLE 4:

OPEN FIELD TEST SITE MEASUREMENT DATA

Empire LG-105-A
35 inch diameter loop antenna
15 kHz to 150 kHz

Frequency: 15 kHz							
		Magnetic Field Intensity					
Antenna Separation	Antenna Factor	Radial Theor.	Radial Meas.	Radial Diff.	Theta Theor.	Theta Meas.	Theta Diff.
meters	dB	dBuA/m	dBuA/m	dB	dBuA/m	dBuA/m	dB
1.66	59.0	45.7	45.5	0.2	39.7	40.5	-0.8
3.30	59.0	27.8	27.5	0.3	21.8	21.5	0.3
4.99	59.0	17.0	17.0	0.0	11.0	11.5	-0.5
6.44	59.0	10.4	10.5	-0.1	4.4	4.0	0.4
9.43	59.0	0.5	0.5	-0.0	-5.6	-5.0	-0.6
12.46	59.0	-6.8	-6.5	-0.3	-12.8	-7.0	-5.8

Frequency: 82 kHz							
		Magnetic Field Intensity					
Antenna Separation	Antenna Factor	Radial Theor.	Radial Meas.	Radial Diff.	Theta Theor.	Theta Meas.	Theta Diff.
meters	dB	dBuA/m	dBuA/m	dB	dBuA/m	dBuA/m	dB
1.66	50.0	45.7	45.0	0.7	39.7	39.5	0.2
3.30	50.0	27.8	28.5	-0.7	21.8	21.5	0.3
4.99	50.0	17.0	17.5	-0.5	11.0	10.5	0.5
6.44	50.0	10.4	11.0	-0.6	4.4	4.5	-0.1
9.43	50.0	0.5	0.5	-0.0	-5.6	-4.5	-1.1
12.46	50.0	-6.8	-7.5	0.7	-12.8	-9.5	-3.3
15.46	50.0	-12.4	-13.0	0.6	-18.4	-12.5	-5.9
18.60	50.0	-17.2	-17.5	0.3	-23.3	-16.0	-7.3

TABLE 4: (continued)

OPEN FIELD TEST SITE MEASUREMENT DATA

Frequency: 150 kHz							
		Magnetic Field Intensity					
Antenna Separation	Antenna Factor	Radial Theor.	Radial Meas.	Radial Diff.	Theta Theor.	Theta Meas.	Theta Diff.
meters	dB	dBuA/m	dBuA/m	dB	dBuA/m	dBuA/m	dB
1.66	50.0	45.7	45.5	0.2	39.7	42.0	-2.3
3.30	50.0	27.8	28.0	-0.2	21.8	23.0	-1.2
4.99	50.0	17.0	17.5	-0.5	11.0	12.0	-1.0
6.44	50.0	10.4	10.5	-0.1	4.4	6.0	-1.6
9.43	50.0	0.5	0.5	-0.0	-5.6	-2.5	-3.1
12.46	50.0	-6.8	-7.0	0.2	-12.8	-7.5	-5.3
15.46	50.0	-12.4	-12.5	0.1	-18.4	-10.5	-7.9

NOTES TO TABLE 4:

1. The H field in microamperes per meter is calculated from the measured FIM value by summing the antenna factor in dB and the FIM value in dBm and then adding 55.5 dB to the the sum. [55.5 dB is 107 dB - 20*Log(120*pi)].
2. The theoretical values listed in the third and sixth columns of the table are obtained from the simple single turn loop antenna model.
3. This table is Table 4 in the Internal Technical Note of March 31, 1988.

TABLE 5:

OPEN FIELD TEST SITE MEASUREMENT DATA

Stoddart Loop 92200-3
15 inch diameter loop antenna
150 kHz to 30 MHz

Frequency: 150 kHz

Antenna Separation	Antenna Factor	Magnetic Field Intensity: Radial Theor.	Radial Meas.	Radial Diff.	Theta Theor.	Theta Meas.	Theta Diff.
meters	dB	dBuA/m	dBuA/m	dB	dBuA/m	dBuA/m	dB
1.66	60.0	45.7	43.5	2.2	39.7	38.5	1.2
3.30	60.0	27.8	26.5	1.3	21.8	20.5	1.3
4.99	60.0	17.0	15.5	1.5	11.0	10.5	0.5
6.44	60.0	10.4	8.5	1.9	4.4	4.0	0.4
9.43	60.0	0.5	-1.5	2.0	-5.6	-4.0	-1.6
12.46	60.0	-6.8	-8.5	1.7	-12.8	-8.0	-4.8

Frequency: 500 kHz

Antenna Separation	Antenna Factor	Magnetic Field Intensity: Radial Theor.	Radial Meas.	Radial Diff.	Theta Theor.	Theta Meas.	Theta Diff.
meters	dB	dBuA/m	dBuA/m	dB	dBuA/m	dBuA/m	dB
1.66	55.5	45.7	46.5	-0.8	39.7	41.5	-1.8
3.30	55.5	27.8	29.0	-1.2	21.8	20.5	1.3
4.99	55.5	17.1	18.0	-0.9	11.0	13.0	-2.0
6.44	55.5	10.4	11.5	-1.1	4.4	7.5	-3.1
9.43	55.5	0.5	1.5	-1.0	-5.6	1.5	-7.1
12.46	55.5	-6.7	-6.0	-0.7	-12.9	-3.0	-9.9
15.46	55.5	-12.3	-11.0	-1.3	-18.6	-4.0	-14.6

TABLE 5: (continued)

OPEN FIELD TEST SITE MEASUREMENT DATA

Frequency: 1 MHz							
		Magnetic Field Intensity					
Antenna Separation	Antenna Factor	Radial Theor.	Radial Meas.	Radial Diff.	Theta Theor.	Theta Meas.	Theta Diff.
meters	dB	dBuA/m	dBuA/m	dB	dBuA/m	dBuA/m	dB
1.66	51.5	45.7	45.0	0.7	39.7	40.0	-0.3
3.30	51.5	27.8	27.0	0.8	21.8	22.0	-0.2
4.99	51.5	17.1	16.5	0.6	11.0	12.0	-1.0
6.44	51.5	10.5	9.5	1.0	4.3	7.0	-2.7
9.43	51.5	0.6	0.0	0.6	-5.7	3.5	-9.2
12.46	51.5	-6.5	-7.0	0.5	-13.1	-1.5	-11.6

NOTES TO TABLE 5:

1. The H field in microamperes per meter is calculated from the measured FIM value by summing the antenna factor in dB and the FIM value in dBm and then adding 55.5 dB to the sum. [55.5 dB is 107 dB - 20*Log(120*pi)].
2. The theoretical values listed in the third and sixth columns of the table are obtained from the simple single turn loop antenna model.
3. This table is Table 5 in the Internal Technical Note of March 31, 1988.

Table 6

The Measured Values of the Radiation from a Small Portable TV in a Normal and in a Face Down Position

Freq.	Dist. = 3.35 m.			Dist. = 5.05 m.			Dist. = 7.95 m.		
(kHz)	Up	Down	Diff.	Up	Down	Diff.	Up	Down	Diff.
15.7	31.2	42.2	-11.0	18.2	31.2	-13.0	5.2	19.2	-14.0
31.4	6.5	35.5	-29.0	0.5	24.5	-24.0	-2.0	12.5	-14.5
47.1	21.5	30.0	-8.5	12.5	20.0	-7.5	3.5	8.0	-4.5
62.8	26.3	27.3	-1.0	16.8	17.3	-0.5	5.3	5.8	-0.5
78.5	25.5	22.0	3.5	15.5	11.5	4.0			
94.2	25.5	18.5	7.0	16.0	8.5	7.5	4.0	-1.0	5.0
109.9	25.0	15.5	9.5	14.5	5.0	9.5	3.0	-5.0	8.0
125.6	22.5	9.5	13.0	11.5	-0.5	12.0	-0.5	-9.5	9.0
141.3	18.5	3.0	15.5	8.0	-7.5	15.5	-4.0	-16.5	12.5

NOTES TO TABLE 6:

1. The measured values in the table are in db(uA/m).
2. This table is Table 6 in the Internal Technical Note of December 30, 1988.

REFERENCES for PART 2

1. Part 9 of this report, The Measurement of Radiated Emissions on Frequencies below 30 MHz Using Loop Antennas, Materials for the ANSI C63 Committee, Part 9: Draft of a Proposed Measurement Procedure

2. F. M. Greene, The Near-Zone Magnetic Field of a Small Circular-Loop Antenna, NBS Journ. Res., Vol 71C, No. 4, pgs 319-326, October/December, 1967

3. H. E. Taggart and J. L. Workman, Calibration Principles and Procedures for Field Strength Meters (30 Hz to 1 GHz), NBS Technical Note 370, National Bureau of Standards, Boulder, Colorado, March 1969

4. Part 5 of this report, The Measurement of Radiated Emissions on Frequencies below 30 MHz Using Loop Antennas, Materials for the ANSI C63 Committee, Part 5: Preliminary Checks on the Validity and Use of the Simple Loop Antenna Model

5. Part 5 of this report, The Measurement of Radiated Emissions on Frequencies below 30 MHz Using Loop Antennas, Materials for the ANSI C63 Committee, Part 5: Preliminary Checks on the Validity and Use of the Simple Loop Antenna Model, Table 3

6. Antenna Engineering Handbook, Henry Jasik, Editor, 1st edition, pgs 2-5,2-6, McGraw-Hill Book Co., 1961. [Jasik's equations for the E and H fields are expressed in terms of the differential magnetic-dipole moment, dm, which, for a loop whose circumference is small compared to the wavelength of the excitation current, is equal to the product of the area of the loop, A, times the magnitude of the driving current, I.]

7. Part 3 of this report, The Measurement of Radiated Emissions on Frequencies below 30 MHz Using Loop Antennas, Materials for the ANSI C63 Committee, Part 3: The Calibration of Loop Antennas

8. Part 3 of this report, The Measurement of Radiated Emissions on Frequencies below 30 MHz Using Loop Antennas, Materials for the ANSI C63 Committee, Part 3: The Calibration of Loop Antennas, Table 7

9. Part 4 of this report, The Measurement of Radiated Emissions on Frequencies below 30 MHz Using Loop Antennas, Materials for the ANSI C63 Committee, Part 4: The Utility of the Simple Loop Antenna Model

10. Part 6 of this report, The Measurement of Radiated Emissions on Frequencies below 30 MHz Using Loop Antennas, Materials for the ANSI C63 Committee, Part 6: Open Field Measurements Using Intentional Radiators

11. Part 5 of this report, The Measurement of Radiated Emissions on Frequencies below 30 MHz Using Loop Antennas, Materials for the ANSI C63 Committee, Part 5: Preliminary Checks on the Validity and Use of the Simple Loop Antenna Model

12. Part 7 of this report, The Measurement of Radiated Emissions on Frequencies below 30 MHz Using Loop Antennas, Materials for the ANSI C63 Committee, Part 7: Open Field Measurements Using Unintentional Radiators

The Measurement of Radiated Emissions on Frequencies below 30 MHz Using Loop Antennas

Materials for the ANSI C63 Committee
Part 3: The Calibration of Loop Antennas*

I. Introduction

Loop antennas are commonly used for the detection and measurement of radiated emissions on frequencies below 30 MHz and they are the only antenna which the Commission has recommended for use below 18 MHz in the measurement of radiated emissions from ISM equipment.[1] The Commission has also recommended their use for radiated measurements in the frequency range from 18 to 30 Mhz, although here a shortened dipole can be used. The ANSI measurement standard C63.2-1980[2] recommends that either a loop antenna or a shortened dipole be used for radiated measurements made below 30 MHz.

There are some difficulties in using these antennas for the accurate measurement of radiated emissions. One of the main difficulties is that we have very little information concerning the electrical characteristics of the loop antennas which we use in our measurements. The impedances of our loop antennas are not known and these impedances do perhaps vary appreciably over over the frequency ranges in which the antennas are designed to be used. Also, we do not appear to have any information on the baluns that may have been incorporated into these antennas. And judging from the experimental behavior of our loop antennas, whatever baluns that have been provided do not produce an adequate match between the antenna and a 50 Ohm transmission line. Whether such matching baluns even exist is an item that apparently has not yet been fully investigated.

Lacking a knowledge of the mismatch conditions at the antenna-transmission line interface, theoretical antenna factors cannot be used to relate the voltage read by a field intensity meter to the actual E or H field present at the antenna. These antenna factors must be obtained experimentally for each antenna that is to be used. There are two ways of measuring these experimentally determined antenna correction factors. They can be measured in a fixed calibration geometry or in the actual geometry that is to be used in the measurements. As the Laboratory does not have any radiation sources

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* Compiled from work done in December 1986 by Joseph Mc Nulty at the FCC Laboratory in Columbia, Maryland

available for the 10 kHz to 30 MHz frequency range that are easily transportable to an actual measuring site, the antenna correction factors that are obtained for these loops are usually measured indoors in a fixed calibration geometry.

In measuring the antenna correction factors in a fixed calibration geometry, three questions must be addressed:

1. are the antenna correction factors that are obtained in a calibrated geometry consistent or do they change when changes are made in the calibration geometry?

2. if the antenna correction factors are geometry dependent, how does this dependence affect the accuracy of the measurements which will be made with this antenna out in the field?

3. can the antenna correction factors which are measured in a near field close geometry be used to determine the field in a far field geometry?

Partial answers to these questions will be attempted here. However, in-depth answers to all of these questions must await future work.

II. The Historical Background of the Loop Calibration Procedure

The present FCC Laboratory loop calibration procedures closely follow the methods and procedures developed in the early 1960's by the National Bureau of Standards at their Boulder Colorado laboratory.[3] At the time when NBS was developing these procedures, there apparrantly was a considerable amount of sharing of both ideas and work between the National Bureau of Standards personnel and the staff at the FCC Laboratory. This is evidenced by some of the Laboratory's work that paralleled and extended NBS's work on loop calibration.[4] Because of this shared effort, the Laboratory's had perhaps greater and more advanced technical expertise in all of its measurement areas at that time than it has today.

The setup which is used for our loop calibrations is shown in Figure 1. The field in which the loops are to be calibrated is established by a small single turn loop of 0.133 meters radius which is excited by a fixed frequency, 100 milliampere sinusoidal current. The current in the loop is adjusted manually and is measured by sensing the output of a thermocouple which is fastened to the loop. Following NBS's nomenclature, this loop is called the standard loop.

The loop that is to be calibrated is called the receiving loop. This loop is positioned parallel to the transmitting loop and is coaxial with it. It is coupled to a field intensity meter with a 50 Ohm cable. The field intensity meter measures the voltage which is induced in the receiving loop by the electromagnetic field that is produced by the standard loop. The value of the magnetic field at the receiving loop is known from the theoretical work of

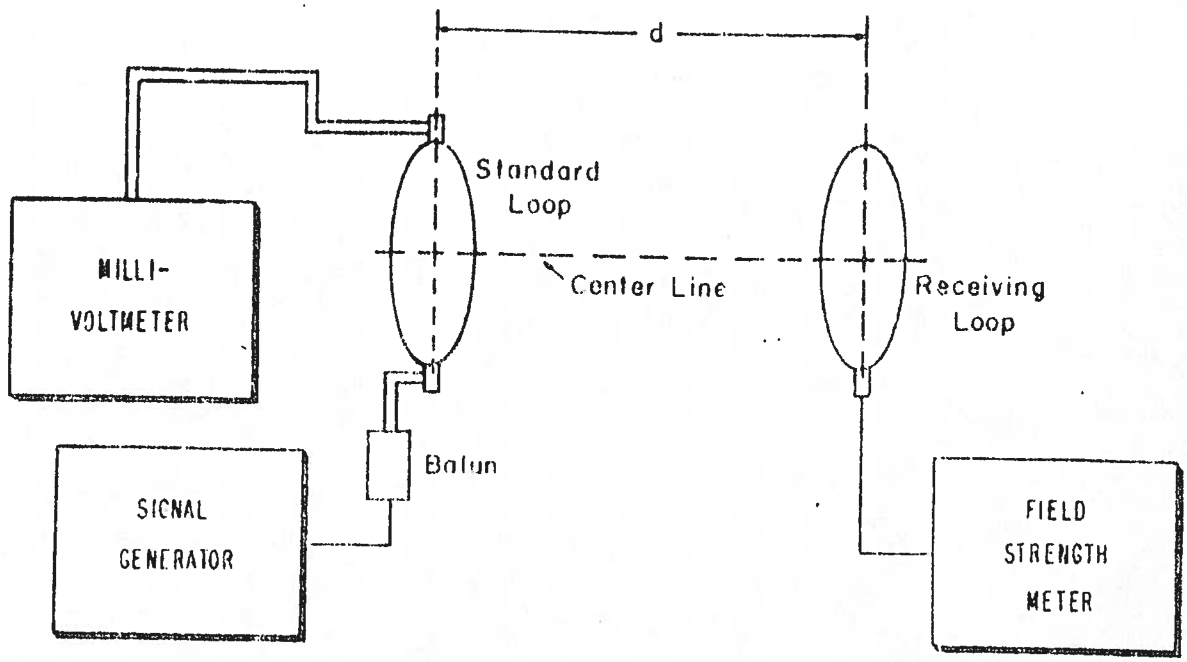

FIGURE 1

The Measurement System for the Calibration

of Loop Antennas

Greene.[5] A calibration value for the receiving loop at this frequency can thus be obtained by taking the ratio of the calculated value of the magnetic field intensity at the receiving loop to the voltage measured on the field intensity meter. Of course, for the calibration to work, it is assumed that a linear relationship exists between these two quantities. It will be shown below that this is a fairly good assumption to make.

In Greene's paper[5], the magnetic field equations that are the basis for the loop calibration procedure are not derived in a three dimensional vector form. Rather, what Greene derives is a single equation for the average magnetic field which is produced in space by a single turn loop of radius, r1. The average, H(av), is taken of the magnetic field components that are normal to a flat circular surface of radius, r2. This surface is parallel to the single turn loop and is coaxial with it. Thus Greene's field equation is unusual as it is not, strictly speaking, a vector equation and as it contains the radii of both the transmitting and the receiving loop. The equation for the average magnetic field which Greene obtains after making suitable approximations is[6]

$$H(av) = \frac{r1^2 I}{2 R^3} \{ 1 - (\beta R)^2 \}^{1/2} \qquad (1)$$

where

$$R = \sqrt{r1^2 + r2^2 + D^2} \qquad (2)$$

and $\beta = (2\pi F(MHz)/300$, where F(MHz) is the frequency of the excitation current in megahertz.

Unfortunately, instead of remaining with this equation, Greene converts it into one expressed in terms of an average Electric field intensity, E(av). This can be legitimately done only if the exact relationships between the E and H fields and their averages are known. However, these relationships are not known for the case in which Greene is interested. Consequently, the resulting conversion that he makes is not valid and his conversion must be treated as having been made to an assumed, fictitious E field.

However, following Greene, let it be assumed that the receiving loop is in free space (that is, there is no contribution to the field at the receiving loop due to reflections from the ground) and that the receiving loop is far enough from the standard loop so that the wave impinging upon the loop is a plane wave. The E field and the H field are then simply related as

$$E = 120\pi H \qquad (3)$$

Now if it is also assummed that the field averages are thus similiarly related (not an obvious assumption), we can write

$$E(av) = 120\pi H(av) \qquad (4)$$

With this assumption, equation 1 can then be written as

$$E(av) = \frac{60\pi r1^2 I}{R^3} \{ 1 - (\beta D)^2 \}^{1/2} \qquad (5)$$

In arriving at equation 5, the R term under the radical was reduced to D. This simplification was introduced by Taggart and Workman[7] and for frequencies below 30 MHz it does not appear to significantly affect the accuracy of the calculation. (However, the legitimacy of this approximation should be further investigated at a future time.) The advantage of using this approximation is that it allows equation 5 to be written as

$$E(av) = E0(r1,r2,D,I)*FC(D,f) \qquad (6)$$

where the equation has been divided into a frequency independent part, E0, and a frequency dependent part, FC. The frequency dependent part, FC, is the radical term in equation 5. It depends only on the frequency and the separation between the loops and not upon the radius of the receiving loop. Consequently, the frequency correction factors, FC, need to be calculated only once for a given loop separation. Tables of these frequency correction factors can be prepared in advance for various chosen loop separations and used in the calibration of loops of various sizes as long as the loops are calibrated at the same distance from the standard loop.

In Table 1, the frequency correction factors in dBs have been calculated for loop separations of 1.48, 1.87 and 3.20 meters. These loop separations were chosen because they are the ones that are used at the Laboratory for all of our loop calibrations. In this report, they will be referred to as Positions 1, 2 and 3 respectively. These three particular loop separations were selected originally for the loop calibration positions because at these distances the average E field at the receiving loop is 100,000*FC, 50,000*FC and 10,000*FC uV/m respectively when the standard loop and receiving loop both have a radius of 0.113 meters and the standard loop is excited with a current of 100 milliampere. From Table 1 it can be seen that at these distances the frequency correction factor is negligible for frequencies below 1 MHz and below 1 MHz the average E field at these positions has the constant values of 100,000, 50,000 and 10,000 uV/m respectively and is independent of frequency.

Loops with a radius of less than that of the standard loop are normally calibrated at Position 1, those with a radius close to that of the standard loop are calibrated at Position 2 and those with a radius greater than that of the standard loop are calibrated at Position 3. No theoretical justification could be found for this convention.

TABLE 1

The Frequency Correction Factors Expressed in dBs for the Three Loop Calibration Positions

Frequency (MHz)	Position 1	Position 2	Position 3
1	0.0	0.0	0.0
2	0.0	0.0	0.1
3	0.0	0.1	0.2
4	0.1	0.1	0.3
5	0.1	0.2	0.5
6	0.2	0.2	0.7
7	0.2	0.3	0.9
8	0.3	0.4	1.1
9	0.4	0.6	1.6
10	0.4	0.6	1.6
11	0.5	0.7	1.9
12	0.6	0.9	2.2
13	0.7	1.0	2.5
14	0.8	1.1	2.7
15	0.9	1.3	3.0
16	1.0	1.4	3.3
17	1.1	1.6	3.6
18	1.2	1.8	3.9
19	1.4	2.1	4.5
20	1.4	2.1	4.5
21	1.5	2.3	4.7
22	1.7	2.4	5.0
23	1.8	2.6	5.3
24	1.9	2.8	5.5
25	2.1	2.9	5.8
26	2.2	3.1	6.1
27	2.3	3.3	6.3
28	2.4	3.4	6.6
29	2.6	3.6	6.8
30	2.7	3.8	7.0
31	2.9	3.9	7.3
32	3.0	4.1	7.5

Notes to Table 1: The frequency correction factors, FC(dB), are obtained from the equation

$$FC(dB) = 10*\text{Log}\{ 1 + (\beta D)^2 \}$$

where $\beta = (2\pi F(MHz)/300$ and F(MHz) is the frequency of the excitation current in megahertz. The loop separations, D, for Positions 1, 2 and 3 are 1.48, 1.87 and 3.20 meters, respectively.

A brief summary of the calibration geometry parameters used at the present time is given in the following table.

Position	Distance (meters)	E0 (uV/m)	Receiving Loop Size
1	1.48	100,000	r1 < r2
2	1.87	50,000	r1 = r2
3	3.20	10,000	r1 > r2

The present convention used for the placement of the receiving loop for calibration may be too restrictive. Calculations made with equation 5 show that the average Electric field calculated over the surface of loops of up to 14 inches in diameter will not vary by more tha 1 % from the field calculated over a surface of loop at that position that is equal in size to the standard loop. If 2 % accuracy is desired, then loops of up to 16 inches in diameter can be calibrated at this position and for 3 % accuracy, 23 inch diameter loops. A summary of these calculations for all three loop positions is made in the following table. In this table, d2 is the diameter of the receiving loop.

Position	Desired Accuracy		
	1 %	2 %	3 %
1	d2 < 14"	d2 < 17"	d2 < 20"
2	d2 < 16"	d2 < 20"	d2 < 24"
3	d2 < 23"	d2 < 31"	d2 < 37"

One of our loop antennas, an Empire LP-105, has a diameter of 11.5 inches. As such, there should be negligible differences in the field intensity meter readings if this antenna is calibrated in all three calibration positions. Also, the 15 inch Stoddart 92200-3 loop antenna should be able to be calibrated at all three calibration positions. (At position 1, the value of the average E field calculated for a 15 inch diameter antenna differs from the field calculated at this position for a standard loop by only 1.2 %.)

III. Exploration of the Use of Theoretical Antenna Factors inthe Calibration of Loop Antennas

In the use of an antenna for the measurement of an electromagnetic field, it is necessary to be able to transform a reading on a field intensity meter into a value of the electromagnetic field at the antenna. The ratio of the field at the antenna to the field intensity meter voltage is called the antenna factor. In the use of any antenna, it is useful to first look at the theoretical values of these antenna factors, if the particular antenna has a geometry that is suitable for their calculation. If the theoretical values should agree with the experimentally measured ones, the range of an antenna calibration can be greatly extended in many cases by simply using the theoretical values. On the other hand, any disagreements between the theoretical and experimental values can often point to difficulties such as impedance mismatches which may be overlooked or ignored without this comparison. Because of this, the first step taken here in examining the calibration procedures for loop antennas will be an investigation of the theoretical antenna factors for these antennas.

It is well known that if a loop antenna is placed in a time varying electromagnetic field, the H component of the field will induce a voltage in the antenna. The magnitude of this induced voltage depends upon the orientation of the antenna with relation to the field's **H** vector and the number of turns making up the loop antenna. However, unless a loop antenna is electrostatically shielded from the E component of the field, gradients in the E field will also contribute to the voltage that is produced at the antenna terminals. Consequently, a loop antenna that is to be used for measurement purposes is usually electrostatically shielded so that only the H component of the field is detected and not the E field component. Also, these antennas usually have only a single turn of wire in order to eliminate the effect of the capacitive coupling which is present between the loops of an antenna with more than one turn. The elimination of the capacitive coupling effects not only increases the potential accuracy of the measurement but also greatly simplifies the theoretical analysis.

If a single turn loop antenna is placed in an electromagnetic field that is varying at a frequency, f, a voltage, v, will be produced at its terminals that is given by

$$v = -j\omega\mu\int \vec{H}\cdot\vec{dS} \qquad (7)$$

where $\vec{H}$ is the magnetic component of the field at the surface element, $\vec{dS}$, which lies in the plane of the loop and $\omega = 2\pi f$. The integration is carried out over the entire surface of the loop.

Now if H(av) if the average value of normal component of the H field over the surface of the loop and S is the surface of the loop, then we have

$$v = -j\omega\mu H(av)S \qquad (8)$$

The magnitude of V is simply given as

$$V = \omega\mu H(av)S \qquad (9)$$

which can be written in terms of the radius of the loop, r2, and the frequency in megahertz, F(MHz) as

$$V = 0.8\pi^3 r2^2 F(MHz) H(av) \qquad (10)$$

or

$$H(av) = \frac{1}{0.8\pi^3 r2^2 F(MHz)} V \qquad (11)$$

Now if the receiving loop is in free space (that is, if there is no contribution to the field at the receiving loop due to reflections from the ground), and if the receiving loop is far enough from the source so that the wave impinging upon the loop is a plane wave then the E field and the H field are simply related as

$$E = 120\pi H \qquad (3)$$

If it is also assumed that the average E and H fields over the surface of the receiving loop are similiarly related, then equation 10 can be written as

$$E(av) = \frac{150}{\pi^2 r2^2 F(MHz)} V \qquad (12)$$

Now the antenna factor is defined as the ratio of the E field at the antenna to the received voltage. Therefore, the antenna factor of a single turn loop antenna of radius r2 is

$$AF = \frac{150}{\pi^2 r2^2 F(MHz)} \qquad (13)$$

or in terms of dBs

$$AF(dB) = 23.6 - 40\{Log(r2)\} - 20\{Log[F(MHz)]\} \qquad (14)$$

The above equation predicts that the antenna factor of a single turn loop antenna will decrease with increasing frequency at a rate of 20 dB per decade. Experimentally it is found that the measured loop antenna correction factors do indeed decrease with frequency although not at the constant rate of 20 dB per decade and not in a way that is consistent from antenna to antenna. As it was mentioned earlier, this disgreement between the theoretical and experimental antenna factors found for loop antennas could be the result of a poor match between the loop antenna and its 50 Ohm transmission line.

In this series of reports, the term, antenna factor, will be reserved for the theoretical derived ratio of the electric field at the antenna to the measured received voltage. The term, antenna correction factor, will be used for the experimentally determined ratio.

IV. The Basic Theory of Loop Antenna Calibration

If H(av) is the average value of the normal component of the H field over the surface of a loop antenna and V is the voltage induced by the field at the terminals of the antenna, then from equation 8 above we can write

$$H(av) \sim V \qquad (15)$$

But as was discussed in Section II above, the calibration is done in terms of an assummed E field, E(av). The assumed relationship between E(av) and H(av) was given earlier as

$$E(av) = 120\pi H(av) \qquad (4)$$

Therefore we can write

$$E(av) = K\ V \qquad (16)$$

where the constant of proportionality, K, is the loop antenna correction factor which is determined by the loop antenna calibration procedure. If V is measured in microvolts, then E will be measured in microvolts per meter.

$$E(uv/m) = K\ V(uv) \qquad (17)$$

referencing to power above 1 milliwatt, 0 dBm, we have

$$\frac{E(uv/m)}{240000} = K\ \frac{V(uv)}{240000} \qquad (18)$$

or

$$20\text{Log}\left(\frac{E(uv/m)}{240000}\right) = K(dB) + V(dBm) \qquad (19)$$

or rearranging terms as

$$K(dB) = -V(dBm) + 20Log\left(\frac{E(uv/m)}{240000}\right) \qquad (20)$$

From Kraus[8], the total power, W, radiated by a loop of radius, R, when excited by a current, I, of frequency, F(MHz), is

$$W = 0.000019\ F(MHz)^4 \cdot R^4 \cdot I^2 \qquad (21)$$

As such, over the 10 kHz to 30 MHz frequency range, the total maximum power that will be radiated by a loop of 0.113 meters radius when excited by a current of 100 milliamperes will occur at a frequency of 30 MHz and will have a value of 0.025 milliwatts (-16 dBm). Consequently, the total power intercepted by the receiving loop will always be less than 1 milliwatt. Under these conditions, the V(dBm) term in equation 20 will be negative and the total -V(dBm) term will be a positive quantity.

(This point is being made because in our loop calibration procedure it has been observed that the negative field intensity meter readings are at times treated as positive quantities and the field intensity term, which is always a negative quantity for our three calibration geometries, is treated as a positive quantity. This usually has no net effect on the loop calibration procedure providing that the person making the calibration has a feel for the correct relationship between these quantities. Nevertheless, it does present difficulties when an attempt is made to relate experimental quantities to the theoretical ones.)

In the loop calibration procedure, if the loop to be calibrated is placed at distances of 1.48, 1.87 and 3.20 meters from the standard loop, the average value of the assumed E field over the surface of this loop, as calculated from equation 5, is 100,000*FC, 50,000*FC and 10,000*FC uV/m respectively. Equation 22 can thus be written as

$$K(dB) = -V(dBm) + E{:}Factor + FC(dB) \qquad (23)$$

where FC(dB) is the frequency correction factor in dBs and the E:Factor is

$$E{:}Factor = 20Log\left(\frac{E0(uv/m)}{240000}\right) \qquad (24)$$

where E0(uV/m) takes on the values of 100,000, 50,000 and 10,000 uV/m for Positions 1, 2 and 3 respectively.

The values of the E:Factor term for these positions are are

Position	Distance (meters)	E:Factor (dB)
1	1.48	-7
2	1.87	-13
3	3.20	-27

V. Experimental Results

1. The Measurements of the Loop Antenna Correction Factors

The Laboratory has 5 shielded loop antennas. A brief summary of these antennas and their characteristics follows:

Magnetic Field Loop Antennas
Summary

Manufact.	Model	Numb.	Description	Freq Range
Singer	94593-1	1	square 32"/side	10 kHz-- 32 MHz
Empire	LG-105-A	2	circular 36" diam	14 kHz-- 150 kHz
Empire	LP-3-105	1	circular 36" diam	150 kHz--12.7 MHz
Empire	LP-105	1	circular 11.5" d.	150 kHz-- 30 MHz
Stoddart	92200-3	1	circular 15" diam	150 kHz-- 32 MHz

While gathering the data and materials for this report, calibration data were obtained for all of these antennas. In order to show how the various corrections are made to the data to obtain the antenna correction factors for a loop antenna, the calibration data for the Empire LP-3-105 antenna is presented in Table 6.

2. The Variation of the Loop Calibration with Position

It was shown in Section II that for the Empire LP-105 and Stoddart 92200-3 loop antennas, there should not be any significant difference in the antenna correction factors when measured at all three of the calibration positions. This was done for both antennas for 8 frequencies in the 150 kHz to the 25 MHz frequency range. The measurements were not extended above 25 MHz because an oscillator was not available for this range.

TABLE 6
The Antenna Correction Factors Expressed in DBs
for the 35 Inch Diameter Empire Loop LP-3-105

	Frequency	FIM Value (dB)		Corrections E:Factor		Corrections Frequency		Antenna Corr. Factor
	150 kHz	72.9	+	-27.0	+	0.0	=	45.9
R	200 kHz	71.1	+	-27.0	+	0.0	=	44.1
A	300 kHz	70.0	+	-27.0	+	0.0	=	43.0
N	400 kHz	68.0	+	-27.0	+	0.0	=	41.0-
G	500 kHz	68.2	+	-27.0	+	0.0	=	41.2
E	610 kHz	68.5	+	-27.0	+	0.0	=	41.5
	700 kHz	68.1	+	-27.0	+	0.0	=	41.1
1	800 kHz	68.0	+	-27.0	+	0.0	=	41.0
	870 kHz	68.0	+	-27.0	+	0.0	=	41.0
	870 kHz	67.8	+	-27.0	+	0.0	=	40.8
	910 kHz	68.0	+	-27.0	+	0.0	=	41.0
	1 MHz	67.8	+	-27.0	+	0.0	=	40.8
	1.5 MHz	63.0	+	-27.0	+	0.0	=	36.0
R	2 MHz	61.0	+	-27.0	+	0.1	=	34.1
A	3 MHz	59.1	+	-27.0	+	0.2	=	32.3
N	4 MHz	57.4	+	-27.0	+	0.3	=	30.7
G	5 MHz	57.8	+	-27.0	+	0.5	=	31.3
E	6 MHz	58.0	+	-27.0	+	0.7	=	31.6
	7 MHz	55.8	+	-27.0	+	0.9	=	29.7
2	8 MHz	53.8	+	-27.0	+	1.1	=	27.9
	9 MHz	54.2	+	-27.0	+	1.3	=	28.5
	10 MHz	53.5	+	-27.0	+	1.6	=	28.1
	11 MHz	54.2	+	-27.0	+	1.9	=	29.1
	12 MHz	52.0	+	-27.0	+	2.2	=	27.2
	12.7 MHz	54.9	+	-27.0	+	2.4	=	30.3

Notes to Table 6: The antenna was calibrated at Position 3. The antenna correction factors, K(dB), were obtained from the equation

$$K(dB) = -V(dBm) + E{:}Factor + FC(dB)$$

The Field Intensity Meter reading which is recorded in this Table is the negative of the measured FIM value; it is the quantity, -V(dBm). The E:Factor for this calibration position and the frequency correction factor, FC(*dB), are

$$E{:}Factor = 20 \mathrm{Log}\left(\frac{10000}{224000}\right)$$

and

$$FC(dB) = 10 * \mathrm{Log}\{ 1 + (\beta D)^2 \}$$

where $\beta = (2\pi F(MHz)/300$, D is the loop separation, 3.20 meters, and F(MHz) is the frequency of the excitation current in megahertz.

The measurement data are shown in Table 7. From the data it can be observed that for frequencies below 20 MHz there is little difference in the measured antenna correction factors for these three positions. However, for frequencies above 20 MHz, discrepancies in the antenna correction factors that are measured at the three positions begin to appear. At 25 MHz, there is a 2 dB difference in the antenna correction factors measured for the Empire antenna at calibration Positions 1 and 3 and a 4 dB difference in the antenna correction factors measured at these two positions for the Stoddart antenna. The cause of these variations is not known. They should be further investigated.

3. The Effect of the Height above Ground upon Loop Calibration

To properly evaluate our loop antenna calibration procedure, the fundamental question that must be asked is: what effect does the ground have on the loop antenna calibrations that are being made. And even if the effect of ground upon the calibration process does not show up in the tight geometry employed in loop calibrations, this same question must also be asked about any measurement procedure that is based upon the calibration procedure. For, any considerable reflection of energy from the ground could compromise the validity of the extrapolation of the antenna correction factors to actual open field measurement situations where the distances employed are significantly different from those that were used in making the calibration.

To explore the effect of ground reflected energy upon the calibration process, one of the loop antennas was placed at calibration position 3 at a distance of 3.20 meters from the Standard Loop. Measurements were made at eight frequencies over the operational frequency range of the antenna. For a reference value at each frequency, a measurement was made with the receiving antenna coaxial with the standard loop. The receiving antenna was then varied in a vertical plane about this position and readings were taken with the loop located approximately 32 inches above the central position, 32 inches below it, 32 inches to the right of it and 32 inches to the left of it. The data for two of our four loop antennas are shown in Table 8.

If energy that is reflected from the ground has no effect upon the calibration procedure, there should be no difference in the four readings taken when the antenna was varied aboout its central position. Below 10 MHz such is the case. However, above 10 MHz, there are significant differences between the antenna correction factors measured for the up and down positions which indicates that energy reflected from the ground may be making a contribution to the received energy.

TABLE 7

The Variation of the Antenna Correction Factors
with Position

Empire Loop LP-105
11.5 Inch Diameter
150 kHz to 30 MHz

Frequency	Antenna Correction Factors (dB) Pos. 1	Pos. 2	Pos. 3
150 kHz	61.0	61.7	61.0
500 kHz	54.2	54.0	54.0
1 MHz	54.0	53.8	53.2
5 MHz	46.1	46.6	46.5
10 MHz	41.4	41.6	40.6
15 MHz	39.8	40.3	39.8
20 MHz	39.4	39.1	38.4
25 MHz	39.0	38.4	36.8

Stoddart Loop 92200-3
15 Inch Diameter
150 kHz to 32 MHz

Frequency	Antenna Correction Factors (dB) Pos. 1	Pos. 2	Pos. 3
150 kHz	60.0	60.0	60.0
500 kHz	54.2	53.8	55.5
1 MHz	51.8	52.0	51.5
5 MHz	41.1	42.1	41.0
10 MHz	38.5	39.1	37.6
15 MHz	37.8	38.3	37.2
20 MHz	32.9	33.0	31.4
25 MHz	33.5	32.9	29.8

Notes to Table 7: Antenna Correction Factors were determined for these two antennas at all three positions. Theoretical calculations based on equation 6 show that there should be little difference in the measured antenna correction factors for these three positions for antennas of this size. This is borne out for frequencies below 20 MHz. However, for frequencies above 20 MHz, discrepancies in the antenna correction factors that are measured at the three positions begin to appear.

TABLE 8
The Variation of the Antenna Correction Factors
with the Height of the Loop Antenna above Ground

Empire Loop LP-105
11.5 Inch Diameter
150 kHz to 30 MHz

Frequency	Antenna Correction Factors (dB)				
	Center	Rt. 32"	Left 32"	Up 32"	Down 32"
200 kHz	59.0	60.2	61.2	60.8	60.7
500 kHz	54.0	55.0	55.0	55.8	55.5
1 MHz	53.7	55.0	55.1	55.2	55.2
5 MHz	46.6	48.3	48.3	48.5	48.5
10 MHz	40.5	41.0	41.3	42.1	40.4
15 MHz	39.9	40.9	40.7	41.7	39.8
20 MHz	37.5	38.0	38.0	39.7	37.4
24 MHz	38.4	38.5	36.7	40.7	37.5

Stoddart Loop 92200-3
15 Inch Diameter
150 kHz to 32 MHz

Frequency	Antenna Correction Factors (dB)				
	Center	Rt. 32"	Left 32"	Up 32"	Down 32"
200 kHz	59.0	60.5	60.5	60.5	60.2
500 kHz	53.5	55.0	55.0	55.0	54.8
1 MHz	51.5	53.0	53.0	53.0	53.0
5 MHz	40.5	41.7	42.0	42.5	42.0
10 MHz	36.9	38.6	39.1	38.6	37.7
15 MHz	37.0	38.1	38.2	39.0	36.8
20 MHz	30.5	31.0	31.0	32.7	29.7
25 MHz	30.3	30.8	30.8	32.8	29.3

Notes to Table 8: These measurements were made at calibration position 3 at a distance of 3.20 meters from the standard loop. At each frequency, a measurement was made with the receiving antenna coaxial with the standard loop. The receiving antenna was then varied in a vertical plane about this position and readings were taken with the loop located aproximately 32" above the central position, 32" below it, 32" to the right of it and 32" to the left of it. If energy that is reflected from the ground has no effect upon the calibration procedure, there should be no difference in the four readings for the displaced antennas. Below 10 MHz, such is the is the case. However, above 10 MHz, significant differences begin to appear.

VI. Conclusions

The following conclusions may be based upon the theoretical analysis and the collected data.

1. There is a disagreement between the theoretical antenna factors and the measured ones. This indicates that there are effects entering into the calibration process which are not accounted for in the theoretical analysis. Some of these effects might include:

   -- a possible mismatch betrween the antenna to be calibrated and the 50 Ohm transmission line

   -- reflected energy from the ground, and,

   -- coupling between the standard antenna and the receiving antenna.

2. The present theoretical analysis predicts that there will be only negligible differences in the measured antenna correction factors for antennas with a diameter of 15 inches or less when these antennas are calibrated at any one of the three standard calibrating positions. Yet the very rough experimental measurements reported here indicate that for frequencies above 20 MHz such differences may exist. More measureements have to be made to determine the extent of this effect and attempt to ascertain its effect upon the entire calibration procedure.

3. It was reported in an earlier technical note[9] that one of the authorities on the calibration of loop antennas at the National Institute of Science and Technology has stated that radiation reflected from the ground has little effect upon the calibration process for frequencies below 30 MHz. However, the rough measurements reported here indicate that this may not be the case. Further work is needed to resolve this discrepancy.

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5. F. M. Greene, The Near-Zone Magnetic Field of a Small Circular-Loop Antenna, NBS Journ. Res., Vol 71C, No. 4, pgs 319-326, October December 1967

6. F. M. Greene, op. cit., page 323, equation 26

7. H. E. Taggart and J. L. Workman, op. cit., page 65, equation 6

8. J. D. Kraus, <u>Antennas</u>, pg 167, equation 6-47, McGraw-Hill, 1950

9. Part 1 of this report, The Measurement of Radiated Emissions on Frequencies below 30 MHz Using Loop Antennas, Materials for the ANSI C63 Committee, Part 1: Introduction

The Measurement of Radiated Emissions on Frequencies below 30 MHz Using Loop Antennas

Materials for the ANSI C63 Committee Part 4: The Utility of the Simple Loop Antenna Model*

I. Introduction

The work in this project is directed towards the development of a measurement procedure for the measurement of radiated emissions on frequencies below 30 MHz. Single turn loops are the antennas which are normally used for making radiated measurements on these frequencies. This project was not initiated to resolve all of the difficulties which may be encountered in the use of these antennas in making radiated measurements but rather to develop a sufficient understanding of their operation so that an adequate and consistent test procedure can be developed concerning their use.

In this and in previous stages of this project, various spectrum analyzers, preamplifiers and field intensity meters have been evaluated for their suitability in making these measurements. At this time, a final choice of the test equipment has been made. Initial sets of measurement data have been made and are reported here and the procedures for handling and reducing the data have been developed.

II. Equipment Selection

Many people have ready access to spectrum analyzers and because of their visual displays find them easier to use than field intensity meters. The Laboratory has several spectrum analyzers, one of which is usually readily available. Thus, it would be desirable to use a spectrum analyzer in making some of the radiated emissions on frequencies below 30 MHz and to specify the spectrum analyzer in the final measurement procedure as an alternative piece of test equipment that can be used for making these radiated measurements.

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* Compiled from work done in September 1987 by Joseph Mc Nulty at the FCC Laboratory in Columbia, Maryland

However, loop antennas are not very efficient detectors of radiated signals and a preamplfier is needed in most instances to bring the signal up to a level where it can be accurately measured with a spectrum analyzer. The Laboratory has several Hewlett-Packard 8447A and 8447E preamplifiers on hand which are suitable for use in the 100 kHz to 30 MHz frequency range. In this frequency range, the gains of the two preamplifiers, as specified by the manufacturer, are flat and are approximately 20 dB. The gain for these two preamplifiers was also measured at selected frequenciees in the 100 kHz to 30 MHz range by inserting the premplifiers between a signal generator and a spectrum analyzer and observing the change in the signal when the premplifier was in and out of the circuit. For both preamplifiers, the gain at all these frequencies was found to be within a few dB of the 20 dB value.

But when each of these preamplifiers was placed between a loop antenna and a spectrum analyzer, the gain of the preamplifier was no longer 20 dB but varied with the frequency. At some frequencies, the gain that was measured when the preamplifier was inserted between a loop antenna and a spectrum analyzer was as high as 28 dB. This same gain anomaly occurred when a field intensity meter was used as the measuring device.

The cause of the preamplifier insertion loss (or gain) is not known at this time but may be related to the poor mismatch of the loop antennas to a 50 Ohm line. In any event, the unpredictability of the performance of the preamplifiers when used with loop antennas precludes their use at this time in any of our radiated measurements. And without a preamplifier, a spectrum analyzer would only be of limited use in making these measurements. As such, the use of a spectrum analyzer in making radiated measurements on frequencies below 30 MHz will not be investigated further at this time.

On the other hand, our field intensity meters have sufficient sensitivity so that they can be used for these measurements without the use of a preamplifier. However, of our field intensity meters (FIM), only the Singer/Stoddart NM 17/27 FIM is state of the art and is commercially available. The Laboratory has only one NM 17/27 and it is currently being used by three different Laboratory groups. Nevertheless, this field intensity meter appears to be the best measuring instrument that we have available for making radiated measurements below 30 MHz. It will definitely be one of the instruments recommended for use in the forthcoming measurement procedure.

III. Some Theoretical Considerations

The theoretical model that is used in the calibration of our loop antennas, was developed by Greene[1] at the National Bureau of Standards' Laboratories in Boulder, Colorado. Greene's treatment deals with the magnetic field that is set up in space by a single turn loop antenna that is being driven by a sinusoidally varying current. However, Greene's work can not be considered as a general analysis of this case since he only derives the average of the **H** field vector that is normal to a circular surface oriented parallel to the transmittting antenna and coaxial with it. Also, he does not make any separate derivation of the **E** field and obtains its value by multiplying the derived **H** field quantity by 120 pi.

Greene made a near field simplification of his model that can be used in the calibration of loop antennas. Taggart and Workman[2] simplified Greene's equations even further and it is their form of Greene's model which we currently use in our antenna calibration procedure. Undoubtedly, Greene's model is very useful for loop calibrations but for other applications the underlying physical principles are often obscure and where the conversion of the **H** to the **E** field occurs, it appear to be wrong.

In an attempt to obtain a better understanding of the behavior of the fields that they are trying to measure with loop antennas, people frequently use the equations for the **E** and **H** fields that are set up by a circular loop whose diameter is small compared to the wavelength of the sinusoidal current that is driving it. These equations are:[3]

$$E_\phi = 30\beta^3 IA\left[\frac{1}{\beta r} - \frac{j}{(\beta r)^2}\right]\sin\theta\, e^{-j\beta r} \tag{1}$$

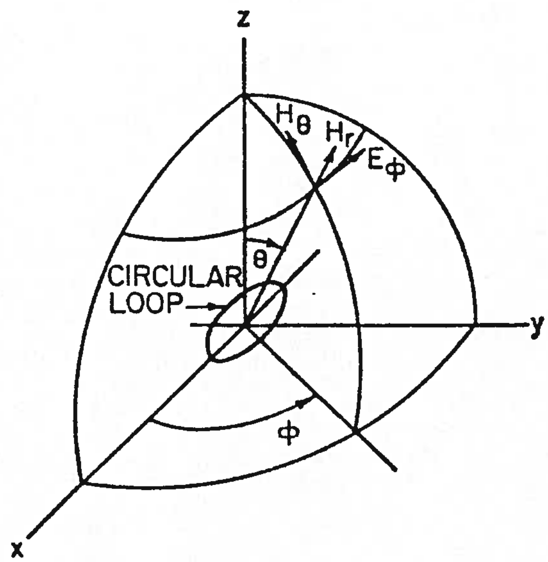
$$H_r = \frac{\beta^3 IA}{2\pi}\left[\frac{j}{(\beta r)^2} + \frac{1}{(\beta r)^3}\right]\cos\theta\, e^{-j\beta r} \tag{2}$$

$$H_\theta = -\frac{\beta^3 IA}{4\pi}\left[\frac{1}{\beta r} - \frac{j}{(\beta r)^2} - \frac{1}{(\beta r)^3}\right]\sin\theta\, e^{-j\beta r} \tag{3}$$

These equations are the **E** and **H** fields that are set up at a point in space by a circular loop antennna of surface area, A, that is being fed by a sinusoidal current, I. The wavenumber, beta, is 2 pi divided by the wavelength. The loop antenna is located in the x-y plane and is centered about the origin. Theta is the angle between the field point vector, r, and the z axis which is normal to the surface of the loop and passes through the center of it. The field point vector, r,is measured from the origin. The orientation of the loop with respect to the spatial coordinate system is shown in Figure 1.

These equations of Jasik are expressed in terms of the differential magnetic-dipole moment, dm. However, for a loop whose circumference is small compared to the wavelength of the excitation current, the magnetic dipole moment is equal to the product of the area of the loop, A, times the magnitude of the driving current, I. Hence, in equations 1 through 3, the quantity, I*A, has been substituted for the differential magnetic-dipole moment, dm.

With reference to equations 1 through 3, Jasik states that these "expressions are accurate for loop diameters which are considerably less than one-tenth wavelength." Now the transmitting loop antenna which is used for our loop antenna calibrations has a radius of 0.133 meters and this is also the same antenna which is being used as the transmitting antenna for the open-site measurements being made in this project. For a starting point, it will be assumed here that Jasik's criterion will hold for a transmitting loop antenna that has a diameter which is one-hundredth of a wavelength. Such an antenna is considerably smaller in size than an antenna having a diameter that is



$$E_\phi = 30\beta^3\, dm \left[\frac{1}{\beta r} - \frac{j}{(\beta r)^2}\right] \sin\theta\, e^{-j\beta r}$$

$$H_r = \frac{\beta^3}{2\pi}\, dm \left[\frac{j}{(\beta r)^2} + \frac{1}{(\beta r)^3}\right] \cos\theta\, e^{-j\beta r}$$

$$H_\theta = -\frac{\beta^3}{4\pi}\, dm \left[\frac{1}{\beta r} - \frac{j}{(\beta r)^2} - \frac{1}{(\beta r)^3}\right] \sin\theta\, e^{-j\beta r}$$

$$E_r = E_\theta = H_\phi = 0$$

Figure 1

Radiation from a Small Circular Loop Antenna

(The loop is centered at the origin and is located in the X-Y plane.)

one-tenth of a wavelength since it has only one-hundreth the surface area. Hence it can be inferred that equations 1 through 3 should characterize the fields which are produced by our 0.133 meter radius loop antenna for all frequencies up to 23 MHz, providing of course, that any field distortions due to reflection from the ground or other surfaces are negligible, and that any coupling between the transmitting loop antenna and the receiving loop antenna that is being used can be ignored. These are rather large assumptions but nevertheless, due to the lack of a more adequate theory, these simple equations will be used at times to approximate the fields produced by our 0.133 meter radius loop antenna on all frequencies below 30 MHz.

IV. Near Field Considerations

In the near field of the transmitting antenna, the first power term in 1/r in equation 3 can be neglected. For distances and frequencies where this is the case, the radial and angular components of the magnetic field reduce to:

$$H_r = \frac{\beta^3 IA}{2\pi}\left[\frac{j}{(\beta r)^2} + \frac{1}{(\beta r)^3}\right]\cos\theta\, e^{-j\beta r} \tag{4}$$

$$H_\theta = \frac{\beta^3 IA}{4\pi}\left[\frac{j}{(\beta r)^2} + \frac{1}{(\beta r)^3}\right]\sin\theta\, e^{-j\beta r} \tag{5}$$

At zero degrees and at 90 degrees, we have

$$H(0^\circ) = H_r(0^\circ) = \frac{\beta^3 IA}{2\pi}\left[\frac{j}{(\beta r)^2} + \frac{1}{(\beta r)^3}\right]e^{-j\beta r} \tag{6}$$

$$H(90^\circ) = H_\theta(90^\circ) = \frac{\beta^3 IA}{4\pi}\left[\frac{j}{(\beta r)^2} + \frac{1}{(\beta r)^3}\right]e^{-j\beta r} \tag{7}$$

Therefore, if the receiving antenna is parallel to the transmitting antenna and coaxial with it, only the radial component of the **H** field will be measured; and, if the receiving antenna is parallel to the transmitting antenna and coplanar with it, only the theta component of the **H** field will be detected. From equations 6 and 7 it can be seen that in the near antenna field, these two measurements of the **H** field should differ by 6 dB. Consequently, these two measurements of the **H** field might provide an insight into the adequacy of this simple model and also yield a better definition of what we mean by the near field limits.

V. Measurements

The transmitting antenna that was used in the measurements reported in this technical note was a single turn loop antenna of 0.133 meters radius. Measurements were made at various frequencies thoughout the 10 kHz to 30 MHz frequency range using the following four receiving antennas.

Manufact-urer	Model Number	Operational Frequency Range	Diameter (inches)
Empire	LP-105	150 kHz to 30 MHz	11.5
Stoddart	92200-3	150 kHz to 32 MHz	15
Empire	LG-105-A	14 kHz to 150 kHz	36
Empire	LP-3-105	150 kHz to 12.7 MHz	36

For frequencies of 20 MHz and below, the transmitting antenna current was adjusted to 100 mA. At 25 MHz it was not possible to drive the transmitting loop with 100 mA of current and so at this frequency, the transmitting antenna current was adjusted to 80 mA and 2 dB was added to the measured values of the field intensity. (Assuming that the field at any point in space is proportional to the magnitude of the transmitting current that is producing the field, then the field at a point in space due to a 100 mA tranmsmitting antenna current will be 1.25 times (or 1.93 db) that which is produced by an 80 mA antenna current.)

To gain a feel for the measuring equipment and for the parameters that would affect the measurements, all of the field intensity measurements reported here were made indoors in the controlled geometry of the loop calibration building. The antenna separations were 1.48, 1.87 and 3.2 meters. Although some of these measurements will be repeated when the final measurements are made oudoors on the open field test sites, no significant differences are expected between the measurements that will be made on the open sites and those that were made in the loop building.

VI. What is Actually Being Measured

Shielded loop antennas that are used for field strength measurements are constructed so that they will only detect the **H** field component of the radiated signal. Nevertheless, people making radiated measurements with these antennas will usually take the signal strengths that are measured with a field intensity meter that is coupled to the antenna and convert it to an **E** field value, not an **H** field value. They will then present their results this way. However, the simple conversion factor that they use to make this conversion will generally not yield a true **E** field value. Consequently, this method of presentation, although generally used, does not constitute good physics. But since most people that make radiated measurements with loop antennas appear to be more familiar and comfortable with interpreting the data in terms of E field representations rather than H field representation, they will perhaps continue to do it this way.

The analysis of the data obtained thus far is presented in Tables 1 through 8. In keeping with the standard method of analysis, the data In Tables 1 through 4,has been presented in the traditional way in terms of the E field vector. But in Tables 5 through 8, the analysis has been done in terms of the H field vector as it is felt here that this is a more valid and accurate way of representing the phenomena.

However, no matter what representation is used, it should be recognized that the choice of an E field approach to the problem or an H field approach is really a choice as to where it is perceived that the least confusion will lie. This confusion will always exist until our measurement procedures are based upon better theoretical models and both the government and the public are adequately instructed in their use. Thus at the present time, if a strictly H field approach is made to the problem, then the physics of the measurements will be on a much more sounder footing, but some of the concepts that must be introduced in making this approach may not be meaningful to those who are working in the field. Yet, with a strictly E field approach, there is a very real danger that the physics of the problem may become meaningless. As a case in point, Greene derives the average value of the H field over the surface of a receiving loop antenna and converts the H field value to an E field value by multiplying it by 120 pi. But for transmitting and receiving loops that are both parallel and coaxial (which is the normal configuration used for loop antenna calibrations), Greene's E field equation yields relatively large values of the E field over the surface of the receiving loop (of the order of millivolts per meter) even though the actual average value of the E field over the surface of the loop in this configuration is very close to zero.

VII. Presentation of the Results

The antenna factors that are used in Tables 1 through 4 to adjust the data are those that were measured earlier in this project for antenna separations of 3.2 meters. The "magnetic field antenna factors" used in Tables 5 through 8 are these same antenna factors reduced by 51.5 dB (20*log{120*pi}).

At each of the selected measuring frequencies, two measurements were made. One measurement was made with the receiving antenna parallel to the transmitting antenna and coaxial with it. The value of the field that was measured in this configuration is referred to in the Tables as the radial component of the field. A second measurement was made with the receiving antenna parallel to the transmitting antenna and coplanar with it. The value of the field that was measured in this configuration is referred to in the Tables as the theta component of the field.

The theoretical values that are used in the tables are based upon the equations of Taggart and Workman[2]. In the fifth column of the tables, the differences between the measured radial values and the theoretical values are listed. These differences give an indication of the applicability of Greene's model to the situation. In the last column of the tables, there are listed the deviations from the expected value of 6 dB of the difference between the measured radial and measured theta values of the field. The differences shown in this column give an indication of how well the simple loop antenna model given in equations 1 through 3 applies to the situation.

In general, for the frequencies and distances for which measurements were made, the agreement between the predicted values of Greene's model and the measured values was very good. And for frequencies of 5 MHz and lower, the measured radial and theta values of the field differed by 6 dB as expected by the simple model.

As a further check on the behavior of the antennas and on the consistency of the measurement procedure, the antennas were rotated 45 degrees at each of the two locations at each of the frequencies of measurement. In each case, the measured value of the field intensity dropped by 3 dB as it was expected.

Above 15 MHz, it was observed that cable placement had a rather significant effect upon the measurements. This phenomenon has not yet been fully explored although it was noted that the magnitude of the disturbance appeared to decrease when double shielded RG/U 55 cable was used in place of the single shielded RG/U 58 cable.

VII. Further Work

The measurements reported in this technical note were made indoors and were limited to antenna separations of 3.2 meters. In the coming quarter, these same measurements should be repeated outdoors on the open test sites and extended to antennas separations of at least 30 meters. At the conclusion of these additional measurements, a more in-depth analysis of the data could perhaps be possible. If no unsurmountable difficulties are encountered in either the measurements or the analysis, then at that time work could be initiated on drafting a test procedure for the measurement of radiated emissions on frequencies below 30 MHz using loop antennas.

TABLE 1: RANGE MEASUREMENT DATA

STANDARD METHOD OF ANALYSIS

¶ Stoddart Loop 92200-3 ¶
¶ 15 inch diameter loop antenna ¶
¶ 150 kHz to 30 MHz ¶

¶ Antenna Separation: 1.48 meters ¶

Frequency	Antenna Factor	Electric Field Intensity: Radial Theor.	Radial Meas.	Radial Diff.	Theta Meas.	6dB - [(R-T) Diff]
///////	dB	dBuV/m	dBuV/m	dB	dBuV/m	dB
150 kHz	60.0	100.0	99.5	0.5	93.5	0.0
500 kHz	55.5	100.0	101.0	-1.0	95.5	0.5
1 MHz	51.5	100.0	100.0	0.0	93.5	-0.5
5 MHz	41.0	100.1	100.0	0.1	94.0	0.0
10 MHz	37.6	100.4	99.1	1.3	92.6	-0.5
15 MHz	37.2	100.9	100.2	0.7	93.7	-0.5
20 MHz	31.5	101.4	99.5	1.9	94.5	1.0
25 MHz	29.8	102.1	98.8	3.3	94.8	2.0

¶ Antenna Separation: 1.87 meters ¶

Frequency	Antenna Factor	Electric Field Intensity: Radial Theor.	Radial Meas.	Radial Diff.	Theta Meas.	6dB - [(R-T) Diff]
///////	dB	dBuV/m	dBuV/m	dB	dBuV/m	dB
150 kHz	60.0	94.0	93.0	1.0	87.5	0.5
500 kHz	55.5	94.0	95.5	-1.5	89.5	0.0
1 MHz	51.5	94.0	94.0	0.0	88.0	0.0
5 MHz	41.0	94.2	94.0	0.2	88.0	0.0
10 MHz	37.6	94.6	92.6	2.0	85.6	-1.0
15 MHz	37.2	95.3	95.2	0.1	88.2	-1.0
20 MHz	31.5	96.1	94.5	1.6	90.5	2.0
25 MHz	29.8	96.9	93.8	3.1	92.8	5.0

¶ Antenna Separation: 3.20 meters ¶

Freq- uency	Antenna Factor	Radial Theor.	Electric Field Intensity: Radial Meas.	Radial Diff.	Theta Meas.	6dB - [(R-T) Diff]
///////	dB	dBuV/m	dBuV/m	dB	dBuV/m	dB
150 kHz	60.0	80.1	80.0	0.1	74.0	0.0
500 kHz	55.5	80.1	81.5	-1.4	75.5	0.0
1 MHz	51.5	80.1	80.0	0.1	74.0	0.0
5 MHz	41.0	80.6	80.5	0.1	75.0	0.5
10 MHz	37.6	81.7	79.6	2.1	72.6	-1.0
15 MHz	37.2	83.1	84.2	-1.1	83.2	5.0
20 MHz	31.5	84.6	83.5	1.1	83.5	6.0
25 MHz	29.8	85.9	83.8	2.1	83.8	6.0

NOTES:

1. The E field in microvolts per meter is calculated from the measured value by summing the antenna factor in dBs and the FIM value in dBm and then adding 107 dBs to this sum.
2. The fifth column of the table lists the differences between the measured value of the radial E field and Greene's theoretical value for this field component.
3. The differences listed in the last column of the table are the deviations of the difference of the radial and theta E field values from the 6 dB value that is predicted by the simple loop antenna model.

TABLE 2: RANGE MEASUREMENT DATA

STANDARD METHOD OF ANALYSIS

¶ Empire LP-105 ¶
¶ 11.5 inch diam. loop antenna ¶
¶ 150 kHz to 30 MHz ¶

¶ Antenna Separation: 1.48 meters ¶

Frequency	Antenna Factor	Electric Field Intensity: Radial Theor.	Radial Meas.	Radial Diff.	Theta Meas.	6dB - [(R-T) Diff]
///////	dB	dBuV/m	dBuV/m	dB	dBuV/m	dB
150 kHz	61.0	100.0	100.0	0.0	95.0	1.0
500 kHz	54.0	100.0	100.0	0.0	94.0	0.0
1 MHz	53.2	100.0	100.2	-0.2	94.2	0.0
5 MHz	46.5	100.1	101.5	-1.4	95.5	0.0
10 MHz	40.6	100.4	100.1	0.3	93.1	-1.0
15 MHz	39.8	100.9	100.8	0.1	93.8	-1.0
20 MHz	38.4	101.4	100.9	0.5	97.9	3.0
25 MHz	36.8	102.1	100.8	1.3	96.3	1.5

¶ Antenna Separation: 1.87 meters ¶

Frequency	Antenna Factor	Electric Field Intensity: Radial Theor.	Radial Meas.	Radial Diff.	Theta Meas.	6dB - [(R-T) Diff]
///////	dB	dBuV/m	dBuV/m	dB	dBuV/m	dB
150 kHz	61.0	94.0	93.5	0.5	88.0	0.5
500 kHz	54.0	94.0	94.0	0.0	88.0	0.0
1 MHz	53.2	94.0	94.2	-0.2	88.2	0.0
5 MHz	46.5	94.2	95.5	-1.3	90.0	0.5
10 MHz	40.6	94.6	94.1	0.5	87.1	-1.0
15 MHz	39.8	95.3	95.8	-0.5	88.3	-1.5
20 MHz	38.4	96.1	95.9	0.2	94.4	4.5
25 MHz	36.8	96.9	95.8	1.1	92.8	3.0

¶ Antenna Separation: 3.20 meters ¶

Frequency	Antenna Factor	Electric Field Intensity: Radial Theor.	Radial Meas.	Radial Diff.	Theta Meas.	6dB - [(R-T) Diff]
///////	dB	dBuV/m	dBuV/m	dB	dBuV/m	dB
150 kHz	61.0	80.1	80.0	0.1	74.0	0.0
500 kHz	54.0	80.1	80.0	0.1	74.0	0.0
1 MHz	53.2	80.1	80.2	-0.1	74.2	0.0
5 MHz	46.5	80.6	81.5	-0.9	76.5	1.0
10 MHz	40.6	81.7	82.6	-0.9	73.6	-3.0
15 MHz	39.8	83.1	84.8	-1.7	82.8	4.0
20 MHz	38.4	84.6	85.4	-0.8	88.4	9.0
25 MHz	36.8	85.9	86.8	-0.9	87.3	6.5

NOTES:

1. The E field in microvolts per meter is calculated from the measured value by summing the antenna factor in dBs and the FIM value in dBm and then adding 107 dBs to this sum.
2. The fifth column of the table lists the differences between the measured value of the radial E field and Greene's theoretical value for this field component.
3. The differences listed in the last column of the table are the deviations of the difference of the radial and theta E field values from the 6 dB value that is predicted by the simple loop antenna model.

TABLE 3: RANGE MEASUREMENT DATA

STANDARD METHOD OF ANALYSIS

¶ Empire LP-3-105 ¶
¶ 35 inch diameter loop antenna ¶
¶ 150 kHz to 30 MHz ¶

¶ Antenna Separation: 3.20 meters ¶

Frequency	Antenna Factor	Electric Field Intensity: Radial Theor.	Radial Meas.	Radial Diff.	Theta Meas.	6dB - [(R-T) Diff]
///////	dB	dBuV/m	dBuV/m	dB	dBuV/m	dB
150 kHz	45.9	80.1	79.9	0.2	74.9	1.0
200 kHz	44.1	80.1	79.1	1.0	73.1	0.0
300 kHz	43.0	80.1	79.0	1.1	73.5	0.5
400 kHz	41.0	80.1	80.0	0.1	74.0	0.0
500 kHz	41.2	80.1	79.2	0.9	73.2	0.0
610 kHz	41.5	80.1	79.0	1.1	73.0	0.0
700 kHz	41.1	80.1	79.1	1.0	73.1	0.0
800 kHz	41.0	80.1	79.0	1.1	73.5	0.5
870 kHz	41.0	80.1	79.0	1.1	73.0	0.0
870 kHz	40.8	80.1	79.8	0.3	73.3	-0.5
910 kHz	41.0	80.1	80.0	0.1	74.0	0.0
1 MHz	40.8	80.1	79.8	0.3	74.3	0.5
1.5 MHz	36.0	80.1	80.0	0.1	74.0	0.0
2 MHz	34.1	80.2	79.6	0.6	74.6	1.0
3 MHz	32.3	80.3	80.3	-0.0	75.3	1.0
4 MHz	30.7	80.4	79.7	0.7	72.7	-1.0
5 MHz	31.3	80.6	81.3	-0.7	76.3	1.0
6 MHz	31.6	80.8	82.6	-1.8	77.6	1.0
7 MHz	29.7	81.0	80.7	0.3	75.7	1.0
8 MHz	27.9	81.2	79.4	1.8	74.4	1.0
9 MHz	28.5	81.5	80.5	1.0	74.5	0.0
10 MHz	28.1	81.7	81.1	0.6	74.6	-0.5
11 MHz	29.1	82.0	82.6	-0.6	76.1	-0.5
12 MHz	27.2	82.3	81.7	0.6	77.2	1.5
12.7 MHz	30.3	82.5	85.3	-2.8	81.3	2.0

NOTES:

1. The E field in microvolts per meter is calculated from the measured value by summing the antenna factor in dBs and the FIM value in dBm and then adding 107 dBs to this sum.
2. The fifth column of the table lists the differences between the measured value of the radial E field and Greene's theoretical value for this field component.
3. The differences listed in the last column of the table are the deviations of the difference of the radial and theta E field values from the 6 dB value that is predicted by the simple loop antenna model.

TABLE 4: RANGE MEASUREMENT DATA
STANDARD METHOD OF ANALYSIS

¶ Empire LP-105-A ¶
¶ 35 inch diameter loop antenna ¶
¶ 15 kHz to 150 kHz ¶

¶ Antenna Separation: 3.20 meters ¶

Freq-uency	Antenna Factor	Radial Theor.	Electric Field Intensity Radial Meas.	Radial Diff.	Theta Meas.	6dB - [(R-T) Diff]
///////	dB	dBuV/m	dBuV/m	dB	dBuV/m	dB
15 kHz	59.0	80.1	79.5	0.6	74.0	0.5
20 kHz	57.0	80.1	80.0	0.1	75.0	1.0
30 kHz	54.3	80.1	80.3	-0.2	75.3	1.0
40 kHz	52.2	80.1	80.2	-0.1	74.2	0.0
52 kHz	51.2	80.1	79.7	0.4	74.2	0.5
60 kHz	51.0	80.1	80.0	0.1	75.0	1.0
70 kHz	50.2	80.1	79.2	0.9	74.2	1.0
80 kHz	50.0	80.1	79.0	1.1	74.0	1.0
90 kHz	50.0	80.1	79.5	0.6	74.5	1.0
100 kHz	50.0	80.1	79.5	0.6	74.0	0.5
110 kHz	50.0	80.1	79.5	0.6	74.5	1.0
120 kHz	50.0	80.1	79.5	0.6	74.0	0.5
134 kHz	50.0	80.1	79.5	0.6	74.5	1.0
140 kHz	50.0	80.1	79.5	0.6	74.5	1.0
150 kHz	50.0	80.1	80.0	0.1	75.0	1.0

NOTES:

1. The E field in microvolts per meter is calculated from the measured value by summing the antenna factor in dBs and the FIM value in dBm and then adding 107 dBs to this sum.
2. The fifth column of the table lists the differences between the measured value of the radial E field and Greene's theoretical value for this field component.
3. The differences listed in the last column of the table are the deviations of the difference of the radial and theta E field values from the 6 dB value that is predicted by the simple loop antenna model.

TABLE 5: RANGE MEASUREMENT DATA

ANALYSIS IN TERMS OF THE H FIELD VECTOR

¶ Stoddart Loop 92200-3 ¶
¶ 15 inch diameter loop antenna ¶
¶ 150 kHz to 30 MHz ¶

¶ Antenna Separation: 1.48 meters ¶

Frequency	Antenna Factor	Radial Theor. (Magnetic Field Intensity)	Radial Meas. (Magnetic Field Intensity)	Radial Diff. (Magnetic Field Intensity)	Theta Meas. (Magnetic Field Intensity)	6dB - [(R-T) Diff]
///////	dB	dBuA/m	dBuA/m	dB	dBuA/m	dB
150 kHz	60.0	48.5	48.0	0.5	42.0	0.0
500 kHz	55.5	48.5	49.5	-1.0	44.0	0.5
1 MHz	51.5	48.5	48.5	0.0	42.0	-0.5
5 MHz	41.0	48.6	48.5	0.1	42.5	0.0
10 MHz	37.6	48.9	47.6	1.3	41.1	-0.5
15 MHz	37.2	49.4	48.7	0.7	42.2	-0.5
20 MHz	31.5	49.9	48.0	1.9	43.0	1.0
25 MHz	29.8	50.6	47.3	3.3	43.3	2.0

¶ Antenna Separation: 1.87 meters ¶

Frequency	Antenna Factor	Radial Theor. (Magnetic Field Intensity)	Radial Meas. (Magnetic Field Intensity)	Radial Diff. (Magnetic Field Intensity)	Theta Meas. (Magnetic Field Intensity)	6dB - [(R-T) Diff]
///////	dB	dBuA/m	dBuA/m	dB	dBuA/m	dB
150 kHz	60.0	42.5	41.5	1.0	36.0	0.5
500 kHz	55.5	42.5	44.0	-1.5	38.0	0.0
1 MHz	51.5	42.5	42.5	-0.0	36.5	0.0
5 MHz	41.0	42.7	42.5	0.2	36.5	0.0
10 MHz	37.6	43.1	41.1	2.0	34.1	-1.0
15 MHz	37.2	43.8	43.7	0.1	36.7	-1.0
20 MHz	31.5	44.6	43.0	1.6	39.0	2.0
25 MHz	29.8	45.4	42.3	3.1	41.3	5.0

¶ Antenna Separation: 3.20 meters ¶

Frequency	Antenna Factor	Magnetic Field Intensity: Radial Theor.	Radial Meas.	Radial Diff.	Theta Meas.	6dB - [(R-T) Diff]
///////	dB	dBuA/m	dBuA/m	dB	dBuA/m	dB
150 kHz	60.0	28.6	28.5	0.1	22.5	0.0
500 kHz	55.5	28.6	30.0	-1.4	24.0	0.0
1 MHz	51.5	28.6	28.5	0.1	22.5	0.0
5 MHz	41.0	29.0	29.0	0.0	23.5	0.5
10 MHz	37.6	30.2	28.1	2.1	21.1	-1.0
15 MHz	37.2	31.6	32.7	-1.1	31.7	5.0
20 MHz	31.5	33.0	32.0	1.0	32.0	6.0
25 MHz	29.8	34.4	32.3	2.1	32.3	6.0

NOTES:

1. The H field in microamperes per meter is calculated from the measured value by summing the antenna factor in dBs and the FIM value in dBm and then adding 55.5 dBs to this sum. [55.5 dBs is 107 dB minus 20*Log(120*pi).]
2. The fifth column of the table lists the differences between the measured value of the radial H field and Greene's theoretical value for this field component.
3. The differences listed in the last column of the table are the deviations of the difference of the radial and theta H field values from the 6 dB value that is predicted by the simple loop antenna model.

TABLE 6: RANGE MEASUREMENT DATA

ANALYSIS IN TERMS OF THE H FIELD VECTOR

¶ Empire LP-105 ¶
¶ 11.5 inch diam. loop antenna ¶
¶ 150 kHz to 30 MHz ¶

¶ Antenna Separation: 1.48 meters ¶

Freq-uency	Antenna Factor	Magnetic Field Intensity				
		Radial Theor.	Radial Meas.	Radial Diff.	Theta Meas.	6dB - [(R-T) Diff]
///////	dB	dBuA/m	dBuA/m	dB	dBuA/m	dB
150 kHz	61.0	48.5	48.5	0.0	43.5	1.0
500 kHz	54.0	48.5	48.5	0.0	42.5	0.0
1 MHz	53.2	48.5	48.7	-0.2	42.7	0.0
5 MHz	46.5	48.6	50.0	-1.4	44.0	0.0
10 MHz	40.6	48.9	48.6	0.3	41.6	-1.0
15 MHz	39.8	49.4	49.3	0.1	42.3	-1.0
20 MHz	38.4	49.9	49.4	0.5	46.4	3.0
25 MHz	36.8	50.6	49.3	1.3	44.8	1.5

¶ Antenna Separation: 1.87 meters ¶

Freq-uency	Antenna Factor	Magnetic Field Intensity				
		Radial Theor.	Radial Meas.	Radial Diff.	Theta Meas.	6dB - [(R-T) Diff]
///////	dB	dBuA/m	dBuA/m	dB	dBuA/m	dB
150 kHz	61.0	42.5	42.0	0.5	36.5	0.5
500 kHz	54.0	42.5	42.5	-0.0	36.5	0.0
1 MHz	53.2	42.5	42.7	-0.2	36.7	0.0
5 MHz	46.5	42.7	44.0	-1.3	38.5	0.5
10 MHz	40.6	43.1	42.6	0.5	35.6	-1.0
15 MHz	39.8	43.8	44.3	-0.5	36.8	-1.5
20 MHz	38.4	44.6	44.4	0.2	42.9	4.5
25 MHz	36.8	45.4	44.3	1.1	41.3	3.0

¶ Antenna Separation: 3.20 meters ¶

Magnetic Field Intensity

Freq-uency	Antenna Factor	Radial Theor.	Radial Meas.	Radial Diff.	Theta Meas.	6dB - [(R-T) Diff]
///////	dB	dBuA/m	dBuA/m	dB	dBuA/m	dB
150 kHz	61.0	28.6	28.5	0.1	22.5	0.0
500 kHz	54.0	28.6	28.5	0.1	22.5	0.0
1 MHz	53.2	28.6	28.7	-0.1	22.7	0.0
5 MHz	46.5	29.0	30.0	-1.0	25.0	1.0
10 MHz	40.6	30.2	31.1	-0.9	22.1	-3.0
15 MHz	39.8	31.6	33.3	-1.7	31.3	4.0
20 MHz	38.4	33.0	33.9	-0.9	36.9	9.0
25 MHz	36.8	34.4	35.3	-0.9	35.8	6.5

NOTES:

1. The H field in microamperes per meter is calculated from the measured value by summing the antenna factor in dBs and the FIM value in dBm and then adding 55.5 dBs to this sum. [55.5 dBs is 107 dB minus 20*Log(120*pi).]
2. The fifth column of the table lists the differences between the measured value of the radial H field and Greene's theoretical value for this field component.
3. The differences listed in the last column of the table are the deviations of the difference of the radial and theta H field values from the 6 dB value that is predicted by the simple loop antenna model.

TABLE 7: RANGE MEASUREMENT DATA

ANALYSIS IN TERMS OF THE H FIELD VECTOR

¶ Empire LP-3-105 ¶
¶ 35 inch diameter loop antenna ¶
¶ 150 kHz to 30 MHz ¶

¶ Antenna Separation: 3.20 meters ¶

		Magnetic Field Intensity				
Freq-uency	Antenna Factor	Radial Theor.	Radial Meas.	Radial Diff.	Theta Meas.	6dB - [(R-T) Diff]
///////	dB	dBuA/m	dBuA/m	dB	dBuA/m	dB
150 kHz	45.9	28.6	28.4	0.2	23.4	1.0
200 kHz	44.1	28.6	27.6	1.0	21.6	0.0
300 kHz	43.0	28.6	27.5	1.1	22.0	0.5
400 kHz	41.0	28.6	28.5	0.1	22.5	0.0
500 kHz	41.2	28.6	27.7	0.9	21.7	0.0
610 kHz	41.5	28.6	27.5	1.1	21.5	0.0
700 kHz	41.1	28.6	27.6	1.0	21.6	0.0
800 kHz	41.0	28.6	27.5	1.1	22.0	0.5
870 kHz	41.0	28.6	27.5	1.1	21.5	0.0
870 kHz	40.8	28.6	28.3	0.3	21.8	-0.5
910 kHz	41.0	28.6	28.5	0.1	22.5	0.0
1 MHz	40.8	28.6	28.3	0.3	22.8	0.5
1.5 MHz	36.0	28.6	28.5	0.1	22.5	0.0
2 MHz	34.1	28.7	28.1	0.6	23.1	1.0
3 MHz	32.3	28.8	28.8	-0.0	23.8	1.0
4 MHz	30.7	28.9	28.2	0.7	21.2	-1.0
5 MHz	31.3	29.0	29.8	-0.8	24.8	1.0
6 MHz	31.6	29.2	31.1	-1.9	26.1	1.0
7 MHz	29.7	29.4	29.2	0.2	24.2	1.0
8 MHz	27.9	29.7	27.9	1.8	22.9	1.0
9 MHz	28.5	29.9	29.0	0.9	23.0	0.0
10 MHz	28.1	30.2	29.6	0.6	23.1	-0.5
11 MHz	29.1	30.5	31.1	-0.6	24.6	-0.5
12 MHz	27.2	30.7	30.2	0.5	25.7	1.5
12.7 MHz	30.3	30.9	33.8	-2.9	29.8	2.0

NOTES:

1. The H field in microamperes per meter is calculated from the measured value by summing the antenna factor in dBs and the FIM value in dBm and then adding 55.5 dBs to this sum. [55.5 dBs is 107 dB minus 20*Log(120*pi).]
2. The fifth column of the table lists the differences between the measured value of the radial H field and Greene's theoretical value for this field component.
3. The differences listed in the last column of the table are the deviations of the difference of the radial and theta H field values from the 6 dB value that is predicted by the simple loop antenna model.

TABLE 8: RANGE MEASUREMENT DATA

ANALYSIS IN TERMS OF THE H FIELD VECTOR

Empire LP-105-A
35 inch diameter loop antenna
15 kHz to 150 kHz

¶ Antenna Separation: 3.20 meters ¶

Frequency	Antenna Factor	Radial Theor.	Magnetic Field Intensity Radial Meas.	Radial Diff.	Theta Meas.	6dB - [(R-T) Diff]
///////	dB	dBuA/m	dBuA/m	dB	dBuA/m	dB
15 kHz	59.0	28.6	28.0	0.6	22.5	0.5
20 kHz	57.0	28.6	28.5	0.1	23.5	1.0
30 kHz	54.3	28.6	28.8	-0.2	23.8	1.0
40 kHz	52.2	28.6	28.7	-0.1	22.7	0.0
52 kHz	51.2	28.6	28.2	0.4	22.7	0.5
60 kHz	51.0	28.6	28.5	0.1	23.5	1.0
70 kHz	50.2	28.6	27.7	0.9	22.7	1.0
80 kHz	50.0	28.6	27.5	1.1	22.5	1.0
90 kHz	50.0	28.6	28.0	0.6	23.0	1.0
100 kHz	50.0	28.6	28.0	0.6	22.5	0.5
110 kHz	50.0	28.6	28.0	0.6	23.0	1.0
120 kHz	50.0	28.6	28.0	0.6	22.5	0.5
134 kHz	50.0	28.6	28.0	0.6	23.0	1.0
140 kHz	50.0	28.6	28.0	0.6	23.0	1.0
150 kHz	50.0	28.6	28.5	0.1	23.5	1.0

NOTES:

1. The H field in microamperes per meter is calculated from the measured value by summing the antenna factor in dBs and the FIM value in dBm and then adding 55.5 dBs to this sum. [55.5 dBs is 107 dB minus 20*Log(120*pi).]
2. The fifth column of the table lists the differences between the measured value of the radial H field and Greene's theoretical value for this field component.
3. The differences listed in the last column of the table are the deviations of the difference of the radial and theta H field values from the 6 dB value that is predicted by the simple loop antenna model.

REFERENCES for PART 4

1. F. M. Greene, The Near-Zone Magnetic Field of a Small Circular-Loop Antenna, NBS Journ. Res., Vol 71C, No. 4, pgs 319-326, October December 1967, page 323, equation 26

2. H. E. Taggart and J. L. Workman, Calibration Principles and Procedures for Field Strength Meters (30 Hz to 1 GHz), NBS Technical Note 370, National Bureau of Standards, Boulder, Colorado, March 1969, page 65, equation 6

3. <u>Antenna Engineering Handbook</u>, Henry Jasik, Editor, 1st edition, pgs 2-5,2-6, McGraw-Hill Book Co., 1961

The Measurement of Radiated Emissions
on Frequencies below 30 MHz
Using Loop Antennas

Materials for the ANSI C63 Committee
Part 5: Preliminary Checks on the Validity and Use of the Simple Loop Antenna Model*

I. Introduction

In the past quarter, field strength measurements were made on the open field test sites with three of our loop antennas on selected frequencies in the 10 kHz to 30 MHz frequency range. The results of the analysis of these data are presented in this tecnical note. As part of the analysis, the data were compared with some of the available theoretical models. Such comparisons are important as they can provide a valid basis for any extrapolation of the emission limits from the distances of 30 and 300 meters that are specified in the Rules to more workable distances of 3 and 10 meters. Also because the use of loop antennas in making radiation measurements depends so heavily upon the meaningfulness of the calibration that is used, a closer look was made of our loop calibration procedures.

The limitations of the test equipment that is used in making measurements with loop antennas was also to be examined, particularly the performance of the NM 17/27 Field Intensity Meter for possible nonlinearities at low signal levels. These nonlinearities were noticed in the previous quarter when measurements of the field strength were being made with this instrument on the open field test sites. However, this phase of the work could not be completed because the heating system in the Laboratory's Loop Calibration Building was defective and it took a considerable amount of time to have it repaired.

II. Loop Antenna Calibration Procedures

The procedures which we use in the calibration of our loop antennas are based upon the theoretical work of Greene[1] which he developed at the National Bureau of Standards. His derivation assumes that a magnetic field is being produced

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* Compiled from work done in March 1988 by Joseph Mc Nulty at the FCC Laboratory in Columbia, Maryland

by a current, I, flowing in a single turn loop antenna of radius, r1. A second loop antenna of radius, r2, is placed parallel to the transmitting loop antenna and is coaxial with it. After making some suitable approximations, Greene found that the average value of the magnetic field components, H(av), that are normal to the surface of this second loop antenna, is found to be

$$H(av) = \frac{r1^2 I}{2\ R^3}(1+(\beta R)^2)^{1/2} \quad (1)$$

where

$$R = \sqrt{r1^2 + r2^2 + D^2} \quad (2)$$

and β = (2*pi*F(MHz)/300, where F(MHz) is the frequency of the excitation current in megahertz.

Greene's equation for the magnetic field intensity gives the average value of the radial component of the magnetic field at points along the axis of the transmitting loop. However, it gives no infomation concerning the azimuthal and polar components of the magnetic field along the axis of the transmitting loop nor of the radial component at points away from the transmitting loop's axis. His expression for the magnetic field intensity is also unusual in that it contains the radius of the receiving loop antenna. This occurs because his equation is an average of the normal componet of the magnetic field over the surface of the receiving loop antenna.

Taggart and Workman[2] removed a portion of this dependence of the magnetic field intensity on the radius of the receiving antenna by simply equating the R term under the radical in the numerator of equation 1 to the separation distance between the antennas, D. However, they did not make this same approximation in the R term which appears in the denominator of equation 1, and this term still retains its dependence on r1, r2 and D. For frequencies below 30 MHz this simplification introduced by Taggart and Workman does not appear to significantly affect the accuracy of the calculation. With this approximation, equation 1 can be written as

$$H(av) = \frac{r1^2 I}{2\ R^3}(1+(\beta D)^2)^{1/2} \quad (3)$$

or

$$H(av) = H0(r1,r2,D)*FC(D,f) \quad (4)$$

where the equation has been divided into a frequency independent part, H0, and a frequency dependent part, FC. The frequency dependent part, FC, depends only upon the frequency and the separation between the loops and not upon the radius of the receiving loop. It is given as

$$FC(D,f) = (1+(\beta D)^2)^{1/2} \qquad (5)$$

Loop antennas are calibrated at the Laboratory at the three fixed distances from the transmitting antenna of 1.484, 1.875 and 3.199 meters. Tables of the frequency correction factors, FC(D,f), are prepared for these three antenna separations and can be used in the calibration of loop antennas of any size as long as the loops are calibrated at one of the three calibration positions.

The remaining portion of equation 3 is the frequency independent part, H0(r1,r2,D). This term. however, does depend upon the radii of both the transmitting and receiving loop antennas as well as the distance between them. It is given as

$$H0(r1,r2,D) = \frac{r1^2 I}{2R^3} \qquad (6)$$

where the term, R, in the denominator of this expression has been previously defined in equation 2.

Since the magnetic field intensity term defined by equation 6 depends upon the size of the antenna that is to be calibrated, this has to be taken into account when a loop antenna is being calibrated. There are two general ways of doing this:

1. the radius of each antenna to be calibrated is measured and the value of H0(r1,r2,D) calculated for that particular antenna and calibration position, or,

2. an average value of r2 is assumed for the radii of the antennas that are to be calibrated at each of the fixed calibration positions. Fixed values of H0(r1,D) are then calculated for each of the calibration positions using the assumed average values of r2. The resulting values of H0(r1,D) that are thus obtained will be independent of the size of the receiving antenna. However, an adjustment must be made to the antenna calibrations obtained by this means to account for the difference between the actual size of the antenna that is being calibrated and the antenna size that was assumed for that calibration position.

In our calibration procedures, the second of these two approaches is taken with the exception that no adjustment is made to the calibration data to account for the difference between the actual size of the antenna that is being calibrated and the assumed antenna size for that calibration position. However, it will be shown below that the error which this introduces is less than 0.3 dB.

When our present calibration procedure was being established[3], the assumed values of the radii of the receiving antennas for each of the three calibration positions were chosen to be 0.130, 0.130 and 0.318 meters. (For comparison purposes, these radii correspond to antennas whose diameters are 10.2, 10.2 and 25.0 inches.)

All of the above analysis was made in terms of the H field and not the E field for the simple reason that Greene did not derive an expression for the H field over the surface of the receiving loop antenna. To obtain an expression for the E field, he arbitrarily converted his resulting H field expression to an E field equation by multiplying it by 102*pi. Although this conversion is only valid if making measurements in the far field of the radiating source, most of those utilizing Greene's analysis have made this same conversion and equations 1 through 6 are usually found expressed in terms of the E field vector. With this conversion, equations 4 and 6 become

$$E(av) = E0(r1,r2,D)*FC(D,f) \qquad (7)$$

where

$$E0(r1,r2,D) = \frac{60\pi r1^2 I}{R^3} \qquad (8)$$

and FC(D,f) is given by equqtion 5 above.

III. Application to the Analysis of the Experimental Data

The transmitting antenna that is used in our loop antenna calibrations is a single turn loop antenna of 0.13315 meters radius. If this antenna is driven with a sinusoidal current of 100 milliamperes rms, the values of the H0 and E0 fields that are obtained from equations 6 and 8 for antenna separations of 1.4834, 1.8744 and 3.2025 meters are given in the following table. The values of the radii of the receiving antennas at these three calibration positions are assumed to be 0.130, 0.130 and 0.348 meters.

Table 1					
Pos. ////	Distance (meters)	Transmitting Loop radius	Receiving Loop radius	H0 (uA/m)	E0 (uV/m)
1	1.4834	0.13315 m.	0.130 m.	265.28	100008
2	1.8744	0.13315 m.	0.130 m.	132.64	50004
3	3.2025	0.13315 m.	0.318 m.	26.53	10000

The accuracy quoted for the radius of the transmitting antenna (one-hundreth of a millimeter) and for the separation between the two antennas (one-tenth of a millimeter) is considerably beyond the capabilities of our measuring capabilities. The loop antennas that are used in these types of measurements are not constructed with this type of precision nor can they be positioned with respect to one another to this degree of accuracy. Nevertheless, in the older Laboratory reports[3] (and in our current loop antenna calibration procedures), the radius of the transmitting loop antenna and the separations between the antennas at the three calibration positions are stated with this degree of precision. Undoubtedly this was originally done so that the calculated values of the E0 term became as close to 100,000, 50,000 and 10,000 uV/m at the three antenna positions as possible. (In actual practice, a more realistic value of 0.1332 meters should be used for the radius of the transmitting antenna and 1.483, 1.874 and 3.203 meters for the three antenna separations.)

Now as it was explained above, when an antenna is being calibrated at one of the three calibration positions, a geometrical correction factor should be used to account for the difference in the actual receiving antenna size and the assumed size of the antenna at that calibration position. Although this is not done in our present loop antenna calibration procedures, it will now be shown that this omission does not appear to cause any significant calibration error.

For purposes of illustration, it will be assumed that a 15 inch diameter loop antenna is being calibrated at positions 1 and 2 and a 35 inch diameter antenna at position 3. These two antennas were chosen as they are representative of the antennas which we frequently use in making field strength measurements. The electric field strength will be calculated from equation 8 at each of these three positions subject to the following conditions:

Case 1: the diameters of the receiving antennas are the ACTUAL DIAMETERS of the antennas that are being calibrated, that is, r2 = 7.5, 7.5 and 17.5 inches.

Case 2. the radii of the receiving antennas are the values of the ASSUMED RADII, that is, r2 = 0.130, 0.130 and 0.318 meters.

Case 3. the radii of receiving antennas at all three positions are ZERO, that is, r2 =0. (E0 is independent of r2.)

Case 4. in the denominator of equations 6 and 8, the radii of both the transmitting and receiving antennas are considered to be small compared to the separation between the two antennas and hence the value of R found from equation 2 is approximately equal to the antenna separation distance, D. (That is, in the denominator of equations 6 and 8 both r1 and r2 are zero.)

In the following table, the calculated value of the electric field strength is listed for each of the these four cases. For cases 2, 3 and 4 where simplifying asummptions have been made on the radii of the transmitting and receiving loop antennas, the error in dB that occurs because of these assumptions is listed in parentheses following the calculated values of the field strength.

Table 2

		E0(r1,r2,D) in uV/m and (Differences in dB)			
		Case 1	Case 2	Case 3	Case 4
Pos. ////	Dist. (m.)	r1=0.1332 r2(actual)	r1=0.1332 r2(assumed)	r1=0.1332 r2=0	r1=0 r2=0
1	1.483	98734	100008 (.1)	101154 (.2)	102378 (.3)
2	1.874	49601	50004 (.0)	50364 (.1)	50745 (.2)
3	3.203	9863	10000 (.1)	10148 (.2)	10175 (.3)

From the last column of this table it should be apparant that at the calibration distances that are being used, the R term in the denominator of equations 6 and 8 is not very sensitive to the value of the radii that are used for either the transmitting or receiving loop antenna and that the error in calculating the E or H field from equations 6 or 8 will be less than 0.3 dB for the calibration distances which we are using even for the extreme case where both r1 and r2 are considered to be zero iln the denominator of equations 6 and 8. Since the error in making this assumption is so small, Greene's equation can be simplified even further and written as

$$H(av) = \frac{r1^3\, I}{2\, D^3} \left(1+(\beta D)^2\right)^{1/2} \qquad (9)$$

where D is the separation between the two antennas. $\beta = (2\pi F(MHz)/300$ and F(MHz) is the frequency of the excitation current in megahertz.

As it might be expected, the equation that is obtained as a result of these approximations is the equation for the radial component of the magnetic field that is produced by a small loop antenna at a point along its axis, the diameter of the loop being small compared to the wavelength of the excitation current. A comparison of this simple loop antenna model and Greene's model is made in Table 3 for a 15 and a 35 inch diameter loop antenna for frequencies of 10 kHz, 150 kHz and 25 MHz. The agreement between the two models is excellent and for most frequencies and distances it is well within 0.3 dB and is within 1 dB for all of the frequencies and antenna separations considered. (It should be noted that the antenna separation of 1.66 meters where the 1 dB difference occurs for the larger antenna is far far closer to the source than this antenna would ever be in practice.)

The above analysis simply shows that along the antenna axis there is a full agreement between these two models. It does not mean that either model correctly decribes the behavior of the magnetic field even at points along the loop antenna's axis. What it does indicate though is that there is a good possibility that the simple loop model can be used to accurately characterize the behavior of the field at the lower frequencies and at the higher frequencies for cases where the antenna separation is not too great. However, this remains to be shown by a comparison with experimental data. And for cases where it can be shown, then the simple loop model can provide a means for extrapolating the emission limits in the Rules from the specified distances of 30 and 300 meters to distances of 3 and 10 meters where field strength measurements with these antennas are sometimes made.

IV. Analysis of the Experimental Data

In the previous quarter, measurements of the magnetic field strength were made on the openfield test sites using these three loop antennas:

1.	Empire	LG-105-A	35" diam	14 kHz -- 150 kHz
2.	Empire	LP-3-105	35" diam	150 kHz -- 12.7 MHz
3.	Stoddart	92200-3	15" diam	150 kHz -- 32 MHz

The field strength measurements were made at antenna separations from 1.7 to 21.8 meters. In some cases though because of ambient noise or equipment limitations, reliable field strength measurements could not be made out to the full distance of 21.8 meters.

Sets of typical data for the Empire LG-105-A and Stoddart 92200-3 antennas are shown in Tables 4 and 5. In the tables, the H field along the axis of the transmitting loop antenna is referred to as the radial field since the magnetic field along this axis is entirely radial and does not have an angular component. Likewise, the magnetic field at the receiving loop antenna, when the transmitting and receiving loops are positioned in a side-by-side configuration, is called the theta field, since the magnetic field does not have a radial component when the antennas are in this configuration. All of the measurements made on the open field test sites were made with the antennas in these two configurations. In Tables 4 and 5, these measurements are compared with the field strengths predicted by the simple loop antenna model.

For the data presented in these two tables it can be seen that there is very good agreement between the measured values of the radial H field using these two antennas and the theoretical values of the H field as predicted by the simple loop antenna model (equation 9). For the full set of data taken with these two antennas in the 10 kHz to 1 MHz frequency range, the agreement is within 1 dB for measurements made with the Empire LG-105-A antenna and 2 dB for measurements made with the Stoddart 92200-3 antenna. When the Empire LP-3-105 antenna was used, the agreement between the measured and theoretical values of the radial H field was also good for frequencies up to 880 kHz, but there are anomalies at 500 kHz that need to be further investigated.

For measurements made with the loop antennas in a side-by-side configuration, the agreement between the measured values of the H field and the theoretical values is not as good as when the antennas were in the radial configuration and decreases much more rapidly with increasing frequency and antenna separation. But for frequencies up to 1 MHz at least this should not pose any type of a measurement problem since in this frequency range the radial field is the dominant field and is at least 6 dB larger than the theta field for the largest antenna separations that are used (21.81 meters).

From the data gathered at this time, it seems that with our present measuring equipment, reliable magnetic field strength measurements can be made with single turn loop antennas of moderate size down to about about -5 dBuA/m. Using 120*pi (or 20*log(120*pi)=51.5 dB) for the conversion of uA/m to uV/m, this corresponds to an electric field strength of 200 uV/m or in terms of dB and dBm, an electric field intensity of 46 dBuV/m and -61 dBm. But as single turn loop antennas have antenna factors of 40 to 60 dB, the actual level of the signal that is being ultimately detected is -100 to -120 dBm.

For purposes of comparison, the general restricitons on the emissions from low power communication devices given in Section 15.111 of the Rules are shown in Table 6.

Table 6

Frequency	Distance (meters)	Field Strength (uV/m)
10 kHz to 490 kHz	300	2400/F(kHz)
510 kHz to 1.705 MHz	30	24000/F(kHz)

Above 1.705 MHz, the field strength limits are vague, but in Section 15.114 of the Rules there are limits of 10 and 15 uV/m at 30 meters for emissions from devices operating in the 1705 kHz to 10 MHz range.

The emission limits in Table 6 are below the limits of detectability of our loop antennas and field strength meters when the emissions are being measured at the specified distances of 300 and 30 meters. However, where it can be shown that the magnetic field strength falls off in an inverse cubic fashion as indicated by equation 9, then radiated emission measurements on these frequencies can be made at distances which are closer than those specified in Table 6. If this is done, then the emission limits at the new measurement distance must be increased accordingly. For example, if the measurement distance is decreased by a factor of 10, the emission limits at this distance will be 1000 times larger than those listed in Table 6, or 27 times larger if the distance is decreased by a factor of 3. Emissions at these levels will be sufficiently robust so that they can be accurately measured with our present equipment. However a more extended analysis of the data and comparison with the theoretical models needs to be performed, before measurements can be legitimately made at any distances that are different than those specified in the Rules.

TABLE 3

A COMPARISON OF THE SIMPLE LOOP ANTENNA MODEL
AND GREENE'S MODEL

FOR A 15 INCH DIAMETER RECEIVING ANTENNA

Dist.	Magnetic Field Intensity (dBuA/m) 10 kHz		150 kHz		25 MHz	
meters	Loop Model	Greene	Loop Model	Greene	Loop Model	Greene
1.66	45.8	45.5	45.8	45.5	48.2	47.9
3.30	27.8	27.8	27.8	27.8	33.9	33.8
4.99	17.1	17.0	17.1	17.0	26.0	26.0
6.44	10.4	10.4	10.4	10.4	21.4	21.3
9.43	0.5	0.5	0.5	0.5	14.5	14.5
12.46	-6.8	-6.8	-6.8	-6.8	9.6	9.6
15.46	-12.4	-12.4	-12.4	-12.4	5.8	5.8
18.60	-17.2	-17.2	-17.2	-17.2	2.6	2.6
21.81	-21.4	-21.4	-21.3	-21.3	-0.2	-0.2

FOR A 35 INCH DIAMETER RECEIVING ANTENNA

Dist.	Magnetic Field Intensity (dBuA/m) 10 kHz		150 kHz		25 MHz	
meters	Loop Model	Greene	Loop Model	Greene	Loop Model	Greene
1.66	45.8	44.8	45.8	44.8	48.2	47.2
3.30	27.8	27.6	27.8	27.6	33.9	33.6
4.99	17.1	17.0	17.1	17.0	26.0	25.9
6.44	10.4	10.4	10.4	10.4	21.4	21.3
9.43	0.5	0.5	0.5	0.5	14.5	14.5
12.46	-6.8	-6.8	-6.8	-6.8	9.6	9.6
15.46	-12.4	-12.4	-12.4	-12.4	5.8	5.8
18.60	-17.2	-17.2	-17.2	-17.2	2.6	2.6
21.81	-21.4	-21.4	-21.3	-21.3	-0.2	-0.2

TABLE 4:

OPEN FIELD TEST SITE MEASUREMENT DATA

Empire LG-105-A
35 inch diameter loop antenna
15 kHz to 150 kHz

Frequency: 15 kHz

Antenna Separation	Antenna Factor	Magnetic Field Intensity: Radial Theor.	Radial Meas.	Radial Diff.	Theta Theor.	Theta Meas.	Theta Diff.
meters	dB	dBuA/m	dBuA/m	dB	dBuA/m	dBuA/m	dB
1.66	59.0	45.7	45.5	0.2	39.7	40.5	-0.8
3.30	59.0	27.8	27.5	0.3	21.8	21.5	0.3
4.99	59.0	17.0	17.0	0.0	11.0	11.5	-0.5
6.44	59.0	10.4	10.5	-0.1	4.4	4.0	0.4
9.43	59.0	0.5	0.5	-0.0	-5.6	-5.0	-0.6
12.46	59.0	-6.8	-6.5	-0.3	-12.8	-7.0	-5.8

Frequency: 82 kHz

Antenna Separation	Antenna Factor	Magnetic Field Intensity: Radial Theor.	Radial Meas.	Radial Diff.	Theta Theor.	Theta Meas.	Theta Diff.
meters	dB	dBuA/m	dBuA/m	dB	dBuA/m	dBuA/m	dB
1.66	50.0	45.7	45.0	0.7	39.7	39.5	0.2
3.30	50.0	27.8	28.5	-0.7	21.8	21.5	0.3
4.99	50.0	17.0	17.5	-0.5	11.0	10.5	0.5
6.44	50.0	10.4	11.0	-0.6	4.4	4.5	-0.1
9.43	50.0	0.5	0.5	-0.0	-5.6	-4.5	-1.1
12.46	50.0	-6.8	-7.5	0.7	-12.8	-9.5	-3.3
15.46	50.0	-12.4	-13.0	0.6	-18.4	-12.5	-5.9
18.60	50.0	-17.2	-17.5	0.3	-23.3	-16.0	-7.3

Frequency: 150 kHz

Antenna Separation	Antenna Factor	Magnetic Field Intensity					
		Radial Theor.	Radial Meas.	Radial Diff.	Theta Theor.	Theta Meas.	Theta Diff.
meters	dB	dBuA/m	dBuA/m	dB	dBuA/m	dBuA/m	dB
1.66	50.0	45.7	45.5	0.2	39.7	42.0	-2.3
3.30	50.0	27.8	28.0	-0.2	21.8	23.0	-1.2
4.99	50.0	17.0	17.5	-0.5	11.0	12.0	-1.0
6.44	50.0	10.4	10.5	-0.1	4.4	6.0	-1.6
9.43	50.0	0.5	0.5	-0.0	-5.6	-2.5	-3.1
12.46	50.0	-6.8	-7.0	0.2	-12.8	-7.5	-5.3
15.46	50.0	-12.4	-12.5	0.1	-18.4	-10.5	-7.9

1. The H field in microamperes per meter is calculated from the measured FIM value by summing the antenna factor in dB and the FIM value in dBm and then adding 55.5 dB to the the sum. [55.5 dB is 107 dB - 20*Log(120*pi)].

2. The theoretical values listed in the third and sixth columns of the table are obtained from the simple single turn loop antenna model.

TABLE 5:

OPEN FIELD TEST SITE MEASUREMENT DATA

Stoddart Loop 92200-3
15 inch diameter loop antenna
150 kHz to 30 MHz

Frequency: 150 kHz

Antenna Separation	Antenna Factor	Magnetic Field Intensity: Radial Theor.	Radial Meas.	Radial Diff.	Theta Theor.	Theta Meas.	Theta Diff.
meters	dB	dBuA/m	dBuA/m	dB	dBuA/m	dBuA/m	dB
1.66	60.0	45.7	43.5	2.2	39.7	38.5	1.2
3.30	60.0	27.8	26.5	1.3	21.8	20.5	1.3
4.99	60.0	17.0	15.5	1.5	11.0	10.5	0.5
6.44	60.0	10.4	8.5	1.9	4.4	4.0	0.4
9.43	60.0	0.5	-1.5	2.0	-5.6	-4.0	-1.6
12.46	60.0	-6.8	-8.5	1.7	-12.8	-8.0	-4.8

Frequency: 500 kHz

Antenna Separation	Antenna Factor	Magnetic Field Intensity: Radial Theor.	Radial Meas.	Radial Diff.	Theta Theor.	Theta Meas.	Theta Diff.
meters	dB	dBuA/m	dBuA/m	dB	dBuA/m	dBuA/m	dB
1.66	55.5	45.7	46.5	-0.8	39.7	41.5	-1.8
3.30	55.5	27.8	29.0	-1.2	21.8	20.5	1.3
4.99	55.5	17.1	18.0	-0.9	11.0	13.0	-2.0
6.44	55.5	10.4	11.5	-1.1	4.4	7.5	-3.1
9.43	55.5	0.5	1.5	-1.0	-5.6	1.5	-7.1
12.46	55.5	-6.7	-6.0	-0.7	-12.9	-3.0	-9.9
15.46	55.5	-12.3	-11.0	-1.3	-18.6	-4.0	-14.6

Frequency: 1 MHz

Antenna Separation	Antenna Factor	Radial Theor.	Radial Meas.	Radial Diff.	Theta Theor.	Theta Meas.	Theta Diff.
meters	dB	dBuA/m	dBuA/m	dB	dBuA/m	dBuA/m	dB
1.66	51.5	45.7	45.0	0.7	39.7	40.0	-0.3
3.30	51.5	27.8	27.0	0.8	21.8	22.0	-0.2
4.99	51.5	17.1	16.5	0.6	11.0	12.0	-1.0
6.44	51.5	10.5	9.5	1.0	4.3	7.0	-2.7
9.43	51.5	0.6	0.0	0.6	-5.7	3.5	-9.2
12.46	51.5	-6.5	-7.0	0.5	-13.1	-1.5	-11.6

(Columns 3–8: Magnetic Field Intensity)

1. The H field in microamperes per meter is calculated from the measured FIM value by summing the antenna factor in dB and the FIM value in dBm and then adding 55.5 dB to the the sum. [55.5 dB is 107 dB - 20*Log(120*pi)].

2. The theoretical values listed in the third and sixth columns of the table are obtained from the simple single turn loop antenna model.

REFERENCES for PART 5

1. F. M. Greene, The Near-Zone Magnetic Field of a Small Circular-Loop Antenna, NBS Journ. Res., Vol 71C, No. 4, pgs 319-326, October/December 1967

2. H. E. Taggart and J. L. Workman, Calibration Principles and Procedures for Field Strength Meters (30 Hz to 1 GHz), NBS Technical Note 370, National Bureau of Standards, Boulder, Colorado, March 1969

3. From work done in October 1962 by K. L. Leidy at the FCC Laboratory in Columbia, Maryland

The Measurement of Radiated Emissions on Frequencies below 30 MHz Using Loop Antennas

Materials for the ANSI C63 Committee
Part 6: Open Field Measurements using Intentional Radiators*

I. Producing the Fields to be Measured

During this quarter, measurements of the magnetic field intensity as a function of distance were made outdoors on the Laboratory's open field test site at frequencies from 10 kHz to 25 MHz. A single turn loop antenna of 0.133 meters radius was used to produce the magnetic field. This antenna is a duplicate of the antenna which is used by both the FCC and the National Bureau of Standards for the calibration of loop antennas.

For most of the measurements, the transmitting loop antenna was driven with a 100 ma (rms) sinusoidal signal. For frequencies above 50 kHz, the signal was obtained from a Hewlett-Packard 606A signal generator; for frequencies below 50 kHz, a Hewlett-Packard 651B signal generator was used. At 25 MHz, the HP 606A signal generator was unable to deliver a 100 ma signal to the transmitting antenna and so at this frequency, the antenna current was adjusted to 80 ma (rms) and 2 dB was added to the measured values of the field intensities. (For a linear antenna, the field at any point in space is proportional to the magnitude of the transmitter current that is producing the field. Hence, the field at a point in space due to a 100 mA tranmsmitting antenna current will be 1.25 times (or 1.93 db) that which is produced by an 80 mA antenna current.)

The HP 606A signal generator has a signal modulation capability. On all frequencies where this signal generator was used, the output signal was amplitude modulated with a 400 Hz audible tone at a 25% modulation level. This was done to assist in detecting the desired signal and to help screen out any undesired interfering ambient signals. The modulation was kept on while the measurements were being made as it effected the measurements by only a fraction of a dB.

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* Compiled from work done in December 1987 by Joseph Mc Nulty at the FCC Laboratory in Columbia, Maryland

II. The Measurement of the Magnetic Fields

The receiving antennas that were used in making these measurement are listed in the following table.

Manufacturer	Model Number	Operational Frequency Range	Diameter (inches)
Empire	LG-105-A	14 kHz to 150 kHz	36
Empire	LP-3-105	150 kHz to 12.7 MHz	36
Stoddart	92200-3	150 kHz to 32 MHz	15

For measurements where the Stoddart 92200-3 antenna was used, both the transmitting and the receiving antenna were mounted with their centers 1.2 meters above ground. For measurements made with the Empire LG-105-A and LP-3-105 antennas, the transmitting and the receiving antenna were mounted with their centers 1.5 meters above ground.

The field intensity measurements were made for several different transmitting and receiving antenna separations ranging from a close distance of 1.7 meters to a far distance of 21.8 meters. At each antenna separation, one set of field intensity measurements was made with the antennas facing one another, with the planes containing the antenna loops parallel to one another. A second set of measurements at this distance was also made except with the antennas rotated 90 degrees so that the antennas were in a side-by-side configuration. These two measurement configurations were chosen because simple theoretical considerations show that in the near antenna field there should be a 6 dB difference in the value of the magnetic field that is measured with these antenna placements. As an additional control check on the data, measurements were also made in these two antenna configurations with the transmitting antenna rotated through an angle of 45 degrees. As rotating a transmitting loop antenna through any arbitrary angle will change the angle at which the magnetic flux intercepts a receiving loop antenna by the same amount, then rotating the transmitting antenna by 45 degrees will decrease the received signal by 20*log(Cos(45)) or 3 dB.

All of the field intensity measurements were made using a Stoddart NM-17/27 Field Intensity Meter (FIM). But as the Laboratory has only one of these Field Intensity Meters and it is currently being shared by four different Laboratory groups, the scheduling of this instrument proved to be a problem. Fortunately, the Field Operations Bureau did have an NM-17/27 FIM at the Laboratory which was awaiting the repair of its damaged case. They generously allowed us the use of this instrument until the present set of measurements were completed. However, the total amount of data that could be taken was limited both by the equipment scheduling diffficulties which were initially encountered and by the weather.

III. The Presentation and Analysis of the Data

The measured values of the magnetic field intensity for the three receiving loop antennas are listed in Tables 1 through 3. In these Tables, the field intensity meter readings have been adjusted with the appropriate antenna factors and converted to field intensities. The antenna factors that were used to adjust the data are the ones that were measured for these antennas earlier in this project for antenna separations of 3.2 meters. In the Tables, the values of the magnetic field intensity have been listed rather than the values of the electric field intensity as is usually done since in these measurements, the magnetic field intensity is the meaningful quantity. If the value of the pseudo electric field intensity is required, it can be readily obtained from the magnetic field intensity values by simply adding 51.5 dB to all of the magnetic field intensity values. (51.5 dB = 20*log{120*pi}.)

There was insufficient time in this quarter to obtain all of the data that is needed for a full analysis of the measurements made with these antennas. No measurements at all were made with the large Singer 94593-1 square loop antenna or with the small Empire LP-105 circular loop antenna. However, since the 11.5 inch Empire LP-105 antenna covers the same frequency range as the 15 inch Stoddart 92200-3 antenna, and in past measurements both of these two antennas had very similiar performances, the lack of any extensive data for this antenna should not affect the analysis. However, the large square Singer 94593-1 antenna is much different in design than any of our other loop antennas and it also is the only loop antenna that we have that has been designed to operate over the entire frequency range from 10 kHz to 32 MHz. Data on this antenna is important for the analysis.

Although time did not allow for anything more than a cursory analysis of the measured data at this point, nevertheless from a brief preliminary analysis of the data, the following tentative conclusions can be made:

1. the simple model of the radiation produced by a single turn loop antenna, whose diameter is small in comparison to its wavelength, appears to be sufficient to accurately predict both the values of the magnetic field that were measured and their falloff with distance.

2. the antenna factors that are measured in the closed, tight geometry of the loop calibration building can be used to convert field intensity meter reading into true values of the magnetic field intensity at distances up to 72 feet from the radiation source.

3. at least one of our loop antennas may not be usable throughout its entire range. Although the Empire LP-3-105 antenna is designed to operate over the 150 kHz to 12.7 MHz frequency range, it has a somewhat anomalous behavior at 12.7 MHz and the readings made at this frequency may be 7 dB too high.

IV. Measurement Difficulties

As more familiarity was gained with the measurements made on the open field test site, several questions arose concerning the behavior of the instrumentation and the resulting accuracy and meaning of the measurement data. Some of the observations that have been made are:

1. the accuracy with which field intensity readings can be made with the NM 17/27 should be determined. The field intensity measurements made with this instrument are dependent upon the input attenuator setting and can vary by as much as 2 db. There were also differences of 2 dB in the readings that were made with the Laboratory's NM 17/27 and FOB's 17/27.

2. the measurement limits of the NM 17/27 is -147 dbm yet the limits of detectability observed in these measurements was approximately -115 dbM. Apparently, a better knowledge of the ambient signals and their effect on the NM 17/27 is needed. Only in this way can we understand the true limits of the measurements that are being made with this instrument.

3. A 1 kHz IF filter was used on frequencies below 1 MHz and a 10 kHz filter on frequencies above 1 MHz. It was expected that such tight filtering would have improved the interference rejection of the NM 17/27 considerably. Yet, interfering signals arising outside of the these bandwidths were apparently still getting through.

Before any meaningful and useful measurement procedure for the measurement of radiated emissions on frequencies below 30 MHz can be drawn up, a much better knowledge of our instrumentation should be obtained and satisfactory answers to these questions found.

V. Conclusions and Further Work

Although several important but tentative conclusions were able to be made on the basis of the work done in this project up to this time, it should be emphasized that our knowledge of the behavior of loop antennas is still incomplete and further work is needed before an adequate and meaningful measurement procedure can be drafted for the measurement of radiated emissions on frequencies below 30 MHz. The following areas of investigation still remain:

1. the accuracy with which we can make these measurements should be determined. This includes determining the reproducibility of the measurements when different measurent scales are used on the same instrument as well as the reproducility of the measurements when different field intensity meters are used,

2. the open site measurements should be automated if possible,

3. measurements should be made using the large square loop Singer 94593-1 antenna throughout the entire 10 kHz to 30 MHz frequency range and the behavior of this antenna should be determined,
4. a better knowledge of the instrumentation that is used in these measurements should be obtained and the effect of the instrumentation on the measurements determined,
5. a certain amount of monitoring and measurements of the ambient signals should be done and the information documented. (A useful measurement procedure cannot be drawn up without this information.), and,
6. whether the falloff of the magnetic field with distance follows a simple theoretical model needs to be ascertained. If it does not, then the falloff will have to be empirically determined.

All of this work is needed and desirable. However, not all of it is has to be done before a useful and meaningful measurement procedure can be drafted.

TABLE 1

OPEN FIELD TEST SITE MEASUREMENT DATA

Empire LG-105-A
35 inch diameter loop antenna
15 kHz to 150 kHz

Frequency	Antenna Separation	Antenna Factor	FIM Values Radial	FIM Values Theta	H Field Values Radial	H Field Values Theta
/////////	meters	dB	dBm	dBm	dBuA/m	dBuA/m
15 kHz	1.66	59.0	-69.0	-74.0	45.5	40.5
	3.30	59.0	-87.0	-93.0	27.5	21.5
	4.99	59.0	-97.5	-103.0	17.0	11.5
	6.44	59.0	-104.0	-110.5	10.5	4.0
	9.43	59.0	-114.0	-119.5	0.5	-5.0
	12.46	59.0	-121.0	-121.5	-6.5	-7.0
30 kHz	1.66	54.3	-64.5	-68.5	45.3	41.3
	3.30	54.3	-81.0	-87.0	28.8	22.8
	4.99	54.3	-92.5	-98.0	17.3	11.8
	6.44	54.3	-99.0	-105.0	10.8	4.8
	9.43	54.3	-109.0	-115.0	0.8	-5.2
	12.46	54.3	-116.0	-121.5	-6.2	-11.7
	15.46	54.3	-121.5	-126.5	-11.7	-16.7
	18.60	54.3	-126.5	-130.0	-16.7	-20.2
50 kHz	1.66	51.2	-62.0	-66.0	44.7	40.7
	3.30	51.2	-79.0	-84.5	27.7	22.2
	4.99	51.2	-90.5	-96.0	16.2	10.7
	6.44	51.2	-96.5	-102.0	10.2	4.7
	9.43	51.2	-107.0	-111.0	-0.3	-4.3

82 kHz	1.66	50.0	-60.5	-66.0	45.0	39.5
	3.30	50.0	-77.0	-84.0	28.5	21.5
	4.99	50.0	-88.0	-95.0	17.5	10.5
	6.44	50.0	-94.5	-101.0	11.0	4.5
	9.43	50.0	-105.0	-110.0	0.5	-4.5
	12.46	50.0	-113.0	-115.0	-7.5	-9.5
	15.46	50.0	-118.5	-118.0	-13.0	-12.5
	18.60	50.0	-123.0	-121.5	-17.5	-16.0
100 kHz	1.66	50.0	-60.0	-64.0	45.5	41.5
	3.30	50.0	-77.0	-82.0	28.5	23.5
	4.99	50.0	-88.0	-93.5	17.5	12.0
	6.44	50.0	-94.5	-99.5	11.0	6.0
	9.43	50.0	-104.0	-107.0	1.5	-1.5
120 kHz	1.66	50.0	-59.5	-65.0	46.0	40.5
	3.30	50.0	-77.0	-82.5	28.5	23.0
	4.99	50.0	-88.0	-93.0	17.5	12.5
	6.44	50.0	-94.5	-100.0	11.0	5.5
	9.43	50.0	-104.5	-108.5	1.0	-3.0
	12.46	50.0	-112.5	-113.5	-7.0	-8.0
	15.46	50.0	-118.0	-116.5	-12.5	-11.0
150 kHz	1.66	50.0	-60.0	-63.5	45.5	42.0
	3.30	50.0	-77.5	-82.5	28.0	23.0
	4.99	50.0	-88.0	-93.5	17.5	12.0
	6.44	50.0	-95.0	-99.5	10.5	6.0
	9.43	50.0	-105.0	-108.0	0.5	-2.5
	12.46	50.0	-112.5	-113.0	-7.0	-7.5
	15.46	50.0	-118.0	-116.0	-12.5	-10.5

NOTES:

1. The H field in microamperes per meter is calculated from the measured FIM value by summing the antenna factor in dB and the FIM value in dBm and then adding 55.5 dB to the sum. [55.5 dB is 107 dB - 20*Log(120*pi)].

TABLE 2

OPEN FIELD TEST SITE MEASUREMENT DATA

Empire LP-3-105
35 inch diameter loop antenna
150 kHz to 12.7 MHz

Frequency	Antenna Separation	Antenna Factor	FIM Values Radial	FIM Values Theta	H Field Values Radial	H Field Values Theta
/////////	meters	dB	dBm	dBm	dBuA/m	dBuA/m
150 kHz	1.66	45.9	-56.0	-60.5	45.4	40.9
	3.30	45.9	-75.5	-79.0	25.9	22.4
	4.99	45.9	-84.0	-90.0	17.4	11.4
	6.44	45.9	-91.0	-96.0	10.4	5.4
	9.43	45.9	-101.0	-104.5	0.4	-3.1
	12.46	45.9	-109.0	-109.5	-7.6	-8.1
	15.46	45.9	-114.5	-112.5	-13.1	-11.1
500 kHz	1.66	41.2	-57.0	-58.0	39.7	38.7
	3.30	41.2	-74.0	-76.0	22.7	20.7
	4.99	41.2	-85.0	-87.0	11.7	9.7
	6.44	41.2	-91.0	-92.5	5.7	4.2
	9.43	41.2	-101.0	-99.5	-4.3	-2.8
	12.46	41.2	-108.0	-103.0	-11.3	-6.3
	15.46	41.2	-113.0	-105.5	-16.3	-8.8
	18.60	41.2	-117.0	-109.0	-20.3	-12.3
	21.81	41.2	-120.0	-113.0	-23.3	-16.3
880 kHz	1.66	40.8	-49.5	-55.0	46.8	41.3
	3.30	40.8	-67.0	-74.0	29.3	22.3
	4.99	40.8	-79.0	-84.0	17.3	12.3
	6.44	40.8	-86.0	-90.0	10.3	6.3
	9.43	40.8	-96.0	-96.0	0.3	0.3
	12.46	40.8	-102.5	-99.5	-6.2	-3.2
	15.46	40.8	-108.0	-103.0	-11.7	-6.7
	18.60	40.8	-112.0	-108.0	-15.7	-11.7
	21.81	40.8	-115.0	-113.0	-18.7	-16.7

1 MHz	1.66	40.8	-50.5	-52.0	45.8	44.3
	3.30	40.8	-67.5	-70.0	28.8	26.3
	4.99	40.8	-78.5	-80.5	17.8	15.8
	6.44	40.8	-85.0	-86.0	11.3	10.3
	9.43	40.8	-92.5	-92.0	3.8	4.3
	12.46	40.8	-99.0	-96.0	-2.7	0.3
	15.46	40.8	-104.0	-99.0	-7.7	-2.7
	18.60	40.8	-108.0	-105.0	-11.7	-8.7
	21.81	40.8	-111.0	-111.0	-14.7	-14.7
5 MHz	1.66	31.3	-40.0	-45.0	46.8	41.8
	3.30	31.3	-57.0	-62.5	29.8	24.3
	4.99	31.3	-67.0	-73.0	19.8	13.8
	6.44	31.3	-72.0	-77.5	14.8	9.3
	9.43	31.3	-77.5	-86.0	9.3	0.8
	12.46	31.3	-82.0	-90.0	4.8	-3.2
	15.46	31.3	-88.0	-92.0	-1.2	-5.2
	18.60	31.3	-92.0	-93.0	-5.2	-6.2
	21.81	31.3	-95.0	-94.0	-8.2	-7.2
10 MHz	1.66	28.1	-39.5	-45.5	44.1	38.1
	3.30	28.1	-56.0	-62.0	27.6	21.6
	4.99	28.1	-63.0	-69.0	20.6	14.6
	6.44	28.1	-67.5	-72.0	16.1	11.6
	9.43	28.1	-75.0	-76.0	8.6	7.6
	12.46	28.1	-79.5	-78.5	4.1	5.1
	15.46	28.1	-83.5	-80.0	0.1	3.6
	18.60	28.1	-87.0	-82.0	-3.4	1.6
	21.81	28.1	-90.0	-83.5	-6.4	0.1
12.7 MHz	1.66	30.3	-38.0	-42.5	47.8	43.3
	3.30	30.3	-53.0	-58.0	32.8	27.8
	4.99	30.3	-60.5	-64.0	25.3	21.8
	6.44	30.3	-65.0	-66.5	20.8	19.3
	9.43	30.3	-70.5	-69.0	15.3	16.8
	12.46	30.3	-75.5	-72.0	10.3	13.8
	15.46	30.3	-79.0	-74.0	6.8	11.8
	18.60	30.3	-82.0	-76.0	3.8	9.8
	21.81	30.3	-85.0	-77.5	0.8	8.3

NOTES:

1. The H field in microamperes per meter is calculated from the measured FIM value by summing the antenna factor in dB and the FIM value in dBm and then adding 55.5 dB to the sum. [55.5 dB is 107 dB - 20*Log(120*pi)].

TABLE 3

OPEN FIELD TEST SITE MEASUREMENT DATA

Stoddart Loop 92200-3
15 inch diameter loop antenna
150 kHz to 30 MHz

Frequency	Antenna Separation	Antenna Factor	FIM Values Radial	FIM Values Theta	H Field Values Radial	H Field Values Theta
/////////	meters	dB	dBm	dBm	dBuA/m	dBuA/m
150 kHz	1.66	60.0	-72.0	-77.0	43.5	38.5
	3.30	60.0	-89.0	-95.0	26.5	20.5
	4.99	60.0	-100.0	-105.0	15.5	10.5
	6.44	60.0	-107.0	-111.5	8.5	4.0
	9.43	60.0	-117.0	-119.5	-1.5	-4.0
	12.46	60.0	-124.0	-123.5	-8.5	-8.0
500 kHz	1.66	55.5	-64.5	-69.5	46.5	41.5
	3.30	55.5	-82.0	-90.5	29.0	20.5
	4.99	55.5	-93.0	-98.0	18.0	13.0
	6.44	55.5	-99.5	-103.5	11.5	7.5
	9.43	55.5	-109.5	-109.5	1.5	1.5
	12.46	55.5	-117.0	-114.0	-6.0	-3.0
	15.46	55.5	-122.0	-115.0	-11.0	-4.0
1 MHz	1.66	51.5	-62.0	-67.0	45.0	40.0
	3.30	51.5	-80.0	-85.0	27.0	22.0
	4.99	51.5	-90.5	-95.0	16.5	12.0
	6.44	51.5	-97.5	-100.0	9.5	7.0
	9.43	51.5	-107.0	-103.5	0.0	3.5
	12.46	51.5	-114.0	-108.5	-7.0	-1.5

5 MHz	1.66	41.0	-51.0	-57.0	45.5	39.5
	3.30	41.0	-69.0	-74.5	27.5	22.0
	4.99	41.0	-79.0	-83.5	17.5	13.0
	6.44	41.0	-83.0	-89.0	13.5	7.5
	9.43	41.0	-88.5	-97.5	8.0	-1.0
	12.46	41.0	-94.0	-100.0	2.5	-3.5
	15.46	41.0	-100.0	-103.0	-3.5	-6.5
	18.60	41.0	-104.0	-105.0	-7.5	-8.5
	21.81	41.0	-106.5	-106.5	-10.0	-10.0
10 MHz	1.66	37.6	-48.0	-56.0	45.1	37.1
	3.30	37.6	-64.0	-71.0	29.1	22.1
	4.99	37.6	-71.0	-78.5	22.1	14.6
	6.44	37.6	-76.0	-81.0	17.1	12.1
	9.43	37.6	-82.0	-82.5	11.1	10.6
	12.46	37.6	-86.5	-85.0	6.6	8.1
	15.46	37.6	-91.0	-87.0	2.1	6.1
	18.60	37.6	-95.0	-88.5	-1.9	4.6
	21.81	37.6	-97.5	-90.0	-4.4	3.1
15 MHz	1.66	37.2	-47.0	-53.0	45.7	39.7
	3.30	37.2	-61.5	-66.5	31.2	26.2
	4.99	37.2	-68.5	-71.0	24.2	21.7
	6.44	37.2	-73.0	-73.5	19.7	19.2
	9.43	37.2	-79.5	-77.0	13.2	15.7
	12.46	37.2	-85.0	-80.0	7.7	12.7
	15.46	37.2	-89.0	-81.5	3.7	11.2
	18.60	37.2	-93.0	-83.5	-0.3	9.2
	21.81	37.2	-96.0	-86.0	-3.3	6.7
20 MHz	1.66	31.5	-42.5	-47.0	44.5	40.0
	3.30	31.5	-57.0	-57.5	30.0	29.5
	4.99	31.5	-63.5	-61.0	23.5	26.0
	6.44	31.5	-66.5	-63.5	20.5	23.5
	9.43	31.5	-77.0	-68.0	10.0	19.0
	12.46	31.5	-82.0	-71.5	5.0	15.5
	15.46	31.5	-85.5	-74.0	1.5	13.0
	18.60	31.5	-89.5	-76.5	-2.5	10.5
	21.81	31.5	-92.5	-78.0	-5.5	9.0

25 MHz	1.66	29.8	-42.0	-47.0	43.3	38.3
	3.30	29.8	-54.5	-55.5	30.8	29.8
	4.99	29.8	-61.5	-59.0	23.8	26.3
	6.44	29.8	-66.0	-61.0	19.3	24.3
	9.43	29.8	-71.5	-64.5	13.8	20.8
	12.46	29.8	-76.0	-66.5	9.3	18.8
	15.46	29.8	-80.0	-68.5	5.3	16.8
	18.60	29.8	-84.0	-70.5	1.3	14.8
	21.81	29.8	-86.5	-72.5	-1.2	12.8

NOTES:

1. The H field in microamperes per meter is calculated from the measured FIM value by summing the antenna factor in dB and the FIM value in dBm and then adding 55.5 dB to the sum. [55.5 dB is 107 dB - 20*Log(120*pi)].

The Measurement of Radiated Emissions
on Frequencies below 30 MHz
Using Loop Antennas

Materials for the ANSI C63 Committee
Part 7: Open Field Measurements Using Unintentional Radiators*

I. Introduction

A procedure for the measurement of radiated emissions on frequencies below 30 MHz was completed in the previous quarter and submitted to the Bureau Chief for review. The measurement procedure builds upon the calibration proceures and measurement techniques using loop antennas that are presently used by the Commission, NBS and industry. It also builds upon the analytical and experimental work that was performed in the previous phases of this project, work which has provided us with a much better understanding of these measurements.

However, before the measurement procedure can be submitted to the public for comments, three things should be done to ensure its adequacy and completeness:

1. the procedure should be reviewed by persons within the Division who have made sufficient radiated measurements using loop antennas to be familiar with some of the problems involved in making these types of measurements,

2. one of the Laboratory's technicians or engineers should test the procedure for its completeness and adequacy by making radiated measurements on frequencies below 30 MHz with loop antennas using only the measurement procedure as their guide,

3. measurements of the radiations emitted from selected EUTs under actual test conditions have to be made to ensure that consistent and reproducible measurements can be made with loop antennas that cover the same frequency range but are of different physical size, and,

* Compiled from work done in December 1988 by Joseph Mc Nulty at the FCC Laboratory in Columbia, Maryland

4. measurements of the radiations emitted from selected EUTs have to be made at various source and antenna separations to ensure that measurements made at 3 or 10 meter distances from the EUT can be validly extrapolated to the distances of 30, 300 and 1600 meters that are specified in some portions of the Rules.

The implemention of this program was begun this quarter. The initial results of this implementation are reported here.

II. Circulation for Review

Several persons within the Division who have had extensive experience making radiated measurements on frequencies below 30 MHz using loop antennas were asked to review the measurement procedure and provide their comments. A summary of the comments that were supplied follows:

a) some stipulation should be made as to the maximum size of the EUT that can be measured with this test procedure. Telepanel's new supermarket pricing system which was recently submitted for certification is so large that it can only be measured in situ.

b) How do you define the boundaries of a device such as the Telepane system which does not have a fixed geometry but varies with the layout of each store? How do you define the EUT-antenna separation distance for such a device?

c) In Section 4.0 of the measurement procedure, it is stipulated that "the electrical power lines to the test site should be buried". However, the effect that cables buried close to the surface have on our measurements has apparantly never been determined even though statments attributed to the former Lab Chief assert that buried cables will have a large effect upon the measurements. Consequently, should a minimum depth for buried cables be specified in the measurement procedure and by what means shall this minimum depth be determined?

d) Although the measurement distances and antenna height variations are clearly spelled out in Sections 5.03 and 5.04 of the measurement procedure, they should be specified again in Section 9.02 where the steps in the test procedure are listed. Persons who are testing an EUT on an open area site, and are carrying out the measurements using the test procedure of Section 9.02, may have skipped over or missed important details such as this in the earlier sections of the measurement procedure. Hence, the test procedure in Section 9.02 should be made as much of a self-contained unit as possible, even though this will create some redundancy within the measurement procedure as a whole.

III. RF Sources for Use in Open-Site Measurements

A search was made for equipment and devices that radiated emissions on frequencies below 30 MHz. Three such pieces of equipment were found:

1. rf light bulbs (fundamental frequencies of 33 and 50 kHz),

2. a small portable Hitachi monochrome TV (fundamental frequency of 15.7 kHz), and,

3. a breadboard oscillator circuit (fundamental frequency of 6.8 MHz)

Several GE and Phillips rf light bulbs that had been submitted to the Laboratory for testing were available for our use. Emissions from these devices up to the tenth harmonic of their operating frequency could be observed when they were placed immediately adjacent to a loop antenna. However, because of the rapid falloff of the fields at these distances and frequencies, these same emissions could not be detected when the distance between the light bulb and the antenna was increased to 3 meters. Consequently, these lighting devices could not be used by us as radiation sources.

The rf light bulbs that we looked at gave off slightly higher levels of radiation during their brief warmup periods, (approx. 1 min.). They may (or may not) also give off significant amounts of radiation during their end of life phase. However, these were not areas of our concern. And although it appears from this study that these particular light bulbs do not radiate sufficient amounts of radiation in their normal operating mode to interfere with other communications devices, no definitive investigation of the interference potential of these devices was made here and consequently no interpretation to that effect should be made on the basis of this report.

All TV receivers emit strong radiations on the fundamental and harmonics of their horizontal line sweep frequency, 15.7 kHz. With some TV sets, these radiations can be observed and detected up to the 10th harmonic of the line sweep frequency. The line sweep frequency emissions from a small Hitachi portable TV set were easily detected when a loop antenna was positioned 3 meters from the set. Consequently, this TV set was able to serve as a satisfactory source of low frequency radiation.

Radiations from the breadboard oscillator circuit were observable and measurable up to the 4th harmonic of the oscillator's designed frequency. This too served as a satisfactory radiation source.

IV. Testing the Measurement Procedure on an Open Field Test Site

Following the measurement procedure exactly, the Branch's technician made several sets of measurements on the Laboratory,s open field test site of the emissions radiating from the Hitachi TV set and the breadboard oscillator circuit. The purpose of these measurements was to ascertain whether the

measurement procedure is complete and whether it can be understood and followed by a person with adequate technical ability but with little previous experience in making measurements with loop antennas.
The technician found no difficulty in understanding and following the test procedure. However, he did suggest that the measurement distances and antenna height variations be spelled out again in Section 9.02 of the measurement procedure where the steps in the test procedure are listed. He suggested this because he initially tried to position the antennas at distances and heights where he was accustomed to position the antennas in other types of measurements. In many cases these antenna positions were not those that were specified in Sections 5.03 and 5.04 of the measurement procedure. His comments are listed above in Section II of this report.

V. Open-Site Measuremnts

In these and in other measurements, the portable monochrome TV and breadboard oscillator were used for the sample EUTs. In general, there was little difficulty in detecting the radiations from these devices with the loop antenna positioned 3 meters from the EUT. However, unexpected and unexplained peaks and nulls were encountered when scanning the loop antenna in the vertical direction. Further measurements need to be made in order to determine the cause and nature of the nulls.

In an attempt to determine the character of the radiation that was causing the nulls, measurements of the emissions from the Hitachi TV were made with the TV set oriented in upright and face down positions at distances of 3.35, 5.05 and 7.95 meters between the TV and the loop antenna. These 3 particular distances were chosen because they were close enough to the EUT for meaningful measurements to be made and were at locations where the receiving antenna could be conveniently placed for the vertical scans.

For these measurements, the height of the TV was not varied but kept at approximately 1.3 meters above the ground, the same height as the center of the receiving loop antenna. The data are presented in Table 1 along with the differences of the measured values with the TV set in the two different positions. No real trend in the data was noted that could explain the nulls in the radiation.

In Tables 2 and 3, measurements made at the 5.05 and 7.95 meter TV/antenna separations are compared with the values one would expect at these two positions if the signal is falling as the inverse cube of the of the distance. The values measured at the 3.35 meter position are taken as the reference values. Although there are some anomalies in the data at the lower frequencies, most of the measured values are within 1 or 2 dB of the expected values which seem to indicate that the emissions in these two positions are behaving as near field radiations.

From the measurements as a whole, it is apparant that the radiation from the Hitachi TV is directed in some direction rather than along the line between the TV and the loop antenna. This may be a major factor contributing of the peaks and nulls in the radiation pattern. However, nothing more definite than this can be said at this point.

In formulating the measurement procedure, it was anticipated that there would be small variations in signal strength with height, but it did not forsee that there would be absolute nulls in the radiation pattern as were observed here. Consequently, the measurement procedure did not require that the loop antenna be scanned in the vertical direction. Furthermore, vertical scanning with these antennas to obtain the maximum level of the received signal has apparently never been done here at the Laboratory in the past when testing devices for compliance. But since it has been now demonstrated that these nulls do exist, the measurement procedure may have to be modified to allow for scanning in the vertical direction. Where nulls in the radiation pattern exist, vertical scanning with the receiving antenna is necessary not only to ensure that the measurements are not being made in a null but also to find the maximum value of the field within the vertical scan range so that a valid comparison can be made with results of others who are carrying out similiar measurements. Further exploratory work to gain a more complete understanding of the radiation patterns of our EUTs could not be done at this time as we do not have any means of moving these antennas smoothly and accurately throughout a vertical range. Our present antenna masts are inadequate for this purpose.

The highly directional character of the radiation being emitted from the EUTs being tested and the necessity of having to scan in the vertical direction brings up questions concerning the comparability of measurements that are made with antennas of different physical sizes. In both the calibration and measuring process, the average effect of the normal component of the H field over the surface of the loop is what is being measured. With a highly distorted field, two loops of different sizes may be encompassing different averaged fields. Some measurements were made in an attempt to determine this. But because of the crudeness of our measuring setup, only general and qualitative observations could be made at the time. Rough preliminary measurements do indicate that measurements of the same field made with loop antennas of different physical sizes can differ by as much as 6 dB. If subsequent measurements confirm this, then the measurement procedure may have to be modified to specify the size of the antennas that can be used at various distances from the EUT.

VI. Summary and Recommendations

Questions are being raised here which apparently have not been adequately addressed in the past concerning the nature of the radiation field that is being measured with our loop antennas. An understanding of this appears to be necessary if we are to be able to intelligently extrapolate the field intensities from the distances specified in the Rules, where the measurements are difficult or perhaps impossible to be made, to the closer measurement distances of 3 and 10 meters. This understanding is also needed if we are to compare measurements submitted to us for review that have been made with antennas of different sizes.

The results reported here also point up that more work is needed in actually measuring sample EUTs on our open field test sites before we can submit the measurement procedure for comments. However, work of this nature should not be undertaken until we have revamped and rebuilt some of our present measuring setups.

To determine the character of the radiations being emitted from an EUT as well as to adequately fix the limits of the error in measurement that will be allowed under the measurement procedure, measurements of the emissions from several EUTs should be made as the loop antenna is being scanned vertically. At the present time, we do not have the capability of making reliable vertical scans with loop antennas. These antennas are in general much heavier and cumbersome than the tuned dipole antennas that we use in most of our measurements and the vertical drives on our antenna masts are not capable of raising them without slippage. Consequently, a more adequate vertical drive mechanism needs to be fashioned as well as a suitable antenna mount to hold the antenna. In addition, we may also have to look into the design and construction of a moveable and easily transportable antenna mast.

Table 1

The Measured Values of the Radiation from a Small Portable TV
in a Normal and in a Face Down Position*

Freq.	Dist. = 3.35 m.			Dist. = 5.05 m.			Dist. = 7.95 m.		
(kHz)	Up	Down	Diff.	Up	Down	Diff.	Up	Down	Diff.
15.7	31.2	42.2	-11.0	18.2	31.2	-13.0	5.2	19.2	-14.0
31.4	6.5	35.5	-29.0	0.5	24.5	-24.0	-2.0	12.5	-14.5
47.1	21.5	30.0	-8.5	12.5	20.0	-7.5	3.5	8.0	-4.5
62.8	26.3	27.3	-1.0	16.8	17.3	-0.5	5.3	5.8	-0.5
78.5	25.5	22.0	3.5	15.5	11.5	4.0			
94.2	25.5	18.5	7.0	16.0	8.5	7.5	4.0	-1.0	5.0
109.9	25.0	15.5	9.5	14.5	5.0	9.5	3.0	-5.0	8.0
125.6	22.5	9.5	13.0	11.5	-0.5	12.0	-0.5	-9.5	9.0
141.3	18.5	3.0	15.5	8.0	-7.5	15.5	-4.0	-16.5	12.5

* The measured values are in db(uA/m).

Table 2

The Expected Values of the Radiation from a Small Portable TV Oriented in a Normal Viewing Position*

Freq.	Distance 5.05 m.			Distance 7.95 m.		
(kHz)	Meas.	Exp.	Diff.	Meas.	Exp.	Diff.
15.7	18.2	20.5	-2.3	5.2	8.7	-3.5
31.4	0.5	-4.2	-4.7	-2.0	-16.0	-14.0
47.1	12.5	10.8	1.7	3.5	-1.0	4.5
62.8	16.8	15.6	1.2	5.3	3.8	1.5
78.5	15.5	14.8	0.7			
94.2	16.0	14.8	1.2	4.0	3.0	1.0
109.9	14.5	14.3	0.2	3.0	2.5	0.5
125.6	11.5	11.8	-0.3	-0.5	0.0	-0.5
141.3	8.0	7.8	0.2	-4.0	-4.0	0.0

* The measured and expected values are in db(uA/m).

Table 3

The Measured Values of the Radiation from a Small Portable TV
Oriented in a Face Down Position*

Freq.	Distance 5.05 m.			Distance 7.95 m.		
(kHz)	Meas.	Exp.	Diff.	Meas.	Exp.	Diff.
15.7	31.2	31.5	-0.3	19.2	19.7	-0.5
31.4	24.5	24.8	-0.3	12.5	13.0	-0.5
47.1	20.0	19.3	0.7	8.0	7.5	0.5
62.8	17.3	16.6	0.7	5.8	4.8	1.0
78.5	11.5	11.3	0.2			
94.2	8.5	7.8	0.7	-1.0	-4.0	3.0
109.9	5.0	4.8	0.2	-5.0	-7.0	2.0
125.6	-0.5	-1.2	0.7	-9.5	-13.0	3.5
141.3	-7.5	-7.7	0.2	-16.5	-19.5	3.0

* The measured and expected values are in db(uA/m).

The Measurement of Radiated Emissions on Frequencies below 30 MHz Using Loop Antennas

Materials for the ANSI C63 Committee
Part 8: Extrapolation of the Field Strength Limits*

I. Introduction

The spatial distribution of spurious radiation from an electronic or electrical device arises from unshielded currents and current loops within the device. The magnitude and orientation of these currents is generally not known and hence the spatial distribution of the spurious radiation emitted from these devices will not be known either. With the lack of any concrete knowledge of the currents that are producing the radiated fields, a suitable working hypothesis is that, in any given device, a significant portion of the spurious radiation is being produced by short unshielded current elements. Assuming that this is the case, then the falloff in the radiation from these short current elements can be approximated by the falloff in the raidation from a short electric dipole of length, l, that is being driven by a sinusoidal current, I, of angular frequency, .

The **E** and **H** fields that are produced by a short dipole of length, dz, that is located at the origin of coordinates and lying along the z axis are:[1]

$$E_r = 60\beta^2 I \, dz \left[\frac{1}{(\beta r)^2} - \frac{j}{(\beta r)^3}\right] \cos\theta \, e^{-j\beta r} \tag{1a}$$

$$E_\theta = j\,30\beta^2 I \, dz \left[\frac{1}{\beta r} - \frac{j}{(\beta r)^2} - \frac{1}{(\beta r)^3}\right] \sin\theta \, e^{-j\beta r} \tag{1b}$$

$$H_\phi = j\frac{\beta^2 I \, dz}{4\pi} \left[\frac{1}{\beta r} - \frac{j}{(\beta r)^2}\right] \sin\theta \, e^{-j\beta r} \tag{1c}$$

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* The analysis made in this part of the report has not been presented previously in any FCC working document. However, the results of the analysis were incorporated in the Draft Measurement Procedure of September 1988, which has been included here as the ninth and final part of this report.

The distance, r, is measured from the origin to the field point where the measurement is being made. The wavenumber, β, is 2 pi divided by the wavelength.

The magnitude of the E field at any distance, r, from the radiating source is

$$E = \sqrt{E_r^2 + E_\theta^2} \qquad (2)$$

Because both of the components of the E field are dependent upon the elevation angle, θ, the maximum magnitude of the E field will not necessarily occur at an elevation angle of 90 degrees, the direction that is broadside to the emitting dipole. (Only in the far field will this be the case.)

II. The Calculation of the Extrapolation Factors

To find the maximum value of the E field at any given frequency and distance from the radiating source, theoretical values of the magnitude of the E field were calculated at one degree intervals from = 0 to = 90 degrees and the maximum value of the field in this angular range was found. The calculations were made at 38 frequencies within the 10 kHz to 30 MHz frequency range at distances from the radiating source of 3, 10, 30, 300 and 1600 meters. The 38 frequencies at which the calculations were made are listed in the following table.

10 kHz	120 kHz	450 kHz	3 MHz	12 MHz
15 kHz	150 kHz	500 kHz	3.5 MHz	13 MHz
30 kHz	200 kHz	700 kHz	4 MHz	15 MHz
50 kHz	250 kHz	800 kHz	4.5 MHz	20 MHz
70 kHz	300 kHz	900 kHz	5 MHz	25 MHz
80 kHz	350 kHz	1 MHz	9 MHz	30 MHz
90 kHz	375 kHz	2 MHz	10 MHz	
100 kHz	400 kHz	2.5 MHz	11 MHz	

At each frequency, the dB differences in the magnitudes of the E field were then found for the following four distance pairs.

1600 and 300 meters
300 and 10 meters
30 and 10 meters
10 and 3 meters

(These five distances were chosen because they are the measurement distances that are stated in the FCC Part 15 and Part 18 Rules.[2])

The dB differences were plotted against frequency on a log-log plot for each of the four distance pairs. Each of the four curves was then broken down into frequency range sections over which the curve was linear on the log-log plot. A satisfactory fit was made to all four of the curves by using a total of 10 frequency range sections for the entire 10 kHz to 30 MHz frequency span. Seventeen equations were needed to fit all 4 of the curves: 3 for the 1600 and 300 meters curve, 6 for the 300 and 10 meters curve, 4 for the 30 and 10 meters curve and 4 for the 10 and 3 meters curve.

The 10 frequency range sections are shown in Tables 1 and 2 along with the 17 equations that were fitted to the four dB difference/frequency curves. The 17 equations allow measurements of the E field that are made at any one of the 5 distances, 3, 10, 30, 300 and 1600 meters, to be extrapolated to the second distance of its corresponding frequency pair.

There are other distance pairs, such as,

300 and 3 meters
30 and 3 meters

where extrapolations of the E field frequently need to be made. These two extrapolation pairs were not included in the tables since they can be deduced from combinations of the extrapolations that are listed in the tables.

The tradeoff made in the choice of the frequency range sections was the simplicity that could be attained in having a minimum number of the frequency range sections as against a minimization of the extrapolation error that would occur if the number of frequency ranges was increased. Obviously, the more frequency range sections that are used to fit the curves, the greater will be the accuracy of the resulting extrapolation.

To determine the error involved in using the 17 extrapolation equations listed in Tables 1 and 2, extrapolation differences in dB were calculated from these equations at 38 frequencies in the 10 kHz to 30 MHz range for the six distance pairs listed above. The extrapolation differences were then compared with the exact theoretical differences in the magnitudes of the E fields which are obtained for these distances and frequencies using equations 1 and 2. The theoretical and curve-fitted values are listed in Table 3 along with the differences between these two sets of values. It can readily be seen from the table that the accuracy of the extrapolation is generally better than 1 dB for those distances and frequencies at which the calculations were made. Only 26 of the 228 differences listed in Table 3 are greater than 0.6 dB and 3 of the differences are greater than 1 dB.

III. The Use of the Extrapolation Tables to Extrapolate Field Strength Limits: The Extrapolation Factors

Tables 1 and 2 list the 17 equations that give the additive factors in dB that should be used to extrapolate values of the E field values from distances of 1600 to 300 meters, 300 to 10 meters, 30 to 10 meters and 30 to 10 meters. The extrapolation factors that are to be used for other pairs of distances such as from 300 to 30 meters can be obtained by using combinations of the four distance pairs in the tables. (In the extrapolation formulas listed in Tables 1 and 2, the character, **, signifies exponentiation. Terms such as, f(MHz)**(0.005), should be interpreted to mean: the frequency in megahertz raised to the 0.005 power.)

Examples Showing the Use of the Additive Extrapolation Factors

Example 1

In Paragraph 15.209 of the Rules, an electric field intensity of 5.3 uV/m at a distance of 300 meters is specified as the radiation emission limit at a frequency of 450 kHz.

(a) What is the radiated emission limit at 10 meters?
(b) At 3 meters?
(c) At 30 meters?

The Solution to Part a is:
In terms of dB, 5.3 uV/m corresponds to 14.5 dB(uV/m). Now from Table 2, in going from 300 to 10 meters the additive extrapolation factor is:

$$\frac{64.1}{(0.450)^{(0.228)}} = 76.9 \text{ dB}$$

Therefore the radiated emission limit in dB at 10 meters is

14.5 + 76.9 = 91.4 dB

or

10**(91.4/20) = 37154 uV/m

or

37154/(120*pi) = 98.6 uA/m

The Solution to Part b is:
From Table 2, in going from 10 to 3 meters the additive factor is 31.4 dB. Therefore the field strength in dB at 3 meters should be

91.4 + 31.4 = 122.8 dB

or

10**(122.8/20) = 1380384 uV/m

or

1380384/(120*pi) = 3662 uA/m

The Solution to Part c is:
From Table 2, the additive factor in going from 30 to 10 meters is 28.6 dB. Consequently, the additive factor in going from 10 to 30 meters is -28.6 dB. But in part a of this example, the additive factor in going from 300 to 10 meters was found to be 76.9 dB. Hence the total additative factor in going from 300 to 30 meters is:

76.9 dB - 28.6 = 48.3 dB

Therefore the radiated emission limit in dB at 30 meters is

14.5 + 48.3 = 62.8 dB

or

10**(62.8/20) = 1380 uV/m

or

1381/(120*pi) = 3.7 uA/m

IV. Calculation of the H Field

In cases where the **H** field is the quantity that is measured, a conversion of the **H** field to The **E** field must be made before a comparison can be made with the field strength limits that are specified in the Rules.[2] This conversion is normally made by multiplying the magnetic field intensity by the free space impedance, 120*pi, even though this relationship between the **E** field vector and the **H** field vector is valid only in the far field.

A better method of converting an **H** field intensity into an **E** field intensity and one that is in keeping with the extrapolation methods developed here would be to relate the magnitudes of the **E** and **H** fields directly from equations 1 and 2. However, this is rather difficult to do without the use of a computer, since the magnitudes of both the **E** and **H** fields vary with the elevation angle theta. It can easily be done with a computer with only a moderate amount of programming.

V. REFERENCES

1. Antenna Engineering Handbook, Henry Jasik, Editor, chapter 2, pg 2-2, 1st ed., McGraw-Hill, 1961, (or, Antenna Engineering Handbook, Richard C. Johnson and Henry Jasik, Editors, chapter 2, pg 2-2, 2nd ed., McGraw-Hill, 1984)

2. Code of Federal Regulations, Title 47, Parts 0 thru 19, Revised as of October 1, 1989, U.S. Government Printing Office, Washington: 1989

Table 1

Field Strength Extrapolation Factors in dB
to be used in going from 1600 meters to 300 meters

Frequency Range	Extrapolation Distances from 1600 meters to 300 meters
10 kHz to 80 kHz	$\frac{26.8 \text{ dB}}{f(MHz)^{**}(0.106)}$
80 kHz to 375 kHz	$\frac{8.3 \text{ dB}}{f(MHz)^{**}(0.570)}$
above 375 kHz	14.5 dB

Notes for Table 1:

1. In the above table, the character, **, signifies exponentiation. Hence, terms like, f(MHz)**(0.106), should be interpreted to mean: the frequency in megahertz raised to the 0.106 power.
2. 20*log10(1600/300) = 14.5 dB Therefore above 375 kHz, the extrapolation has a simple 1/r dependence.

Table 2

Field Strength Extrapolation Factors in dB
to be used in going from: 300 meters to 10 meters
30 meters to 10 meters
10 meters to 3 meters

Frequency Range	Extrapolation Distances: from 300 meters to 10 meters	from 30 meters to 10 meters	from 10 meters to 3 meters
10 kHz to 80 kHz	86.5 dB / f(MHz)**(0.005)	28.6 dB	31.4 dB
80 kHz to 250 kHz	79.8 dB / f(MHz)**(0.037)	28.6 dB	31.4 dB
250 kHz to 375 kHz	71.5 dB / f(MHz)**(0.117)	28.6 dB	31.4 dB
375 kHz to 800 kHz	64.1 dB / f(MHz)**(0.228)	28.6 dB	31.4 dB
800 kHz to 2 MHz	62.8 dB / f(MHz)**(0.317)	27.6 dB / f(MHz)**(0.155)	31.4 dB
2 MHz to 4 MHz	62.8 dB / f(MHz)**(0.317)	27.6 dB / f(MHz)**(0.155)	32.9 dB / f(MHz)**(0.066)
4 MHz to 11 MHz	62.8 dB / f(MHz)**(0.317)	74.0 dB / f(MHz)**(0.865)	37.4 dB / f(MHz)**(0.160)
11 MHz to 30 MHz	29.4 dB	9.3 dB	148.6 dB / f(MHz)**(0.735)

Notes for Table 2:

1. In the above table, the character, **, signifies exponentiation Hence, terms like, f(MHz)**(0.005), should be interpreted to mean: the frequency in megahertz raised to the 0.005 power.
2. 20*log10(30/10) = 9.5 dB and 60*log10(30/10) = 28.6 dB Therefore for the 30 to 10 meters extrapolation pair, the extrapolation has a simple 1/r dependence above 11 MHz and a simple 1/r cubed dependence below 800 kHz.
3. 60*log10(10/3) = 31.4 dB Therefore for the 10 and 3 meter extrapolation pair, the extrapolation has a simple 1/r cubed dependence below 2 MHz.

TABLE 3

A Comparison of the Theoretical Value
of the Magnitude of the Electric Field
with the Values Obtained Using the Formulas in Tables 1 and 2

The Differences in the Magnitudes of the E Field Vector in dBuV/m

Frequency /////////	1600-300 meters	300-3 meters	30-3 meters	300-10 meters	30-10 meters	10-3 meters
10 kHz	43.2	120.0	60.0	88.6	28.6	31.4
10 kHz	43.7	119.9	60.0	88.5	28.6	31.4
	-0.5	0.1	-0.0	0.1	0.0	-0.0
15 kHz	42.7	120.0	60.0	88.6	28.6	31.4
15 kHz	41.8	119.7	60.0	88.3	28.6	31.4
	0.9	0.2	-0.0	0.3	0.0	-0.0
30 kHz	40.7	119.8	60.0	88.5	28.6	31.4
30 kHz	38.9	119.4	60.0	88.0	28.6	31.4
	1.9	0.4	-0.0	0.4	0.0	-0.0
50 kHz	38.2	119.6	60.0	88.2	28.6	31.4
50 kHz	36.8	119.2	60.0	87.8	28.6	31.4
	1.4	0.4	-0.0	0.4	0.0	-0.0
70 kHz	36.3	119.2	60.0	87.9	28.6	31.4
70 kHz	35.5	119.1	60.0	87.7	28.6	31.4
	0.7	0.2	-0.0	0.2	0.0	-0.0
80 kHz	34.0	119.0	60.0	87.7	28.6	31.4
80 kHz	35.0	119.0	60.0	87.6	28.6	31.4
	-1.0	0.0	-0.0	0.0	0.0	-0.0
90 kHz	32.1	118.8	60.0	87.4	28.6	31.4
90 kHz	32.7	118.6	60.0	87.2	28.6	31.4
	-0.6	0.2	-0.0	0.2	0.0	-0.0

TABLE 3 (continued)

Frequency /////////	1600-300 meters	300-3 meters	30-3 meters	300-10 meters	30-10 meters	10-3 meters
100 kHz	30.4	118.6	60.0	87.2	28.6	31.4
100 kHz	30.8	118.3	60.0	86.9	28.6	31.4
	-0.4	0.3	-0.0	0.3	0.0	-0.0
120 kHz	27.7	118.0	60.0	86.7	28.6	31.4
120 kHz	27.8	117.7	60.0	86.3	28.6	31.4
	-0.1	0.3	-0.0	0.4	0.0	-0.0
150 kHz	24.5	117.2	60.0	85.9	28.6	31.4
150 kHz	24.5	117.0	60.0	85.6	28.6	31.4
	0.0	0.2	-0.0	0.3	-0.0	-0.0
200 kHz	20.8	115.9	59.9	84.5	28.6	31.4
200 kHz	20.8	116.1	60.0	84.7	28.6	31.4
	0.0	-0.2	-0.1	-0.2	-0.0	-0.0
250 kHz	18.2	114.6	59.9	83.2	28.5	31.4
250 kHz	18.3	115.4	60.0	84.0	28.6	31.4
	-0.1	-0.8	-0.1	-0.8	-0.1	-0.0
300 kHz	16.2	113.4	59.8	82.1	28.5	31.4
300 kHz	16.5	113.7	60.0	82.3	28.6	31.4
	-0.3	-0.3	-0.2	-0.3	-0.1	-0.0
350 kHz	14.6	112.3	59.8	81.0	28.4	31.4
350 kHz	15.1	112.2	60.0	80.8	28.6	31.4
	-0.5	0.1	-0.2	0.1	-0.2	-0.0
375 kHz	13.9	111.8	59.8	80.5	28.4	31.3
375 kHz	14.5	111.6	60.0	80.2	28.6	31.4
	-0.6	0.3	-0.2	0.3	-0.2	-0.1
400 kHz	13.9	110.6	59.7	79.3	28.4	31.3
400 kHz	14.5	110.4	60.0	79.0	28.6	31.4
	-0.6	0.2	-0.3	0.3	-0.2	-0.1

TABLE 3 (continued)

Frequency /////////	1600-300 meters	300-3 meters	30-3 meters	300-10 meters	30-10 meters	10-3 meters
450 kHz	14.1	108.5	59.7	77.1	28.3	31.3
450 kHz	14.5	108.3	60.0	76.9	28.6	31.4
	-0.4	0.2	-0.3	0.2	-0.3	-0.1
500 kHz	14.1	106.6	59.6	75.2	28.3	31.3
500 kHz	14.5	106.5	60.0	75.1	28.6	31.4
	-0.4	0.1	-0.4	0.1	-0.3	-0.1
700 kHz	14.3	100.5	59.2	69.2	28.0	31.3
700 kHz	14.5	100.9	60.0	69.5	28.6	31.4
	-0.2	-0.4	-0.8	-0.3	-0.6	-0.1
800 kHz	14.4	98.1	59.0	66.9	27.8	31.3
800 kHz	14.5	98.8	60.0	67.4	28.6	31.4
	-0.1	-0.7	-1.0	-0.6	-0.8	-0.1
900 kHz	14.4	96.1	58.8	64.8	27.6	31.2
900 kHz	14.5	96.3	59.5	64.9	28.1	31.4
	-0.1	-0.3	-0.6	-0.1	-0.5	-0.2
1 MHz	14.4	94.2	58.6	63.0	27.4	31.2
1 MHz	14.5	94.2	59.0	62.8	27.6	31.4
	-0.1	0.0	-0.4	0.2	-0.2	-0.2
2 MHz	14.5	82.1	56.0	51.4	25.2	30.7
2 MHz	14.5	81.8	56.2	50.4	24.8	31.4
	0.0	0.3	-0.2	1.0	0.4	-0.7
2.5 MHz	14.5	78.3	54.7	47.9	24.3	30.4
2.5 MHz	14.5	77.9	54.9	47.0	23.9	31.0
	0.0	0.4	-0.2	0.9	0.3	-0.5
3 MHz	14.5	75.2	53.6	45.1	23.5	30.1
3 MHz	14.5	74.9	53.9	44.3	23.3	30.6
	0.0	0.2	-0.3	0.8	0.2	-0.5

TABLE 3 (continued)

Frequency /////////	1600-300 meters	300-3 meters	30-3 meters	300-10 meters	30-10 meters	10-3 meters
3.5 MHz	14.5	72.5	52.5	42.8	22.8	29.7
3.5 MHz	14.5	72.5	53.0	42.2	22.7	30.3
	0.0	0.0	-0.5	0.6	0.1	-0.6
4 MHz	14.5	70.3	50.9	41.0	21.6	29.3
4 MHz	14.5	70.5	52.3	40.5	22.3	30.0
	0.0	-0.2	-1.4	0.5	-0.7	-0.7
4.5 MHz	14.5	68.3	48.8	39.4	19.9	28.9
4.5 MHz	14.5	68.4	49.5	39.0	20.1	29.4
	0.0	-0.1	-0.7	0.4	-0.3	-0.5
5 MHz	14.5	66.5	47.0	38.0	18.4	28.6
5 MHz	14.5	66.6	47.3	37.7	18.4	28.9
	0.0	-0.1	-0.3	0.3	-0.0	-0.3
9 MHz	14.5	57.1	37.3	31.1	11.3	26.0
9 MHz	14.5	57.6	37.4	31.3	11.1	26.3
	0.0	-0.5	-0.1	-0.2	0.2	-0.3
10 MHz	14.5	55.5	35.6	30.0	10.1	25.5
10 MHz	14.5	56.1	36.0	30.3	10.1	25.9
	0.0	-0.6	-0.3	-0.2	0.0	-0.4
11 MHz	14.5	54.1	34.2	29.1	9.2	25.1
11 MHz	14.5	54.8	34.8	29.4	9.3	25.5
	0.0	-0.7	-0.6	-0.3	-0.1	-0.4
12 MHz	14.5	52.9	33.0	28.9	9.0	24.0
12 MHz	14.5	53.3	33.2	29.4	9.3	23.9
	0.0	-0.4	-0.3	-0.5	-0.3	0.0
13 MHz	14.5	51.8	31.8	29.0	9.1	22.8
13 MHz	14.5	52.0	31.9	29.4	9.3	22.6
	0.0	-0.2	-0.0	-0.4	-0.2	0.2

TABLE 3 (continued)

Frequency /////////	1600-300 meters	300-3 meters	30-3 meters	300-10 meters	30-10 meters	10-3 meters
15 MHz	14.5	49.8	29.9	29.1	9.2	20.7
15 MHz	14.5	49.7	29.6	29.4	9.3	20.3
	0.0	0.1	0.3	-0.3	-0.1	0.4
20 MHz	14.5	46.2	26.2	29.3	9.3	16.9
20 MHz	14.5	45.8	25.7	29.4	9.3	16.4
	0.0	0.3	0.5	-0.1	0.0	0.4
25 MHz	14.5	43.6	23.6	29.4	9.4	14.2
25 MHz	14.5	43.3	23.2	29.4	9.3	13.9
	0.0	0.2	0.3	-0.0	0.1	0.2
30 MHz	14.5	41.6	21.6	29.4	9.4	12.2
30 MHz	14.5	41.6	21.5	29.4	9.3	12.2
	0.0	-0.0	0.1	0.0	0.1	-0.0

NOTES for Table 3:

1. The magnitudes of the E field vector given in the table in dBuV/m are normalized values.
2. For each frequency, the values listed in the first row of the table for that frequency are the differences in the theoretical values of the **E** field between the two distances that are listed at the head of each column of the table. The theoretical values were obtained from the fields that are produced by a short dipole. The values listed in the second row of the table for each frequency are the values that are obtained using the empirically derived formulas in Tables 1 and 2. The differences between these two sets of values are listed in the third row of the table.
3. Only 26 of the 228 differences listed in this table are greater than 0.6 dB. Three of the differnces are greater than 1 dB.

The Measurement of Radiated Emissions
on Frequencies below 30 MHz
Using Loop Antennas

Materials for the ANSI C63 Committee
Part 9: Draft of a Proposed Measurement Procedure*

METHODS FOR MEASURING RADIATED ELECTRIC FIELD STRENGTHS ON FREQUENCIES BELOW 30 MHZ USING LOOP ANTENNAS

DRAFT -- FCC/OET MP-13, September 1988

1.0 Scope

This measurement procedure describes the methods for measuring radiated electric field strengths on frequencies from 10 kHz to 30 MHz using loop antennas.

2.0 Definitions and Abbreviations

AF Antenna Factor
The Antenna Factor, AF, relates the voltage, V, detected at the terminals of an antenna to the magnitude of the electric field intensity, E, existing at the surface of the antenna. It is defined by the relationship, E = AF*V.

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* Compiled from work done in September 1988 by Joseph Mc Nulty at the FCC Laboratory in Columbia, Maryland

Antenna Terminals

This term has two common usages:

1. in its theoretical usage, the term, antenna terminals, refers to that point on an antenna where a voltage source is connected for the purpose of exciting the antenna when it is operating in its transmission mode and where a voltage measuring device is connected for the purpose of extracting a signal from the antenna when it is operating in its receiving mode,
2. in its practical usage, the term, antenna terminals, refers to the physical connection on the antenna assembly where the signal cable is connected. This point is usually separated from the actual antenna terminals by some form of passive impedance matching network which has been built into the antenna supporting structure. In this measurement procedure, the practical usage of this term will be used.

Balun A balun is an impedance matching device that is designed to

1. couple a symmetrical antenna which is electrically balanced with respect to ground to a coaxial line which is electrically unbalanced with respect to ground, and,
2. match the impedance of the antenna to a transmission line.

dBm This is the signal power in decibels as measured with reference to a power of 1 milliwatt. A signal of 0 dBm has a power of 1 milliwatt and produces a voltage of 224 millivolts across a 50 Ohm resistor.

dB(uV/m) This is the electric field strength measured in decibels with reference to a field strength of 1 microvolt per meter.

dB(uA/m) This is the magnetic field strength measured in decibels with reference to a field strength of 1 microampere per meter.

EUT The Equipment Under Test

The EUT is the particular piece of electrical or communication equipment that is being tested for radiated emissions.

FSM Field Strength Meter

An FSM is a tuned RF voltmeter that is capable of reading the peak value or the RMS value of an RF voltage. When measuring field strengths, the FSM is used to measure the voltage across the terminals of an antenna. This voltage is proportional to the strength of the electromagnetic field at the surface of the antenna and is related to it through the antenna factor. A Field Strength Meter is also called a Field Intensity Meter or FIM.

NBS The National Bureau of Standards (now The National Institute of Standards and Technology)

NIST The National Institute of Standards and Technology (formerly The National Bureau of Standards)

pi A numerical constant which is the ratio of the circumference of a circle to its diameter and has a value to five decimal places of 3.14159.

RF An abbreviation for radio frequency.

3.0 The Measuring Site Specifications

The radiated measurements are to be made on an open area test site. The site should be a flat open area that is void of all reflecting objects which could affect the measurements, such as, buildings, electric lines, fences, trees and other above ground obstacles and should also be free of all underground cables and pipes except those which are necessary to supply and operate the test apparatus and the EUT. The site should be at a location where the levels of the ambient radio noise as well as all other undesired signals are sufficiently low so as not to interfere with the radiated measurements.

The site does not have to have a metallic ground plane and the measurements can be made over the open ground. However, if a metallic ground plane is present, the site must have been constructed according to the specifications set forth in FCC Bulletin OST 55: Characteristics of Open Field Test Sites. This bulletin is available from the FCC Consumers Assistance Office, Washington, D.C., 20554.[1]

4.0 The Electrical Power to the Measuring Site

Power connecting lines to both the EUT and the test instrumentation are to be kept as short as possible. Although not mandatory, the electrical power to the test site should be buried.

The electrical service to the test site is to be maintained to within 5% of the nominal voltage. Adequate isolation is to be incorporated into the electrical system to ensure that RF signals will not be coupled into the test instrumentation via the power lines.

5.0 Antenna Description and Configuration of the Measuring Antenna and the EUT

5.01 Antennas
Although some measurement procedures allow the use of calibrated, shortened, nonresonant dipoles for field strength measurements from 18 to 30 MHz, the only antennas supported by this measurement procedure are shielded balanced loops. The measurement procedures for using calibrated, shortened, nonresonant dipoles are covered elsewhere.[2]

5.02 Antenna and EUT Configurations
The antenna is to be mounted so that the plane of the antenna is perpendicular to the line separating the antenna from the EUT. The EUT is to be positioned on a wooden or other non-conducting table or framework which in turn is mounted on a rotatable platform. The platform supporting the table and the EUT must be capable of being rotated about its vertical axis with its rotation being controlled remotely from the measuring position. The center of the EUT should be located above the center of rotation of the platform and approximately 1 meter above the ground.

5.03 Measurement Distances
The horizontal distance between the measuring antenna and the EUT shall be either 3, 10 or 30 meters. This distance is to be measured from the center of symmetry of the antenna to the closest point on the EUT as the EUT is rotated on the platform through 360 degrees.

5.04 Antenna Height Variations
The loop antenna is to be mounted with its center positioned 1 meter above the ground. The antenna should be varied about this position when making field strength measurements to ensure that the maximum value of the field strength is being obtained.

5.05 Antenna Factors
All antennas must be calibrated for their antenna factors, AF. The calibration must be shown to be traceable to NIST either by having the antennas calibrated by NIST or by the same method used by NIST. The antenna factors that are supplied by the antenna manufacturers with their antennas may not be acceptable unless it can be shown that the manufacturer's calibration of the antennas is traceable to NIST.

The procedures used by NIST for calibrating loop antennas are given in the NBS Technical Note 370, Calibration Principles and Procedures for Field Strength Meters (30 Hz to 1 GHz), by H. E. Taggart and J. L. Workman, National Bureau of Standards, Boulder, Colorado, March 1969[3]. When calibrating loop antennas using these procedures, one must keep in mind that the NIST calibration procedures require that a single turn loop antenna is to be used to establish the field, and that the current flowing through this loop must be known accurately. Many of the single-turn loop antennas that are commercially available cannot be used to produce the standard magnetic field required by the NIST procedures unless the antenna is first modified. This is because most of the commercial antennas have baluns built into their structures and the electrical characteristics of the baluns are usually not supplied by the manufacturer. When these antennas are used as transmitting antennas, the current which is measured flowing into the antenna structure is the current that is flowing into the antenna balun and not the current which is actually flowing through the antenna loop.

6.0 Measurement Equipment

A Field strength meter that is capable of accurately measuring signals at a level of -120 dBm with 1 dB accuracy is the preferred instrument for making these measurements. Spectrum analayzers may also be used, although their sensitivities are usually not as great as those of an FSM. However, it should be kept in mind that spectrum anlayzers usually have a very poor front end selectivity. Consequently, when they are used in outdoor measurements, they can be easily overloaded when strong ambient signals are present. This overload can be avoided with the use of a suitable preselector or front end filter.

Nevertheless, spectrum analyzers are virtually indispensible in pretesting an EUT indoors in order to determine the frequencies at which significant emissions from the device occur. During this device prescan, estimates of the levels of the emissions can usually be done and a determination made as to whether any of the emissions are high enough to warrant more precise measurements on an open area test site.

If a preamplifier is used with an FSM or spectrum analyzer, then one has to ascertain that the preamplifier does not produce any appreciable insertion loss when it is introduced into the system. Insertion losses as high as 8 dB have been noted with some preamplifiers when they were inserted between a loop antenna and a spectrum analyzer or FSM.

7.0 The Units of Measurement

A field strength meter or a spectrum analyzer that is connected to an antenna measures the voltage at the antenna terminals and converts this voltage into a signal strength in dBm. Thus the power that is being delivered to the antenna terminals is the quantity that is being measured and not the strength of the electromagnetic field that exists in space at the surface of the antenna. However, the radiated emission limits in Parts 15 and 18 of the Rules are stated in terms of the electric field strength and consequently this is the quantity that must be determined when testing a device for FCC compliance. But for any antenna, the voltage at the antenna terminals is related to the electric field existing at the surface of the antenna by means of the antenna factor. In some cases the antenna factors can be obtained from theoretical models, in others, they have to be obtained in the antenna calibration process.

The voltage, V, at the antenna terminals is related to the magnitude of electric field intensity, E, at the surface of the antenna by means of the expression:

$$E = AF * V \qquad (1)$$

(Although it is not correct, it is normally assumed that the electric and magnetic field intensities, E and H, are related to one another by the free space impedance value of 120*pi. Under this assumption, equation 1 could also be written as: H=AF*V/(120*pi).)

In the above expressions, AF is the antenna factor. It has units of reciprocal meters, varies with frequency and has different values for different antennas. Its values are determined for each antenna in the calibration process.

Now since the antenna factor has the units of reciprocal meters, E will be given in the same units as V unless some other conversion is made. Normally, an FSM or spectrum analyzer will measure voltage with respect to a reference level of 1 milliwatt, a power level that will produce a voltage of 224,000 microvolts across a 50 Ohm resistor. Electric field strengths are often expressed as dB above a microvolt per meter and magnetic field strengths as dB above a microampere per meter. A value of 107 dB, 20*log(224000), is needed to convert an E field to dB(uV/m) if the voltage at the antenna terminals, V, is given in dBm and a value of 55.5 dB, 107 - 20*log(120*pi), is needed to convert an H field to dB(uA/m).

7.01 Formulas for the Conversion of FSM and Spectrum Analyzer Readings in dBm to Field Strength Levels in dB(uV/m) and dB(uA/m)

The following formulas can be used to convert FSM values or spectrum analyzer readings in dBm to field strength levels in dB(uV/m) and dB(uA/m).

1. Conversion of the Received Power in dBm to an Electric Field Strength in dB(uV/m)

   E Field in dB(uV/m) = (measured value in dBm) + AF(dB) + 107 (2)

2. Conversion of an Electric Field Strength in dB(uV/m) to a Magnetic Field Strength in dB(uA/m)

   H Field in dB(uA/m) = E Field in dB(uV/m) - 51.5 (3)

3. Conversion of the Received Power in dBm to a Magnetic Field Strength in dB(uA/m)

   H Field in dB(uA/m) = (measured value in dBm) + AF(dB) + 55.5 (4)

7.02 Examples Showing the Use of These Formulas

Example 1:
At a distance of 3 meters from an EUT, a radiated emission of -83.0 dBm is detected with a Singer 94593-1 square loop antenna at a frequency of 40 kHz. What is the electric field strength in dB(uV/m)? What is the electric field strength in uV/m?

From the calibration of this antenna, the antenna factor at this frequency is 55.1 dB. Hence the electric field strength will be:

E Field in dB(uV/m) = (measured value in dBm) + AF(dB) + 107

= -83.0 + 55.1 + 107

= 79.1 dB(uV/m)

and the E Field in uV/m is 9016 microvolts per meter.

Example 2:
At a distance of 10 meters from the EUT, the level of the radiated emission is found to be -113 dBm. What is the magnetic field strength in dB(uA/m)? What is the magnetic field strength in uA/m?

Since the frequency has not changed, the antenna factor will still be 55.1 dB. Hence the level of the radiated emission will be:

H Field in dB(uA/m) = (measured value in dBm) + AF(dB) + 55.5

= -113 + 55.1 + 55.5

= -2.4 dB(uA/m)

and the H Field in uA/m is 0.8 microamperes per meter.

7.03 Some Notes Concerning the Antenna Factors and the Measured Values of the Field Strength

1. the received power in dBm will generally be a negative quantity, that is, the received power will generally be less than 1 milliwatt. Hence it must be entered into the above equations as a negative quantity as was done in the examples if that is the case.

2. at a given frequency, the antenna factor for a particular antenna is a constant and will not change with a change in distance between the radiating source and the antenna.

3. some antennas have frequency range switches with a frequency range overlap between the ranges. For these common frequencies, the antenna factors that are found for the overlapping frequencies will depend upon the range and will be different for different ranges. For example, an antenna may have the two ranges, Range 1: (150 kHz to 5 MHz) and Range

2: (5 MHz to 25 MHz). Here, the frequency of 5 MHz is common to the two ranges and the antenna factor that is found for 5 MHz on the lower frequency range will in general be different from that found on the higher range.

8.0 Extrapolation of the Field Strength Limits

8.01 The Extrapolation Factors.

The field strength limits in the Rules are stated for distances of 3, 10, 30, 300 and 1600 meters. Apparently, the 3, 30 and 1600 meter distances have been chosen as standard distances because they are approximately equal to 10 feet, 100 feet and 1 mile respectively.

Tables 1 and 2 list the additive factors in dB that should be used to extrapolate values of the E or H field from 1600 to 300 meters, 300 to 10 meters, 30 to 10 meters and 30 to 10 meters. The extrapolation factors that are to be used for other pairs of distances such as from 300 to 30 meters can be obtained by using combinations of the listed values.

The extrapolation factors that are listed in the tables were obtained by fitting curves to the theoretical differences in the magnetic field that would be produced at these distances by a simple single turn loop antenna or in the electric field that would be produced by a shortened dipole antenna.[4] The accuracy of the extrapolation is generally better than 1 dB for the stated distances and frequency ranges. Although the tables only list extrapolation factors for 1600 to 300 meters, 300 to 10 meters, 30 to 10 meters and 30 to 10 meters, the extrapolation factors for other pairs of distances such as 300 to 30 meters can be obtained by using combinations of the listed values.

In Tables 1 and 2 and in the following examples, the character, **, signifies exponentiation. Hence, terms like, f(MHz)**(0.005), should be interpreted to mean: the frequency in megahertz raised to the 0.005 power.

8.02 Examples Showing the Use of the Additive Extrapolation Factors

Example 1

In Paragraph 15.209 of the Rules, an electric field intensity of 5.3 uV/m at a distance of 300 meters is specified as the radiation emission limit at a frequency of 450 kHz.

(a) What is the radiated emission limit at 10 meters?
(b) At 3 meters?
(c) At 30 meters?

The Solution to Part a is:

In terms of dB, 5.3 uV/m corresponds to 14.5 dB(uV/m). Now from Table 2, in going from 300 to 10 meters the additive extrapolation factor is:

$$\frac{64.1}{(0.450)^{**}(0.228)} = 76.9 \text{ dB}$$

Therefore the radiated emission limit in dB at 10 meters is

14.5 + 76.9 = 91.4 dB

or

10**(91.4/20) = 37154 uV/m

or

37154/(120*pi) = 98.6 uA/m

The Solution to Part b is:
From Table 2, in going from 10 to 3 meters the additive factor is 31.4 dB. Therefore the field strength in dB at 3 meters should be

91.4 + 31.4 = 122.8 dB

or

10**(122.8/20) = 1380384 uV/m

or

1380384/(120*pi) = 3662 uA/m

The Solution to Part c is:
From Table 2, the additive factor in going from 30 to 10 meters is 28.6 dB. Consequently, the additive factor in going from 10 to 30 meters is -28.6 dB. But in part a of this example, the additive factor in going from 300 to 10 meters was found to be 76.9 dB. Hence the total additative factor in going from 300 to 30 meters is:

76.9 dB - 28.6 = 48.3 dB

Therefore the radiated emission limit in dB at 30 meters is

14.5 + 48.3 = 62.8 dB

or

10**(62.8/20) = 1380 uV/m

or

1381/(120*pi) = 3.7 uA/m

9.0 The Measurement Procedure

9.01 Preliminary Testing

It is often valuable to perform preliminary measurements on the EUT at a closer distance than that specified for compliance in order to determine the emission characteristics of the EUT. At close-in distances, it is often possible to assess the frequencies and levels of the various emissions coming from the EUT and determine which of them are candidates for more accurate measurement on the open area test site. For the pretesting, a site other than the open area test site can be used and the pretesting can even be done indoors. However, during the pretesting, the test engineer must keep firmly in mind that measurements made on this alternate test site cannot be used for compliance purposes unless the alternate site has been formally certified by the FCC for making these measurements. In most instances, it is rather difficult to correlate measurements made on an indoor or other nonstandard site with those made on an outdoor open area site.

9.02 Testing for Compliance on an Open Area Test Site
In testing an EUT for compliance with the FCC Rules, the radiation measurements must be made on an open area test site or an alternate test site that has been accepted by the FCC for the making of these measurements. The following testing procedure should then be used:

a. Mount the EUT in the middle of the rotating platform with the height of the center of the EUT located approximately 1 meter above the ground surface.

b. Position the receiving antenna at a horizontal distance of 3, 10 or 30 meters from the EUT with the plane of the antenna perpendicular to the horizontal line separating the antenna from the EUT.

c. Tune the measuring instrument to the frequency of the emission that is to be measured. Make sure that the emission being measured is actually coming from the EUT and not from some other source by turning off the power to the EUT and then observing the level of the remaining signal. If the signal persists after the power to the EUT has been shut off, then a strong interfering signal is present on a frequency that is close to that of the emission that is to be measured. If this is the case, then steps must be taken, such as narrowing the IF bandwidth of the measuring instrument, to lower the effect of the interfering signal upon the measurement.

d. With power applied to the EUT, rotate the platform and the EUT through an angle of 360 degrees by means of the remote control mechanism and record the level of the maximum received signal.

e. Repeat the measurement of part d two more times but with the receiving loop antenna rotated about its vertical axis from its original orientation by 45 degrees and 90 degrees respectively. Record the levels of the maximum received signals at these two positions also.

f. Reorient the loop antenna to the position where the largest signal level was observed. Again rotate the platform and the EUT through a full 360 degrees. Stop the platform at the position where the received radiation is a maximum.

g. Manually rotate the loop antenna about its vertical axis and record the maximum value of the received signal.

10.0 References

1. FCC Bulletin OST 55: Characteristics of Open Field Test Sites. This bulletin is available from the FCC Consumers Assistance Office, Washington, D.C., 20554

2. FCC/OST MP-5, FCC Methods of Measurements of Radio Noise Emissions from Industrial, Scientific and Medical Equipment, February 1986

3. H. E. Taggart and J. L. Workman, Calibration Principles and Procedures for Field Strength Meters (30 Hz to 1 GHz), NBS Technical Note 370, National Bureau of Standards, Boulder, Colorado, March 1969

4. Antenna Engineering Handbook, Henry Jasik, Editor, chapter 2, pp 2-5, 1st ed., McGraw-Hill, 1961, (or, Antenna Engineering Handbook, Richard C. Johnson and Henry Jasik, Editors, chapter 2, pages 2-6, 2nd ed., McGraw-Hill, 1984)

Table 1

Field Strength Extrapolation Factors in dB to be used in going from 1600 meters to 300 meters

Frequency Range	Extrapolation Distances from 1600 meters to 300 meters
10 kHz to 80 kHz	26.8 dB / f(MHz)**(0.106)
80 kHz to 375 kHz	8.3 dB / f(MHz)**(0.570)
above 375 kHz	14.5 dB

Notes for Table 1:

1. In the above table, the character, **, signifies exponentiation. Hence, terms like, f(MHz)**(0.106), should be interpreted to mean: the frequency in megahertz raised to the 0.106 power.

Table 2

Field Strength Extrapolation Factors in dB
to be used in going from: 300 meters to 10 meters
30 meters to 10 meters
10 meters to 3 meters

Frequency Range	Extrapolation Distances		
	from 300 meters to 10 meters	from 30 meters to 10 meters	from 10 meters to 3 meters
10 kHz to 80 kHz	86.5 dB / f(MHz)**(0.005)	28.6 dB	31.4 dB
80 kHz to 250 kHz	79.8 dB / f(MHz)**(0.037)	28.6 dB	31.4 dB
250 kHz to 375 kHz	71.5 dB / f(MHz)**(0.117)	28.6 dB	31.4 dB
375 kHz to 800 kHz	64.1 dB / f(MHz)**(0.228)	28.6 dB	31.4 dB
800 kHz to 2 MHz	62.8 dB / f(MHz)**(0.317)	27.6 dB / f(MHz)**(0.155)	31.4 dB
2 MHz to 4 MHz	62.8 dB / f(MHz)**(0.317)	27.6 dB / f(MHz)**(0.155)	32.9 dB / f(MHz)**(0.066)
4 MHz to 11 MHz	62.8 dB / f(MHz)**(0.317)	74.0 dB / f(MHz)**(0.865)	37.4 dB / f(MHz)**(0.160)
11 MHz to 30 MHz	29.4 dB	9.3 dB	148.6 dB / f(MHz)**(0.735)

Notes for Table 2:

1. In the above table, the character, **, signifies exponentiation Hence, terms like, f(MHz)**(0.005), should be interpreted to mean: the frequency in megahertz raised to the 0.005 power.