DEVELOPMENT OF NEAR-FIELD ELECTRIC ENERGY DENSITY METER MODEL EDM-2

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Interagency Agreement NIOSH-IA-74-13

U. S. DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE
Public Health Service
Center for Disease Control
National Institute for Occupational Safety and Health
Division of Laboratories and Criteria Development
Cincinnati, Ohio 45202
March 1975

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HEW Publication No. (NIOSH) 75-140

PREFACE

The NBS EDM-2 electric energy density radiofrequency (RF) survey monitor was developed to accurately measure the occupational exposure to electric-fields from 10 to 500 MHz. This publication explains the reasons for fabrication of the electric-field RF survey monitor, describes the characteristics of the completed monitor and elaborates on difficulties in collection and interpretation of survey monitor readings. The EDM-2 monitor was constructed because no survey instruments were available which could be used to make electric-field measurements between 10 and 300 MHz. The Occupational Safety and Health Administration (OSHA) Nonionizing Radiation Exposure Standard (29 CFR 1910.97, June 2, 1974) includes RF radiation from 10 to 300 MHz. The description of the monitor characteristics includes the design goals and final specifications for the monitor, and the calibration of the detector probe and associated meter electronics. The proper usage of the EDM-2 monitor and correct interpretation of the meter readings is given in Appendix A.

Inherent errors resulting from the use of unsuitable electromagnetic (E-M) survey instruments to measure complicated E-M fields often encountered in RF surveys are examined more completely in Appendix B. Methods to eliminate or minimize errors in collection and interpretation of survey monitor readings are also included.

Some of the more significant sources of error analyzed are (1) reactive near field conditions (which occur within approximately one wavelength from the source), (2) multipath interference (standing wave formation), (3) polarization of the field, (4) interactions between the power source and nearby objects and (5) complicated modulation of the field.

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ABSTRACT

The Occupational Safety and Health Administration (OSHA) Nonionizing Radiation Exposure Standard (29 CFR 1910.97, June 2, 1974) includes electromagnetic (E-M) radiation from 10 MHz to 100 GHz. However, no survey monitors presently are manufactured for making electric-field measurements of radiofrequency (RF) radiation from 10 to 300 MHz. Consequently, RF electric-field occupational exposure data can not be collected until suitable monitoring instrumentation is available.

The relationship between the electric and magnetic fields is completely ambiguous for near field surveys (within one wavelength of the source) of RF radiation sources. The electric and magnetic fields must be measured separately to obtain total occupational exposure. An electric-field survey monitor (EDM-2) was developed for the Physical Agents Branch, Division of Laboratories and Criteria Development, NIOSH, by the E-M Division, NBS to be used in assessing occupational exposure from industrial RF power sources.

The monitor employs a set of three orthogonal dipoles to obtain an essentially isotropic response. The dipoles are connected to the meter electronics by special high resistance conductors which have minimal interaction with the RF field. The meter displays electric energy density from 0.003 to 30 $\mu J/m^3$ which corresponds to plane-wave equivalent power density from 0.18 to 1800 mW/cm^2.

The survey monitor was calibrated from 10 to 500 MHz with specific calibration points within the Federal Communication Commission Industrial-Scientific-Medical (ISM) bands at 13.56, 27.12 and 40.68 MHz. The vast majority of high power industrial RF power sources operate within one of these ISM bands because their output power is unlimited if frequency tolerances are rigidly maintained within an ISM band.

1. Introduction

This report describes an electric energy density meter developed by the Electromagnetics Division of the National Bureau of Standards (NBS) for the National Institute for Occupational Safety and Health (NIOSH). (See figure 1.) This meter is intended for use in measuring electric near fields in the frequency range from 10 to 500 MHz. It will be used by NIOSH in their electromagnetic (EM) radiation-exposure programs to gain information about the existing exposure of humans to electromagnetic fields.

The energy density meter (model EDM-2) makes use of a set of three orthogonal dipoles to get an essentially isotropic response. The response signal is transmitted to the preamplifier (located in the probe handle) using high-resistance lines to minimize interaction with the EM fields being measured. The response signal for each dipole is corrected (see Section 3, circuit description) to maintain a square law response before being added to the response of other dipoles. The total response is then amplified and used to drive an analog meter readout. An oscilloscope output is provided as well as a lower-impedance recorder output. Variable time constants are provided to give a controllable averaging for varying signals. In addition, each orthogonal axis signal may be read independently if desired.

The EDM-2 meter has been calibrated in units of microjoules per cubic meter. It is felt that these units best provide for economics of circuitry as well as useful RF field information on an easily readable dial. They are easily converted to milliwatts per square centimeter of equivalent plane wave field (see Appendices A and B) [3,4,5,6].

The EDM-2 meter provides substantial improvement over previous meters of this type. These improvements include a faster rise and fall time for pulse response, a dynamic range of 50 dB, lower noise preamplifiers, a greatly reduced temperature sensitivity, a flat response (to within ± 1.0 dB) from 10 MHz through 500 MHz as well as other refinements. The EDM-2 meter provided

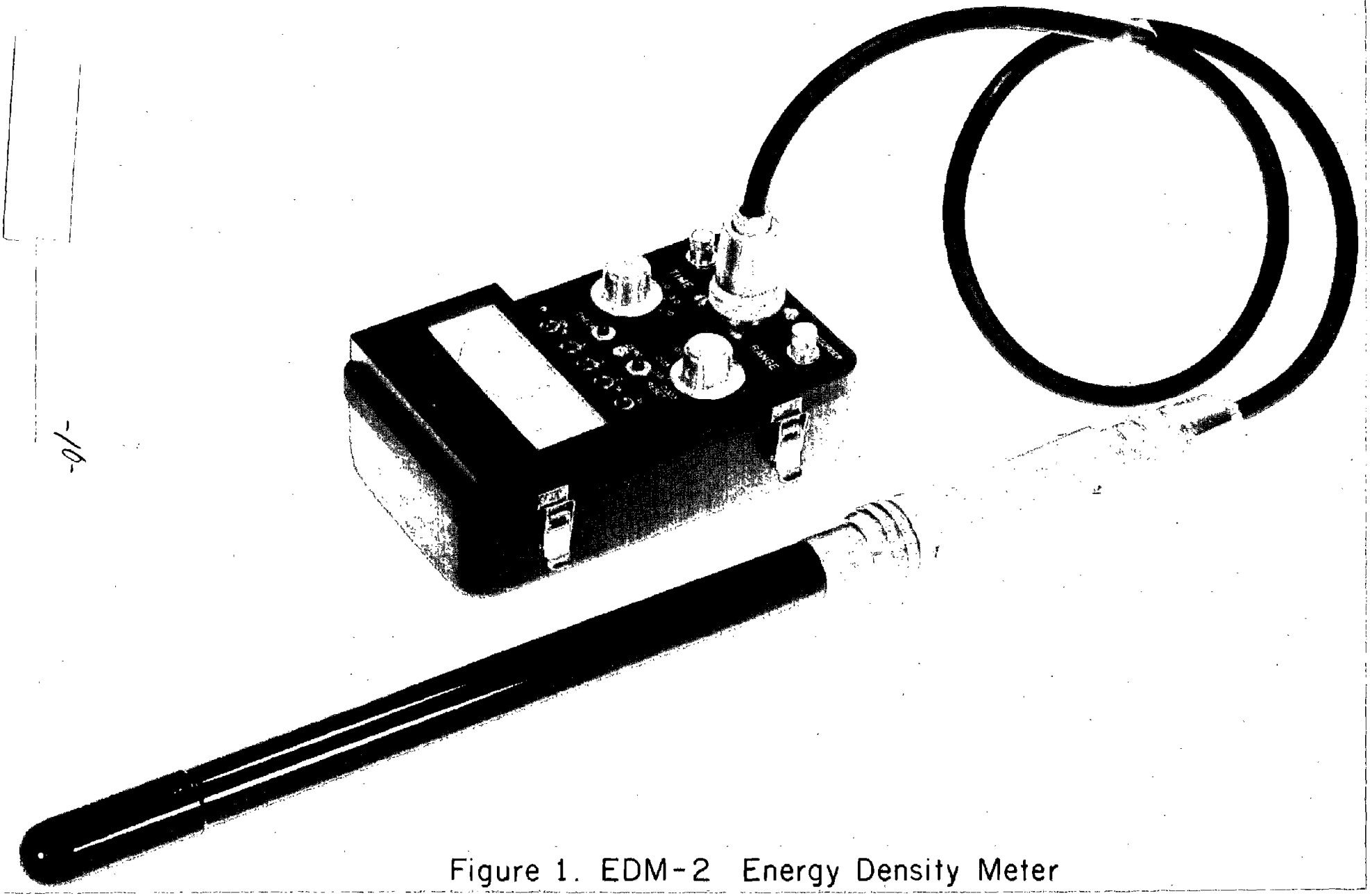

Figure 1. EDM-2 Energy Density Meter

under this contract has been calibrated at frequencies of 13.56 MHz, 27.12 MHz and 40.68 MHz, at the sponsor's request, as well as other selected frequencies from 10 MHz to 500 MHz.

2. Design Goals and Results for the EDM-2 Meter

2.1 Frequency Response. The meter was designed to operate over the frequency range of 10 MHz to 500 MHz with a maximum response variation of ± 1.0 dB. If the response at 40.68 MHz is used as a normalization point, the performance is well within these limits. 40.68 MHz was used as a normalization point since it appears to be the frequency most often encountered in the field. For an average channel the worst case response, with respect to frequency, varies from -0.54 dB at 13.56 MHz to +0.34 dB at 200 MHz. These variations in response are felt to be largely due to calibration equipment limitations rather than actual probe response. Figure 2 shows the EDM-2 correction factors with respect to frequency.

2.2 Frequency Calibration Points. The meter was calibrated at 13.56 MHz, 27.12 MHz and 40.68 MHz. The meter, as supplied, is calibrated to read directly at 40.68 MHz. For more accurate results at 27.12 MHz the reading must be multiplied by 1.047. At 13.57 MHz the correction factor is 1.133. Other correction factors may be estimated from figure 2.

Calibration was done using a TEM cell [1] on the lower dynamic ranges up through the 0.3 $\mu J/m^3$ range. On the upper ranges calibration was obtained by extrapolation from the cell data using a balun and direct connection to the dipoles. It is assumed in using this method that the response of the diode and lines is independent of the source of the voltage impressed on the dipoles. With proper shielding and a good balance at the output of the balun this assumption is felt to be very good.

2.3 Dynamic Range. The design goal was a ± 20 dB range centered at approximately 0.17 $\mu J/m^3$ (0.17 $\mu J/m^3$ = 10 mW/cm^2). This was

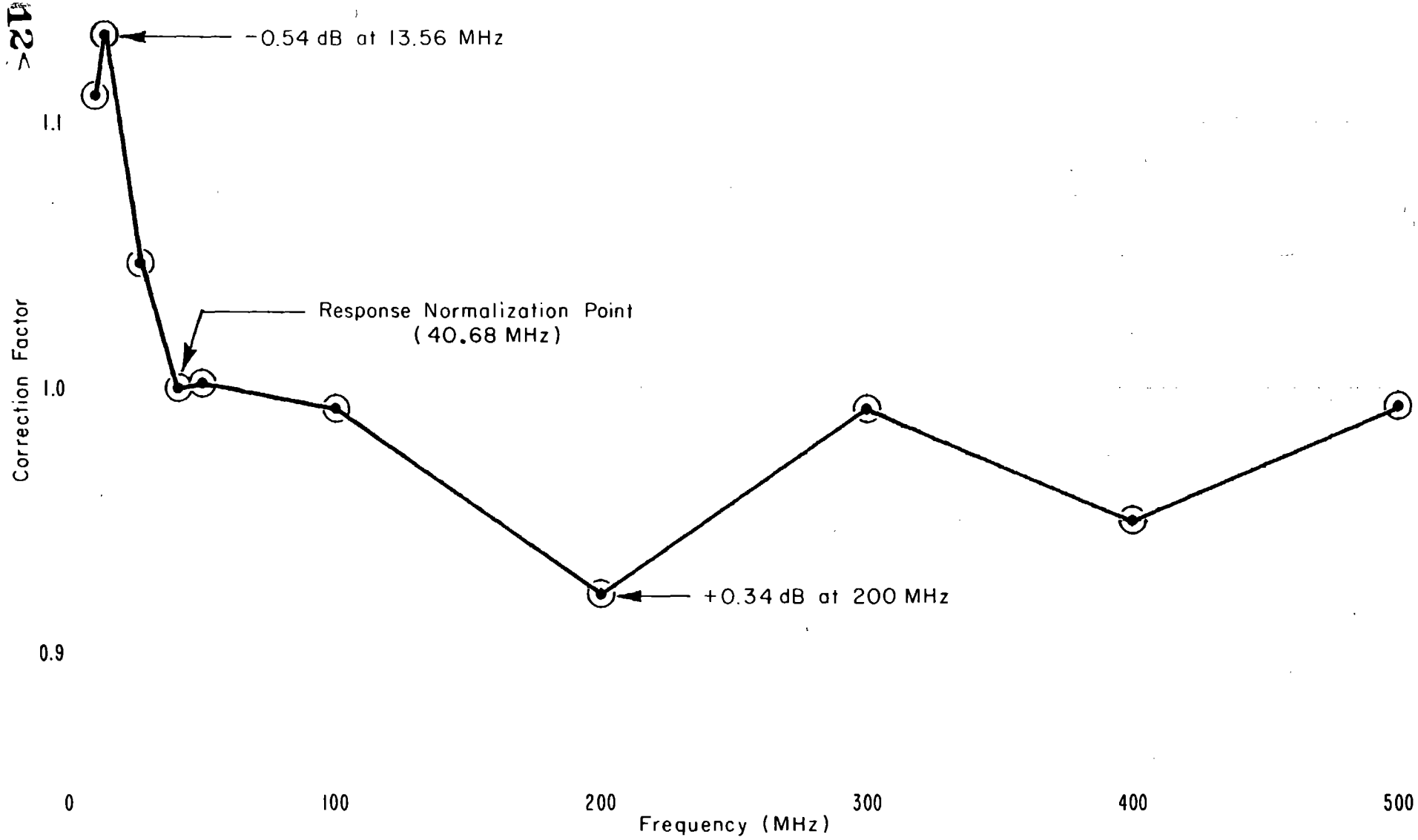

Figure 2 Correction Factor with Respect to Frequency

achieved and the EDM-2 meter has usable full scale ranges in a planewave field of 30, 10, 3, 1, 0.3, 0.1, 0.03, 0.01, 0.003 $\mu J/m^3$. This represents a factor of 10 increase in dynamic range over previous meters of this type. Figure 3 shows the EDM-2 z-channel response with correction to square law over 4 decades of dynamic range. The x and y channels are identical in response. The minor deviation from square law at the low power density end of the curves is due to drift in the zero settings of the meter and recording amplifiers. The two curves shown represent the response on two ranges of the EDM-2.

2.4 Isotropic Response. All patterns were made using a microwave antenna range at 1 GHz. This frequency was used rather than a lower frequency because of equipment limitations. The use of this frequency is felt to be a somewhat more severe test of the response pattern than the use of a lower frequency.

The probe provided with the EDM-2 has an isotropic response to within ± 1.0 dB in all directions except for propagation along the handle towards the sensor.

Figures 6 and 7 indicate the equipment geometry used for generating the E and H patterns. The relative response as measured in the E plane is shown in figure 4. Note that the variation in response with respect to angle is greatest for angles more than 90° but in all cases is within the specified limits of ± 1.0 dB. The relative response in the H plane is shown in figure 5. Both the E and H plane patterns were taken at about midscale on the 0.3 $\mu J/m^3$ range.

Figure 8 shows the "analytic" pattern of the EDM-2. This pattern was taken in free space at 1 GHz but is essentially identical to the same pattern taken in the TEM cell used for the calibration of the lower dynamic ranges. The analytic pattern is made by introducing the probe into the field at an angle such that the individual dipoles are brought into both the full response position and the null position as the probe is rotated about the axis of the handle. The individual response of each channel is shown as well as the total response from all three channels.

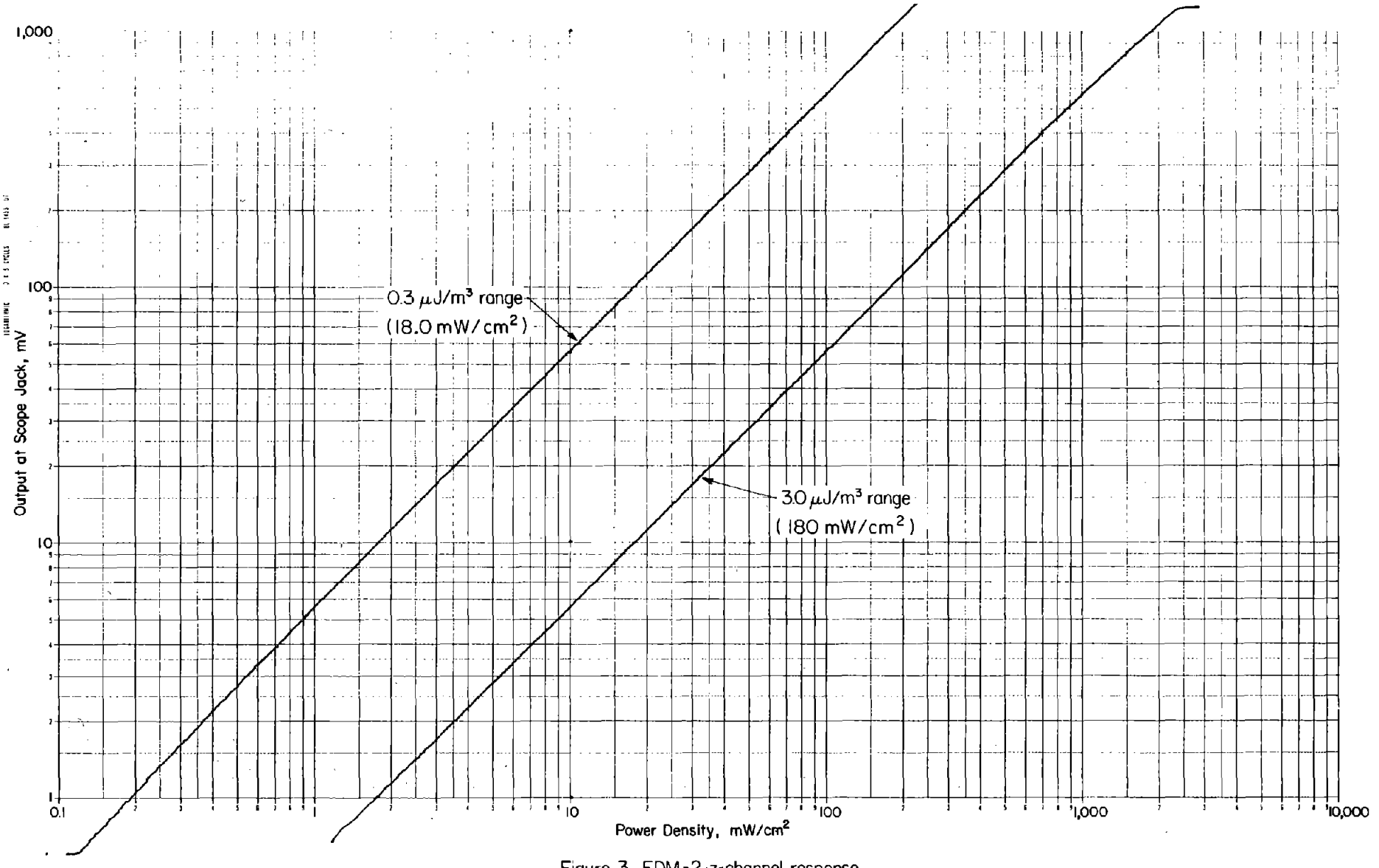

Figure 3. EDM-2 z-channel response.

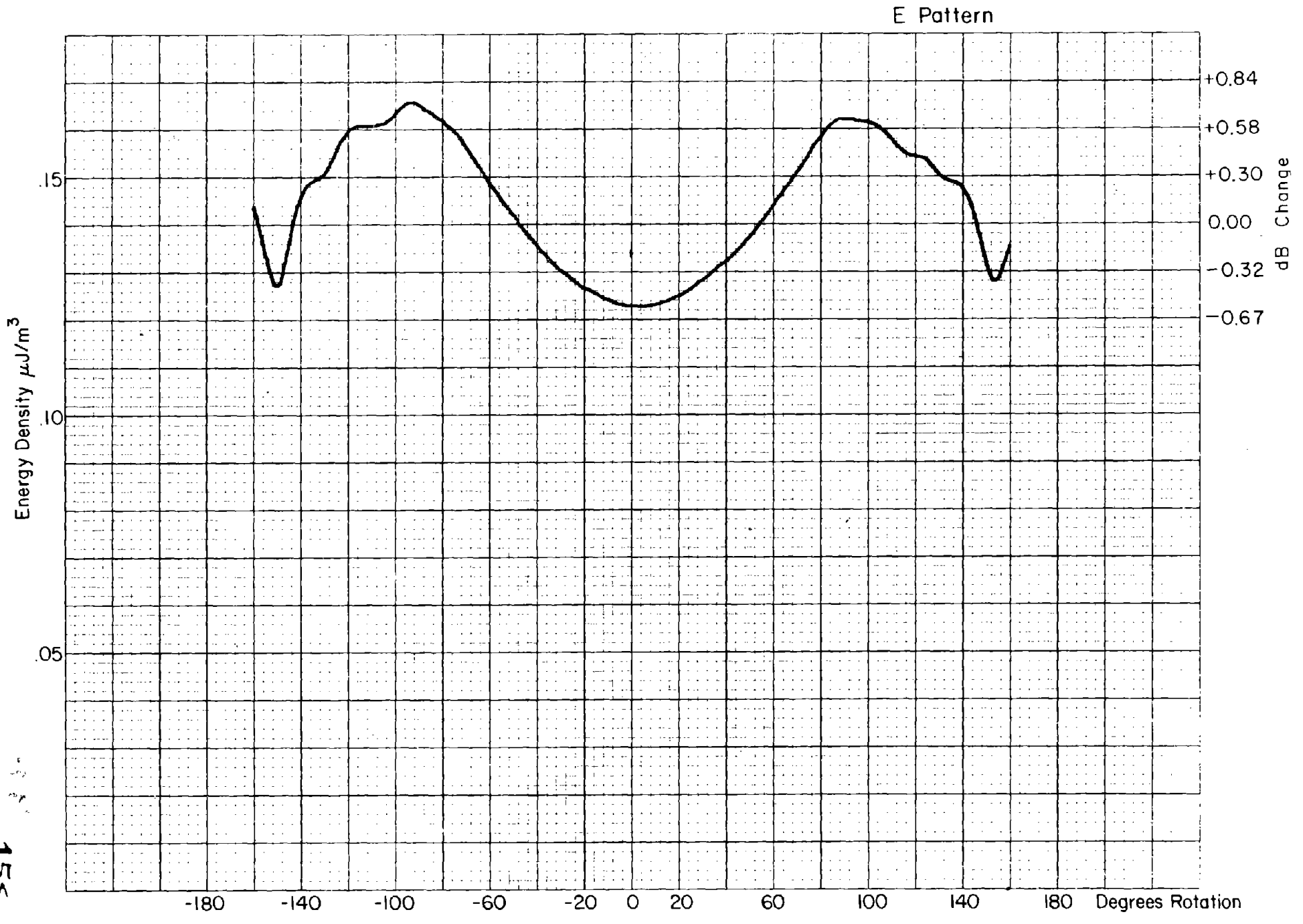

Figure 4. E plane pattern.

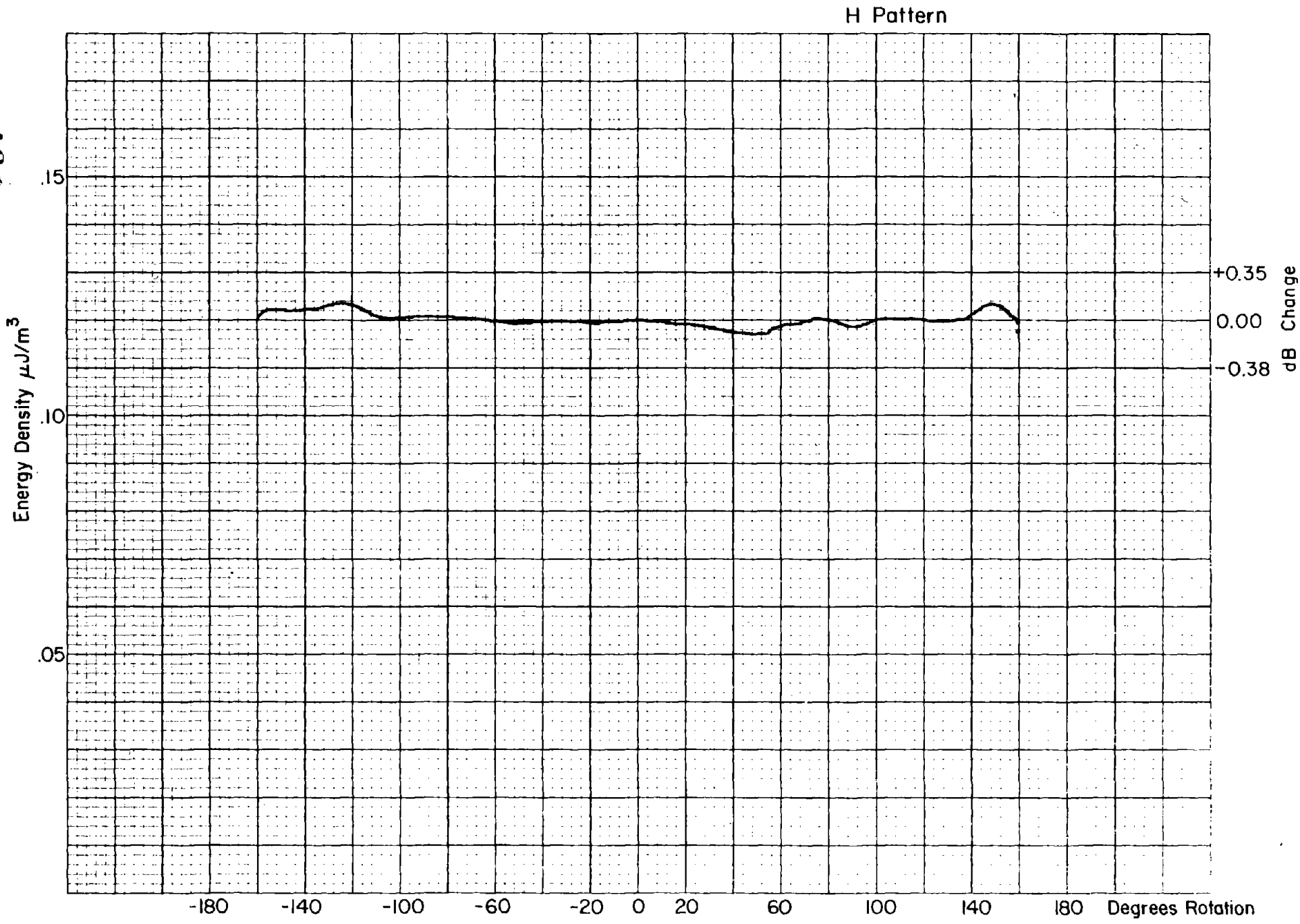

Figure 5. H plane pattern.

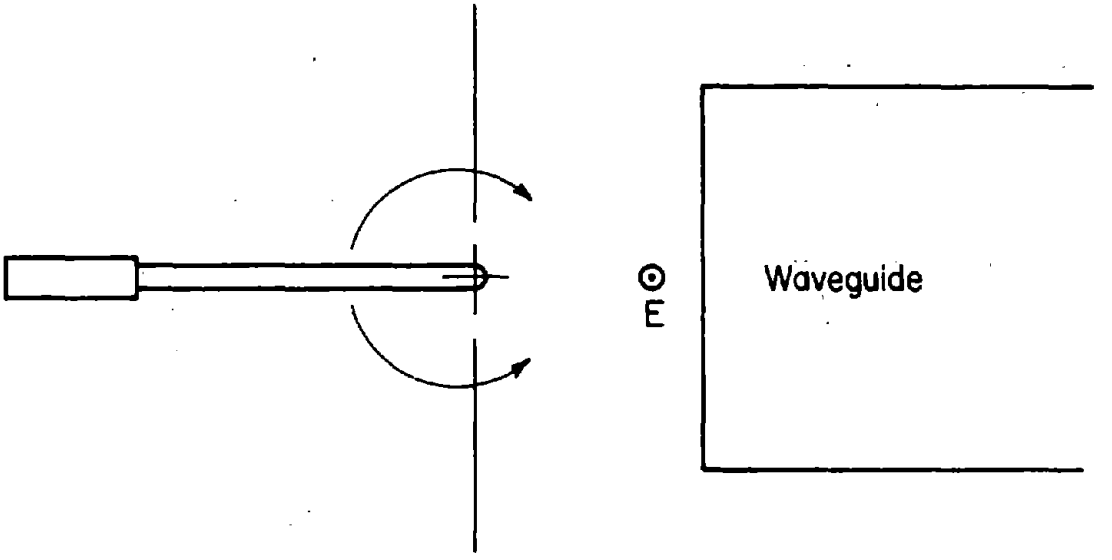

Figure 6. Arrangement for generating H plane pattern. The zero degree position is shown.

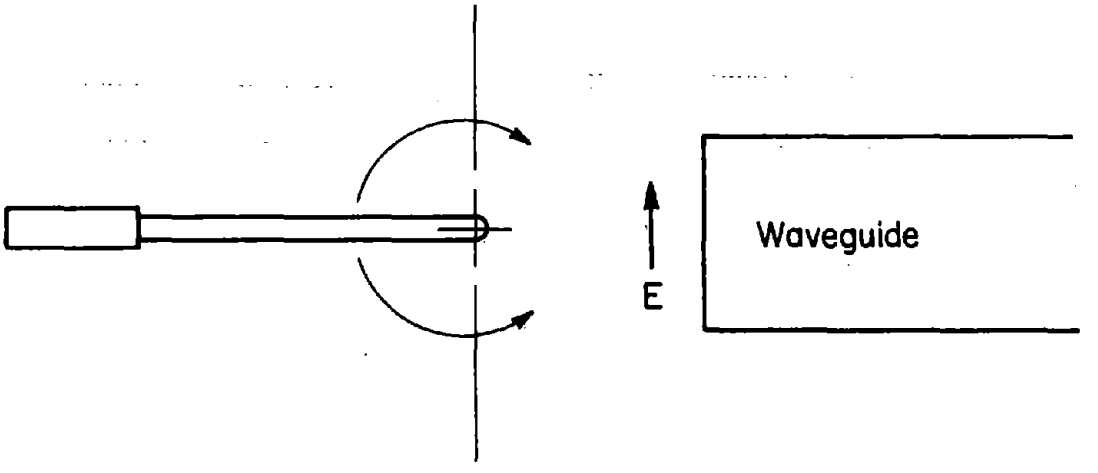

Figure 7. Arrangement for generating E plane pattern.

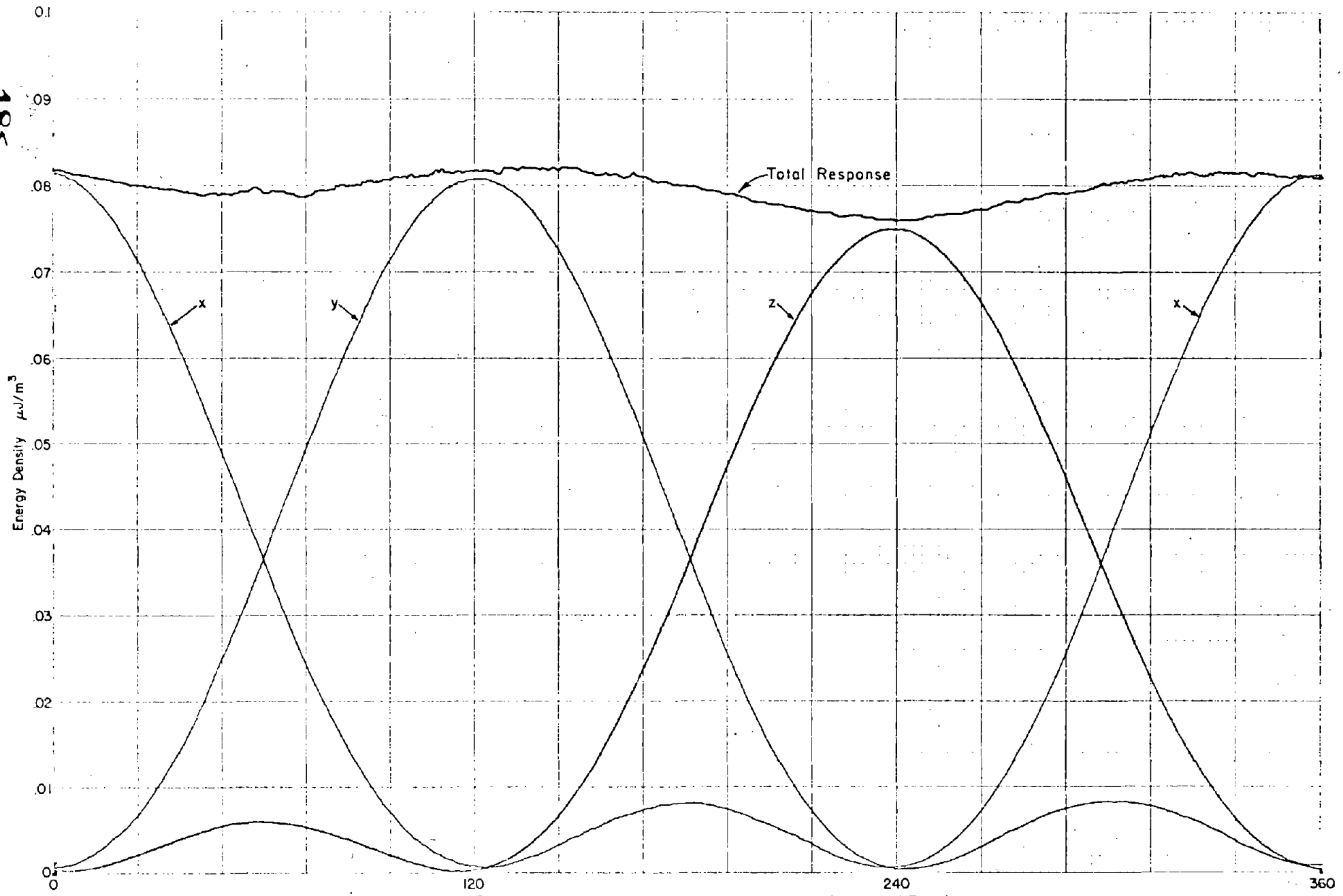

Figure 8. EDM-2 Analytic Pattern at 1 GHz

2.5 Temperature Response. Greatly improved temperature response was achieved in the EDM-2 meter by loading the dipole detector diodes with equivalent load diodes. The load diodes are placed in the circuit near the end of the probe but are shielded so as to give no RF response. (See figure 10.) Measurements show that worst case variations in response due to temperature are less than ± 0.7% per C° in the range of 15 to 35°C, using this technique. Calibration as a function of frequency was carried out at approximately 24°C. Original specifications called for an ambient temperature variation not to exceed ± 3.0% per °C.

2.6 Response Time. The worst case rise time and fall time occurs with a low power density and the meter operating on the lowest range (.003 $\mu J/m^3$). For this case both rise time (10% to 90% of signal) and the fall time (90% to 10% of signal) are less than 0.6 millisecond. For power densities reading on the higher ranges the rise and fall times are less than 0.2 millisecond. Original specifications called for rise and fall times of less than 5 milliseconds. This improvement over the original specifications is due in part to: (a) an improved low-capacity transmission line from the dipoles to the preamplifiers [2], and (b) the use of a detector diode having a lower impedance than previously available.

3. Circuit Description

Each channel of the meter sensor consists of a dipole having two rectifying diodes in parallel across it. The rectified signal is fed along a short length of high resistance line to a pair of shielded load diodes and then along more high resistance line to the preamplifier. (See figure 10.)

The preamplifier is designed to provide proper sensor loading, precise zero adjustment, good common mode rejection ratio (CMRR), low drift and low noise operation. The operational amplifier used is a type having very low popcorn noise. (See figure 9.)

By proper adjustment of both the 7-30 pF CMRR capacitor and the 200 K CMRR resistor in the preamplifier it is easily possible

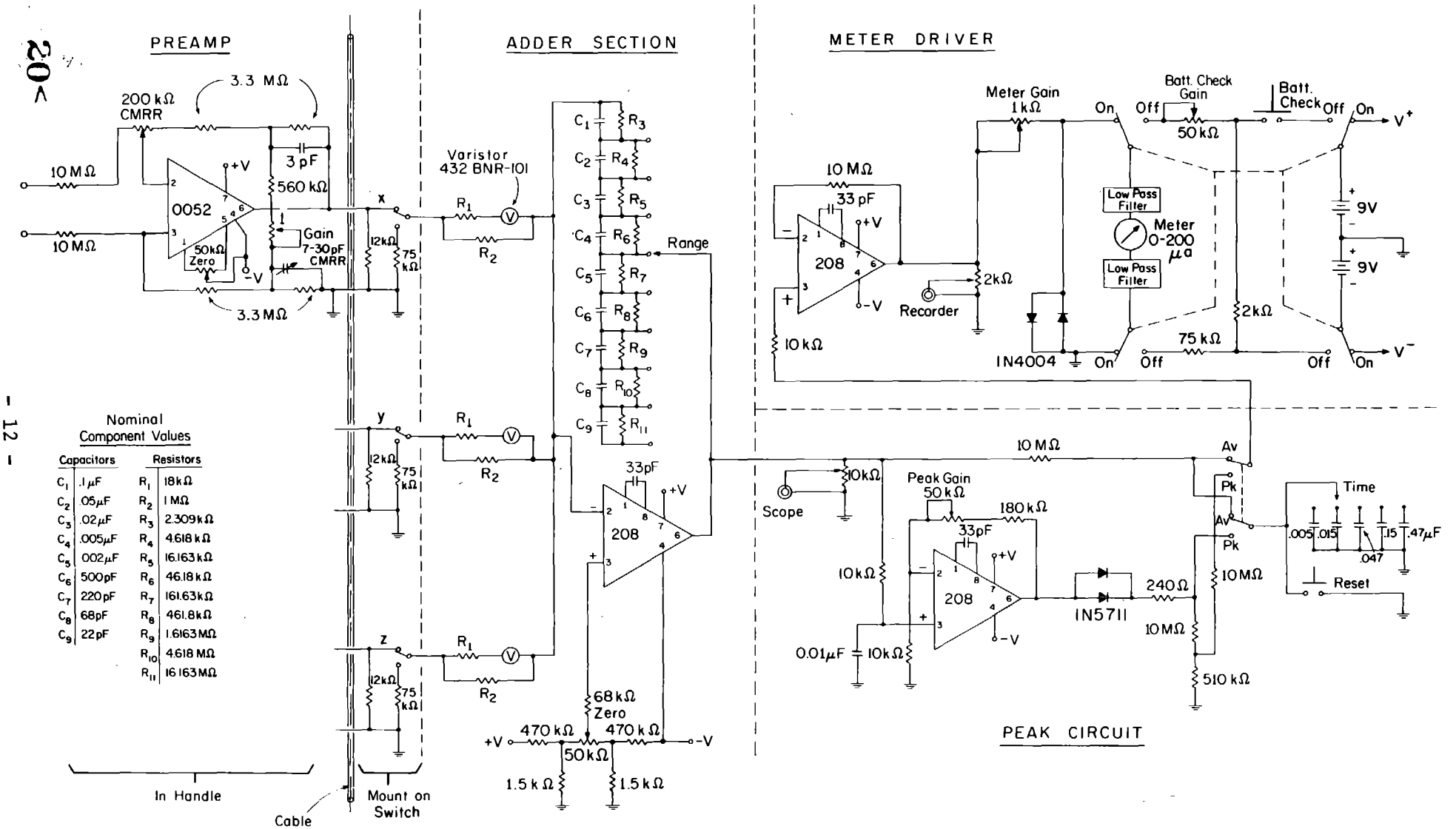

Figure 9. EDM-I Circuit Diagram

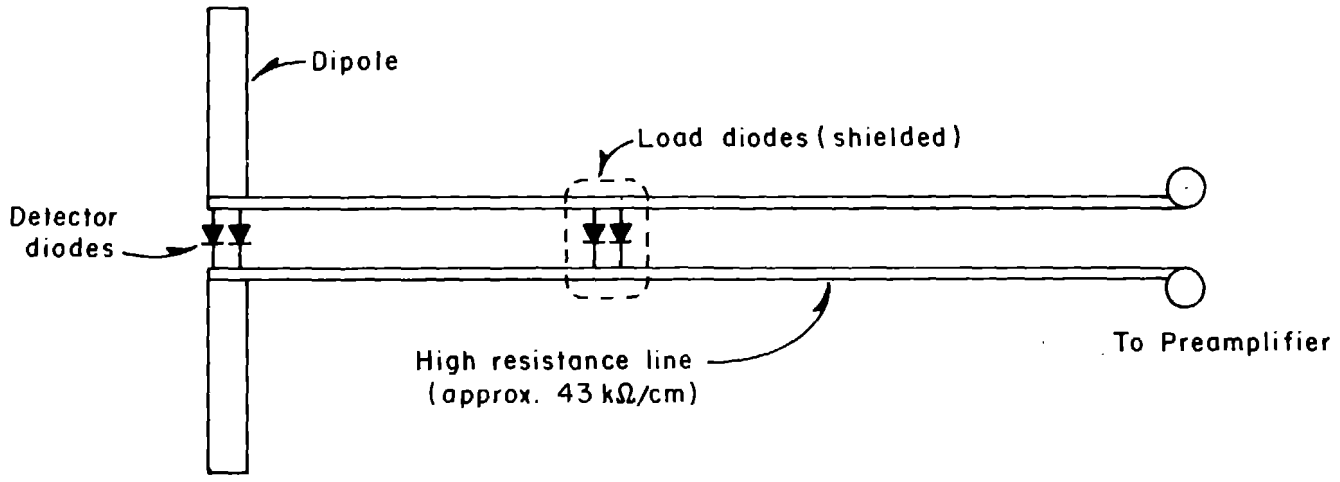

Figure 10 Schematic of an Individual Receiving Dipole

to get greater than 65 dB of "broadband" common mode rejection from DC to approximately 1.5 kHz. Additional CMRR is available in the rest of the circuit.

The varistor network at the input to the adder section is used to force the signal to represent a square law response to the RF field voltage over a greater dynamic range than the detector diodes can provide alone.

The adder section sums the square law response from all three channels. The adder output is available at the "scope" jack if it is desired to monitor rapid signal variations.

The peak circuit section can be switched in to provide a peak reading of a varying RF signal.

The meter driver amplifier provides a low impedance output to drive the meter without loading the previous circuitry. A tap is provided at the output of the meter driver amplifier for use with recorders.

Since all the adjustable resistors are set to values which are critical to maintaining the initial calibration, it is very important not to change the original settings. The one exception is the zeroing resistor which has an adjustment access on the front panel of the meter.

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APPENDIX A

OPERATION INSTRUCTIONS FOR EDM-2 ELECTRIC ENERGY DENSITY METER

APPENDIX A

Operation Instructions for EDM-2 Electric Energy Density Meter

To Operate. Turn on; place X, Y, Z switches "up" towards cable connector; place AV-PK (average-peak) switch in desired position; check meter zero (with field sensor either shielded with metal tube or at position of negligible field intensity); place sensor tip at point of interest and read meter. To use a single X, Y, or Z channel, follow above instructions but place only the desired channel switch in the up position. Note that if the meter has been zeroed for all-channel operation it must be re-zeroed for single channel operation and vice versa.

Plane-wave Fields. If a plane-wave field is being measured (a questionable circumstance), the power density of the plane-wave field is easily obtained by

$$S(\mathrm{mW/cm^2}) = 60.0\ U_E(\mu\mathrm{J/m^3})$$

or

$$S(\mu\mathrm{W/cm^2}) = 60.0\ U_E(\mathrm{nJ/m^3}).$$

Also, for comparison purposes, energy density readings for real fields may be converted to "equivalent-plane-wave" power densities by use of the above formulas. Note that the red mark on the meter dial corresponds to a value of 10 $\mathrm{mW/cm^2}$ for a plane-wave field when the range switch is set to 0.3 $\mu\mathrm{J/m^3}$.

Field Strength for General Fields. The Hermitian magnitude E of any EM field is

$$E \equiv (E_x^2 + E_y^2 + E_z^2)^{\frac{1}{2}}$$

and is related to U_E by

$$E(\mathrm{V/m}) = 475.3[U_E(\mu\mathrm{J/m^3})]^{\frac{1}{2}}$$

or

$$E(\mathrm{V/m}) = 15.03[U_E(\mathrm{nJ/m^3})]^{\frac{1}{2}}$$

Battery Check and Replacement. To check the condition of the batteries turn off the meter and depress the "check" button. The meter indication (10-scale) is equal to the average of the absolute values of the plus and minus voltage supplies. When using either 8.2 volt mercury batteries or 9 volt carbon-zinc batteries, the batteries should be replaced at an indication of approximately 7. Both batteries should be replaced at the same time and with batteries of equal freshness to avoid the condition where one battery might decay much more rapidly than the other. Battery life using mercury batteries should be in excess of 30 hours.

CAUTION: Do not remove the batteries by pulling on them. Instead, use a "pry" placed between the mating connectors on the battery and the battery holder.

Scope and Recorder Outputs. The scope output is driven directly by the amplifier that sums the X, Y, and Z channels. The amplitude modulation of the RF field may be observed here, within the approximate 0.3 ms 90% rise and fall time of the field-sensor output. The recorder output is driven by the meter-driving amplifier and shows either the peak or the average of the waveform observed at the scope output depending on the setting of the AV-PK switch. Both the scope and recorder outputs are 0.1 volts for full scale indication of the meter. To obtain a convenient voltage for external instruments, place the range switch in one of the "10-scale" positions so that, for instance, a 0.1 volt output will correspond to 1 $\mu J/m^3$. When using oscilloscopes, recorders, or DVM's connected to the scope or recorder outputs, the meter of the EDM may be overdriven indefinitely without harm.

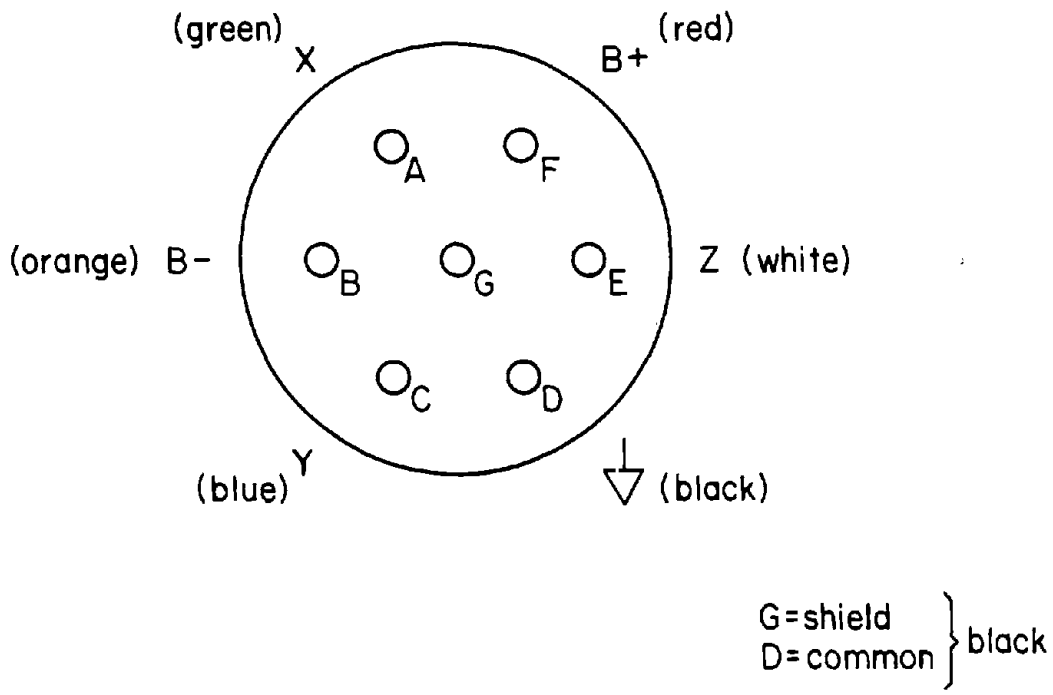
Preamplifier Precautions. If the preamplifier circuit boards (inside the metal handle of the probe) become contaminated, they may develop a large amount of leakage, producing unstable operation or an inoperable condition. Do not open the preamplifier housing unless necessary (for trouble-shooting or

cleaning), and do not touch circuit boards with contaminated objects (such as fingers). DO NOT CHANGE SETTINGS OF ANY OF THE TRIMMING POTENTIOMETERS ON EACH PREAMPLIFIER BOARD.

Case Ground. The circuit common is connected to the case ground at only one point, which is in the meter housing.

Connectors. The cable connectors are modified "military" types. They have been modified to provide good RF shielding characteristics. The connectors are solidly potted with silicone rubber inside, and the cable shield is bonded with silver-loaded epoxy to compression washers inside the connector shell. It is probably not worthwhile to try to repair these connectors in the event of cable failure.

Connector and Cable Wiring.



Conductive Coating. The plastic tube of the probe has been covered with a slightly conductive coating. This coating provides an effective "static noise" suppressor without significantly attenuating waves with frequencies above about 1 MHz. The conductive coating is covered with an epoxy enamel to protect it from abrasion. Because the conductive coating does not have high adhesion to the plastic tube, nor does the epoxy enamel have high adhesion to the conductive coating, the probe should be treated gently to avoid chipping or flaking of the coatings. Also, pressure sensitive tapes should not be used on the coatings (unless the tapes are to be left in place) since these tapes might strip-off the coatings.

DANGER: When using the probe around un-shielded high voltage supplies, the epoxy outer coating must not be relied on to provide protection from a shock hazard. For shock protection, use a styrofoam ball over the tip of the probe. In some cases it might also be advisable to use a thin plastic tube over the probe behind the styrofoam ball. Further, it is advisable to ground the case of the instrument when probing around un-shielded high voltage supplies.

Use of Shields. A set of probe shields has been provided for the EDM-2 meter. The large shield can be placed over the probe with the spring fingers contacting the large knurled nut in front of the preamplifier. With this shield in place the dosimeter may be zeroed while in an EM field, thus eliminating the need to leave the field to obtain a zero setting.

The smaller probe end shield can be used to eliminate the response of the detector diodes when placed over the end of the probe. With this shield in place the level of common mode pickup and RF leakage into the preamplifiers may be checked.

Use in High Level Fields. The EDM-2 dosimeter detector diodes as used in the probe will easily measure a power density at full scale on the meter (30 $\mu J/m^3 \simeq 1800\ mW/cm^2$) with no

risk of burnout. The actual power density required to disable the probe has not been evaluated but is believed to be greater than 500 watts/cm^2 (500 W/cm^2 = 8333 μJ/m^3). Even with a field level high enough to disable the probe, actual burnout may not occur due to the limitation in current through the detector diodes that is provided by the associated circuitry. It should be noted, however, that pulsed fields having a reasonable average power with a low duty cycle may extend into this range during the peak of the duty cycle.

Harmonic Response. The EDM-2 meter has a relatively flat response over a large frequency range. Because of this the meter will respond to the "sum" of all fields present within its range of frequency response. Thus, it should be noted that power densities due to the harmonics of the calibration frequencies, as well as any other frequencies, will be added into the final reading. It should also be noted that the"addition" of these fields, where the total field is above approximately 0.17 μJ/m^3 (0.17 μJ/m^3 = 10 mW/cm^2), will tend to give a high output reading. The reading may be high since the addition of the responses to these fields takes place at the dipoles and if the response exceeds the square law region of the detector diodes the resultant signal may not add properly to give a correct total. When the total reading is below 10 mW/cm^2 and the other frequencies present are within the range of the meter the output reading is felt to be correct.

APPENDIX B

NBS TECHNICAL NOTE 389: QUANTIFYING HAZARDOUS ELECTROMAGNETIC FIELDS: PRACTICAL CONSIDERATIONS

NBS TECHNICAL NOTE 391: QUANTIFYING HAZARDOUS MICROWAVE FIELDS: ANALYSIS

UNITED STATES DEPARTMENT OF COMMERCE
Maurice H. Stans, Secretary
NATIONAL BUREAU OF STANDARDS ● Lewis M. Branscomb, Director

NBS TECHNICAL NOTE 389

ISSUED APRIL 1970

Nat. Bur. Stand. (U.S.), Tech. Note 389, 15 pages (April 1970)
CODEN: NBTNA

Quantifying Hazardous Electromagnetic Fields: Practical Considerations

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QUANTIFYING HAZARDOUS ELECTROMAGNETIC FIELDS: PRACTICAL CONSIDERATIONS * †

Ronald R. Bowman

Abstract- The usefulness of power density to express the hazard potential of electromagnetic fields is limited to simple fields that are approximately uniform and plane wave. For fields that are complicated by having reactive components or by having multipath interference patterns, power density is not a suitable parameter for quantifying the potential hazards because: (a) such fields can be very strong even though the power density is small, and (b) the power density in such fields is very difficult to measure. Since some of the most important hazardous fields can involve very complicated field configurations (for instance, fields near leaking cracks in microwave ovens), it is important to establish a more rational measure for hazardous fields. A qualitative discussion is given of the many issues involved in selecting a suitable field parameter for quantifying hazardous electromagnetic fields in general. It is concluded that the total energy density of the field is the best parameter, but in many instances the electric energy density alone will be adequate. Some general discussion is given concerning "ideal" instrumentation for quantifying hazardous fields.

Key Words: electromagnetic fields; hazards; quantifying; field parameters; instrumentation.

1. Introduction

The discussion by P.F. Wacker in Technical Note 391 is concerned primarily with analysis and with the problem of realizing an accurate probe for quantifying hazardous electromagnetic (EM) fields under very general conditions. In contrast, the present paper is concerned mainly with the problem of making easy, reasonably accurate

* This work was partially supported by the Bureau of Radiological Health.

† This paper is essentially identical to one prepared for the Symposium on the Biological Effects and Health Implications of Microwave Radiation, Richmond, Virginia, September 17 through 19, 1969.

survey measurements of hazardous EM fields. For general survey use, instruments should be rugged, easy-to-use, and should be capable of fast response as well as having long-term averaging capabilities. These, and other considerations to be discussed, place restrictions on practical instrument designs for general survey use.

It is very difficult to determine, even with reasonable accuracy, the biological hazards associated with EM fields. Even in the simple case of a plane-wave field with uniform power density, the energy absorption by biological material is quite complicated[1]. At the present time, only the hazards related to uniform plane waves in free space (i.e., far from the source and any scattering objects) have received extensive study; and the standards, terminology, and most of the measuring instrumentation pertain only to this simple case. Apparently, this is why "power density" (i.e., the time-averaged magnitude of the Poynting vector)[2] is the presently used quantity for stating hazardous EM field levels, despite the serious objections to this practice raised here and by Wacker in Technical Note 391. Since the usefulness of power density to quantify hazardous EM fields is questionable except for uniform plane-wave fields and since some of the most important hazardous EM fields involve very complicated field configurations (for instance, fields near leaking cracks in microwave ovens), it is important to establish a more rational measure.

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[1] See, for instance, H.P. Schwan, "Radiation Biology, Medical Applications, and Radiation Hazards", in Microwave Power Engineering, vol 2, edited by Ernest C. Okress, Academic Press, New York, 1968).

[2] Poynting's interpretation of the energy density and power flow in electromagnetic fields is subject to philosophical difficulties. See footnote 1 in Technical Note 391. Also, see D.S. Jones, The Theory of Electromagnetism, MacMillan, N.Y., N.Y., 1964, pp. 51-53. These considerations are beyond the scope of this paper, and they will not involve us in any concrete errors.

Many complicated issues are involved in selecting a suitable parameter for quantifying hazardous EM fields. The discussion here will be qualitative and is intended merely as a sketchy introduction to the complications considered. It is hoped that the discussion will clarify the basic issues.

2. Complexities of Electromagnetic Fields.

2.0 Discussion.

Undoubtedly, another reason that the use of power density (i.e., energy flow) has become established is that energy flow presents a simple conceptual picture of the interaction of the field with matter. Unfortunately, this conceptual picture is often very inaccurate. EM fields with frequencies below about 10 GHz do not bear much analogy with optical radiation or ionizing radiation. However, they do bear some analogy with audible sonic fields because of the comparable wavelengths involved. The free-space wavelength of a plane-wave 1000 MHz EM field is about 30 cm, and the free-space wavelength of a plane-wave 1000 Hz sonic field is also about 30 cm. Of course, plane-wave EM radiation involves transverse rather than longitudinal vibrations so that polarization is an important additional complication of EM radiation, but otherwise there are useful analogies between microwaves and audio waves. Some of these analogies will be used below in discussing the complexities that will commonly be encountered when surveying for hazardous EM fields.

2.1 Elliptical Polarization.

In general, the tip of the electric vector (or of the magnetic vector) will trace an ellipse if the vector is plotted as a function of time. Except for the rotational sense, the polarization of the field can be specified by the axial ratio of the ellipse. Radar, telemetry, and communications systems normally use antennas with either linear

or circular far-field polarization, which are special cases of elliptical polarization; but at points near the transmitters of these systems, the polarization can be arbitrary. Very often, the polarization of the field will not be known when making hazard surveys. Furthermore, the polarization of the field may change radically from point to point within the field. For instance, if a microwave oven has a leak from a horizontal crack and also a leak from a vertical crack, the polarization of the resulting field will vary in a very complicated way in the region around the oven. (It should be mentioned that polarization is usually only defined with respect to plane wave propagation. However, it is possible to define polarization for arbitrary waves[3], and it is this general situation that is of interest for hazard surveys.)

2.2 Multipath Interference.

Propagation of fields of the same frequency to a given region of space will cause interference patterns ("standing waves"). This is a familiar phenomenon with sound waves, and the spacing between positions of constructive and destructive interference for audible sound waves will be roughly equal to those for microwave multipath interference because of the comparable wavelengths involved. The net power density in multipath fields can be less than the power density of the individual component waves considered separately. In particular, two plane-wave fields of equal amplitude and frequency but opposite propagation directions combine to give a field with zero net power density. However, the combined field will have electric and magnetic field maxima of twice the amplitude of the component waves. Clearly, if the two component waves are each hazardous, then the combined field is also hazardous despite the fact that the power density is zero. Similar difficulties occur in

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[3] Born and Wolf, Principles of Optics (second revised edition), MacMillan, N.Y., N.Y., 1964, pp. 34-36.

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attempting to relate the power density of multipath fields in general to potential hazards. Therefore, power density is a poor indicator of the potential hazards of multipath fields.

2.3 Reactive Near-Field Components.

Within distances of roughly one wavelength of some sources (for instance, inefficient radiators), there can sometimes exist strong EM field components that do not have a time-averaged energy flow (though they will have instantaneous energy flows). That is, the total field in these regions can be divided into a radiation component and reactive components (see almost any text on electromagnetic theory); and the time-average of the Poynting vector for the reactive field components is identically zero. The radiation field represents a flow of energy away from the source, but the reactive field has no corresponding energy loss. The energy associated with reactive fields pulses back and forth between the source and the surrounding space during the period of the oscillation, similar to the energy flow between capacitances and inductances in electrical circuits. (This situation is analagous to the operation of an unbaffled speaker cone. At low audio frequencies, i.e., for wavelengths larger than the dimensions of the cone, a speaker cone operating in open air is an inefficient radiator because the air propelled by the cone merely rushes around to the reverse side of the cone. This produces relatively little sound radiation to points far from the cone even though the instantaneous air flow around the cone can be very great.)

2.4 Interactions Between the Source and Nearby Objects.

A measuring instrument, subject, etc. placed near to a source can establish multiple propagation back-and-forth between the object and the source. This interaction can involve both scattering from the

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external surfaces of the source and also coupling with the internal regions of the source. In one sense, this can be considered as a complicated case of multipath interference, but it should be remembered that the coupling with the internal regions of the source can substantially (even greatly) change the total amount of energy withdrawn from the source. This interaction can be exceedingly complicated and is determined, for a given wavelength, not only by the electrical composition of the source, the object of interest, and other nearby objects but also by the sizes, shapes, positions, and orientations involved.

2.5 Complicated Time Variation of the Configuration and Intensity of the Field.

We are not concerned here with the periodic variation of the field vectors at the radio frequency. Rather, we are concerned with the longer term variation in the configuration of the field and in the amplitudes of the electric and magnetic vectors. Consider, for instance, a microwave oven that has two widely-separated leakage cracks. Since the microwave sources in many ovens are operated from unfiltered power supplies, the field created by the leakage from these cracks may go on and off at twice the power-line frequency. Further, since most ovens have "mode" stirrers (metal vanes that rotate, typically, every few seconds to "stir" the field configuration inside the oven), the phase and amplitude of the field just outside each crack may change radically every few seconds, independently of the other crack. The resulting time variation in the multipath field outside the oven can be extremely complicated. (It is pertinent to note that a leakage crack in an oven may leak only for the fraction of a cycle of the mode stirrer. Therefore, it is possible for the peak-to-average ratio to be quite high for microwave oven leakage.)

3. Approaches to Quantifying EM Hazards.

3.1 The Dosimetry Approach.

In surveying for hazardous EM fields, one wishes to determine as accurately as possible the potential biological dose (e.g., the temperature rise) or the exposure (e.g., the induced currents or the EM field established) that would result at points of interest inside a subject if introduced into the field. In general, because of the complications mentioned in Section 2, it is not practical to accurately predict the biological dose or exposure from knowledge of the parameters of the unperturbed field (i.e., the field before the biological material is introduced). This means that accurate dosimetry for EM field hazards must be done with phantoms that simulate not only the electrical characteristics of the body but also the size and, to a lesser degree, the shape of the body. Probably, a head-sized sphere or ovoid would suffice for a phantom in most situations of interest. At points inside the phantom, the thermal dose could be measured by the temperature rise or the exposure measured by the currents or the EM field established. The usefulness of this type of instrument is limited because the size and weight of the phantom would seriously hamper general survey measurements of potentially hazardous EM fields. Therefore, even though the dosimetry approach is most accurate, it is felt that it will probably not be used much outside of the laboratory.

3.2 The Field Parameter Approach.

This approach assumes that the biological effects, or at least the possible effects, resulting from the EM field can be adequately predicted from knowledge of one or more parameters that describe the field.

Because the biological effects are so difficult to predict, this approach will always involve a conservative standard for the maximum allowable level of the field parameter used to quantify the field. Though this approach is somewhat arbitrary, it is felt that it is the most practical approach to the problem of making general survey measurements. Some discussion about the choice of a suitable field parameter and the general characteristics of suitable instrumentation will be given later.

3.3 The Arbitrary Approach.

This approach would use an instrument that would respond to the EM field but would not, in general, yield an accurate measurement of either the dose that could be expected from the field or one of the parameters of the unperturbed field. For instance, suppose that the instrument is based on the temperature rise in a small piece of material that simulates only the electrical characteristics of biological material. Since a small piece of material cannot adequately mimic the energy absorption of, say, a human head, this instrument could not be expected to yield an accurate measurement of the dose resulting from complicated EM fields. Further, unless the piece of absorbing material is quite small, the instrument will strongly affect the field near, say, a radiating crack; and thus, a measurement of the unperturbed field would be practically impossible. (If the piece of absorbing material is quite small, it could, under certain conditions, provide an accurate measurement of some parameter of the unperturbed field; but then the instrument would satisfy the more stringent approach outlined in Section 3.2).

The arbitrary approach is considered to be the least satisfactory of the three approaches outlined. However, until very recently, it was the approach that was used in practice due to a lack of better instrumentation. That is, until recently, instruments suitable only for uniform plane-wave fields (and in some cases only linearly polarized fields) were used

to measure leakage from ovens at points close to the leaking cracks. Very little quantitative meaning can be assigned to such measurements, though they are probably adequate to establish rough estimates of the hazards involved.

4. Choosing a Suitable Field Parameter for Quantifying Hazardous EM Fields.

4.1 Parameters for Describing Uniform Plane-Wave Fields.

For a uniform plane-wave field traveling in free space, very simple relationships exist between the magnitude E of the electric vector (i.e., the electric field strength), the magnitude H of the magnetic vector (i.e., the magnetic field strength), the time-average S of the energy flow (i.e., the power density), the time-average U_E of the electric field energy density function (i.e., the electric energy density), the time-average U_H of the magnetic field energy density function (i.e., the magnetic energy density), and the time-average U of the electromagnetic field energy density function (i.e., the total energy density). Using root-mean-square values, these simple relationships are as follows:

$$\frac{E}{H} = Z_o \qquad \text{(the intrinsic impedance of vacuum)} \tag{1}$$

$$Z_o = \left(\frac{\mu_o}{\epsilon_o}\right)^{1/2} \tag{2}$$

$$S = \frac{E^2}{Z_o} = Z_o H^2 \tag{3}$$

$$U = \frac{1}{2}\left(\epsilon_o E^2 + \mu_o H^2\right) \equiv \left(U_E + U_H\right) \tag{4}$$

$$\frac{U_E}{U_H} = 1 \tag{5}$$

For such fields, the energy density can be considered as propagating

through the field point with the speed of light, c. That is,

$$S = cU \tag{6}$$

For comparison, if a uniform plane-wave field has a power density of 10 mW per square cm, the total energy density is $\frac{1}{3}$ pJ per cubic cm (picojoules per cubic cm), and the electric field strength is 1.94 volts per cm.

Because of the simplicity of relations (1) through (6), the "intensity" of this very simple type of EM field can be adequately described by any one of the parameters defined above. However, not all of these parameters are adequate for describing the "intensity" of complicated EM fields. Further, in choosing a suitable parameter for characterizing the "intensity" of complicated fields with respect to biological hazards, one must consider the manner in which biological material interacts with EM fields.

4.2 The Interaction of Biological Material with Electromagnetic Fields.

It will be assumed here that there are no significant "non-thermal" biological effects due to the magnetic component of the field. Then, since biological material does not normally contain more than minute amounts of lossy magnetic substances, there is no significant direct interaction of the magnetic field with biological material. It is emphasized, however, that energy associated with the magnetic field will be indirectly absorbed in the biological material. That is, if the electric field penetration into the material is "damped" because of dielectric losses, energy associated with the magnetic field will be absorbed also. This consideration could be particularly important when interference fields or reactive field components exist since the penetration of the electric field could be considerably greater than one would expect based on "plane wave" absorption concepts.

4.3 Choosing Suitable Field Parameters.

As indicated in the last section, both the thermal and the non-thermal biological effects are caused by the internal electric field. The problem is to determine the most suitable parameter or set of parameters for relating unperturbed fields to the maximum possible internal electric fields resulting when a subject is placed at any possible position and with any possible orientation in the unperturbed fields. Because the resulting internal fields are generally extremely difficult to relate to the unperturbed fields, this problem can not be resolved without introducing simplifications, some of them rather arbitrary. Since it would go beyond the scope of this paper to adequately justify the following statement, it will be merely asserted that: the potential hazards of unperturbed electromagnetic fields are, in general, most closely associated with the electric components of the fields except possibly (a) near the magnetic field maxima in multipath fields and (b) for some reactive near-fields. For the exceptions, the magnetic components of the fields may be equally or more important than the electric components.

The "suitability" of a field parameter for quantifying hazardous EM fields is dependent both on the relevancy of the parameter to the potential hazard and on the ease of measuring the parameter. Except for very simple fields, power density is least suitable because (a) the power density of some very strong fields can be small, and (b) power density is a relatively difficult parameter to measure. The difficulties involved in measuring power density[4] follow from the fact that the power density is given by the time average of $|\bar{E} \times \bar{H}|$. Certainly, in complicated

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[4] For some of the difficulties involved in measuring power density, see Moore School Report 63-13, "Study of power density measurement techniques", University of Pennsylvania, Moore School of Electrical Engineering, January 31, 1963 or
Moore School Report No. 63-23, "Feasibility studies of Poynting vector measurements", University of Pennsylvania, Moore School of Electrical Engineering, July 31, 1963.

fields, it is much easier to measure E and H, which are scalars, than it is to measure the time average of $|\bar{E}X\bar{H}|$. The electric and magnetic energy densities are also relatively easy to determine since the simple relations (4) also hold for complicated fields. That is, the electric or magnetic energy density can easily be calculated from E or H; and instruments that respond to E or H can easily be engineered to display U_E or U_H. As shown by Wacker in Technical Note 391, it is even feasible to measure the total energy density with a single sensor. Except, perhaps, for non-thermal biological effects, it is felt that U, U_E, and U_H are the most suitable parameters for quantifying the potential hazards because: (a) the thermal heating is proportional to the squares of E and H, and therefore, directly proportional to U, U_E, and U_H; and (b) it is convenient to have the same units for stating the "intensities" of the total field, the electric field, and the magnetic field. The remaining discussion will be simplified by assuming that the EM field will be quantified in terms of energy density, though it is felt that E and H would also be satisfactory.

At frequencies above about 1 GHz, that is for wavelengths shorter than about 30 cm, a measurement of the electric energy density alone is probably adequate. In part, this simplification is possible because reactive fields are seldom stronger than radiation fields at distances greater than about one half wavelength from the source. Also, for wavelengths shorter than about 30 cm (and longer than about 3 cm), it is usually very easy to probe the interference patterns caused by multipath propagation and thus locate the electric field maxima. Then U_E for each maximum should be a reasonably good indication of the potential hazard in the immediate region of the maximum. Magnetic field maxima will exist between adjacent electric field maxima, but it is very unlikely that these magnetic field maxima will represent a greater hazard than the

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electric field maxima.

For wavelengths longer than about 30 cm, the magnetic energy density becomes increasingly important. At the present time, hazardous electromagnetic fields below about 1 GHz are not nearly so common as those at higher frequencies[5] so that the measurement of total energy density or of magnetic energy density is perhaps not a crucial issue. However, there are important needs for such measurements (for instance, around powerful radars that operate well below 1 GHz).

5. Instruments for Quantifying Hazardous Electromagnetic Fields.

5.1 General Characteristics.

From the preceeding discussions, it is felt that a good instrument for survey measurements of electromagnetic hazards should have the following characteristics;

(1) the instrument should measure in terms of energy density (or, alternatively, E and H);

(2) the sensor of the field probe should be much smaller than the shortest wavelength of the fields to be measured;

(3) the probe should not cause significant scattering of the field;

(4) the probe should be independent of its angular orientation in the field (i.e., independent of both the polarization of the field and the directions of the vectors of the field);

(5) the instrument should be capable of reading either peak or average values for complicated waveforms;

(6) the instrument should have a dynamic range of at least 20 dB without having to change probes;

(7) the instrument should be direct reading, that is it should not need a calibration chart, nulling, or frequent re-zeroing.

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[5] In large part, this situation is due to the existence of large numbers of microwave ovens.

In addition to the above characteristics, the instrument should, of course, be stable, rugged, lightweight, battery operated, etc..

5.2 Realization.

It is not apparent that instruments can be realized that have characteristics even approximating those outlined in the last section. Recently, commercial instruments have become available[6] that provide some of these characteristics, but it would appear that there is no available instrument that approximates a good instrument as defined here. However, these new instruments are vast improvements over previously available instrumentation, and they are considered to be very useful despite their limitations.

There are a number of possibilities for realizing "next generation" instruments (for instance, see the references outlined in Footnote 4). In fact, there are a number of efforts in progress to develop improved or lower cost instruments for measuring hazardous EM fields. It is felt likely that excellent instrumentation, at least for measuring U_E or E, can be realized.[7]

5.3 Dosimetry.

It is worth emphasizing that the problem of measuring the electric field strength E or the electric energy density U_E in complicated unperturbed fields is essentially the same problem as measuring the complicated internal electric field within a phantom. Therefore, if it is

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[6] See the paper by P.W. Crapuchettes presented at the Symposium on the Biological Effects and Health Implications of Microwave Radiation, Richmond, Virginia, September 17 through 19, 1969.

[7] As of January, 1970, a prototype instrument has been developed by the National Bureau of Standards, Boulder, Colorado. This instrument is limited to measuring U_E (or E), but otherwise it appears from preliminary tests to exceed the essential characteristics outlined in Section 5.1. Descriptions of this instrument will soon be available.

possible to realize an electric field measuring instrument having the characteristics outlined in Section 5.1 (having a very small field sensor in particular) it should be fairly easy to incorporate the sensor of this probe into a phantom to accurately measure the potential exposure (i.e., the dose rate) for very complicated fields. The realization of such a dosimeter is very important since much work needs to be done to determine the potential hazards of complicated fields and how these hazards relate to the parameters of the unperturbed fields.

UNITED STATES DEPARTMENT OF COMMERCE
Maurice H. Stans, Secretary
NATIONAL BUREAU OF STANDARDS ● Lewis M. Branscomb, Director

NBS TECHNICAL NOTE 391

ISSUED APRIL 1970

Nat. Bur. Stand. (U.S.), Tech. Note 391, 19 pages (April 1970)
CODEN: NBTNA

Quantifying Hazardous Microwave Fields: Analysis

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QUANTIFYING HAZARDOUS MICROWAVE FIELDS: ANALYSIS*

by

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ABSTRACT

The familiar power density radiation hazard standards are quite satisfactory for a field consisting of a single infinite traveling plane wave. However, for microwave and lower-frequency fields, hazards occur primarily in near fields which cannot be approximated as the aforementioned plane wave. Further, power density can be quite misleading or even meaningless as a measure of hazard in a near field. Thus, power density in a standing wave can be precisely zero, yet the hazard of such a field can be arbitrarily large. Similarly, a reactive field may present a considerable hazard, yet have zero time-average power density.

The major hazard from microwave and lower frequency radiation is believed to arise from dielectric heating of body tissues, and the heating of an isotropic medium is proportional to the sum of the squares of the absolute values of the electric field components $|E_X|^2 + |E_Y|^2 + |E_Z|^2$. Hence, electric field energy density is proposed for a radiation hazard standard.

Analytical limitations of various types of probes are considered and the advantages of a spherically-symmetric probe of lossy dielectric are discussed. For a rather general spherically-symmetric probe in an arbitrary field, both exact and approximate treatments are given for the calibration constant with full correction for the perturbation of the field by the probe. Conditions for a constant factor are also given.

Key Words: Hazards; Electromagnetic Radiation; Microwave Radiation; Radiation; Measurement; Standards; Energy Density; Probe.

* This work was partially supported by the Bureau of Radiological Health.

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I. Inadequacy of Accepted Concepts and Standards.

For a linearly-polarized monochromatic infinite plane wave in a linear homogeneous isotropic medium, the magnitudes of the electric field, magnetic field, energy density,[1] and energy flow[1] (power density) are all readily measured and each of these magnitudes may be computed from any of the others without approximation, given the properties of the medium. Hence, any one of these magnitudes constitutes a valid index of such a field and, in fact, completely specifies the field apart from phase and the directions of propagation and polarization. Further, for such a wave in a lossless medium, only the phase varies with position or time. However, no such computation can be made for an arbitrary field. Rather, the ratios of these magnitudes can vary widely with the detailed nature of the field, i.e., depending upon detailed information seldom available in field monitoring or even in biological exposure experiments. For example, a standing wave formed from two of the preceding plane waves of equal amplitude and the same linear polarization but opposite direction has zero time-average energy flow (power density), yet the amplitudes of both the electric and magnetic fields are double those of the original waves at specific locations. Further, at distances from a source less than a small number of wavelengths (reactive zone), the time-average power flow may be zero, yet the electric and magnetic fields may be arbitrarily large.

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[1] Strictly speaking, the familiar expressions for both energy density and energy flow (in terms of the electric and magnetic fields) can neither be proved nor disproved [J.A. Stratton, Electromagnetic Theory, McGraw-Hill, N.Y., N.Y., 1941, pp, 110, 131 ff.]. However, the expressions for energy absorption have strong foundations and "direct" measurements of energy density and energy flow are usually really measurements of energy absorption. Because the hazard discussed here is indeed related to the hypothetical energy density, we will use the expression energy density without qualification.

The preceding complications are of little or no importance in the far field, i.e., for the usual practical sources, at distances from the source large compared to a^2/λ where λ is the wavelength and a is the greatest distance between points in the source, considering reflectors to be a part of the source. However, hazards and electromagnetic interference[2] (EMI) arising from microwave and lower frequencies tend to be important in the near rather than the far field and a large fraction of biological exposure experiments are carried out under near field conditions to achieve high power levels.

"Measurements" of near fields based upon far field concepts must be regarded as simplistic and are at best semi-quantitative, often not even qualitatively correct. For example, in certain regions, the field arising from a microwave oven in a stainless steel kitchen may increase significantly with increasing distance from the oven. Even for a high gain antenna carefully designed to give a uniform field, the energy density may vary by a factor of two in a region of nominal constancy outside the reactive zone. The near electric field amplitude of such a horn-lens antenna 100 wavelengths on an edge is shown in fig. 1; the horizontal dependence is nominally that of a square wave and all the structure shown is real, not noise. Due to the wavelengths involved, analogies between microwaves and optics, x-ray behavior, or gamma-ray behavior are commonly invalid and normally not as good as those with sound waves, since standing waves, resonances, and echoes occur with both microwaves and sound. Although workers in the field base their hazard measurements upon energy flow and commercial probes have energy flow scales, some of these probes respond primarily or partially to energy density per se.

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[2] Analytical considerations of electromagnetic interference parallel those of radiation hazards to a considerable extent. Thus, most of this paper also applies to EMI.

II. Exposure Measurements in Waveguide and Coaxial Lines.

Perhaps the simplest non-far field situation applicable for exposure experiments with tissues or small animals is inside rectangular waveguide or coaxial line. Here the walls and inner conductor may be a copper mesh, fine compared to a wavelength. For waveguide, the largest inside dimension should be well between one-half and one wavelength so that one and only one mode will propagate. For lower frequencies, rectangular coaxial line such as that used in a Stark cell and shown in fig. 2 may be used; here the longest dimension should be significantly less than half a wavelength to prevent the propagation of more than one mode. If the tissue and its surrounding culture medium constitute a transverse slab which completely fills the cross-section of the guide or coaxial line and has a uniform complex dielectric constant, the field inside the sample may be readily computed from the dielectric constant and the input power. The field varies with the position in the cross-section and, if the slab is not thin compared to a waveguide, often with the longitudinal position as well. However, the longitudinal variation may be minimized by filling the guide with a medium having essentially the same complex dielectric constant and magnetic susceptibility as the slab, minimizing reflections. (In this case, the dimensions of the guide should be related to the wavelength in the medium and the medium should extend far enough on both sides of the tissue slab to insure a pure mode.) Further, attention may be confined to a region of uniform field. In the case of the Stark cell, high fields may be generated where the septum approaches the outside wall; to avoid contamination of the sample being studied by decomposition products from regions of high field, the septum should not be close to the wall and/or the portion of the sample being studied should be separated from the portion in the high field by a thin impervious dielectric. For a whole animal (invariably of irregular shape and varying dielectric constant),

the situation is more complicated in any near field; however, in principle, reflection effects could also be minimized by immersion in a medium with a similar dielectric constant provided that gaps were small compared to a wavelength, that the medium did not cause too great an attenuation, and that thermal effects, respiration, etc. were properly handled.

III. Energy Density as a Measure of Hazard.

Since a field with initially zero energy flow (power density) may be responsible for arbitrarily great hazard to a subject later placed in it or arbitrarily great EMI to an electronic device placed in it, power density is not a suitable index of either hazard or EMI caused by a near field. Preferably the index should be closely related to the hazard and be easy to measure. Electrical energy density is proposed for the index. Since biological materials are essentially non-magnetic, they interact with an electromagnetic field primarily only because of their dipole moments (more strictly, the dipole transition moments), absorbing energy quanta at a rate proportional (for a linear medium) to the electrical energy density in the tissue. Although the quanta are much too small to cause the breaking of a chemical bond, a molecule which has absorbed one or more quanta has an activation energy which may well cause the molecule to be significantly more reactive in a general sense, say for exchange reactions involving the breaking "bonds" between compounds in the protoplasm and loosely held water. If desired, this may be considered to be extremely localized heating. Thus, electrical energy density should be a reasonable hazard index for both thermal and non-thermal effects including resonant absorption by specific molecules.

It is expected that the hazard to each portion of the body will be associated with its own "constant" of proportionality and that this

"constant" will vary with frequency, perhaps sharply. There may well be other effects associated, e.g., with polarization of the field or non-linearity of the tissue (say in pulsed fields). However, such effects can be studied as deviations from those predicted from energy density measurements assuming a linear isotropic medium.

For EMI in a near field, energy flow has the same disadvantages and energy density has many of the same advantages as for hazards.

IV. Measurement of Energy Density.

The preceding energy density discussion is based upon the energy density within the given tissue, not upon that of the field into which the animal or person might enter. In principle, probes might be implanted in an animal or either the animal or person might be simulated in terms of the complex dielectric constant and magnetic susceptibility as a function of position. Since these procedures would be inconvenient for monitoring, the relation between the energy density inside an animal or person to that inside the probe must be considered (including perturbation of the field by the probe, person, or animal) and used in probe design. General principles will be discussed first, then illustrated with an exact treatment of a possible probe.

In principle, a probe should simulate the body or a given electronic instrument in its extraction of electrical energy from the field. Since the body makes only a slight perturbation in a field of hard x-rays or gamma rays, so should a probe used to measure them, i.e., the probe should be analogous to a high resistance voltmeter rather than a shorting ammeter which gives a reading strongly dependent upon the internal impedance of the source. In contrast, from the shortwave radio region through the ultraviolet, the body absorbs almost all the incident energy apart from that which it reflects. (The penetration depth[3] increases steadily from 3000 GHz to 3 MHz with a depth of 10 cm for 30 MHz and 52 cm for 3 MHz

[3] Skin depth as defined in electromagnetics.

[H.P. Schwan, "Survey of Microwave Absorption Characteristics of Body Tissues", in Proc. Second Tri-Service Conference on Biological Effects of Microwave Energy, July 8-10, 1958. ASTIA Document AD 131 477]. Hence, a probe designed for this important frequency range should also absorb most of the non-reflected energy and probably have a low reflectivity as well [H.P. Schwan, "Radiation Biology, Medical Applications, and Radiation Hazards", in Microwave Power Engineering, vol 2, edited by Ernest C. Okress, Academic Press, New York, 1968]. (However, in some circumstances, say in continuous monitoring of a radar beam, it is impractical to use a probe which absorbs large quantities of energy.)

A related phenomenon concerns the magnetic field associated with the electric field. In absorption of a quantum of radiation, both magnetic and electric energy are involved. Further, both the initial electric and magnetic fields and the fields remaining after absorption are related by Maxwell's equations so that absorption of all the electric energy requires absorption of all the magnetic energy. For an infinite plane wave in a vacuum, the magnetic and electric energies are equal. However, the ratio of the energies may vary widely in a near field, say from the predominately magnetic field near an electromagnet to the predominantly electric field between plates of a large capacitor. Thus, a probe which properly simulates the body gives readings partially dependent upon the magnetic field, although the probability of quantum absorption is essentially independent of the magnetic field. For EMI measurements, a probe which reacts directly to the magnetic field may be desirable and is discussed in Section V on probe design.

Any device which measures a single complex voltage or its magnitude may be regarded as a device which measures a single constituent of a field, i.e., the coefficient of a single basis function from

the infinite series of basis functions used to represent the field. Thus, an ideal dipole measures the coefficient of one of the three electric dipole constituents of the field and completely neglects all magnetic multipoles and all but one of the electric multipole constituents of the field, regardless of their strengths. This limitation does not apply (in a practical sense) to a dipole in a linearly polarized plane wave only because the probe has a fixed calibration factor (which may be accurately computed); however, even in an infinite plane wave, a dipole oriented to give maximum amplitude can give an error of a factor of two in the energy density, depending upon whether the field is linearly or circularly polarized. A probe based upon losses (say, resulting in heating or pressure rise) does not have these limitations and so is suitable for direct measurement of total electric energy density; such a probe measures the energy density and adds all components without cancellation, all of the contributions being positive. For any electric (or magnetic) dipolar field, a probe which sums the squares of the absolute values of the voltages from three identical perpendicular dipoles can give an accurate result independent of probe orientation. Note that even an infinitesimal probe need not measure the field at a point, e.g., a quadrupolar probe; thus, a tiny dipole and a tiny quadrupole measure unrelated quantities.

A probe comparable in size to a wavelength will show resonances much the same as a half-wave dipole, i.e., the calibration constant will be a rather strong function of frequency, less so if the medium is lossy.

For convenience, a probe should not require orientation nor discriminate on the basis of direction of the incoming waves. It should be noted that no voltage probe has these properties, but that an energy density probe with spherical symmetry does. A general theory of such a probe is given in Section V, including a procedure for a priori computation of its calibration "constant", i.e., the ratio of the energy

density of the field prior to the introduction of the probe to the energy density in the probe. No calibration constant can be computed for any probe without some knowledge or assumptions concerning the spatial dependence of the field, but an energy density probe with spherical symmetry requires a minimum of knowledge -- much less than is required for a voltage probe.

For pulse power, the analysis is significantly more complicated. The present analysis has been modified to include pulse effects but will not be reported here.

V. Detailed Design of a Possible Probe.

Since previous studies have involved assumptions and approximations inappropriate for near fields, a detailed study is carefully carried out for a mathematically-manageable probe. The study reveals complications which can arise and illustrates some of the general statements of the preceding portions of this paper.

Consider a medium which is linear, isotropic, piecewise homogeneous, source-free, and subject to Ohm's law. For every homogeneous region, every solution of Maxwell's equations is solenoidal and is a solution of the vector Helmholtz equation. For a single frequency and a medium which has spherical symmetry, the complex electric field $\underline{E}$ and magnetic field $\underline{H}$ are conveniently expressed as a linear combination of Hansen's $\underline{m}$ and $\underline{n}$ functions [Stratton, p. 416]. (The time-dependent factor $e^{-i\omega t}$, where ω is the angular frequency, is assumed but suppressed.) Every such function is a solution of Maxwell's equations [Stratton, p. 394], and the set of functions is presumably complete [Stratton, p. 393] for the problem at hand. (The $\underline{L}$ and $\underline{l}$ functions are not solutions of Maxwell's equations.)

Let μ and ϵ be the complex permeability and permittivity and $k = \omega(\mu\epsilon)^{\frac{1}{2}}$ be the propagation constant. As shown in Fig. 3, consider

a probe with instrumentation from radius $R = 0$ to a, a shield S from $R = a$ to b, a lossy material L from $R = b$ to c, and a dielectric D used for thermal insulation from $R = c$ to d, immersed in a medium A, say air. If no internal instrumentation is used, a and b would be zero. Both the media and the propagation constants are indicated by the upper case Latin letters as shown in the diagram. The corresponding lower case Greek letters are used for the permeabilities. For an electrical probe, the permeabilities will ordinarily be essentially that of free space.

In the expression for the electric field, let M_{smnb} and N_{smnb} be the coefficients of the ratios of $\underline{m}_{smnb}$ and $\underline{n}_{smnb}$, respectively, to the square root of $n(n+1)(1+f)2\pi(n+m)!/(2n+1)(n-m)!$, where f is unity for $m = 0$ but otherwise zero [Stratton, pp. 417-418]. The subscript s is used to denote the symmetry, either even (e) or odd (o). The subscript b indicates the kind of the spherical Bessel function, either the first (j) or second (y) kind. (The y's are not needed for the central region of the probe ($R = 0$ to the first discontinuity) nor for the field in the absence of the probe.) The corresponding coefficients for $i\omega\mu\underline{H}/k$ are N_{smnb} and M_{smnb} respectively (note reversal) [Stratton, p. 394].

Given the coefficients in any one region of the probe or the region outside the probe, the coefficients of the other regions can be obtained with the aid of boundary conditions [Stratton, pp. 483-4, (1a), (5), (10)]. Because of symmetry, coefficients with different s, m, or n are independent, as are the M and N coefficients. Thus, for given s, m, and n, the four M (or four N) coefficients corresponding to the two kinds of Bessel functions on the two sides of a boundary are related by two equations. Suppressing the s, m, and n subscripts and adding a subscript to indicate the medium, the following equations are obtained:

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$$(N_{jA} j_A + N_{yA} y_A)\, A/\alpha = (N_{jD} j_D + N_{yD} y_D)\, D/\delta \qquad (1)$$

$$(N_{jA} \partial_{jA} + N_{yA} \partial_{yA})/A = (N_{jD} \partial_{jD} + N_{yD} \partial_{yD})/D \qquad (2)$$

$$M_{jA} j_A + M_{yA} y_A = M_{jD} j_D + M_{yD} y_D \qquad (3)$$

$$(M_{jA} \partial_{jA} + M_{yA} \partial_{yA})/\alpha = (M_{jD} \partial_{jD} + M_{yD} \partial_{yD})/\delta \qquad (4)$$

for the A-D interface, where $j_A = j_n(AR)$, $y_A = y_n(AR)$, and $\partial_{yD} = \frac{\partial}{\partial R} \{R j_n(DR)\}$, all here evaluated for $R = d$.

The coefficients of the field in the presence of the probe may be related to those for the field in the absence of the probe ("unperturbed field") by an integral equation, assuming that the perturbation of the field does not affect the distribution of the sources. (For a similar case, see Morse and Feshbach, Methods of Theoretical Physics, McGraw-Hill Book Co., N.Y., N.Y., 1953, pp. 1897, 1875.) Because of orthogonalities, the equation separates into a number of equations, each involving only M or N coefficients and a single set of s, m, and n values. Thus, a knowledge of the coefficients in any part of the probe, surrounding space, or in the unperturbed field permits determination of all the other coefficients, given the properties of the probe; further, determination of the coefficients splits into separate problems as indicated.

The time-average energy density is given by $(\underline{E} \cdot \overline{\underline{E}}\ \mathrm{Re}\ \epsilon + \underline{H} \cdot \overline{\underline{H}}\ \mathrm{Re}\ \mu/4$, where the overline indicates that the complex conjugate is to be taken and the symbols $\underline{E}$ and $\underline{H}$ represent peak values. The integral of the time-average energy density over the polar and azimuthal angles θ and ϕ is simplified by the fact that the orthonormalities between the $\underline{m}$'s and $\underline{n}$'s given by Stratton [pp. 417-418] also apply for the Hermitian dot products

(including those for solutions involving different kinds of Bessel functions if each square of a Bessel function in Stratton's expressions is replaced by the product of the first Bessel function by the complex conjugate of the second, both of the given order. For any medium, the integral of the time-average electric energy density over θ and ϕ is given by

$$\frac{\mathrm{Re}\ \epsilon}{4} \sum_{s,m,n} \Big[\left| M_{smnj}\, j_n + M_{smny}\, y_n \right|^2 + \frac{n+1}{2n+1} \left| N_{smnj}\, j_{n-1} + N_{smny}\, y_{n-1} + \frac{n}{2n+1} \left| N_{smnj}\, j_{n+1} + N_{smny}\, y_{n+1} \right|^2 \Big] \qquad (6)$$

and the integral of the time-average magnetic energy density is given by the expression obtained by interchanging the symbols M and N and replacing Re ϵ by β. Here $\beta = |k/\omega\mu|^2$ Re $\mu = |\epsilon/\mu|$ Re μ; hence, for real μ, $\beta = |\epsilon|$. The Bessel functions of course have the argument kR. The losses in a medium are given by an expression identical to that for the energy except that Re ϵ is replaced by 2σ and Re μ is replaced by 2χ, where σ is the electrical conductivity and χ is the analogous magnetic quantity, both for the given frequency. Thus, Re ϵ and β are associated with the electrical and magnetic energy density, while σ and χ are associated with the electrical and magnetic losses respectively The possibility of a magnetic probe will be discussed later.

Neither the unperturbed field nor, in the absence of internal instrumentation, the field in L involves y functions. Therefore, the time-average angular integrals of energy density in the unperturbed field and the loss in L depend only upon the sums

$$\sum_{s,m} |M_{smnj}|^2 \text{ and } \sum_{s,m} |N_{smnj}|^2 ,$$

not the individual coefficients. Further, the relations between th

coefficients for the unperturbed field and those for L are independent of both s and m, so that specification of the sums for the unperturbed field determines the sums for L. Thus, neglecting losses in other regions, the calibration constant of the probe is independent of any changes in the unperturbed field which do not change the sums. A wide range applicability of the calibration "constant" is, of course, important for any probe, whether the calibration is computed or measured; such a range seems to be characteristic of the proposed probe.

It is, of course, convenient to be able to use and calibrate a probe in a plane wave and also to be able to specify the class of fields for which the calibration constant is applicable. For a plane wave travelling in the z direction with its electric vector in the x direction, the M_{o1nj}'s are proportional to $i^n((2n+1)(n+1)!/n(n+1)(n-1)!)^{\frac{1}{2}}$, the N_{e1nj}'s proportional to -i times these quantities, and all the other coefficients zero [Stratton, p. 419]. Assuming that $\sum_{s,m}|M_{smnj}|^2 = \sum_{s,m}|N_{smnj}|^2$ for each n requires that the electric and magnetic energies of the unperturbed field be equal if Re $\epsilon = \beta$. Assuming in addition the sums to be zero for n = 0 but proportional to $(2n+1)(n+1)!/n(n+1)(n-1)!$ for other n's permits one to compute a calibration constant (given the propagation constants and susceptibilities), valid for a large class of fields, including plane waves as a special case. (The calibration constant can, of course, also be obtained by direct measurement.) As will be discussed later, these assumptions may be relaxed to a degree for a small probe with low dielectric constants.

Ordinarily the lossy material of the probe would have a complex permittivity and essentially a real permeability and so provide a measure of the electric field.

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It would be desirable to obtain an independent measure of the magnetic field, and this would be possible if a suitable material could be found, i.e., one which is linear and isotropic with a complex permeability but fairly small dielectric loss tangent. Such materials do exist for small fields (low on the hysteresis curve), but only exploratory work could determine whether a practical probe could be developed. The preceding analysis would apply for both kinds of probes, and provide information concerning the relative magnitudes of the M and N sums.

For a probe small compared to each of the $1/|k|$'s, the Bessel functions may be approximated by $j_n(z) \cong z^n/(2n+1)!!$ and $y_n \cong -(2n-1)!!/z^{n+1}$, where $(2n+1)!!$ is the product of the odd integers up to and including $2n+1$. Hence, for the lower microwave frequencies and below, the preceding expressions are significantly simplified. Further, because practical fields have a limited amount of fine structure, at least the higher M and N coefficients tend to decrease with increasing n, much like those for a plane wave. As a result, only the lower terms need be used for a probe tiny compared to both the scale of the field structure and a wavelength. (The wavelength condition is not required for X- or γ-rays, where the wavelength is small compared to the dimensions of the probe, introducing averaging effects).

VI. Summary and Conclusions.

The existing standards for microwave radiation hazards are based upon far-field concepts which may have little or even no validity in near fields. However, hazards occur largely in near fields, and even many dosimetry experiments are carried out in near fields. Because of the great complexity possible in a near field, a probe should, in principle, simulate the individual who might be subject to the possible hazard; however, such a probe is not feasible. Electric energy density

provides a reasonable index of a large class of microwave radiation hazards and is simpler to measure in a near field than is energy flow. Analytical aspects of near field measurements are discussed in general, and design of a possible probe described in detail. So that near-field dosimetry experiments are meaningful and reproducible, great care must be used in field measurements and describing conditions which determine the field in the subject.

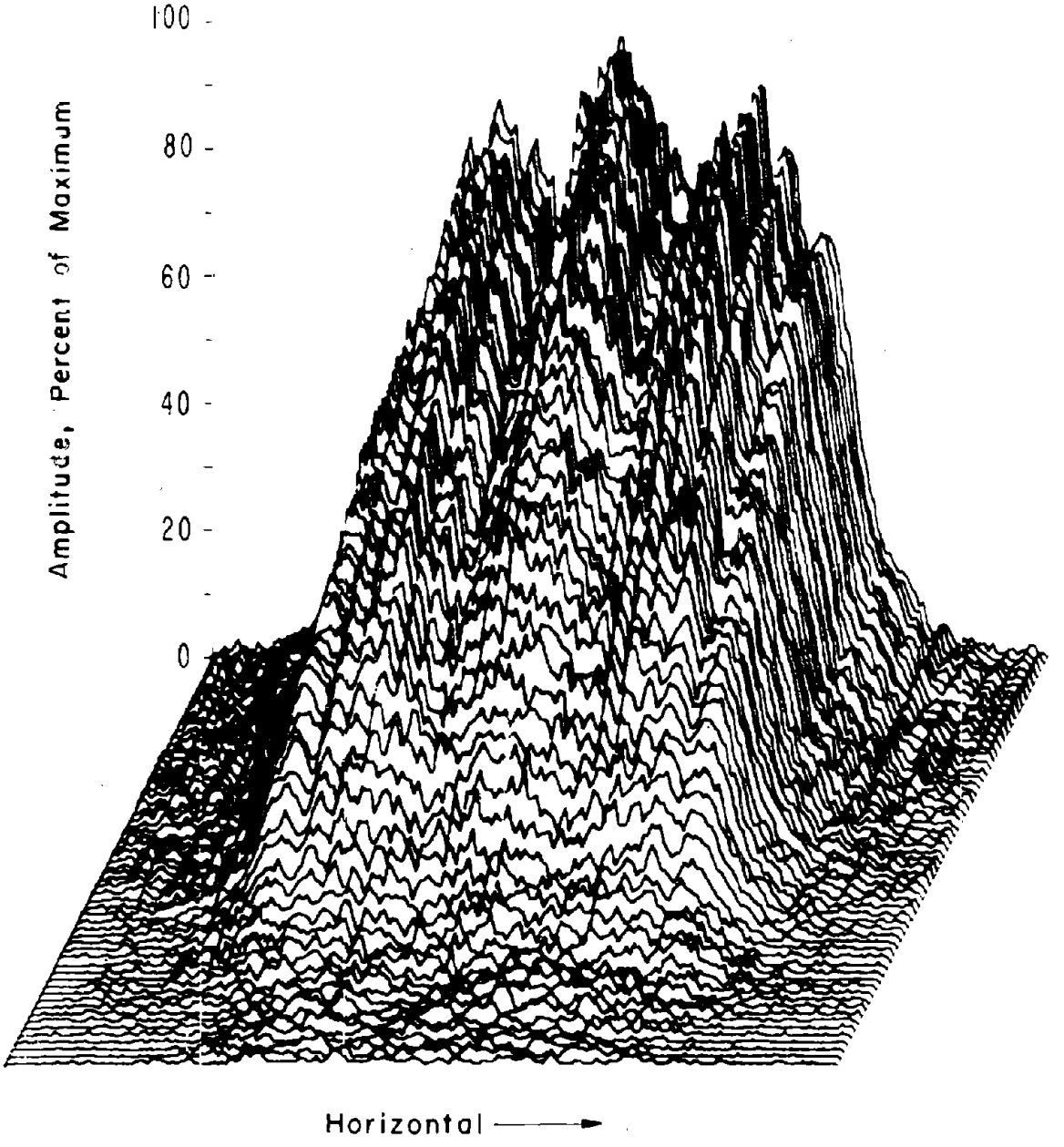

Figure 1. Amplitude Variation Near a Horn-Lens Antenna.

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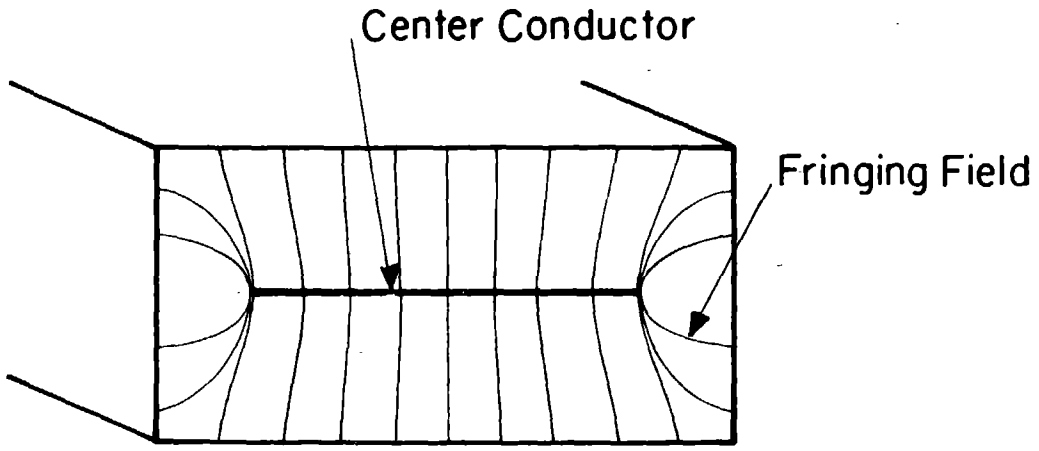

Figure 2a. Cross Section of Stark Cell.

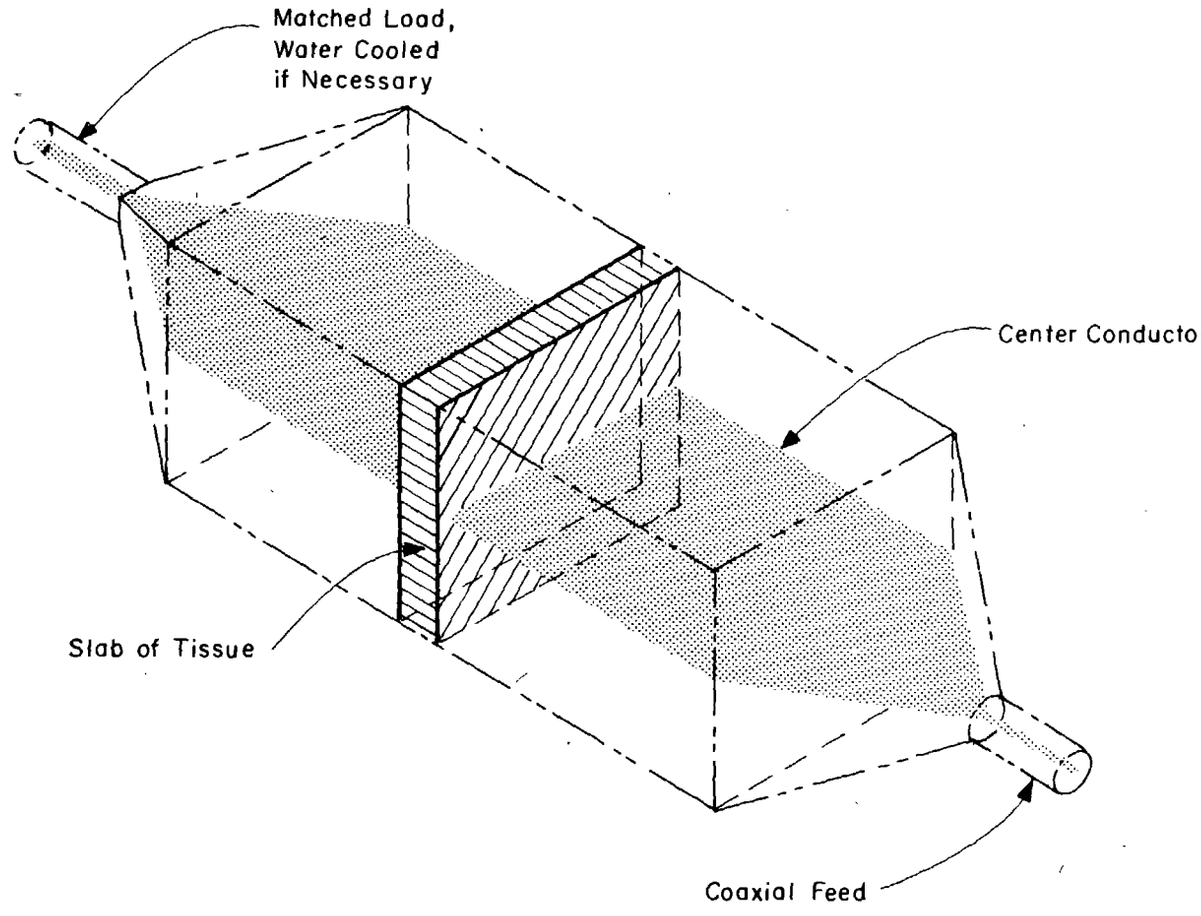

Figure 2b. General Plan of Stark Cell.

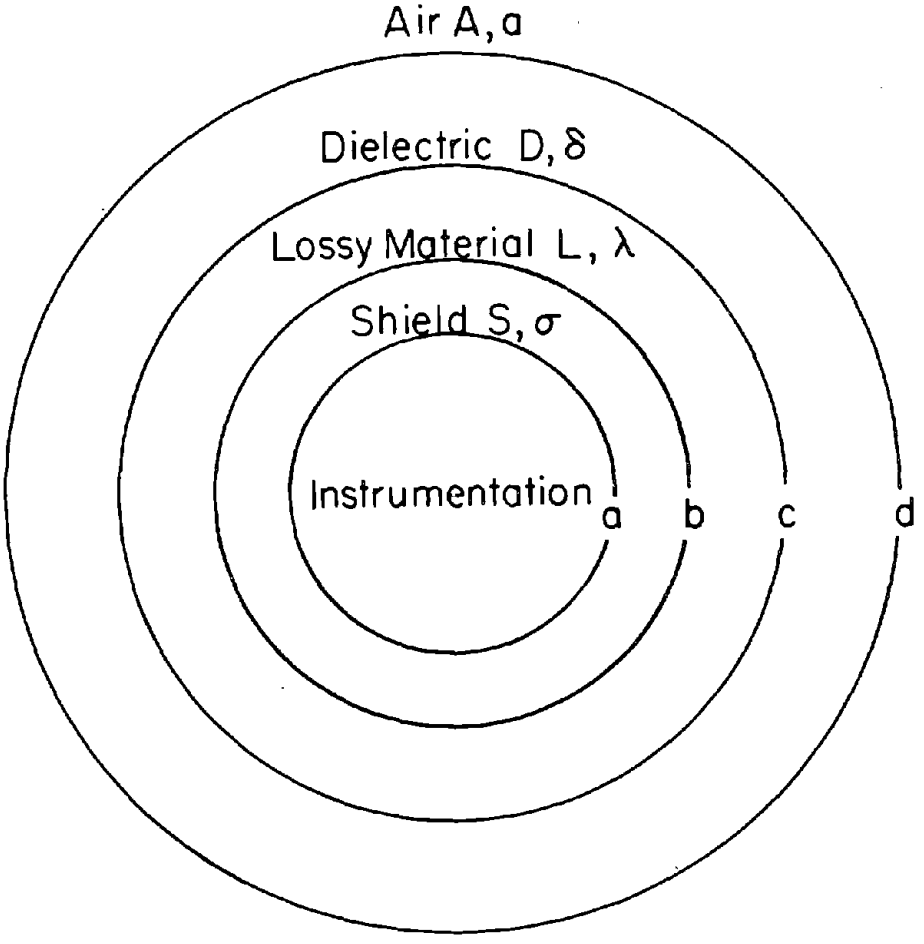

Figure 3. Cross Section of a Spherical Energy-Density Probe.

☆ U. S. GOVERNMENT PRINTING OFFICE: 1975-657-601/5533 Region No. 5-11

GPO 857-542

BIBLIOGRAPHIC DATA SHEET	1. Report No. NIOSH-75-140	2.	3. Recipient's Accession No. PB 266570
4. Title and Subtitle Development of Near-Field Electric Energy Density Meter Model EDM-2			5. Report Date March 1975 6.
7. Author(s) D. R. Belsher			8. Performing Organization Rept. No.
9. Performing Organization Name and Address Electromagnetic Division NATIONAL BUREAU OF STANDARDS Boulder, Colorado 80302			10. Project/Task/Work Unit No. 11. Interagency Agreement NIOSH-IA-74-13
12. Sponsoring Organization Name and Address National Institute for Occupational Safety and Health 4676 Columbia Pkwy. Cincinnati, Ohio 45226			13. Type of Report & Period Covered 14.

15. Supplementary Notes

16. Abstracts

An electric field survey monitor was developed to accurately measure the occupational exposure from industrial radiofrequency power sources. The monitor employs a set of three orthogonal dipoles to obtain an essentially isotropic response. The dipoles are connected to the meter electronics by special high resistance conductors which have minimal interaction with the radiofrequency field. The survey monitor was calibrated from 10 to 500 megahertz. A technical note is included regarding the quantitative analysis of hazardous microwave fields.

17. Key Words and Document Analysis. 17a. Descriptors

Radiofrequency
Measuring instruments
Monitors
Dipoles
Electronics
Quantitative Analysis

17b. Identifiers/Open-Ended Terms

Power sources
Orthogonal Dipoles
Isotropic response
Microwave fields
Density meter
Electric energy

17c. COSATI Field/Group 6J

18. Availability Statement	19. Security Class (This Report)	21. No. of Pages
Release Unlimited	UNCLASSIFIED	71
	20. Security Class (This Page) UNCLASSIFIED	22. Price PC A04 MF A01