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Design and Calibration of the NBS Isotropic Electric-Field Monitor (EFM-5), 0.2 to 1000 MHz

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Design and Calibration of the NBS Isotropic Electric-Field Monitor (EFM-5), 0.2 to 1000 MHz

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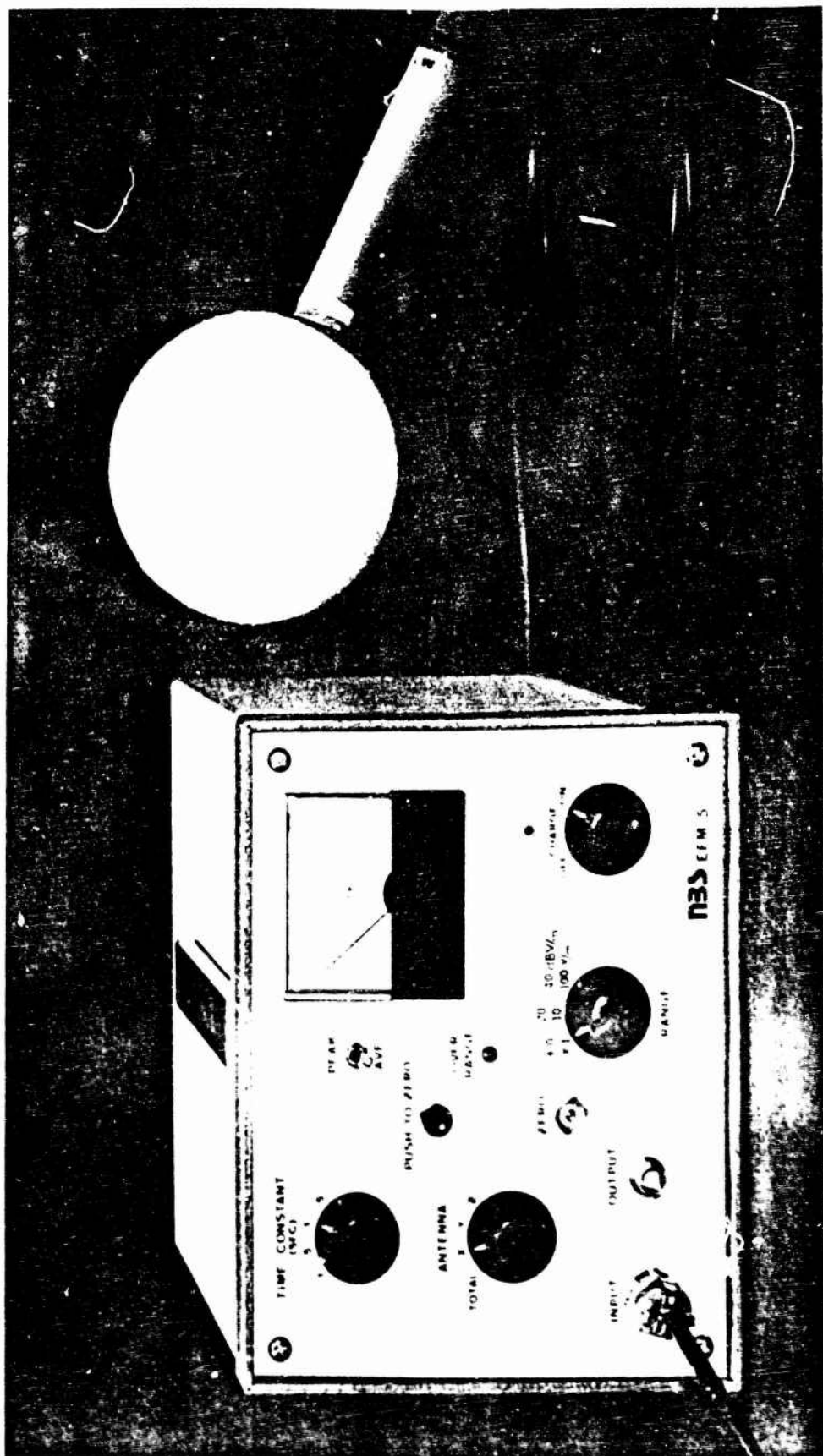
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Frontispiece. Photograph of the EFM-5 rf radiation monitor

DESIGN AND CALIBRATION OF THE
NBS ISOTROPIC ELECTRIC-FIELD MONITOR (EFM-5),
0.2 to 1000 MHz

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A broadband rf radiation monitor was developed at NBS for the frequency range of 200 kHz to 1000 MHz. The isotropic antenna unit consists of three mutually-orthogonal dipoles, each 5 cm long by 2 mm wide. The receiver described in this paper has an accurate measurement range of 1 to 1000 V/m. The readout indication is in terms of the Hermitian or "total" magnitude of the electric (E) field strength, which is equal to the root-sum-square value of three perpendicular E-field components at the measurement point. Previous radiation monitors designed at NBS have demonstrated the accuracy of a crossed-dipole sensor for measuring the total E-field magnitude of complicated electromagnetic fields. Several prototype units of an advanced instrument have been fabricated and tested. This instrument, the EFM-5 Electric Field Monitor, has nearly perfect isotropy over a 60 dB dynamic range. The dial readout units are dB above 1 V/m (dBV/m) and V/m. Three ranges cover 0 to 60 dBV/m (1 to 1000 V/m).

The electronic circuitry of the EFM-5 obtains the total magnitude of all field polarizations and all signals in the entire frequency band. The sensor response is isotropic; that is, there is no preferred field polarization or preferred direction of arrival of the incoming wave. Therefore this probe is well suited for measuring the near field of an emitter, including regions of multiple reflection, standing waves, etc. The EFM-5 can be used to monitor either the weak plane-wave fields in the far zone of a transmitting antenna, or the complicated fields only 5 cm from an rf leakage source. The special features, electronic design, physical construction, and calibration are described in this paper.

Key words: Electromagnetic field; electronic instrument design; field intensity meter; field strength measurement; isotropic antenna; radio frequency radiation; receiver calibration.

1. INTRODUCTION

1.1 Background to RF Probe Development at NBS

This National Bureau of Standards (NBS) project deals with the theory and measurement of electromagnetic (EM) fields over the 100 kHz to 4 GHz frequency range. Our initial work involved a theoretical determination of the most suitable field parameters for quantifying EM fields. The next phase was the design and fabrication of various competing types of measuring instruments. The EFM-5 monitor described here is a third-generation prototype meter which is proving to be a useful addition to those already available for measuring either weak or intense radio frequency (rf) fields. A photograph of the instrument is shown in the frontispiece. Other radiation monitors designed previously at NBS include the XD-1,

EDM-1, EDM-2, EDM-3 and EDM-15. One of the intentions of the NBS project was to develop an instrument design that could be produced by commercial manufacturers; experience showed that the EDM series of meters could not be commercialized readily.

The overall and continuing objective of this project is to design and fabricate portable, isotropic monitors for making accurate field intensity surveys of rf radiation. To satisfy this objective it was decided to first check the adequacy and accuracy of existing field intensity meters (FIM's) including conventional radio receivers and the newer rf radiation hazard meters. The next step was to develop satisfactory procedures for measuring the relatively strong fields near various types of transmitting antennas, over a wide frequency range. The frequency range of greatest concern in this project is 500 kHz to 1 GHz, which covers the majority of high-power emitters such as AM, FM, VHF and UHF television, communications, and other transmitters used for broadcasting. The usable frequency range of the EFM-5 monitor extends from 100 kHz to 4 GHz but the response is not uniform (flat) over this large a frequency range.

The rf probe program at NBS has dealt with both the theoretical and experimental aspects of quantifying fields, including the design and fabrication of prototype instruments. The EFM-5 described here is a useful radiation monitor for measuring ambient fields in the environment and also for checking rf leakage radiation in the vicinity of industrial and consumer devices. The types of instrumentation used in the past to measure these two different situations can be summarized as follows:

- (1) A tunable field strength meter or scanning spectrum analyzer, using an antenna which must be oriented for the local field polarization. These receivers generally have high sensitivity and are not designed as portable instruments for making quick surveys. For example, they are unsuitable for checking the leakage rf field of industrial sources and most other near-zone situations.
- (2) A microwave "hazard meter" which is designed to test the high level fields close to radar antennas and similar emitters, or to test for leakage fields as mentioned above. The frequency of interest is generally above 300 MHz and the measurable levels generally exceed $20 \mu\text{W}/\text{cm}^2$, which is equivalent to a free-space electric field strength of about 9 V/m. This type of instrument is useful near a radiating source but has been used for other applications due mainly to the lack of more suitable instrumentation.

As background information, a brief discussion is given here of the design philosophy and use of a "conventional" field intensity meter (FIM). A single component of electrical field strength is measured by attaching some sort of electrical dipole antenna to a tunable radio receiver. The receiver acts as a frequency-selective voltmeter and the antenna is generally calibrated separately. That is, it is necessary to apply a multiplying factor to the receiver dial indication. The required conversion factor between the antenna pickup (volts) and the electric field strength (V/m) is known as the "antenna factor." It must be determined experimentally for each antenna used, at each orientation angle and signal

frequency, by immersing the antenna in a known (standard) field. Figure 1 is a functional block diagram of a typical FIM, consisting basically of a superheterodyne communications receiver with certain added features. This type of field measurement system is characterized by high sensitivity and sharp selectivity. The measurements are made as a function of signal frequency, for each field polarization desired.

By contrast, a different approach is used for measuring electric field intensity with a so-called "hazard meter." This type of non-tunable rf meter is characterized by low sensitivity and the use of broadband antennas having a "flat" response over a wide frequency range. Also, the "wide-open" measurement system generally employs an isotropic or non-directional type of pickup antenna [1].

The first technical phase in the NBS program was a study of the near-zone measurement problem in order to devise instruments which could furnish repeatable, accurate and convenient measurements near sources of leakage radiation. It is desired to quantify rf fields without distorting them, while providing adequate shielding to the measuring device and telemetering link (or transmission cable). As a result, breadboard models of several types of rf monitors were built and tested. Improved receiving antennas were designed to make meaningful measurements without requiring time-consuming multiple orientation of the pickup antenna. The advent of an isotropic rf probe invented at NBS made it possible to perform rapid field surveying [2].

An investigation was performed at NBS to find a device or phenomenon that could provide a useful sensor of EM fields of complicated structure. Most of the early attempts revealed severe limitations for designing a general-purpose probe. For example, thermal rf sensors based on absorbed heat energy or temperature rise in a lossy material could not be made sufficiently rugged and stable unless the response time was excessive. It was concluded early in the program that the preferred type of rf sensor consists of a short dipole antenna and semiconductor detector, which has a fast response time and good sensitivity.

As explained later, the EFM-5 isotropic probe is based on the use of three orthogonal dipoles, three diode detectors, and special signal processing to obtain the "total magnitude" of the electric field at the measurement point. However, it is advantageous to first review some of the early probe development work at NBS. Brief descriptions are given here of five types of rf probes which were evaluated in addition to the preferred choice using short dipoles and miniature diodes. The five types are as follows:

- (1) Color change in liquid crystals: These probes relied on observing the change in color of liquid crystal material, caused by temperature rise from absorption of rf energy. The probes were found to have a slow reaction time to changes in field level and were difficult to correct for variations in ambient temperature. They also had low sensitivity with only a small dynamic range, and the calibration was not stable over a long period of time.
- (2) Resistance change of a lossy dielectric: This type of sensor also operates on the basis of temperature rise due to absorption of rf energy. The lossy material tested was plastic impregnated with carbon, using resistance change as an

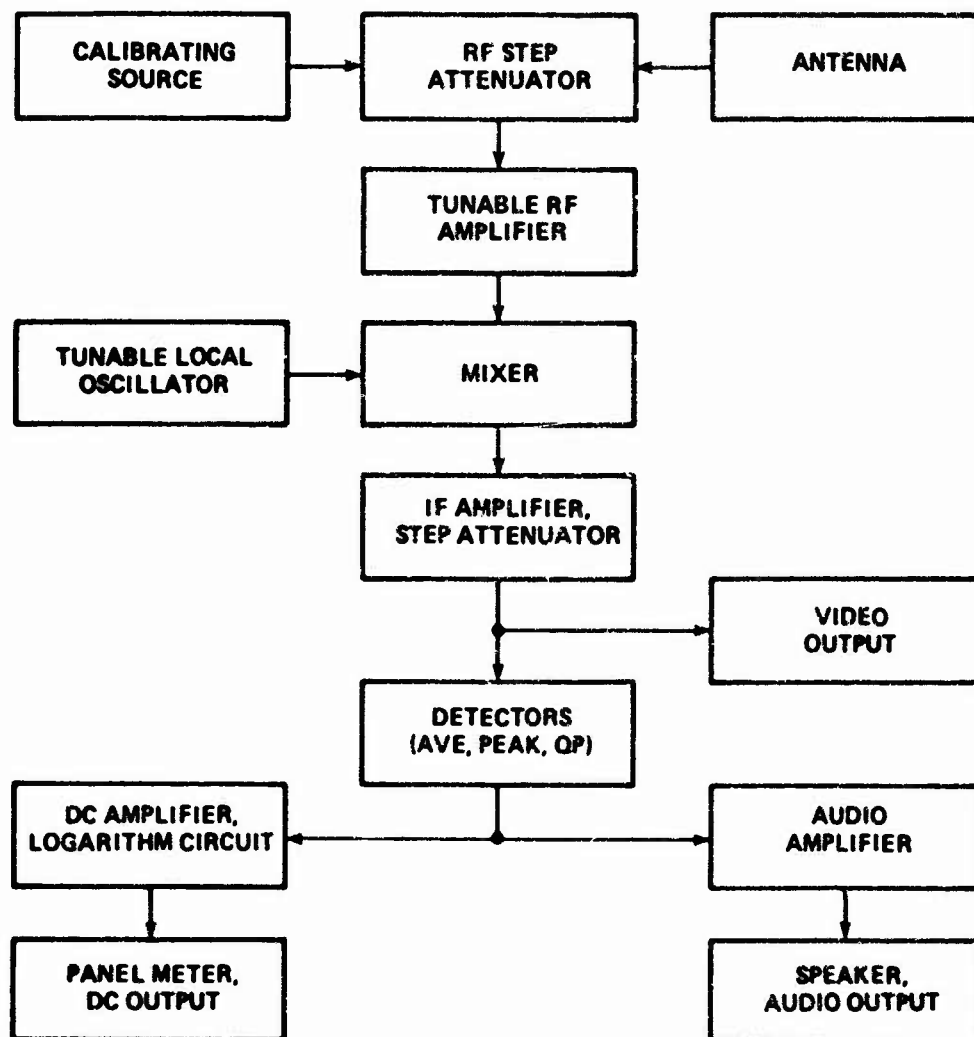


Figure 1. Block diagram of a typical field intensity meter.

indicator of temperature. However, similar to number (1) above, the sensitivity was inadequate and the time constant was excessive.

- (3) Glowing gas probe: Research was done at NBS on a "crossed dipole" probe with a gas tube at the center gap of the dipole antennas. Strong rf fields produced emission of light or change of resistance in noble gases. Progress toward realizing a useful measuring instrument was disappointing, due mainly to lack of stability and repeatability, but also to lack of sensitivity and difficulty in handling the radioactive materials required for generating free electrons in the gas tubes. The sensors tested at NBS consisted of neon (Ne) gas inside a miniature glass bulb located at the center of a set of short dipoles. The metal dipole wires had sharp points at the center gap to enhance the E field. Light from the glowing gas was observed visually, but could have been guided by a fiber-optic bundle to a photodetector. Tests with a 5 cm dipole indicated that the Ne gas would not ignite until the rf power density was nearly 100 mW/cm^2 . After ignition, the glow disappeared when the field was reduced to about 10 mW/cm^2 . Thus the sensitivity was too low, although means could probably be provided for pre-ignition of the gas, such as with a separate RC oscillator. In one such device a high-resistance transmission line was used, and the Ne tube was caused to flash at a low frequency rate in the absence of an rf field. The frequency of oscillation could then be calibrated as a function of rf field level.
- (4) Incandescent bulb probe: Another type of rf sensor functions in terms of the short-circuit current developed at the center of a receiving dipole. In tests at NBS, the dipole was center-loaded with a miniature incandescent bulb having approximate dimensions 2 mm long by 1 mm diameter. The response time of such a sensor was found to be about 1 millisecond. The cold resistance of the filament was about 75Ω , with a white-hot resistance of about 400Ω . The intensity of infrared and visible radiation increased as a function of the rf-induced dipole current. The radiation was guided through a glass fiber-optic bundle to a solid-state photodetector. The phototransistor output voltage, after subtracting the "dark" value, was found to increase approximately in proportion to the fourth power of the incident electric field value. The glass bulb had a lens-style envelope for better transfer of radiation into the fiber light guide. Tests indicated that the usable dynamic range was very small. The range achieved, between "dark" current and full brilliance of the bulb, was only about one decade (20 dB) in E field. It would thus be difficult to provide any burnout protection for the sensor bulb.
- (5) Thermocouple sensor probe: Several versions of rf probes using short dipoles center-loaded with thermocouple heaters were evaluated at NBS. In these probes the heater element and "hot" thermocouple junction were encased in a miniature glass bead, which in turn was enclosed in an evacuated glass bulb. The dc output of each thermocouple was proportional to $(E)^2$, although over only a limited range

in field strength. The total dynamic range between minimum-discernible field strength and burnout level was about 30 dB. In addition, the probes were susceptible to changes in ambient temperature and the sensor response time was quite slow.

The radiation protection guide recommended by the American National Standards Institute (ANSI) for exposure to rf radiation is 10 mW/cm^2 , in the 10 MHz to 100 GHz frequency range [3]. This corresponds to free-space equivalent electric (E) and magnetic (H) field strengths of approximately 200 V/m and 0.5 A/m, respectively. Higher levels are permitted for short time durations if the power density averaged over a six-minute period does not exceed 10 mW/cm^2 (100 W/m^2). According to the ANSI C95.1 standard, "Radiation characterized by a power level tenfold smaller will not result in any noticeable effect on mankind. Radiation levels which are tenfold larger than recommended are certainly dangerous" [3].

General purpose instrumentation for monitoring exposure to rf radiation should also be capable of measuring weak fields [4]. The EFM-5 monitor measures accurately from a level of only 1 V/m up to 1000 V/m (0 to 60 dBV/m). This is equivalent to a plane-wave power density range of 0.000265 to 265 mW/cm^2 . Recently, instruments employing isotropic probes have become available commercially which permit practical measurement of either plane waves or complex fields, including the near zone of large antenna arrays. Most conventional FIM's with directive antennas cannot reliably measure EM fields with reactive near-field components, multipath reflections, unknown field polarization, complicated modulations, and large field gradients. The EFM-5 monitor was developed by NBS for measuring these complicated E fields at frequencies from 200 kHz to 1000 MHz.

1.2 Definitions of Field Intensity Units

The mathematical relationships between the field intensity units of a plane-wave field, using RMS values for E and H, are given by

$$S = \frac{E^2}{Z_0} = Z_0 H^2, \quad (1)$$

where

- S = magnitude of the power density in the radiated field, W/m^2 ,
- E = magnitude of the electric field, V/m,
- Z_0 = intrinsic free-space wave impedance $\approx 376.7 \text{ } \Omega$, and
- H = magnitude of the magnetic field, A/m.

Plane-wave conditions generally exist in the far zone of a transmitting antenna. In this case, the E and H field vectors are orthogonal to each other, and both are perpendicular to the direction of propagation. In addition, the ratio of the magnitudes, E/H, is a constant, given by the free-space wave impedance Z_0 . In this plane-wave case, E and H have the definite relation to average power density given by eq (1).

For an isotropic E-field radiation monitor, the total magnitude of the electric field is defined by (and measured in terms of) the root-sum-of-squares (RSS) value of three mutually-orthogonal E-field components, as follows:

$$(\text{Total } E) \equiv E = \sqrt{E_x^2 + E_y^2 + E_z^2}. \quad (2)$$

Mathematically, this quantity is known as the Hermitian magnitude of the vector E field. The electronic circuitry of the EFM-5 radiation monitor has been designed to produce a meter readout in terms of the above RSS value of E.

For an H-field isotropic probe, a similar expression can be given for the total magnitude, as follows:

$$(\text{Total } H) \equiv H = \sqrt{H_x^2 + H_y^2 + H_z^2}. \quad (3)$$

A knowledge of the transmitter power and antenna gain is useful for estimating the field intensity produced by a radiating antenna. The following formula can be used for large distances from the antenna:

$$S = \frac{PG}{4\pi d^2}, \quad (4)$$

where P = power delivered to the transmitting antenna, W,
 G = far-zone gain of the transmitting antenna with respect to an isotropic radiator, and
 d = distance from the antenna to the field point, m.

For calculating the power density at points closer to the antenna, within the near field, more complicated techniques are required. These generally involve expressions for the near-zone, antenna-gain reduction. As a first approximation for determining the possible existence of an rf hazard, the intensity calculated from eq (4) may be considered as a worst-case value, since the "effective" antenna gain is generally less at distances within $2a^2/\lambda$. Here "a" is the aperture or largest dimension of the antenna and λ is the wavelength. It may be noted that a system of "mixed" units, involving mW/cm^2 , is generally used to express power density for rf hazards work, where $10 \text{ mW}/\text{cm}^2 = 100 \text{ W}/\text{m}^2$. The equivalent plane-wave field strength is 194.1 V/m.

1.3 Discussion of Near-Zone Effects and Measurements

If electromagnetic fields always had a plane-wave configuration, the choice of which physical quantity to measure and how to relate it to biological effects would be simplified. The regions close to radiating sources are most likely to have high intensity. Unfortunately, such locations are generally characterized by complicated field structure, including reactive (stored) and real (propagated) energies, standing and traveling waves, irregular phase surfaces, and unknown field polarization. The most practical approach to accomplish field intensity surveys under these conditions is to use rf probes that are independent of orientation in the field and the direction of energy propagation. It is also important that the probe be small and thus able to resolve the fine-structure spatial variations in field intensity. Further, it is important that the

field is not perturbed by the operator or equipment associated with the measurement, such as antenna, cables, meter case, etc.

It is generally assumed that the potential for rf interference and the susceptibility of electronic equipment to rf fields are proportional to the field strength. On the other hand, the heating of a lossy dielectric material (such as human tissue) is proportional to the time-average value of $(\text{total } E)^2$ as defined by eq (2). This is related mathematically to the available electric field energy density, another scalar quantity which involves E and the complex permittivity of the medium. Similarly, the heating of a partially conducting material is proportional to the time-average value of $(\text{total } H)^2$. The familiar power density or Poynting vector is not directly related to the electric or magnetic field magnitude, except when the field structure is quite simple, as with a single plane wave.

It is possible to convert a measured field in E or H to an "equivalent" plane-wave power density, but this common practice is not necessarily valid. That is, it is often convenient (for comparison purposes only) to express field intensity in terms of power density, even for a nonplane-wave situation. However, no commercially available instrument is designed to measure true power density, which is a vector quantity involving direction of power flow as well as amplitude. This is especially important when surveying reactive near-zone fields. In some cases the net power flow through a region may be zero, at a point where the E field intensity is high, that is, where a hazard may exist. Consequently the chosen readout unit of the EFM-5 meter is in terms of the total electric field magnitude in V/m , rather than "power density" in mW/cm^2 .

Two antenna developments now permit more accurate measurement of field strength of arbitrary rf sources. The first development is an "isolated" antenna system, that is, one which has electrical isolation between a small antenna and the receiver. The second development is that of an rf sensor having isotropic response [2], in which the rf pickup is independent of field polarization and arrival direction for the incoming EM wave. Thus it is not necessary to determine experimentally the antenna orientation giving maximum response, or map an elliptically polarized field, or make separate measurements of three orthogonal field components.

Two different techniques were considered at NBS for designing an isolated non-perturbing probe. Both types of probes are useful for mapping near-zone fields and for measuring far-zone electromagnetic interference (EMI). One of these techniques makes use of a fiber-optic transmission link between the active antenna and a conventional rf receiver [5]. However, another technique is covered in this report, in which the total antenna pickup, at all frequencies, is detected at the center of the dipole. It is then not possible to measure the amplitude as a function of signal frequency. No frequency or phase information can be recovered but the E field polarization can be determined, if desired, by taking separate measurements with various dipole orientations. This technique makes use of a high-resistance transmission line, such as carbon-impregnated plastic, to convey the detected antenna voltage to a high-impedance readout meter [6].

Several approaches for convenient measurement of the electric field magnitude of an EM field have thus been evaluated at NBS. The type of sensor found to be optimum for

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constructing a portable rf probe employs three electrically-short dipole antennas, with a shunt diode detector connected across the center gap of each dipole. The dipoles are mounted in an orthogonal arrangement, that is, mutually perpendicular to each other, with approximately a common center. The first work phase of the present project was to modify and improve the previous NBS isotropic probes, for example to increase the measurement sensitivity. The second phase involved improvement of the instrument package and electronic circuitry. The earliest type of isotropic probe bore the nomenclature XD-1 (for crossed dipole) and had readout units of mW/cm^2 . The next series of meters were called EDM-1, EDM-2, EDM-3, and EDM-15, standing for energy density meter, and had readout units of $\mu\text{J}/\text{m}^3$ [1]. The latest version is known as EFM-5, for electric field monitor using 5 cm dipoles, with readout units of V/m.

2. GENERAL SPECIFICATIONS OF THE EFM-5 MONITOR

2.1 Design Goals

The portable rf "hazard" meters which are commercially available for measuring field strength at frequencies down to 100 kHz all appear to have one or more of the following deficiencies:

- (1) They are not sensitive enough to measure weak fields, down to 1 V/m, which are becoming of greater concern.
- (2) Some instruments respond only to magnetic fields at the lower frequencies, for example, below 300 MHz.
- (3) They do not offer a choice of measuring either a single field component or the total vector magnitude.
- (4) They are not capable of measuring the peak value of modulated fields, with a choice of several time constants, permitting measurement of either a cw or a modulated field.

On the other hand, conventional FIM's also have deficiencies for most types of field strength measurements. They tend to be large, heavy, expensive, and difficult to operate in complex fields. To qualify as a good general-purpose monitor of EM fields, it is felt that the instrument should satisfy certain minimum characteristics. The main design goals which served as guidelines during development of the EFM-5 instrument are summarized in Table 1.

2.2 Description of the Instrument

The EFM-5 isotropic field strength monitor consists basically of three units. The first is the rf "probe." It includes three crossed-dipole antennas and three detectors imbedded in a 10-cm diameter polyfoam sphere. The probe unit also includes three high-resistance plastic twinleads inside a dielectric handle which is about 15 cm long. The overall probe length is about 21 cm, including the foam sphere.

TABLE 1. DESIGN GOALS FOR THE EFM-5 RADIATION MONITOR

(1) Type of field to be measured:	The instrument should measure the electric field strength of CW, AM, FM and TV signals, including those having more than one source or frequency.
(2) Field parameter to be measured:	A single component of electric field strength, or the root-sum-square value of three orthogonal E-field components.
(3) Field perturbation by the measuring antenna:	The probe should be invisible to rf; that is, it should cause no scattering or perturbation of the field being measured.
(4) Probe proximity effect:	Small sensor, capable of measuring within 5 cm of an object without distorting the field.
(5) Field polarization capability:	Provide accurate measurement of linear or elliptical polarization, either vertical or horizontal, or any other polarization angle.
(6) Antenna response pattern:	The probe response should be independent of its angular orientation in the field or the direction of the arriving signal.
(7) Measurement sensitivity:	Capable of measuring fields as weak as 1 V/m at any frequency in the band.
(8) Measuring range:	Dynamic range of 0 to 60 dBV/m (1 to 1000 V/m) without requiring any antenna change.
(9) Sensor size:	The rf sensor in the probe should be small compared with the shortest wavelength of the field being measured.
(10) Frequency range and bandwidth:	Should have broadband frequency coverage, with a response that is essentially independent of frequency, requiring no tuning or bandswitching.
(11) Measurement accuracy:	Within ± 2 dB from 500 kHz to 1000 MHz, without use of correction curves.
(12) Peak-average capability:	The instrument should be capable of reading either the peak or time-average value of modulated signals.
(13) Pulse response capability:	Accurate measurement of time-modulated signals with pulse duration greater than 0.3 milliseconds.
(14) Shielding of case:	Adequate shielding for self protection and proper operation for fields up to at least 1000 V/m.
(15) Power supply:	Should operate from rechargeable self-contained batteries for a period up to 8 hours.
(16) Size and weight:	Must be strictly portable, for one-man field use.

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The second part of the EFM-5 is the "metering unit" or "electronic package." It contains the electronic circuitry, readout meter, front panel controls, batteries, etc. The third part of the overall instrument is a "shielded" six-conductor transmission line connecting the probe with the metering unit. The line is made entirely of partially-conducting plastic. The resistance per unit length of this flexible line is much less than that of the RC filter line inside the probe handle, but sufficiently high to be essentially transparent to rf fields.

The EFM-5 monitor is a versatile instrument for determining the electric field magnitude of either a plane wave or a complex EM field. This portable meter provides accurate measurements in near or far field environments. The isotropic sensor employs three balanced, mutually-orthogonal dipoles to provide capability for measuring the "total" magnitude of a wave arriving from any direction. The instrument response is independent of field polarization and signal frequency within wide limits.

The overall frequency range of 0.1 to 4000 MHz includes most of the higher power rf radiators now in use. For example, it covers the AM, FM and TV broadcast stations, plus the CB, HF and land mobile communications services. This frequency range also includes most of the navigation aids, and Industrial, Scientific and Medical (ISM) bands. The bands at 13.5, 27, 41, and 75 MHz are used by industry for drying of plywood, curing plastics and for sealing operations [7], while the 915 and 2450 MHz bands are used primarily for microwave ovens.

The amplitude measuring range of the EFM-5 has intentionally been limited to signal levels between 1 and 1000 V/m. The measurement accuracy and readout precision are constant over this entire range. It is seldom necessary to measure fields exceeding the upper value, which is equivalent to a plane wave power density of 265 mW/cm^2 . The lower field strength capability of 1 V/m is equivalent to $0.265 \text{ } \mu\text{W/cm}^2$, which is considered to have no biological consequence. The total dynamic range of 60 dB is greater than that of most commercially available radiation monitors.

The crossed dipoles in the antenna system have a length of 5 cm each. The rf pickups on the three electrically-short dipoles are detected and processed electronically to produce a readout corresponding to the RSS value of the three orthogonal E-field components. The dial indication, dBV/m or V/m, is similar to that of conventional field strength meters. However, the EFM-5 indication includes the total effect of fields at all possible polarizations and arrival directions, and for all frequencies within the overall passband of the antenna and transmission line.

2.3 Applications of the EFM-5 Monitor

The EFM-5 portable monitor may be used to search for potential rf hazards from industrial high-power sources. However, it also has sufficient sensitivity to measure weaker fields which might produce interference or an undesirable rf "smog." The antenna can be switched to measure either a single far-zone field component (similar to a conventional field strength meter having a directional antenna) or a near-zone leakage field (similar to the usual isotropic hazard meter). The instrument has features similar to a microwave oven

probe for quick testing, but is designed for the lower frequencies used by broadcasting stations and medical or industrial heating. These rf sources operate at frequencies down to 200 kHz, and include diathermy equipment, plastic sealers, and chambers for drying and curing dielectric materials.

As mentioned previously,* the EFM-5 probe also provides higher sensitivity for measuring weak fields at greater distances from a transmitting antenna. These fields include AM and FM radio, VHF and UHF television, and other broadcasting services. The EFM-5 can be used to monitor the environment in rf sensitive areas containing electroexplosive devices, flammable fluids, etc. It can also be used for electromagnetic compatibility (EMC) tests and to check sites containing sensitive instruments that are susceptible to radio frequency interference (RFI) or suffer degraded operation when exposed to EM radiation.

An example can be cited of recent susceptibility tests performed by NBS on a digital data acquisition system. An EFM-5 was used to measure the field intensity in the vicinity of the magnetic tape drive, checking for data errors or spurious mechanical motion of the tape, caused by transmission from a nearby hand-held communications transceiver at a frequency of 162 MHz. Quick tests with the EFM-5 revealed that these effects were caused by rf fields at the tape drive unit exceeding 4 V/m, produced when the transceiver was within 10 ft of the digitizer rack.

An important application of the EFM-5 isotropic probe is searching for locations of high field intensity caused by reflecting objects and standing waves. These localized regions of higher rf level are known as "hot spots." Another application is to monitor the field level while tuning a transmitter or antenna for maximum radiated output. Also, comparisons can be made of the gain and efficiency of various antenna types. The monitor can even be used to make limited checks of field polarization and transmitting antenna pattern.

The EFM-5 has a front panel switch for selecting measurement of either the time-averaged field value or the peak value of a modulated field. The RC time constant is switch-selectable to several values from 0.1 to 5 seconds. Most commercially available hazard meters employ rf sensors with a long overall response time. Thus they cannot measure the "momentary" high field of a scanning antenna nor the peak value of rf ovens, which generally use unfiltered power supplies. By contrast, the EFM-5 meter has an electronic peak-reading circuit with a response time as short as 0.1 second. An example of a special situation benefiting from the short peak-response time is the checking of safety interlock switches on the doors of rf heating chambers. Improper design of the interlock switch may permit a burst of rf energy to escape when the door is jerked open suddenly. The field value of this rf pulse would not be indicated on an instrument with slow response time, but it might bear on the safety of persons wearing electronic heart pacers. A similar situation occurs in testing rf fields near a rotating or scanning antenna of a transmitter.

The biological importance of measuring peak-burst rf levels has not yet been established, mainly because the measuring instrumentation is not commercially available. However, improved meters similar to that of the EFM-5 design could lead to future limits on rf burst level. It is thus considered advantageous to have the capability for observing the

modulation on a signal being measured.

2.4 Electronic and Physical Specifications

One important characteristic of the EFM-5 instrument is its relatively high sensitivity (1 V/m) compared with most radiation hazard meters. The rf sensor consists of three mutually orthogonal dipoles, each 5 cm long and 2 mm wide. A diode detector is connected across the center gap of each dipole. The type used for the EFM-5 probe is a 5082-2837 beam-lead, Schottky diode. These diodes will withstand a peak reverse voltage of 70 volts, which is about 17 dB above the voltage produced by a cw field of 1000 V/m. The field sensors are thus virtually "burnout" proof for high-level cw fields. The overload level for pulsed signals has not been determined, but such fields with a low duty factor may have an extremely high level during each pulse on-time.

The pattern response of the EFM-5 is isotropic, within ± 1 dB, except for radiation arriving at the sensor through the probe handle. The meter dial has units of dBV/m (decibels above 1 V/m) and V/m. The total dynamic range is 0 to 60 dBV/m (1 to 1000 V/m), in three switch-selectable ranges. This is equivalent to a free-space power density range of $0.265 \mu\text{W}/\text{cm}^2$ to $265 \text{ mW}/\text{cm}^2$. Figure 2 shows the field strength range of the EFM-5 radiation monitor. This graph is also useful for comparing electric field units of V/m with free-space power density units of mW/cm^2 .

The amplitude response of the rf sensor is flat, within ± 2 dB, from 200 kHz to 1000 MHz. The response decreases at lower signal frequencies, but begins increasing at frequencies above 1 GHz where each dipole is approaching self-resonance. As shown in figure 3, the sensitivity increases by about 15 dB at the resonant frequency near 2.45 GHz.

The frontispiece is a photograph of the three major components of the measurement system. The metering unit is in the metal case on the left. The probe unit, including the antenna sphere and short handle, is on the right. The resistance line used to convey the detected signals from the probe to the front panel of the metering unit is barely visible. Figure 4 is a sketch of the instrument giving the overall dimensions of the present prototype model. The case size is approximately 21 cm wide x 17 cm high x 29 cm deep. A summary of the pertinent specifications for the EFM-5 is given in table 2.

3. OVERALL DESIGN AND OPERATION

3.1 Functional Block Diagram and Description of Operation

Figure 4 is a sketch showing the general appearance of the EFM-5 radiation monitor. Figure 5 is a simplified block diagram of the major components. The probe unit consists of the crossed-dipole antenna system, the shunt diode detectors, and the high-resistance plastic twinleads. These resistance lines not only convey the detected signal through the handle but also serve as a balanced RC filter to attenuate rf signals on the line.

The center portion of figure 5 shows the flexible plastic lines of lower resistance which convey the signals to the metering unit. These lines can be of any convenient length since their resistance is low compared with that used for the RC filter in the probe

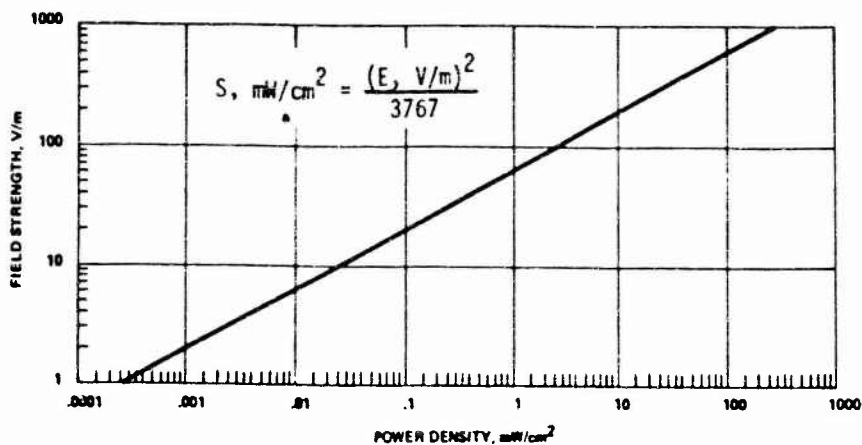


Figure 2. Graph of the EFM-5 field intensity range, comparing units of V/m and mW/cm².

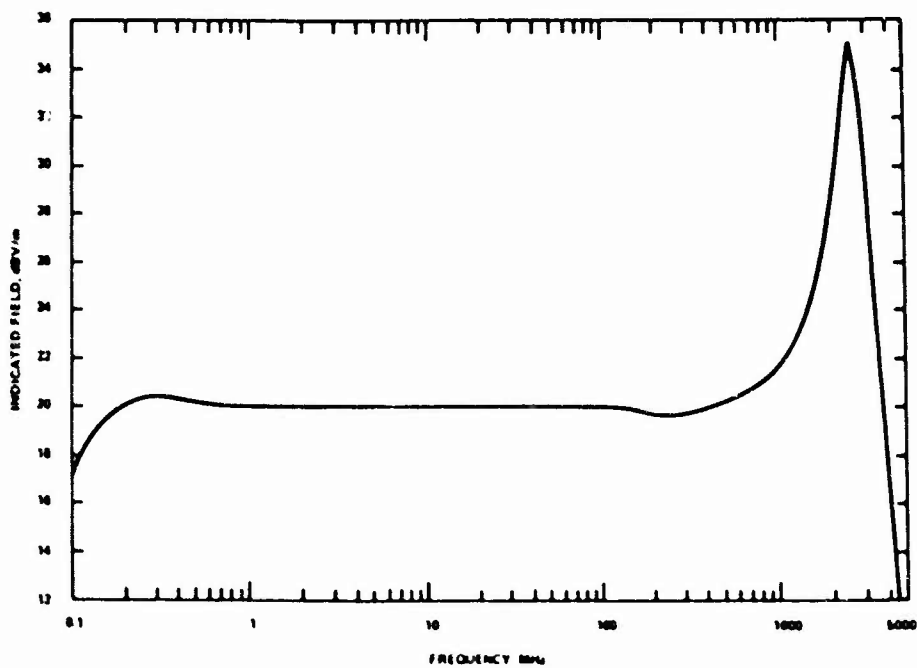


Figure 3. Typical response of an EFM-5 monitor vs frequency, at a field strength of 20 dBV/m (10 V/m).

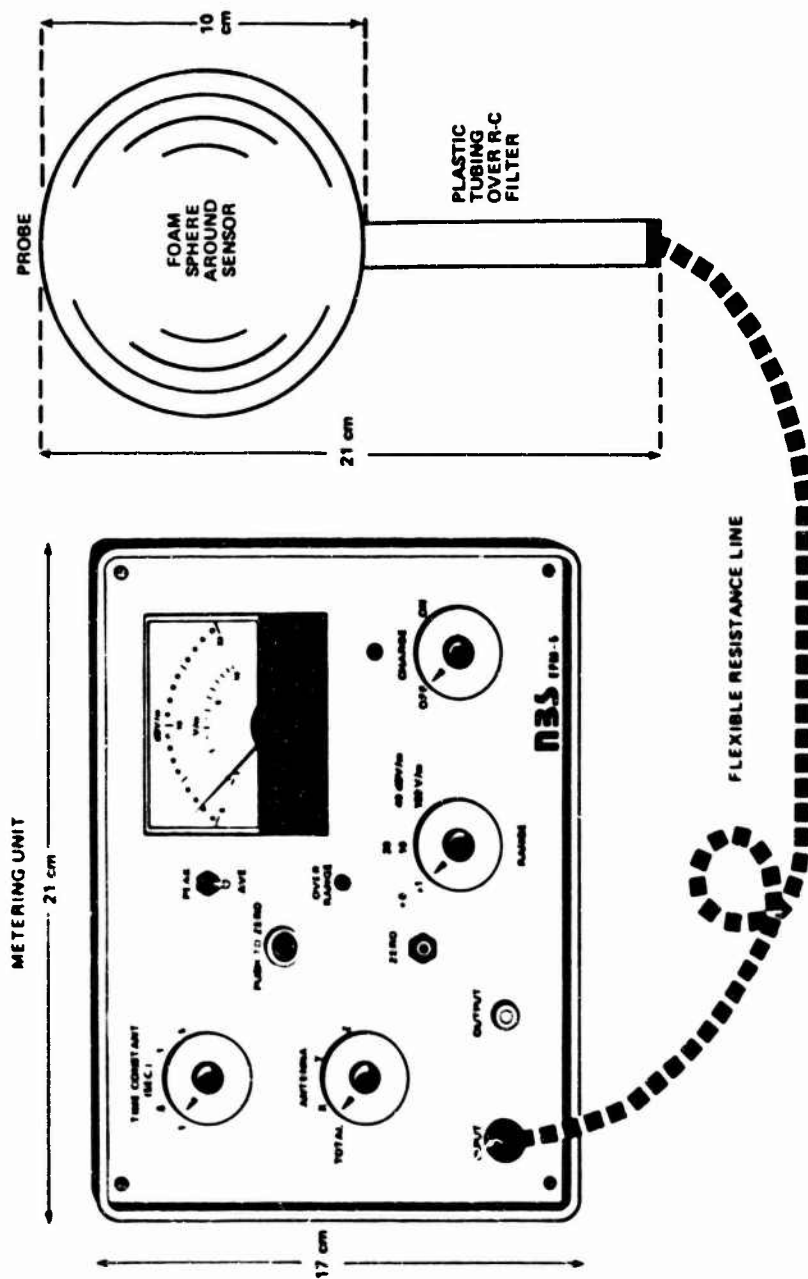


Figure 4. Sketch showing general construction of the EFM-5 meter.

TABLE 2. SPECIFICATIONS OF THE EFM-5 RADIATION MONITOR

(1) Field parameter measured:	Hermitian magnitude of the electric field, or a single component of the E field.
(2) Meter readout:	Analog indicator, dBV/m and V/m.
(3) Monitor full-scale values:	20, 40 and 60 dBV/m; also 10, 100 and 1000 V/m.
(4) Type of rf field sensor:	Three mutually orthogonal dipoles.
(5) Dimensions of each dipole:	5 cm long x 2 mm wide.
(6) Type of detector diode:	No. 5082-2837 beam-lead Schottky diode.
(7) Overall probe length:	21 cm.
(8) Probe pattern response:	Either single polarization or fully isotropic.
(9) Probe isotropy:	Within ± 0.5 dB, except through the handle.
(10) Probe 10-90% response time:	0.3 milliseconds.
(11) Instrument time constant:	0.1, 0.5, 1 or 5 seconds, peak or average.
(12) Total dynamic range:	60 dB.
(13) Amplitude measuring range: Indicated equivalent power density	0 to 60 dBV/m and $\uparrow$ to 1000 V/m, 0.000265 to 265 mW/cm ² .
(14) Frequency range: for ± 3 dB response for ± 2 dB response for ± 1 dB response	0.15 to 1300 MHz. 0.2 to 1000 MHz. 0.3 to 900 MHz.
(15) Measurement uncertainty: without correction curve with correction curve from standard field calibration	± 2 dB from 0.2 to 1000 MHz. ± 1 dB from 0.1 to 4000 MHz.
(16) Battery type:	Rechargeable Ni-Cd cells.
(17) Battery use time:	7 hours.
(18) Metering unit dimensions:	21 cm wide x 17 cm high x 29 cm deep.
(19) Instrument total weight:	Approximately 5 kg.

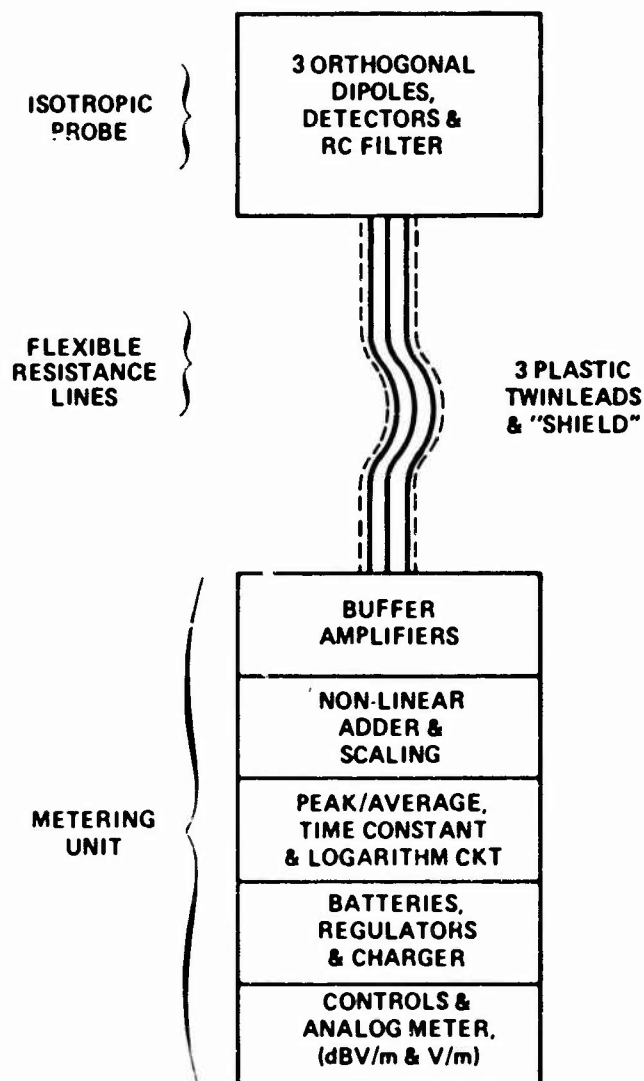


Figure 5. Major components of the EFM-5 electric field monitor

handle. However, these lines are also essentially invisible to EM fields, causing no appreciable distortion of the field being measured. The third and largest component, the metering unit, is contained in a metal case. It consists essentially of three balanced dc amplifiers plus electronic circuitry which processes the voltages to produce the desired E-field reading.

Figure 6 is a more detailed block diagram of the rf monitor. As shown, the isotropic probe consists of the X-, Y- and Z-component dipoles with their associated detectors, filters and transmission lines. It can be seen by examining the figure that the metering unit provides five major functions, namely:

- (1) Amplification, including differential pre-amplifiers of high input impedance.
- (2) Processing of the detected signals to produce a voltage proportional to E^2 over the entire amplitude range.
- (3) Switching to choose a single field component or combine the three voltages from the three coordinate channels to obtain a single "total magnitude."
- (4) RC time constants and circuitry to obtain either the time-average or the peak value of a modulated signal.
- (5) Analog circuitry to calculate and produce a meter indication in units of dB with respect to 1 V/m (dBV/m).

Figure 7 is similar to figure 6 but shows additional features of the metering unit. The front-panel range switch has three amplitude positions which are labeled 0 dB, + 20 dB, and + 40 dB. These correspond to the dB value which must be added to the dial indication in dBV/m. The channel selector switch on the front panel has four positions, labeled X, Y, Z and TOTAL. These correspond to measurement of either a single E-field component or the RSS magnitude of all three orthogonal components.

Figure 8 is a simplified schematic diagram of the overall instrument. A brief description of the electronic functions is given in this section. The three 5-cm dipoles are depicted at the left side of the figure. After the rf signals have been detected and filtered by the sandwich-type lines in the probe handle, the three dc components are passed through lower resistance lines to preamplifiers (pre-amps) in the metering unit. As shown, each pre-amp is a balanced differential amplifier configured from three individual operational amplifiers (op-amps). The voltage gain is about 12 for the two lower ranges (1-10 V/m and 10-100 V/m) and unity on the upper range (100-1000 V/m). The mid-amp gains are adjustable so that the outputs of the three channels can be equalized (in a 10 V/m E field) and also to obtain an overall gain which results in optimum "shaping" (square law output) from the following circuit.

The three component signals are then summed in the "adder" of figure 8 to yield a dc voltage which is proportional to the sum of squares of the three induced fields at the dipoles. The function performed by the varistors is described in section 5.2. The gain of the adder has three step values corresponding to the range chosen by the front-panel range

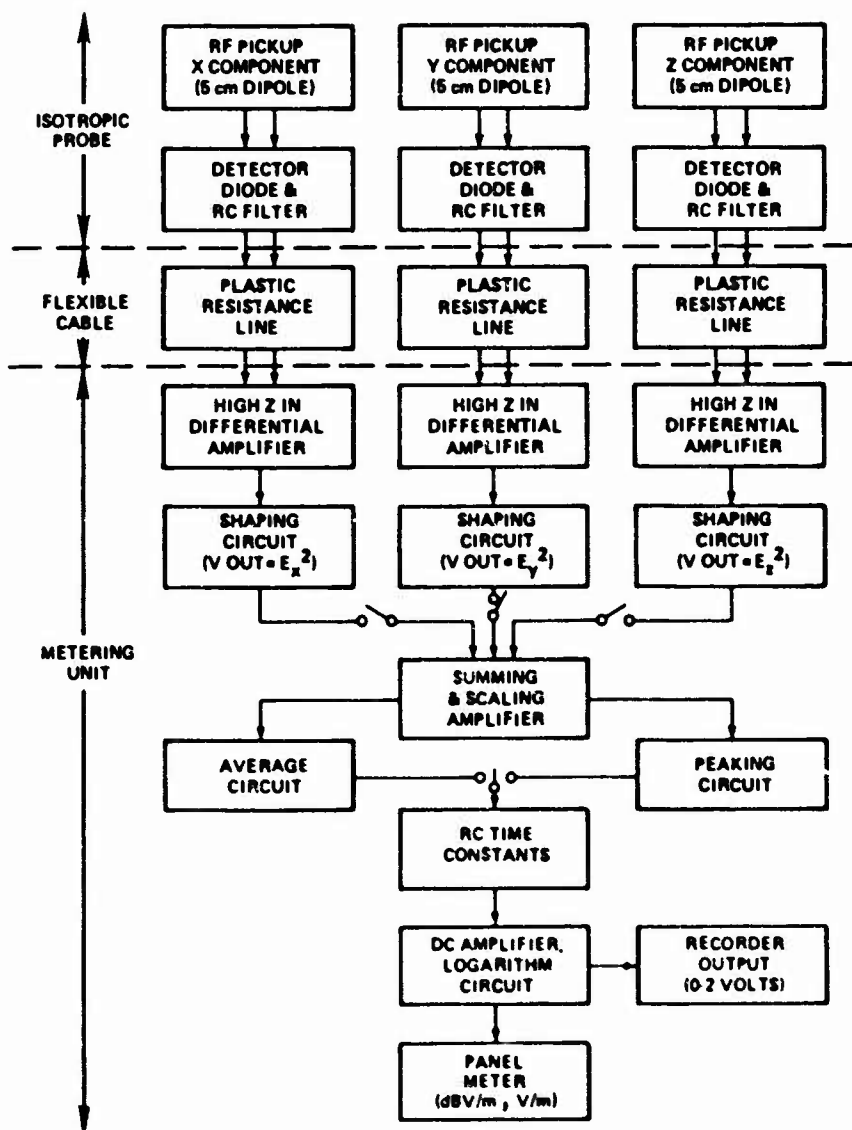


Figure 6. Functional block diagram of the EFM-5.

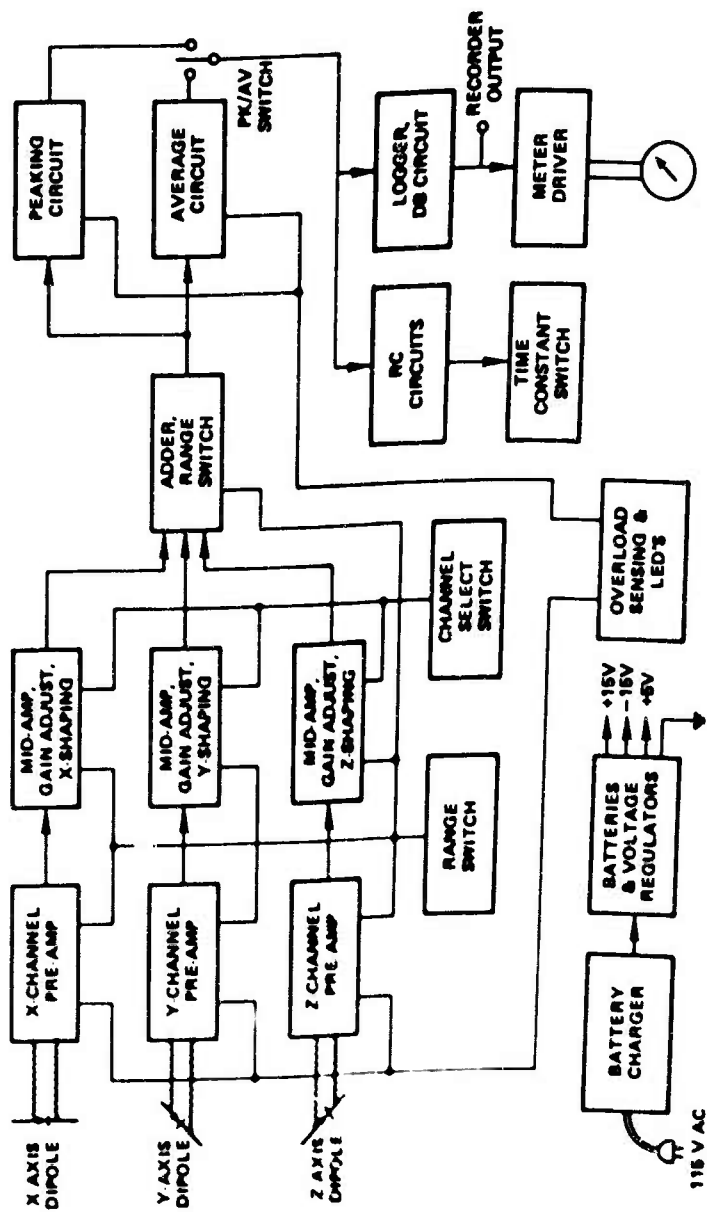


Figure 7. Overall block diagram of the EFM-5 monitor.

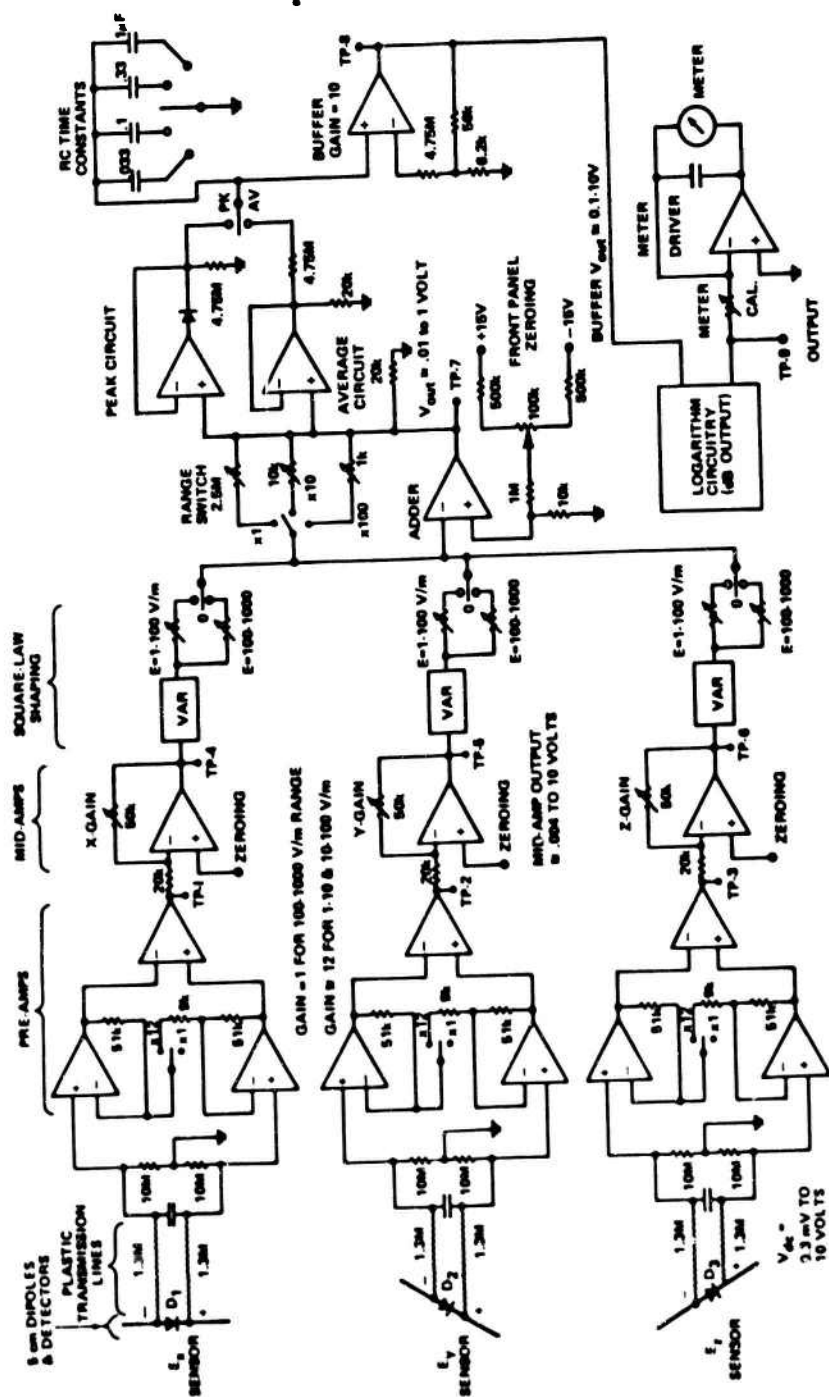


Figure 8. Simplified schematic diagram of the EFM-5 instrument.

switch. The adder output voltage extends over a two-decade ratio, from approximately 0.01 to 1 volt, for each position of the range switch. This corresponds to a 20 dB variation in field strength (one decade ratio) for each range.

The next stage in figure 8 extracts either the peak or average value of a cw or modulated signal, with a choice of four RC time constants. A cw signal will produce the same reading for both positions of the PEAK/AVE switch. Any amplitude modulation of the rf field can be observed at the OUTPUT jack, within the 0.1 second limitation of the time-constant circuitry. After a buffer amplifier stage which has a voltage gain of 10, analog circuitry is provided to produce a voltage which is proportional to the logarithm of the input voltage. That is, the output voltage is proportional to the E field expressed in dBV/m. The meter dial reading corresponds to electric field magnitude in dB above 1 V/m on the lower range, dB above 10 V/m on the middle range, and dB above 100 V/m on the upper range. For each decade range of E field the actual output voltage varies linearly from 0 to 2 volts. It is this "linear" voltage which appears at the OUTPUT jack on the front panel. In other words, this voltage level, times 10, is numerically equal to the dial dB indication.

The logarithm and dB computations are performed by an analog circuit shown as a single block in figure 8. It consists of op-amps, IC logarithm module, reference voltage generator, etc. A second meter scale has non-linear dial markings from 1 to 10 V/m. It has been provided to indicate the E field directly in V/m, with x1, x10 and x100 multiplier markings on the range switch. The three field intensity ranges are thus 0 to 20 dBV/m (1-10 V/m), 20 to 40 dBV/m (10-100 V/m) and 40 to 60 dBV/m (100-1000 V/m). Section 7 gives the complete schematic diagrams of the electronic circuitry.

3.2 Operating Instructions

The front panel layout of the EFM-5 radiation monitor is shown in figure 4. All of the operating controls and the analog readout meter can be seen. The INPUT connector in the lower left corner is for the six-conductor resistive line from the probe unit. The OUTPUT connector furnishes the 0-2 V signal which is proportional to the 0-20 dB scale of the readout dial. The 3-position switch in the lower right corner is the power ON/OFF switch, plus a battery charging position. The instrument is inoperative when this switch is rotated to the CHARGE position. A 115 V power cord must be plugged in the rear of the metering unit to recharge the batteries. For normal operation, during field strength measurement, the power cord should be disconnected from the instrument in order to reduce field perturbations.

The step-by-step procedure for operating the EFM-5 as a field intensity meter can be summarized as follows:

- (1) Connect the plastic transmission line from the probe to the INPUT connector of the metering unit, located in the lower left corner of the front panel. For accurate measurements of field strength, be sure that the probe serial number agrees with the serial number on the metering unit.

- (2) If desired, a coax cable (or other dc line) may be used to connect an x-y recorder (or other voltage monitor) to the BNC OUTPUT jack, adjacent to the INPUT connector.
- (3) Turn the power switch (lower right corner of the front panel) to the ON position. A red light-emitting diode (LED) located near this switch will light up if the battery voltage is low, indicating that the batteries should be recharged. (NOTE: If the batteries are nearly completely discharged, there may not be enough voltage to ignite the LED.) This warning light also glows when the switch is in the CHARGE position and a power cord is plugged into a 115 V outlet, to indicate that the batteries are being charged.
- (4) Rotate the ANTENNA channel selector switch to the TOTAL position. This switch is located on the left side of the panel. The TOTAL position is used for measuring the RSS value of three orthogonal E-field components.
- (5) Place the PEAK/AVE toggle switch to the desired position for measuring either the time-average value of field strength, or the maximum value of a modulated field.
- (6) Rotate the TIME CONSTANT switch to the desired RC weighting value in seconds. The variable decay time is operative (and useful) with either the peak or average position of the switch.
- (7) Before zeroing the instrument, rotate the RANGE selector switch to the most sensitive (0 dB) position. Check the meter zero by holding in the PUSH TO ZERO button. If necessary, turn the zeroing potentiometer with a small screwdriver until the indication is at 0 dB or 1 V/m on the meter dial. This ZERO adjustment is accessible on the front panel below the PUSH TO ZERO switch.
- (8) To measure field intensity, place the polyfoam sphere surrounding the probe tip at the desired measurement location, and read the meter. To measure a single x, y, or z field component, follow the above procedure and rotate the channel selector switch to the desired component position. If the meter has been zeroed for all-channel operation, it should be re-zeroed for single-channel operation, and vice versa; this is especially true for measurement of a very weak field on the most sensitive range.

The zeroing operation of the EFM-5 is different from the rf radiation monitors previously designed at NBS; the minimum indication on the meter dial is 0 dBV/m (1 V/m) rather than zero V/m. When the front-panel PUSH TO ZERO switch is held in, the logarithm circuit is disengaged and the ZERO control should then be adjusted for a 0 dBV/m dial indication. It is still necessary to place the probe in a shielded or zero-field environment during the zeroing process.

Measurements of ambient fields are generally made by using the instrument to find the higher E-field values present at any location within reach of the hand-held probe. For such measurements, a rigid plastic tube is connected between the short probe and the flexible

line. This extension handle is usually 50 to 75 cm long. During the field measurement process, the sensor end of the probe is moved from side-to-side by the operator, at several elevations. This tests a vertical plane region about 2 x 2 meters. The ambient field measurements reported then represent the highest levels found during the above scanning process. (See section 3.4 for a discussion of "hot spots.")

3.3 Possible Errors in Measurement of Multifrequency Fields

The EFM-5 monitor has a fairly flat response over a wide frequency range of 0.2 to 1000 MHz but responds to the sum of all fields present within a total frequency range of 0.1 to 4000 MHz. Therefore, rf fields due to harmonics and other frequencies will contribute to the meter indication. A field strength reading may thus not agree with that measured on a frequency-selective FIM. Also, the measurement accuracy is reduced for pulsed fields that have pulse widths less than about 0.3 milliseconds, due to the limited charging time of the RC filter line in the probe. In addition, a possible erroneous increase in meter indication occurs when measuring multifrequency fields. The meter indication will generally be too high because the lightly loaded sensor tends to respond as a peak-reading device. The error may be as much as 3 dB when measuring a cw field having two frequency components of equal magnitude [8].

However, experimental results of a recent field intensity survey made by NBS were in reasonable agreement with the data reported by a private corporation using a tunable receiver. The fields were radiated mainly by several nearby broadcast band antennas. The NBS measurements with an EFM-5 monitor were taken at a height two meters above the roof of a building. The measured "total" field strength was 11 dBV/m, or approximately 3.5 V/m. After reducing the amplitude-vs-frequency data reported by the private corporation, using the RSS value of all their readings, the calculated total E field was 3 V/m at the same height above the roof. These two values (3.5 V/m and 3.0 V/m) agree well enough to indicate the usefulness of the EFM-5 probe for measuring the total electric field, in spite of the multifrequency type of field present.

The technique mentioned in the previous paragraph involves measurement of many individual signals found during a frequency scan with a tunable receiver. A similar approach is used by the Environmental Protection Agency (EPA) for making surveys of ambient fields with an automated van system [9]. It uses three mutually orthogonal dipoles for frequencies below 1 GHz. The EPA computes a total integrated power density in $\mu\text{W}/\text{cm}^2$ from a large number of electric field measurements in each frequency band.

3.4 General Measurement Uncertainties and Precautions

In addition to a possible error when measuring multifrequency fields, as discussed in the previous section, there is a perturbation error when the probe is hand held. This is caused by the presence of the operator and/or cable between the probe and metering unit. The error is generally less than ± 0.5 dB when taking measurements close to a transmitting antenna where the field gradient is high and the operator can place himself in a weaker field than that of the probe sensor. The perturbation due to the presence of the operator

may be as great as 1 dB or more when measuring at a large distance from a transmitting antenna, where the probe and operator are in equal fields [10].

The method of field scanning described in section 3.2 is not greatly influenced by the presence of the operator. The field perturbation is greatly reduced if the short EFM-5 probe is mounted on a longer dielectric tube and extended a few feet away from the body. The EFM-5 has a relatively long non-perturbing transmission line which permits greater operator separation than most radiation monitors. This plastic line is one to three meters long and field distortion can thus be kept to a negligible value. It should be noted, however, that environmental parameters such as tree foliage, moisture, etc. can introduce rf absorption and other effects into the measurement process.

When using radiation monitors with isotropic probes, it is easy to search for and locate "hot spots." These are localized regions of higher field intensity or "fine structure" created by constructive interference. They are due to multiply reflected waves or a standing wave pattern of enhanced field strength from metal objects serving as reflectors or antennas. The true power density in a hot spot is not necessarily high, but a high E-field level is an indication of a potential rf hazard.

The sensor of the EFM-5 probe is embedded in a styrofoam sphere 10 cm in diameter. The minimum distance for which field measurements are meaningful is thus 5 cm (2 inches). In addition to acting as a 5-cm spacer when measuring leakage fields, the foam sphere surrounding the probe tip serves to protect the internal dipole antennas and helps prevent electrical shock to the operator. However, it is advisable to ground the case of the metering unit when probing around unshielded high-voltage circuits and wiring.

The PEAK/AVE switch on the front panel selects the waveform parameter desired for measurement. If the peak-to-average ratio of a modulated waveform being measured is too large, the average reading of the instrument may be in error. This problem exists for high level fields because the amplifiers in the metering unit become saturated when the instantaneous field level exceeds 100 V/m. That is, the signal peaks of a modulated wave form are "clipped" at this level, causing the average reading to be too low if the peak value exceeds 1000 V/m.

For antennas which rotate through 360°, or oscillate in a sector scan, or in which the beam is scanned electronically, a special duty factor is sometimes defined which relates the "momentary" boresight value to the overall time-average value of field intensity. However, such a theoretical correction factor is not very useful or accurate unless the pulse response characteristics of the measuring instrument have been evaluated for the particular type of modulated signal being measured.

4. DESIGN OF THE ELECTRICALLY-ISOLATED ANTENNA

4.1 Characteristics of a Good Field Monitor

Several characteristics of a good probe for surveying near-zone fields are described in this section. The first three characteristics given are considered to be essential. The

remainder are desirable and are listed somewhat in decreasing order of importance, as follows:

- (1) Isotropic sensor: The E-field response should be independent of probe orientation, requiring no knowledge of the field polarization.
- (2) Small sensor: The rf sensor should be small in order to minimize scattering; that is, it should not perturb the field being measured. If dipoles are used, they should be electrically small. This is important for a non-uniform fringing field, such as that encountered near a narrow aperture or small source.
- (3) Isolated sensor: The antenna should not require a conducting transmission line. If a transmission line is used, it should be "transparent" to rf radiation so that it also does not perturb the field. (The NBS EFM-5 probe uses plastic twinleads to convey information from the antenna to the metering unit.)
- (4) Broad bandwidth: The sensor should be capable of measuring over a large frequency range, with no required tuning, in order to perform rapid field surveys.
- (5) Flat response: The meter indication should be independent of the frequency being monitored. It is desirable that the antenna have no resonant-frequency effects. (The EFM-5 response increases at frequencies above 1 GHz where the dipoles begin approaching a self-resonant length. However, the frequency response curve is quite flat over a wide range, being within ± 2 dB from 0.2 to 1000 MHz.)
- (6) Large dynamic range: The instrument should have a wide range between the weakest measurable field and a field strong enough to cause overloading. (The EFM-5 is capable of measuring amplitudes from 1 to 1000 V/m, a 60 dB dynamic range, with the same readability precision across the entire range.)
- (7) Good sensitivity: The response should be adequate to measure fields as weak as 1 V/m, which is equivalent to a free-space power density of about $1/4 \text{ } \mu\text{W}/\text{cm}^2$.
- (8) Burnout-proof sensor: Exposure of the probe to extremely intense radiation should not damage the instrument nor cause a change in the meter calibration.
- (9) Fast sensor response: The response time of the probe should be short, permitting rapid spatial probing and rapid frequency scanning. (The EFM-5 is limited by the 0.3 millisecond response time of the resistance line filter used).
- (10) Selectable time constant: The overall response time of the instrument should be switch-selectable by the operator. (Four time constants are available on the EFM-5, from 0.1 to 5 seconds).
- (11) Peak/average capability: The instrument should have the capability for direct measurement of a peak field value, as well as the time-average value, for either cw or modulated fields.
- (12) Good stability: The measurement system should be stable with respect to both time and environmental conditions.

(13) Direct reading: The instrument should not require a calibration chart or auxiliary readout device.

(14) Other considerations: The instrument should be rugged, lightweight, well shielded electrically, and be battery operated.

Existing radiation monitors do not possess all of the above desirable characteristics. Perhaps the most serious shortcoming is the long response time of most probes. The 90 percent response time of the EFM-5 to an instantaneous change in field level is about 0.3 ms. The response time of monitors employing thermocouple sensors is generally much longer. For example, the specified response time of the sensing element in a well known commercial meter is approximately 35 ms. However, the overall response time for that instrument is about 750 ms with the time constant switch in the "fast" position. It would thus not be possible to measure directly the peak-to-average ratio of a modulated field, nor the "momentary" maximum-envelope intensity in the beam center of a scanning antenna.

Some commercial "power density" meters utilize several separate antennas, each covering a restricted band of frequency or amplitude. To our knowledge, no commercially-available monitor offers the ability to measure the peak or average field level, with a choice of several time constants. In addition to the characteristics listed above, it is desirable that the sensor measure a scalar rather than a vector quantity. This is inherent in the concept of an isotropic probe. The meter indication of the EFM-5 is a quantity known as the Hermitian magnitude of the electric field, defined in section 1.2.

4.2 Technical Approach of the EFM-5 Isotropic Antenna

A brief description of the EFM-5 field intensity meter was given in section 3.1. The rf sensor consists of a set of three mutually-orthogonal dipoles, each 5 cm long x 2 mm wide. The dipoles are etched from copper-clad circuit-board material. Since each dipole is electrically short, the probe achieves a flat response over a large bandwidth.

The crossed dipoles are arranged with approximately a common center and mounted symmetrically, that is with equal angles to the probe handle. The acute angle between each dipole element and the resistance-line bundle leaving the antenna unit (along the probe handle) is 54.74°. This angle results in orthogonality between the three dipoles. The three transmission lines are positioned to minimize any unbalance or interaction between the lines and dipoles.

Each dipole of the antenna unit responds to the electric field independently of the other two dipoles. This can be seen from the following argument: The net voltage induced across the center gap of one of the dipoles is the phasor sum of the voltage induced by the impressed field plus voltages induced by currents in the other two dipoles. However, because of the orthogonality of the three dipoles, current produced by an E field which is parallel to one of the dipoles cannot induce a potential across the center gaps of the other two dipoles. It is assumed here that the antennas are "thin" (high length-to-diameter ratio) so that the induced currents flow only in the lengthwise direction on the dipoles.

Since a good E-field sensor must be able to measure close to a radiating source or

reflecting surface without perturbing the field, it is necessary that the scattering from the probe be small. This criterion is satisfied by an antenna made of electrically-short dipoles. It has been shown experimentally and theoretically [11] that the scattering cross section of a dipole decreases rapidly as the length decreases below $1/2$ wavelength. A 5 cm dipole causes no appreciable scattering at frequencies below 1000 MHz.

A Schottky beam-lead diode, type 5082-2837, is connected across the center gap of each dipole. As described by the manufacturer, this semiconductor diode offers the speed of a majority carrier device and low turn-on voltage of germanium, but with the high breakdown voltage and temperature-independent characteristics of silicon (Si). It has good rectification efficiency at low voltage combined with a high peak reverse voltage (PRV). The 70 volt PRV results in an rf sensor which is virtually burnout proof. The very high resistance of the diode helps to match the inherent source impedance of the dipole, making possible a sensor with wide dynamic range. A 5 cm dipole is capable of producing stable, rectified outputs at field levels ranging from 1 V/m up to 1000 V/m.

The type of detector used is somewhat sensitive to ambient light. Exposing an uncovered probe sensor to bright sunlight would cause a zero drift on the meter. That is, a change of indication due to varying ambient light would occur even for zero rf field conditions. It was found necessary to wrap the "inner" sensor sphere of the EFM-5 with a layer of opaque plastic tape. The type of diode chosen functions well in this application, but NBS has not made exhaustive tests to determine if it is an optimum choice.

Beam-lead diodes are silicon chips with gold plated tabs on two sides for the leads. The chip has dimensions of about 250 μm square by 10 μm thick. The tab leads extend approximately 200 μm beyond each edge of the chip and are mounted to the metal dipole by ultrasonic bonding. The resistance of the diode at 0 volts (no applied field) varies between 10 and 15 M Ω . The shunt capacitance is quite low, resulting in a detector that is sensitive to weak rf fields. The capacitance at 0 volts has a specified maximum value of 2 μF .

Figure 9A is a sketch of one dipole and high-resistance carbon-loaded plastic line. The plastic material is Polytetrafluorethylene (PTFE) to which carbon granules have been added. A stainless steel ferrule is crimped on each end of the line to serve as a compression contact to the partially-conducting plastic. These ferrules have been cut from the tips of hypodermic needles. The tiny steel ferrules are then bonded to the metal dipole arms with conducting (gold-loaded) epoxy adhesive. The two resistance lines connected to each dipole are equal in length (about 1 cm) and brought symmetrically away from the junction point.

The specially fabricated sandwich line shown in figure 9B consists of two layers of carbon-loaded PTFE separated by a spacer of non-conducting PTFE [12]. This high-resistance twinlead forms a distributed RC filter, removing the rf but passing the dc signal to the metering unit. The three resistive twinleads from the three dipoles are spaced away from each other throughout the 15 cm length of the probe handle. Tests at NBS indicate that these transmission lines are essentially transparent to rf radiation. They produce little interaction with the dipoles and little distortion of the field. The two resistances in

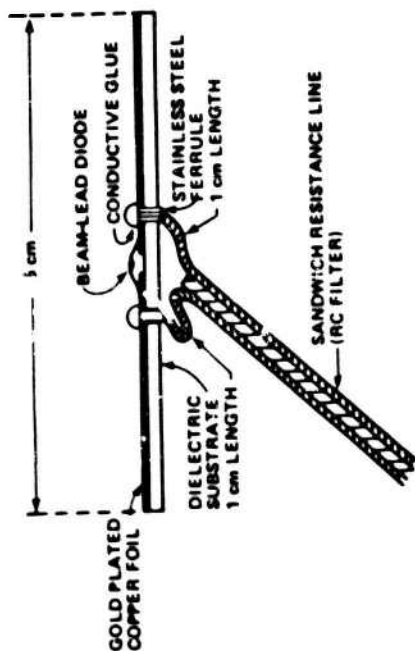


Figure 9A. Sketch of an individual receiving dipole.

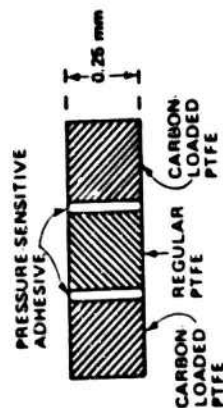


Figure 9B. Sketch of cross-section of the high-resistance plastic twinlead.

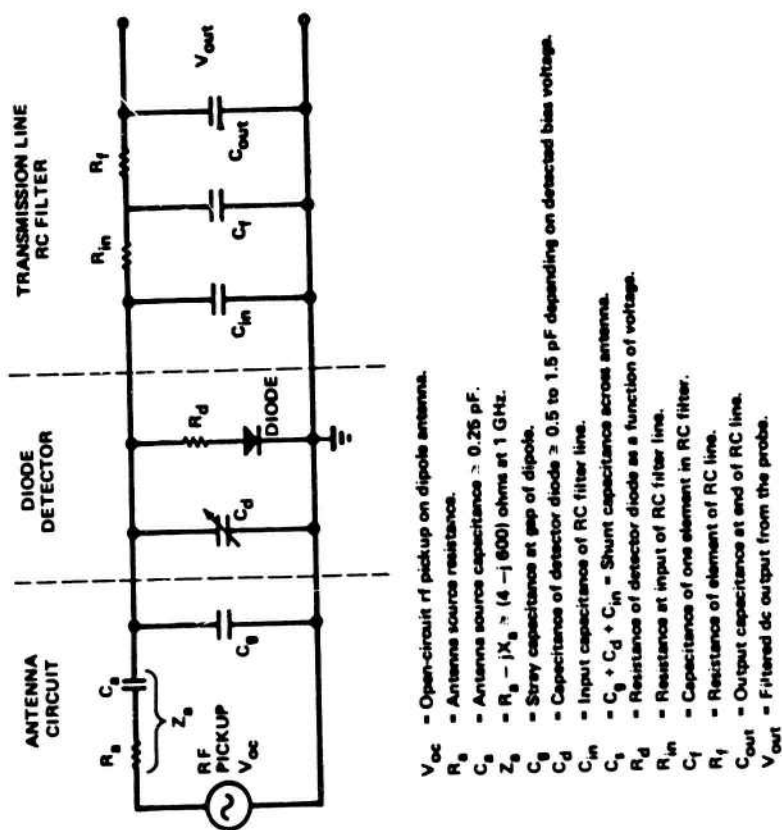


Figure 10. Equivalent circuit of each receiving dipole.

each two-wire line, near the center of each dipole, have been matched in order to minimize common-mode pickup. Great care is taken in antenna construction to prevent common-mode voltage of the line from causing an rf signal across the detector diode. This is especially important at frequencies below 500 kHz where the dipole source impedance (capacitive reactance) becomes extremely high.

The line resistance of each filament in the filter line is about 80,000 Ω /cm. However, the voltage drop on the line is small because the input resistance to the metering unit (20 $\text{k}\Omega$) is high compared with the total loop resistance of the line (about 2.6 M Ω). Since the antenna operates in nearly an open-circuit mode, there is little scattering by the field-induced dipole currents. Also, the use of Si diodes and the fairly large detected voltage of the 5-cm dipoles, result in a sensor which is not highly temperature dependent. Weaker rf fields could be detected with higher-sensitivity germanium diodes, but it would be difficult to overcome problems caused by changes in ambient temperature and by the low detector impedance compared with the high antenna source impedance.

Figure 9 gives an approximate equivalent circuit of each rf sensor, consisting of a dipole, diode and filter. The electrical equivalent circuit of each dipole antenna is essentially an rf voltage source in series with a small capacitance. The diagram is shown as unbalanced, to ground, although the actual dipole circuit is (or should be) electrically balanced. The antenna source impedance depends on frequency, dipole length, and the length-to-width ratio. The 5-cm dipole of figure 9A has a source capacitance of roughly 0.25 pF. Since the antenna source resistance is low compared with its reactance, and in quadrature with it, C_s and C_d of figure 10 ($C_s = C_g + C_d + C_{in}$) form a capacitive voltage-divider network which is independent of signal frequency over a wide band. The source impedance of the EFM-5 antenna is essentially capacitive at all frequencies below 1 GHz. The impedance is about (0 + j 1,000,000) ohms at 0.2 MHz and about (4-j 600) ohms at 1 GHz. Thus, even at 1 GHz the radiation resistance of 4 Ω increases the antenna impedance by only 0.002 percent, to 600.01 Ω . The value of shunt capacitance, C_s , depends on the detected bias voltage, which in turn depends on the rf field level. It is about 1.5 pF at 0 volts, decreasing to about 0.5 pF when a back bias of 10 volts is produced by a strong field.

The operating principle of a shunt diode detector can be seen by examining figure 10. When the dipole is immersed in an rf field, the diode forward resistance decreases and the back resistance increases, producing a net dc output voltage across the shunt capacitance [13]. Measured values of the detector dynamic resistance vary with field level but are generally greater than 1 M Ω for the type of diode used. The measured dc resistance a 5082-2837 diode is 10 to 15 M Ω at zero volts, increasing to greater than 100 M Ω for a back bias of only 0.24 volt. The shunt capacitance, C_s , becomes charged to nearly the peak rf voltage, producing the dc output signal.

In addition to field level, the value of detected voltage depends somewhat on the frequency and amount of probe loading. The theoretical value of open-circuit rf voltage, V_{oc} , induced in a dipole antenna is approximately equal to the product of the field strength, E , and half-dipole length. In other words, at frequencies up to 1000 MHz,

$$V_{oc} = E L_{eff} \hat{=} E \left[\frac{L_a}{2} \right], \quad (5)$$

where L_{eff} = effective length of each dipole, and
 L_a = physical length of each dipole.

The actual rf input level, V_{in} , to the diode detector is reduced by a capacitive voltage-divider effect, as shown in figure 10, and is given by the equation

$$V_{in} \hat{=} V_{oc} \left[\frac{C_a}{C_a + C_g + C_d + C_{in}} \right] = V_{oc} \left[\frac{C_a}{C_a + C_s} \right], \quad (6)$$

where C_a = effective antenna source capacitance ≈ 0.25 pF,
 C_g = stray capacitance at the center gap of the dipole,
 C_d = capacitance of the detector diode ≈ 1 pF,
 C_{in} = input capacitance of the RC filter line, and
 C_s = total shunt capacitance = $C_g + C_d + C_{in} \approx 2$ pF.

The induced voltages developed across the center gaps of the individual dipoles are given by

$$V_x = E_x L_{eff}, \quad V_y = E_y L_{eff} \quad \text{and} \quad V_z = E_z L_{eff}, \quad (7)$$

where E_x , E_y , and E_z are the amplitudes of the E-field components along the three orthogonal dipoles. An effective field strength magnitude can be defined as the root-sum-square (RSS) value of the three electric field components according to eq (2), which is repeated here.

$$(\text{Total } E) = \sqrt{E_x^2 + E_y^2 + E_z^2}. \quad (2)$$

The scalar quantity (total E) is also known as the Hermitian magnitude of the electric field [14]. The square of this quantity is proportional to the available electric-field energy density at the measurement point. Each dipole of the isotropic probe must be calibrated in a known "standard" field. The detected voltages from the three dipoles are then processed electronically according to equation (2).

4.3 Description of the Semiconducting Transmission Line

In the past it has been difficult to design an electrically isolated probe for measuring near-zone electromagnetic fields, which tend to have a complex spatial distribution. It is even more difficult to make an isotropic probe requiring three antennas and three transmission lines. One method of avoiding the difficulty is to use some sort of optical, radio or acoustical telemetering in place of metal transmission lines. However, the NBS EFM-5 monitor avoids the complexity of telemetering by using non-metallic transmission lines between the antenna and receiver. Such lines are semiconducting in the sense that the resistance has the same order of magnitude as that of solid-state semiconductors. The transmission lines are "transparent" to an rf field in the sense that they cause no scattering or perturbation of the field being measured.

As mentioned previously, the EFM-5 instrument makes use of special plastic transmission

lines. Even though the line has extremely high attenuation for rf energy, the detected dc and low frequency modulation can be passed without appreciable loss to a high impedance readout circuit. Each detector diode of the antenna is connected to one input channel of the metering unit by a high resistance twinlead. These lines are fabricated of Polytetrafluoroethylene (PTFE) plastic which has been rendered slightly conductive by carbon loading. Two different types of plastic line are used in the EFM-5 instrument. The first type of line, inside the probe handle, is about 15 cm long. The other type has much lower resistivity and is used in the flexible extension cable between the probe and metering unit. This flexible line can be of any desired length, generally between 1 and 3 meters.

Both types of plastic resistance line were developed at NBS [6,12]. Finely divided particles of carbon and powdered PTFE are sintered to form a homogeneous mixture. Electrical conductivity results from physical contact between the particles of carbon. The resistive material used for the twinlead in the probe handle has about 3 percent carbon by weight, while the lower resistance lines in the flexible cable have about 20 percent carbon by weight. The resistance of each filament in the probe handle is about 80,000 Ω /cm, while the resistance of each filament in the extension line is about 700 Ω /cm.

As shown in figure 9, a sandwich line is used for each twinlead in the probe handle. This type of construction produces a transmission line capacitance of about 0.3 pF/cm. The line provides rf filtering, permitting only dc and low frequencies to be conducted to the metering unit. The leads inside the probe handle are about 15 cm long by 0.25 mm wide x 0.25 mm thick. The three plastic ribbons in each parallel-conductor line are held together with non-conductive adhesive [12]. The long flexible extension line between the probe and metering unit uses nylon-jacketed PTFE filaments. Each 0.75 mm diameter monofilament is covered with a nylon film approximately 0.13 mm thick. The nylon jacketing improves the mechanical strength and electrical stability [6].

To reduce the "electrometer effect" of the sensor wand, caused by dc fields and low frequency fields, a slightly-conducting, heat-shrinkable tubing is placed around the six-conductor resistance line. This carbon-loaded polyolefin tubing is connected to the circuit ground of the metering unit. There is a "flexural" noise which causes fluctuations in the meter indication whenever the resistance line is bent or flexed. This type of noise is apparently caused by electrostatic/capacitive currents between the carbon granules of the resistance line, and can thus be eliminated by keeping the line stationary.

Common-mode voltages on the flexible resistance line may cause detected signals by the diodes if the dipole and twin-conductor lines are not well balanced. Such common-mode signals are also minimized by using well balanced instrumentation preamplifiers in the metering unit.

5. DESIGN OF THE ELECTRONIC PACKAGE

5.1 DC Buffer Amplifiers

The detected output from each of the three sensors in the antenna is filtered by a

high-resistance sandwich line inside the probe handle. The three filtered voltages are conveyed through flexible resistance lines into the metal case of the metering unit. Figure 11 is a sketch of the controls and front panel layout, showing the INPUT terminal for the resistance line. The instrument case is portable and normally held by the operator. Each of the three dc signals is applied to the input of an integrated-circuit (IC) preamplifier in the metering unit. .

As shown in figure 8, each preamplifier is configured from three op-amps to form an extremely high impedance differential amplifier. The high input impedance prevents an excessive voltage drop on the plastic resistance line. If the PREAMP circuit board becomes contaminated, it may permit leakage current, making it difficult to zero the instrument. The actual loading of each short dipole antenna is 20 M Ω , set by the two resistors at the input of each pre-amp. The balanced input of the pre-amp helps to prevent common-mode pickup on the transmission line from being detected by the diode in the probe. Great care is exercised in the construction and circuitry of the EFM-5 to achieve a high common-mode rejection ratio (CMRR). That is, the differential mode pickup of the 5 cm dipole is large compared with any signal resulting from common-mode voltage on the line.

Since the antenna source impedance, Z_a in figure 10, is proportional to the reciprocal of frequency, the differential mode V_{in} decreases at very low signal frequencies where Z_a becomes larger than R_d . The EFM-5 probe has acceptable V_{in} compared with common-mode effects down to a frequency of about 100 kHz. Because the instrument has individual channel-selector switches, it is easy to compare the unwanted common-mode response with the desired dipole response. This test is done by placing the antenna in a strong field and aligning the probe so that one dipole is parallel to the E field while the other two dipoles are perpendicular to the field. Any response or meter indication from a dipole which is oriented perpendicular to the E field is an indication of poor CMRR. This test is described in section 6.2.

The gain control potentiometers shown in the feedback circuit of the mid-amp buffers in figure 8 are used to obtain equal sensitivity in the three channels. That is, during the instrument calibration in a standard field, each dipole is aligned parallel to the E field and the variable resistor is adjusted to obtain the correct indication. This adjustment compensates for slight differences in dipole length, diode sensitivity, dipole shunt capacitance, etc. The three-position channel selector switch permits two antennas at a time to be disconnected when making this adjustment in a field of known magnitude.

As described in section 6.2, the overall gain of the EFM-5 is adjusted for correct indication of each channel at a field level of 10 V/m and frequency of 100 MHz. Most of the circuitry required for this gain adjustment, and to obtain electrical zeroing of all the op-amps, has been omitted from figure 11 for purposes of simplicity. The X, Y, Z and TOTAL rotary switch is useful for several uses. In addition to channel selection, it is used when setting the gain control and checking the common mode rejection. The channel selector switch is also useful during trouble shooting and checking the general operation of the antenna.

The semiconductor diodes in the antenna are somewhat temperature sensitive. The sensors are relatively independent of ambient temperature in high level fields, where the

TIME CONSTANT
(SEC.)

5 1



PEAK



AVE.

PUSH TO ZERO



ANTENNA

X Y

Z

TOTAL



OVER
RANGE



ZERO



20 10 40 dBV/m
+0 x1 100 V/m

CHARGE ON
OFF



RANGE

OUTPUT



INPUT



NBS EFM

Figure 11. Front panel layout of the EFM-5 metering unit.

dynamic source impedance of the detectors is low. However, there is some measurement error and zero drift on the lower 1-10 V/m range. Additional evaluations are planned to determine the exact amount of this temperature effect.

5.2 Non-linear Adder and Scaling Circuitry

Figure 12 gives the detected dc output voltage produced by a typical EFM-5 sensor, as a function of field strength, from 1 to 1000 V/m. Several close-spaced curves are used to show the amplitude response at several signal frequencies between 0.5 and 1000 MHz. The response is "flat" or independent of frequency between 0.5 and 50 MHz, but increases slightly for frequencies above 50 MHz. As shown in figure 3, the response is less at frequencies below 0.5 MHz and more at frequencies above 1 GHz.

It can be seen in figure 12 that the detected voltage for weak fields has an accurate square-law response. The lower range covering 1 to 10 V/m requires hardly any "shaping" before being applied to the adder circuit. The lower dashed line in the figure has a slope of two, corresponding to exact square-law response. When the field strength is between 10 and 1000 V/m, however, the detected output departs from square law, approaching a linear response at the upper end. The upper dashed line in the figure has a slope of one, or linear response, corresponding to a detected output which is proportional to E . The gains of the adder must therefore be tailored to produce the required square-law output over the entire amplitude range.

The output signal of each of the three mid-amp buffers in figure 8 is applied to a special non-linear summing amplifier. The op-amp used for the adder has a field effect transistor (FET) input stage. The overall purpose of the circuit is to produce a single voltage which is proportional to the sum of the squares of the three separate E-field components incident on the three orthogonal dipoles. Before adding the signals from the three channels (x, y and z), it is necessary to process or "shape" each detected voltage to make the amplitude proportional to the square of the field component. This is accomplished by using a special non-linear resistor (varistor) at the input circuit of each adder channel, as shown in figure 8.

The varistor (VAR) in figure 8 is a component made of silicon carbide (SiC) dispersed in a ceramic matrix. It is commonly used for lightning or surge protection of an electronic circuit. Electrically it is a voltage-dependent resistor (VDR). That is, above the turn-on voltage the resistance decreases as the voltage increases, but acts as a fixed resistor at all lower voltage values. Figure 13 gives the measured resistance vs voltage for a typical type 432BNR-101 varistor. The theoretical gain for each channel of the adder is equal to the op-amp feedback resistance divided by the input resistance (VAR and fixed resistor in series). The varistor is used to achieve higher gain when the voltage across the VAR increases above 0.1 volts. It provides a smooth transition in gain value which can be matched experimentally to obtain the required shaping. One value of series resistor is switched into the adder input circuit for the two lower field strength ranges, and another series resistor is connected for the upper (100 to 1000 V/m) range.

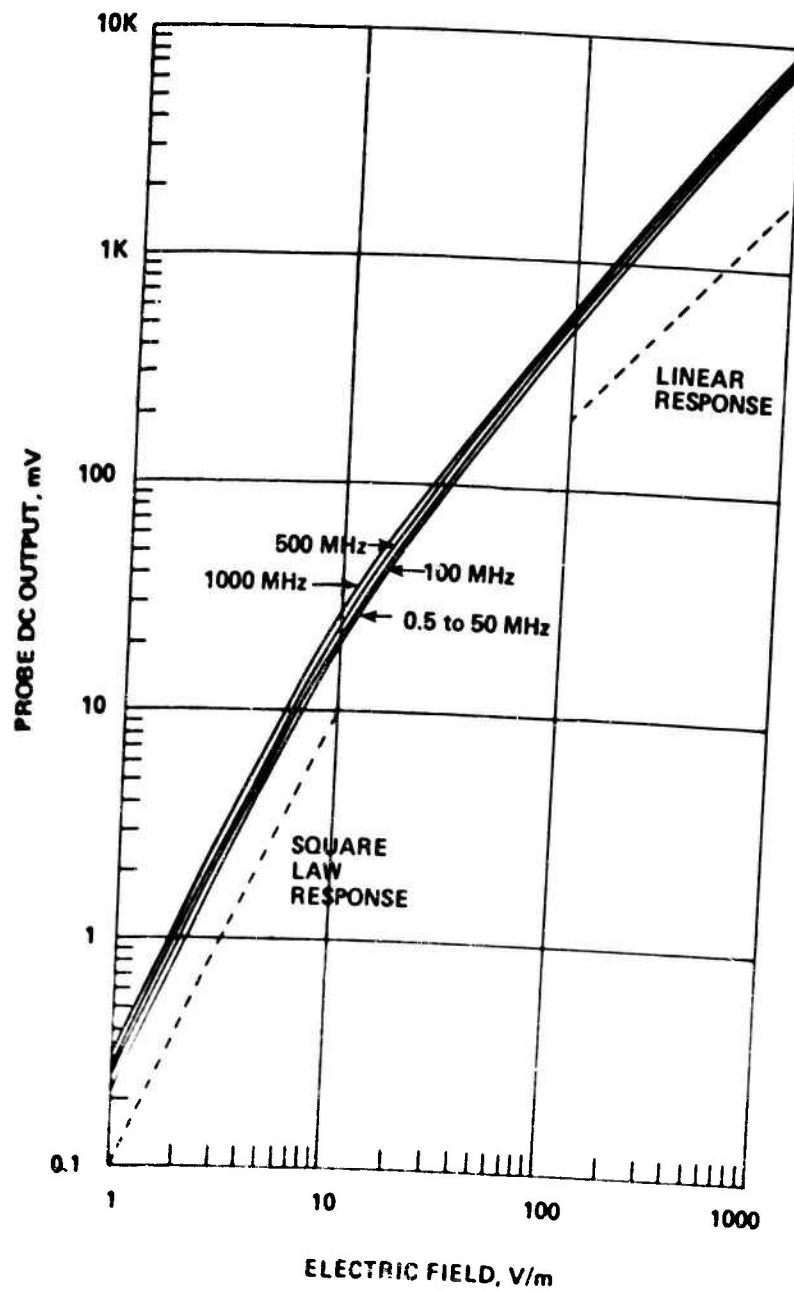


Figure 12. Typical detected output of an EFM-5 dipole as a function of field strength, at several frequencies.

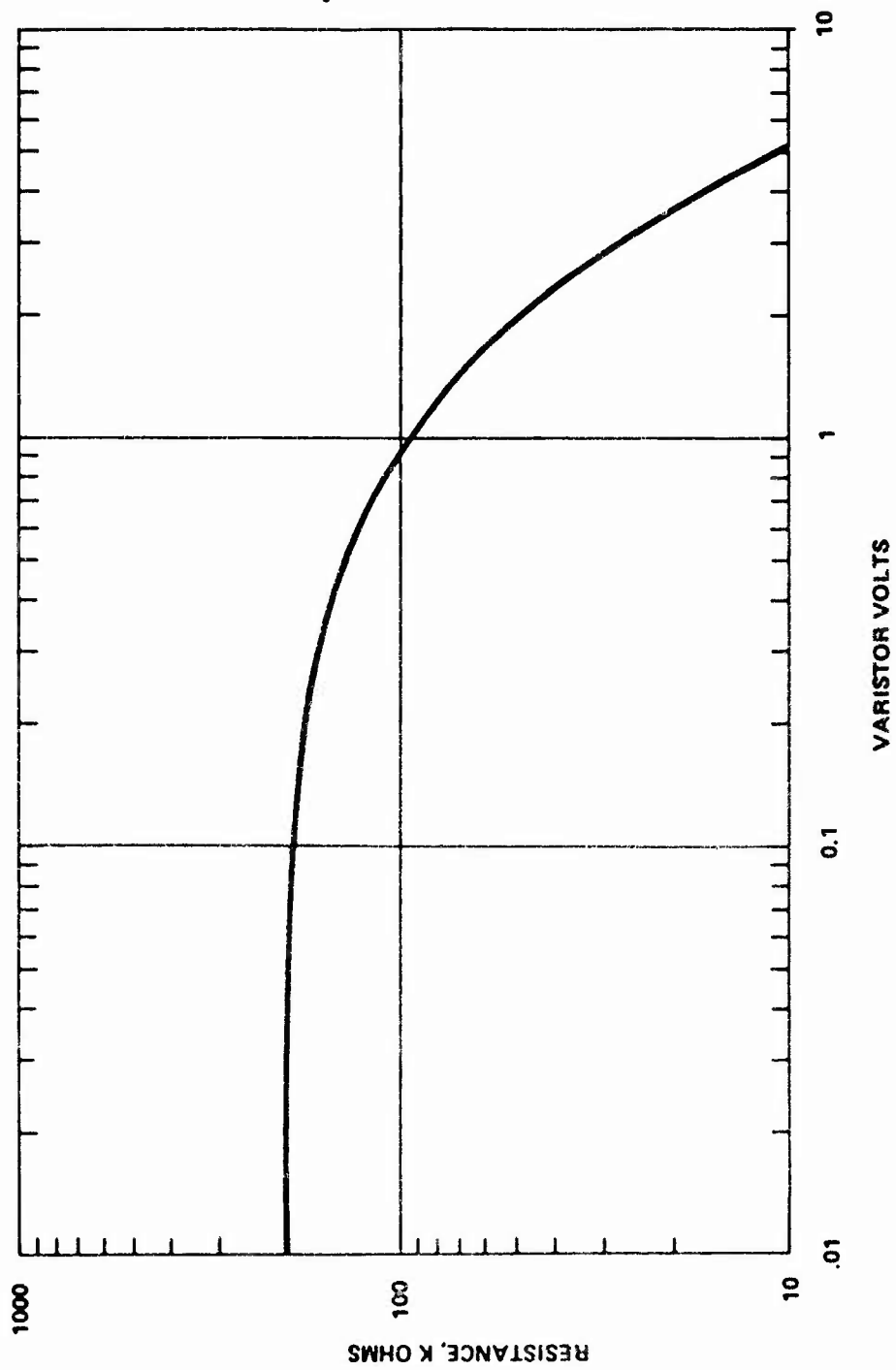


Figure 13. Typical resistance vs voltage of a type 432 BNR-101 varistor.

NBS purchased a group of 100 varistors and the resistances of these were measured as a function of voltage and temperature. It was found that the resistance values for a given voltage and temperature are not uniform. However, the percentage change of resistance vs voltage (slope of curve) is quite uniform. The 100 varistors were thus grouped into sets of three according to the measured resistance at 1 volt. One matched set was then used for each EFM-5 unit constructed. It is not known whether the above selection process is essential for achieving good shaping curves. However, little difficulty was experienced in obtaining square-law operation over the entire 60 dB dynamic range. The maximum shaping error permitted at any field strength level was 0.5 dB. It could be mentioned that a shaping circuit matched on a steady (cw) signal also functions properly for pulse-modulated signals. This is true up to the point where either the average field value or the pulse field value exceeds 1000 V/m.

Because many non-linear circuit elements are temperature sensitive, some difficulty was experienced at NBS in choosing an optimum type of VDR. The shaping circuits chosen for the EFM-5 meter, which use SiC varistors for the non-linear element, appear to be relatively temperature insensitive. The SiC material has a temperature coefficient that is nearly an order of magnitude less than that of Si, and Si is better than Ge by about an order of magnitude. The data of figure 13 were taken at a temperature of 25°C. Higher or lower temperatures will displace the entire curve vertically compared with that given.

The output of the adder covers a two-decade voltage range for each single decade of field strength. That is, the voltage varies as the square of the field level. As shown in figure 8, the adder output voltage extends from about 0.01 to 1 volt for each position of the three-position range switch. Also shown in the figure is the circuit for the adder op-amp zeroing. The remaining op-amps also require zeroing, but only one zeroing circuit is shown on the simplified schematic diagram because it is the only one which is adjustable by a front-panel control. This zeroing control should be set with the three-position range switch on its most sensitive range (1-10 V/m) and with the PEAK/AVE switch in the AVE position.

5.3 Time Constants and Peak/Average Circuitry

The EFM-5 meter provides a choice of measuring either the time-average field value or the pulse-peak intensity, with four switch-selectable RC time constants. When the PEAK/AVE switch on the front panel is set to the PEAK mode, it is possible to make approximate measurements of the peak value of pulse-modulated signals. However, there is an additional uncertainty for this type of measurement due to the relatively slow response time of the instrument of about 0.3 millisecond. The diode detectors in the rf sensors have a fast risetime, but the overall meter response time is limited by the high-resistance line (RC filter) between the detectors and the metering unit.

The peak detector circuit is an adaptation of what is usually called a quasi-peak detector. Four values of discharge time can be chosen with the 'front-panel' switch, namely 0.16, 0.5, 1.6 and 5 seconds. As shown in figure 8, the peaking circuit consists of a diode in series with a shunt RC combination. The charging time through the diode is short

compared with the RC discharge times. The capacitor thus becomes charged quickly to nearly the peak voltage.

The longest time constant in the EFM-5 is ($4.75 \text{ M}\Omega \times 1 \mu\text{F}$) or approximately 5 seconds. The available time constants permit an operator to follow modulated signals on the output meter or at the OUTPUT jack whenever desired. The type of diode chosen for the peaking circuit, 5082-2800, provides a very high reverse resistance and a relatively low turn-on voltage. Measurements indicate that the back resistance is greater than $100 \text{ M}\Omega$ when the back bias exceeds 0.25 volt. Circuitry for obtaining the average signal value is also given in figure 8. It develops an output voltage proportional to the time-average value of either a cw signal or a train of pulses.

5.4 Logarithm and Metering Circuitry

The output of the peak or average circuit is a voltage that increases from about 0.01 to 1 volt over each of the three available one-decade ranges in field strength. The output in each range is proportional to the square of the measured E-field value. The next stage of the EFM-5 is an op-amp buffer with a gain of ten, producing a voltage which varies from 0.1 to 10 volts across each decade range in field strength. This voltage is, of course, also proportional to E^2 . Following this is the logarithm circuitry required to produce a voltage proportional to dBV/m at the OUTPUT jack. This circuitry is shown as a single block in the simplified schematic of figure 8.

The complete logarithm circuit is given in section 7, figure 27. It consists basically of an integrated-circuit logarithmic amplifier, two op-amps, and two potentiometer adjustments. One potentiometer (LOG ZERO) sets a regulated voltage to obtain zero volts output for a 0.1 volt input. Any rf field which has a magnitude less than 1 V/m will cause a negative deflection on the output meter. The type 4357 module produces an output which varies in direct proportion to the logarithm of the input voltage. Another potentiometer (LOG SLOPE) sets the gain of the logarithm module to obtain 2 volts output for 10 volts input. The voltage at the OUTPUT jack of figure 8 thus varies linearly across each range in direct proportion to the E field expressed in dB above 1 V/m, which is the desired answer.

An op-amp is used to drive the low-impedance panel meter. The analog indicator used in the EFM-5 is a D'Arsonval type microammeter with a full scale value of $200 \mu\text{A}$. The dial has a linear scale marked from 0 to 20 dBV/m, and a non-linear scale marked from 1 to 10 V/m.

5.5 Power Supply, Operating Controls and Special Features

Power to operate the EFM-5 electric field monitor is furnished by a series string of 32 rechargeable nickel cadmium (Ni Cd) cells. The individual cells are size AA, which have a nominal 1.3 volts and 450 mA hour capacity. The battery voltage is about ± 21 volts. Electronic regulators are used to supply regulated ± 15 volts for the EFM-5 circuitry and + 5 volts for the FET switches. The battery drain is about 80 mA from the positive side and about 70 mA from the negative side. The battery life is about seven hours for continuous operation of the field strength meter, and the time required for recharging the batteries is

about 10 hours. To recharge the batteries after use, a power cord is connected to the back panel of the metering unit, plugged into a 115 V AC outlet, and the three-position power switch on the front panel is turned to the CHARGE position.

The field strength meter does not operate with the three-position power switch turned to the CHARGE position. Also, the battery charging circuit is not operative with the power switch in the ON position, even if a power cord is plugged into a 115 V outlet. An LED located above the power switch glows whenever the batteries are being charged. The same LED glows if the instrument is turned ON and the battery voltage is low, indicating that the batteries should be recharged (NOTE: It is possible that the batteries may be so completely discharged that the voltage is insufficient for lighting the LED.)

The battery charging circuit consists of a commercially available power supply and two constant-current sources, each supplying 40 mA of current. Diodes are used at the charger output terminals to prevent the batteries from discharging back into the charger when the power switch is on CHARGE but no power cord is plugged into the metering unit. Diodes also prevent the LED from glowing unless the batteries are actually being recharged. Schematic diagrams of the battery charger and other power supply circuitry are given in section 7, figure 29.

Several self-checking features have been built into the EFM-5 circuitry, such as the LED located above the power switch. Another LED labeled OVER RANGE can be seen in the center of the front panel in figure 11. This warning light indicates that the output meter is pegged full scale, on any of the three ranges. A voltage comparator circuit was included for automatic range switching on later models of this instrument. The present EFM-5 model is a portable, analog version of a future model which will permit auto-ranging and computer control.

Three removable "cards" in the metering unit contain most of the electronic circuitry. These may be connected on extender boards to the back plane for calibration, adjustment and trouble shooting. The power supply, charger and batteries are mounted directly on the main chassis. Connections between the front panel, back plane, etc. are made with flat cables of multiconductor wire.

As shown in figure 11, the EFM-5 monitor has a four-position ANTENNA switch on the front panel for selecting the measurement mode. Either a single field component or the RSS value of three orthogonal components (TOTAL) may be measured. The TIME CONSTANT switch and PEAK/AVE switch are also visible in figure 11. The other switches, controls, jacks etc. in the figure have been described previously.

6. CALIBRATION AND PERFORMANCE TESTS OF THE EFM-5

6.1 Description of NBS Standard-Field Calibrations

The EFM-5 monitor is normally calibrated with respect to the following parameters: (1) dial indication vs field level, (2) response vs frequency, and (3) probe isotropy, that is, antenna directivity and field polarization sensitivity. The calibration provides data for

corrections which may be applied to the dial indication to obtain more accurate measurements of field strength.

It is assumed here that the original alignment and adjustments of the EFM-5 instrument have been completed. The initial "shaping" or linearizing procedure is described in section 8; in general it is required only once, as part of the instrument manufacturing process. A calibration as described in this section is done more routinely, perhaps once a year for each radiation monitor. Such a "routine" calibration determines the extent to which the monitor does not indicate the true or correct value at a given field intensity and EFM-5 range, at a given frequency, for a given field polarization.

Theoretically it would be possible to calibrate rf radiation monitors in far-zone, plane-wave fields at all frequencies and levels; however, the transmitter power required to produce intense fields (up to 200 V/m and higher) would generally exceed 1 kW. An alternative approach is used at NBS in which lower-power rf sources of 20 to 200 W are adequate. It involves calculation of the field intensity within a transmission line or in the near zone of a transmitting antenna. The probe to be calibrated is inserted in this field of known magnitude. The optimum instrumentation for generating a standard (calculable) field depend on the frequency, intensity and required accuracy. Some techniques being used at NBS are described briefly in this report for three different (overlapping) frequency ranges.

(a) TEM Cells, 100 kHz to 450 MHz.

At frequencies up to about 450 MHz, a transverse electromagnetic (TEM) cell is a convenient device for calibrating a radiation monitor. This type of calibrating chamber consists of a large "coaxial" 50 Ω transmission line in which the center conductor is a flat metal strip and the outer (grounded) conductor has a rectangular cross section [15,16,17,18,19]. At frequencies sufficiently low so that only the principal wave (TEM mode) will propagate through the cell, it produces a fairly uniform EM field which can be calculated easily and quite accurately. Both the E and H field magnitudes are given in terms of the plate spacing and measured voltage or throughput power. The standard field is then used to calibrate a radiation monitor directly, or to calibrate a small dipole probe for use as a transfer standard.

A block diagram of the instrumentation used to produce a standard field in a TEM cell is given in figure 14. The electric field strength at the calibrating point shown (midway between the center conductor and bottom of the cell, and midway between the input and output connectors) is given by the equation

$$E = \frac{V}{D} = \sqrt{\frac{50P}{D}}, \quad (8)$$

where E = electric field strength, V/m,

V = voltage between the center conductor and outer walls of the TEM cell, V,

D = distance between the center conductor and bottom of the cell, m,

P = power conveyed through the cell, W, and

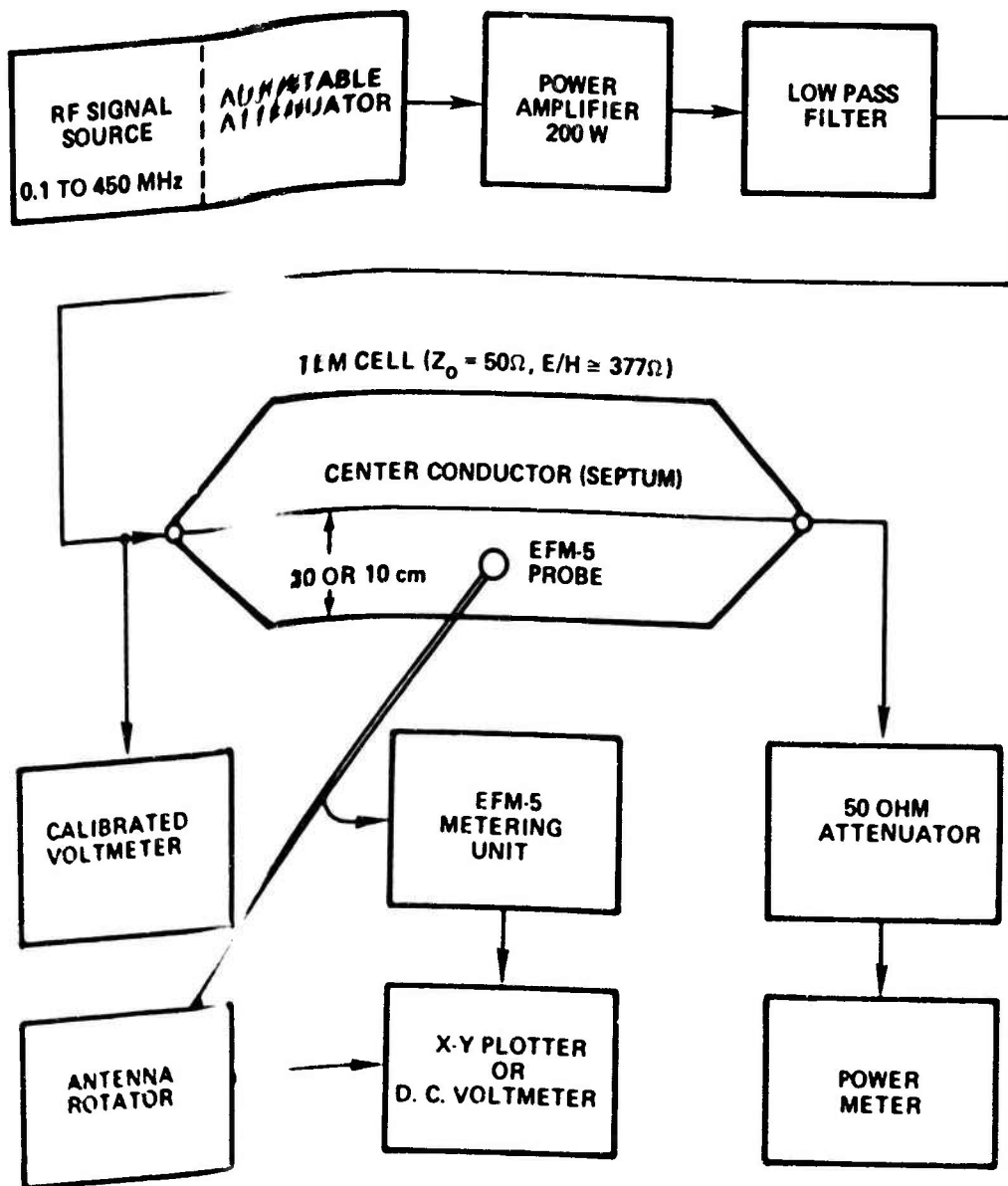


Figure 24. Calibration for generating a standard field in a TEM cell
 Figure 24. Calibrating an EFM-5 monitor.

50 = characteristic impedance of the transmission cell and resistance of the cell termination, ohms.

Two TEM cells are used at NBS to cover the lower frequency bands. The larger cell has a 0.6 m x 1 m cross section and a length of 2 meters. The value for D in eq (8) is thus 0.3 meters. This cell is accurate for frequencies up to about 150 MHz, but above this frequency higher-order waveguide modes may cause errors. This is similar to the unwanted resonances which occur at higher frequencies in shielded rooms. A smaller cell with a 0.2 x 0.3 m cross section can be used in the 150 to 450 MHz band, but the EFM-5 probe causes some field enhancement in such a small cell. Appropriate corrections should be made in this case, as explained later.

(b) Waveguide Cells, 300 to 1100 MHz.

In this frequency range, rectangular-waveguide transmission cells are convenient for use as calibrating chambers. The E and H magnitudes can be calculated approximately in terms of the guide dimensions, frequency and power flow [15,17,20,21]. NBS makes use of three waveguide cells to cover the 300 to 1100 MHz range. Each cell has a rectangular cross section with a width-to-height (aspect) ratio of two-to-one. A block diagram of the instrumentation is given in figure 15. The upper frequency in each guide is limited to that in which the operation is in the dominant TE₁₀ mode. In this case the direction of the E-field vector is across the narrow face of the guide, and the magnitude at the guide center is given by the following two equations:

$$E = \frac{2}{w} \sqrt{PZ}, \quad (9)$$

$$Z = \frac{377}{\sqrt{1 - \left(\frac{150}{F_w}\right)^2}}, \quad (10)$$

where E = electric field strength, V/m,
w = width (larger side) of the 2-to-1 waveguide, m,
P = power conveyed through the cell, W,
Z = wave impedance in the cell, Ω , and
F = frequency, MHz.

For a given transmitter power, a higher field intensity will be produced in a waveguide cell than in a 50 Ω TEM cell or by a radiating horn, because the wave impedance is higher than 377 Ω . However, the uncertainty of the calculated field in a waveguide is rather large, up to 2 dB at certain frequencies. It is thus necessary to check the field strength with a short dipole probe which is known to be flat over the frequency band in use [15,17]. By this procedure the magnitude of the calibrating field can be established with an uncertainty of ± 0.5 dB.

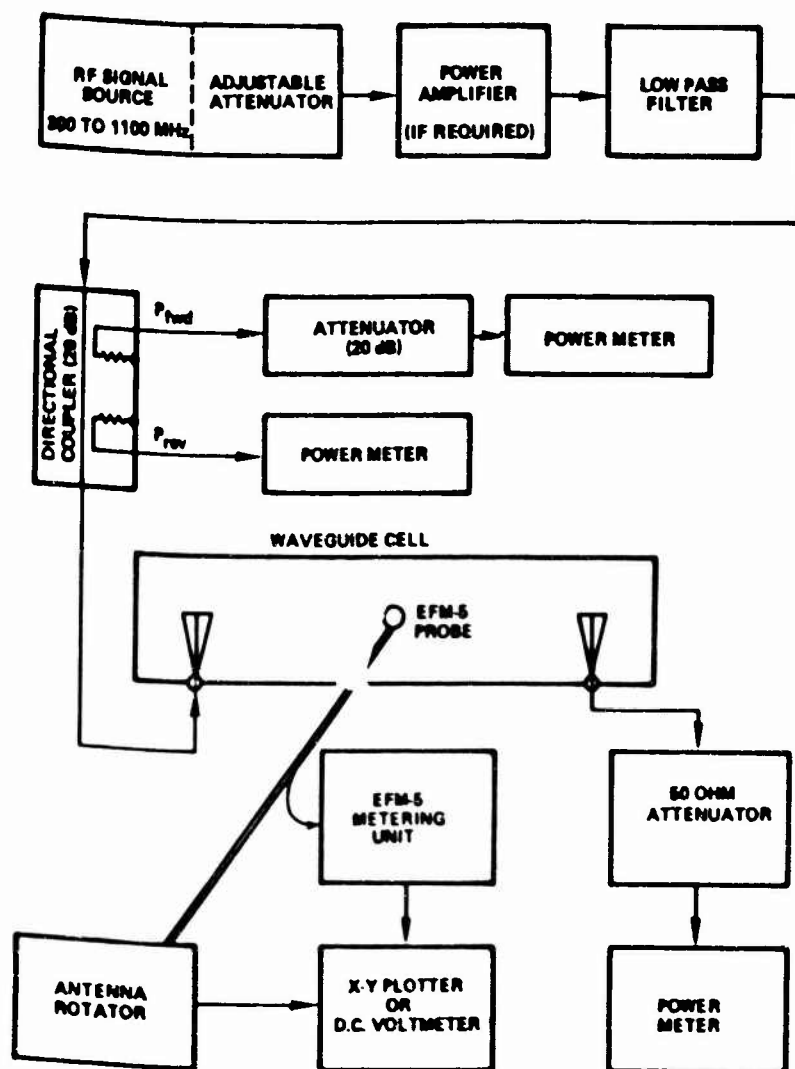


Figure 15. Instrumentation for generating a standard field in a waveguide cell for calibrating an EFM-5 monitor.

(c) Anechoic Chamber, 200 to 4000 MHz.

The main approach used at NBS to generate a standard field at frequencies above 200 MHz is to calculate the radiated intensity in the near zone of standard-gain antennas, within a small anechoic chamber. A set of two rectangular open-end-guides (OEG's) is available to cover the 200 to 500 MHz range, and a series of five rectangular pyramidal horns is used from 450 to 4000 MHz. To calibrate an EFM-5 monitor, the probe sensor is placed in the beam center of the radiating OEG or horn, at a measured distance from the antenna aperture to the center of the EFM-5 sensor. The on-axis field intensity is calculated in terms of the net power delivered to the transmitting antenna and the calibrated gain of the pyramidal horn or OEG "launcher" [15,17,22,23,24,25,26].

Figure 16 is a sketch of the instrumentation used to calibrate a radiation monitor, or to plot the pattern response of a probe. The field intensity in the center of the beam is calculated, at each frequency, using power equation techniques. Figure 16 does not designate any specific brand of equipment; however, all of the instrumentation is readily available commercially except for the large OEG launchers. The value of standard field is given by the equation

$$E = \frac{5.475 \sqrt{PG}}{d}, \quad (11)$$

where E = on-axis magnitude of the radiated field, V/m,
 P = net power delivered to the transmitting horn or OEG, W,
 G = calibrated gain of the transmitting antenna, including appropriate near-zone correction factors, and
 d = distance from the horn or OEG aperture to the calibrating field point (center of probe sensor), m.

Accurate standard fields of high intensity can be produced near a transmitting antenna, even with low power, if the near-zone gain of the antenna is known accurately. Simple algebraic equations are given later for calculating the near-zone gain, including the restriction on minimum distance for which eq (11) is accurate. However, an explanation is given here of a "bootstrapping" technique to achieve a more intense field at distances which are so close that the value of horn gain, G in eq (11), is not known accurately. When using this approach, the EFM-5 probe being calibrated is used as a temporary transfer device to achieve a "boost" of 10 to 20 dB in field strength.

The bootstrapping method can be described as follows. A strong standard field is produced by using the maximum transmitter power available and the closest distance for which the horn gain is known accurately. The probe response for this field intensity is noted. The transmitter power is then reduced by exactly 10 dB (1/10 of its previous value) and the distance between the transmitting antenna and probe is decreased until the probe response returns to its previous (noted) value. Then the transmitter power is increased 10 dB to its original value, producing a known field intensity which is

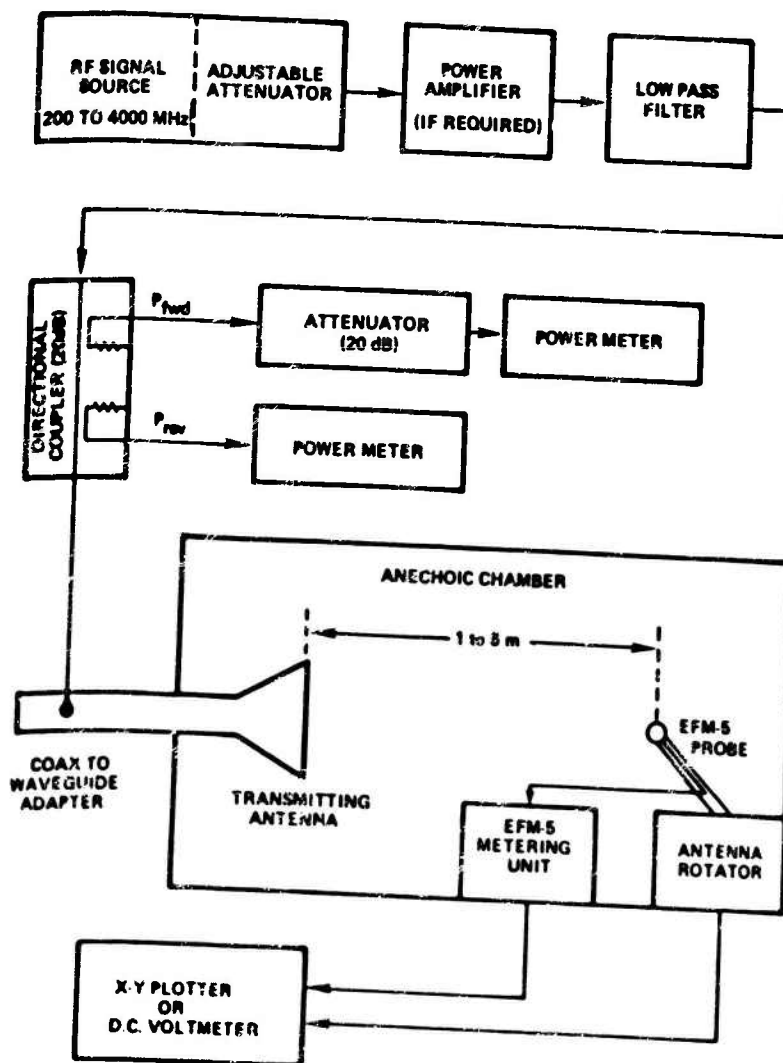


Figure 16. Instrumentation for generating a standard field in an anechoic chamber for calibrating an EFM-5 monitor.

10 dB greater than that obtainable by the use of eq (11) alone.

The effects of multipath reflections in the NBS anechoic chamber have been analyzed and are taken into account for each experimental setup and frequency. Briefly, this involves an envelope-averaging process, making use of a movable cart on rails in the anechoic chamber [23,24,26,27]. An X-Y plot of the probe response vs distance is made at each calibration frequency, using the instrumentation of figure 16. Because of near-zone variations in horn gain and rf reflections within the imperfect anechoic chamber, the probe response curve has a small "sinusoidal" variation in amplitude superimposed on the (E vs 1/d) response. Increased probe response occurs when the direct and reflected rays arrive in phase, and decreased response when they are out of phase. The true, corrected response corresponds to the smoothed curve obtained by averaging the lower and higher points on the X-Y plot of measured E vs 1/d. It could be mentioned that the small "invisible" probe of the EFM-5 experiences very little multipath interference with the transmitting horn. This can be seen by examining figure 20, in which the "sinusoidal" amplitude variation is greater at larger distances from the horn aperture. By contrast, larger variations in response usually occur at very close distances when measuring the gain of two horns, caused to a great extent by horn-to-horn interactions and reflections.

(1) Gain of Open-End-Guide Launchers, 200 to 500 MHz.

Early work to determine the field pattern and gain of large OEG radiators, both theoretically and experimentally, is described in reference [22]. An equation giving the gain of open-ended waveguides as a function of frequency and aperture dimensions has been determined experimentally at NBS. The original data for this equation comes from a two-antenna calibration using two "identical" open-end guides [25]. Later calibrations have been made with two specially-fabricated OEG's, each having a length of about 2 m. The larger OEG has an aperture of 91.44 x 45.72 cm (36 x 18 inches) and the smaller is 53.34 x 26.67 cm (21 x 10.5 inches). All the OEG's used at NBS have a 2-to-1 aspect ratio. In this case, the equation for calculating the antenna gain is

$$\text{GAIN} = 21.6 Fw, \text{ or} \quad (12a)$$

$$\text{GAIN, dB} = 10 \log (Fw) + 13.34, \quad (12b)$$

where F = frequency, GHz, and

w = width (larger side) of the 2-to-1 OEG, m.

Equation (12) is accurate to ± 0.5 dB if the distance, d , from the OEG aperture to the field point is greater than double the width, w . It could be noted that the near-zone corrections for an OEG are much less than those of a pyramidal horn, for a given distance and frequency. However, an OEG generally has a higher voltage-standing-wave-ratio (VSWR) than a horn and the sinusoidal ripple on the X-Y recording, caused by chamber wall reflections, is generally greater at the lower frequencies used for an OEG antenna. Figure 17 is a plot of measured gain values as a function of distance in the

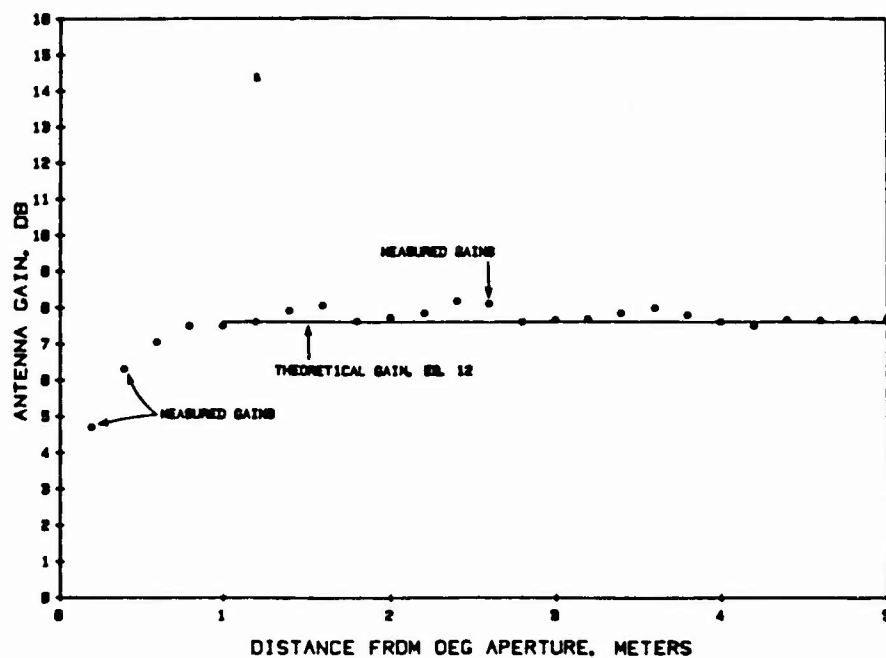


Figure 17. Graph of WR-2100 OEG gain vs distance at 500 MHz.

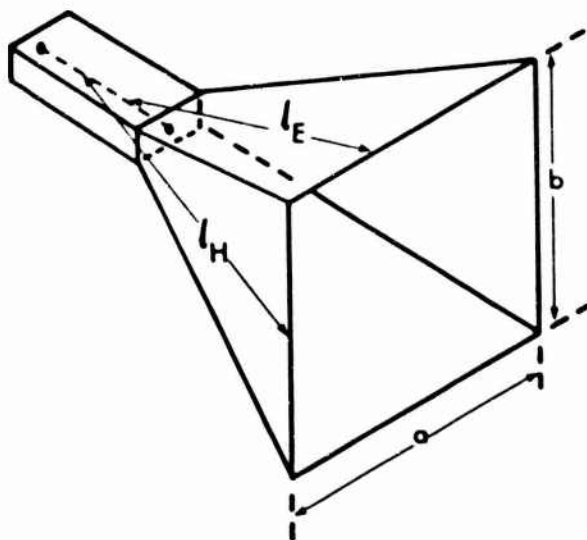


Figure 18. Sketch of a pyramidal horn showing the pertinent dimensions.

anechoic chamber. For purposes of comparison with pyramidal horns, the ordinate scale is the same as that of later figures 19 and 20.

(2) Gain of Pyramidal Horns, 450 to 4000 MHz

Calibrating fields above 450 MHz are produced in an anechoic chamber by a series of standard-gain pyramidal horns. A complication known as near-zone gain reduction applies to calculation of field strength very close to a transmitting antenna. Unlike a far-zone field or a field traveling in a waveguide, the EM field across a horn aperture has a somewhat spherical (rather than planar) wavefront. The phase at the rim of the horn lags that at the center, causing a non-equiphase front across the aperture, which reduces the effective gain in the near-field (Fresnel) region. A further reduction occurs, even for an equiphase aperture, due to the difference in distance between the various elements in the radiating aperture and the on-axis field point in question. Both of these "defects" reduce the field intensity to less than that predicted by the simple inverse-distance relation of a far-zone source.

The authors have generated simple polynomial expressions to determine the near-zone gain-reduction factors, R_H and R_E , for pyramidal horns [15]. The pertinent horn dimensions used in the equations are shown in figure 18. The procedure involves a computation of the intensity produced by an in-phase aperture and then applying two near-zone correction factors. The values of these gain-reduction factors depend on frequency, horn dimensions and distance to the on-axis field point. The two gain-reduction factors, R_H and R_E , are given by

$$R_H = (0.01a) (1 + 10.19a + 0.51a^2 - 0.097a^3), \quad (13a)$$

$$R_E = (0.1b^2) (2.31 + 0.053b), \quad (13b)$$

$$\text{where } \alpha = \left(\frac{a^2 F}{0.3} \right) \left[\frac{1}{l_H} + \frac{1}{d} \right] \text{ and } \beta = \left(\frac{b^2 F}{0.3} \right) \left[\frac{1}{l_E} + \frac{1}{d} \right],$$

a, b, l_H and l_E = horn dimensions of figure 18, m,

F = frequency, GHz, and

d = distance from the horn aperture to the field point, m.

The theoretical gain of the horn, near zone or far zone, is then given by

$$\text{GAIN} = (113.3 a b F^2) \left[10^{(-R_H - R_E)} \right], \text{ or} \quad (14a)$$

$$\text{GAIN, dB} = 10 \log(ab) + 20 \log F + 20.54 - R_H - R_E. \quad (14b)$$

The above equations have been checked experimentally using several different standard-gain horns covering the frequency range of 450 to 4000 MHz. The horns were also calibrated at NBS by the well-known, three-antenna method [23,24,26] and these gains compared with that given by eq (14). For distances greater than 0.5 m, the difference between the

experimentally calibrated gain and the value calculated from eq (14) was less than 0.5 dB. Plots of horn gain vs distance are shown in figures 19 and 20, comparing the theoretical curve with measurements made in the NBS anechoic chamber. The SGH-0.5 standard gain horn used for figure 19 has the following measured dimensions: $a = 122.5$ cm, $b = 90.75$ cm, $l_H = 142.0$ cm and $l_E = 121.3$ cm. The SGH-0.75 horn used for figure 20 has the following dimensions: $a = 82.78$ cm, $b = 61.18$ cm, and $l_H = 94.3$ cm and $l_E = 81.2$ cm.

6.2 Calibration of the EFM-5 Response as a Function of Frequency and Field Intensity

The calibration of a radiation monitor consists of comparing the field intensity indicated on the dial with the correct value, at each desired signal frequency and field level. To accomplish this, the probe is immersed in the standard field (known level) of a calibrating chamber, as described in section 6.1. A 0.6×1 m TEM cell is generally used for frequencies up to 150 MHz. Radiated fields in an anechoic chamber are generally used for calibrating at frequencies from 200 to 4000 MHz.

During a calibration the EFM-5 probe is mounted with dielectric supports on an antenna rotator/positioner. The polyfoam sphere of the probe is located at the point indicated in figure 14 for a TEM cell, or on the boresight of the transmitting antenna in figure 16. The field strength in a TEM cell is calculated from eq (8); the intensity of the transmitted beam in the anechoic chamber is calculated, at each frequency, from eq (11). The proper gain value to use for the latter equation, at any distance, is obtained from eq (12) or (14). For a routine calibration of an EFM-5, the response is measured at the desired frequencies, checking several levels at each frequency. For example, if 10 and 100 V/m levels (20 and 40 dBV/m) are requested, the EFM-5 RANGE switch would be in its most sensitive position (1-10 V/m) for the lower level and in the middle position (10-100 V/m) for the higher value.

The EFM-5 probe is generally mounted in the TEM cell or anechoic chamber with the probe handle aligned at the "analytic angle." The analytic angle is defined as the angle which the diagonal of a cube makes with the three intersecting edges at one corner of the cube. It is also the angle at which the probe handle makes equal angles with the E-field vector, H vector, and Poynting vector. For each calibration point (given frequency and intensity) the probe is held at the analytic angle and rotated 360° on an axis through the probe handle. An X-Y recording is made of the probe response vs rotation angle. A separate plot is made for each individual channel of the probe (X, Y or Z) and a fourth plot is made with the ANTENNA selector switch in the TOTAL position. The latter recording corresponds to the usual isotropic response of the probe.

One critical test of probe isotropy (non-directivity) is to record, separately, the response of each of the three dipoles as a function of field orientation. For this test, the probe handle is set at the analytic angle and the probe is rotated axially in the test field. At 120° intervals in the rotation, one dipole of the probe will be parallel to the E vector (maximum response) and the other two dipoles will be perpendicular to it (minimum response). For example, a calibration curve is given in figure 21 for a frequency of 100 MHz and field intensity of 10 V/m. The curves show the separate dipole responses, each

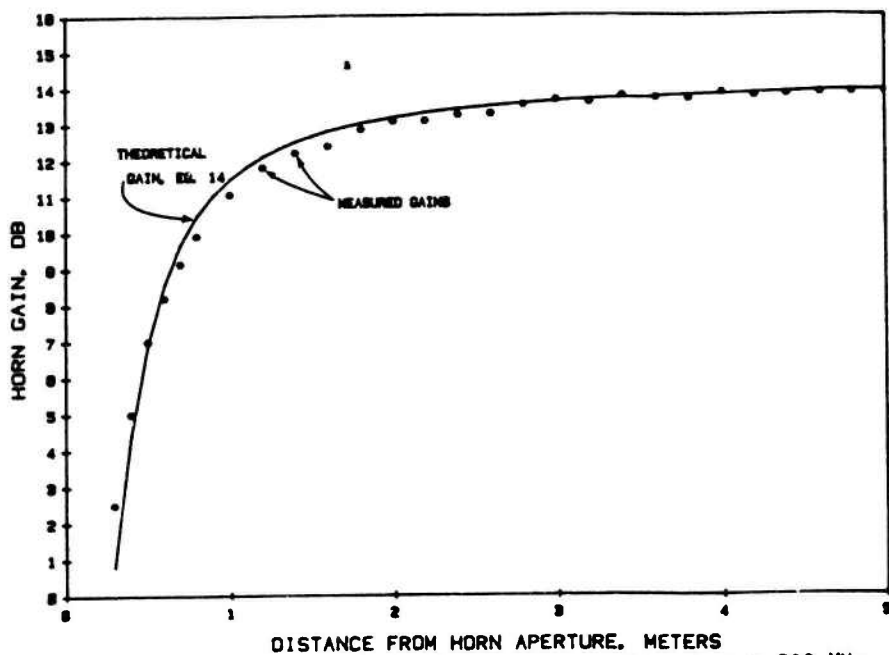


Figure 19. Graph of SGH-0.5 horn gain vs distance at 500 MHz.

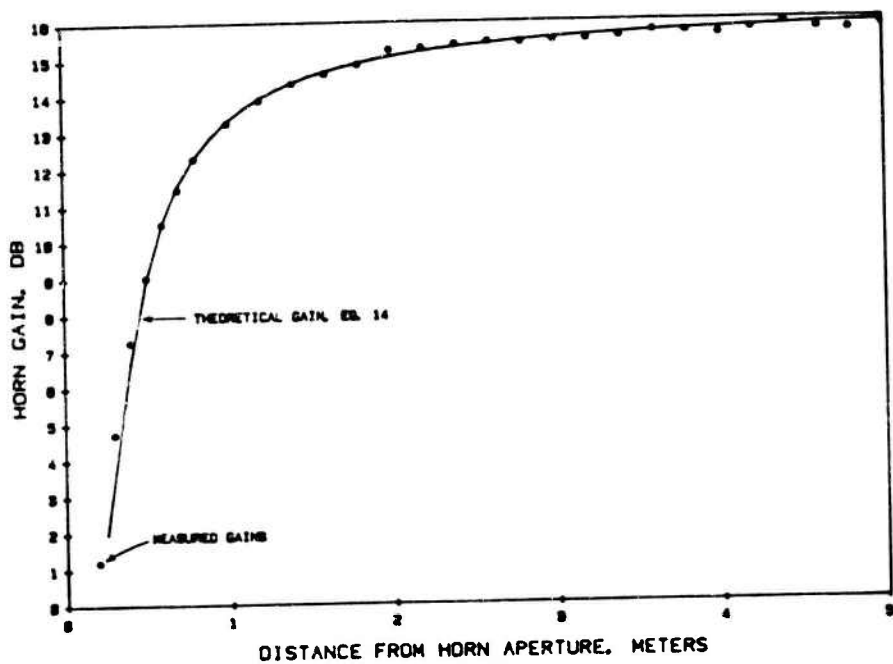


Figure 20. Graph of SGH-0.75 horn gain vs distance at 1000 MHz.

of which should ideally peak at the standard field value but should equal zero when the dipole is oriented orthogonally to the E field. The curves also show the RSS output for total E (upper line) for normal operation of the EFM-B meter. As seen in figure 21, the maximum response for a 10 V/m field, with the ANTENNA switch in the TOTAL position, was 20.25 dBV/m at a rotation angle of 340°. The minimum response was 19.86 dBV/m at a rotation angle of 240°.

The following procedure was used to obtain the calibration curve in figure 21. It is recommended that this type of "checkout" calibration be made at 100 MHz preceding each probe calibration.

- (1) Turn the EFM-5 power switch ON at least 15 minutes before starting the calibration.
- (2) Note: It is recommended that all the op-amps within the electronic package of the EFM-5 be zeroed. Otherwise it is possible that the overall zeroing of the instrument has drifted outside the range of adjustment of the front panel control. The necessary procedure for zeroing the op-amps on the three electronic circuit cards of the metering unit is given in section 8.
- (3) Set up the instrumentation of figure 14 to obtain a standard field at 100 MHz in the 0.6 x 1 m TEM cell.
- (4) Mount the probe in the TEM cell with the handle fixed at the analytic angle.
- (5) With no power into the TEM cell, rotate the ANTENNA selector switch to the X-channel position, depress the PUSH TO ZERO switch, and adjust the ZERO control for no indication of the meter.
- (6) Adjust the intensity of the standard field to the desired calibrating level. For the initial check point at $F = 100$ MHz and $I = 10$ V/m, the transmitter power should be adjusted to obtain a true 3 volts on the calibrated voltmeter.
- (7) Rotate the probe axially (manually) until the angle of maximum response corresponds with 0° on the X-Y recorder.
- (8) Record the pattern response of the X channel only, from 0° to 360° axial rotation angle. The response should ideally peak at the standard field value at 0° rotation angle. The indication should drop to less than 2 dBV/m at angles of 120° and 240°. At 120° the X channel dipole is perpendicular to the E field but parallel to the H field. At 240° the X channel dipole is also perpendicular to the E field but parallel to the propagation vector.
- (9) Repeat the response recordings for the Y channel alone and the Z channel alone, zeroing the meter with the front panel control before each recording.
- (10) Rotate the ANTENNA switch to the TOTAL position to obtain the vector magnitude of all three channels. Re-zero the meter if necessary and record the nominal isotropic response pattern.

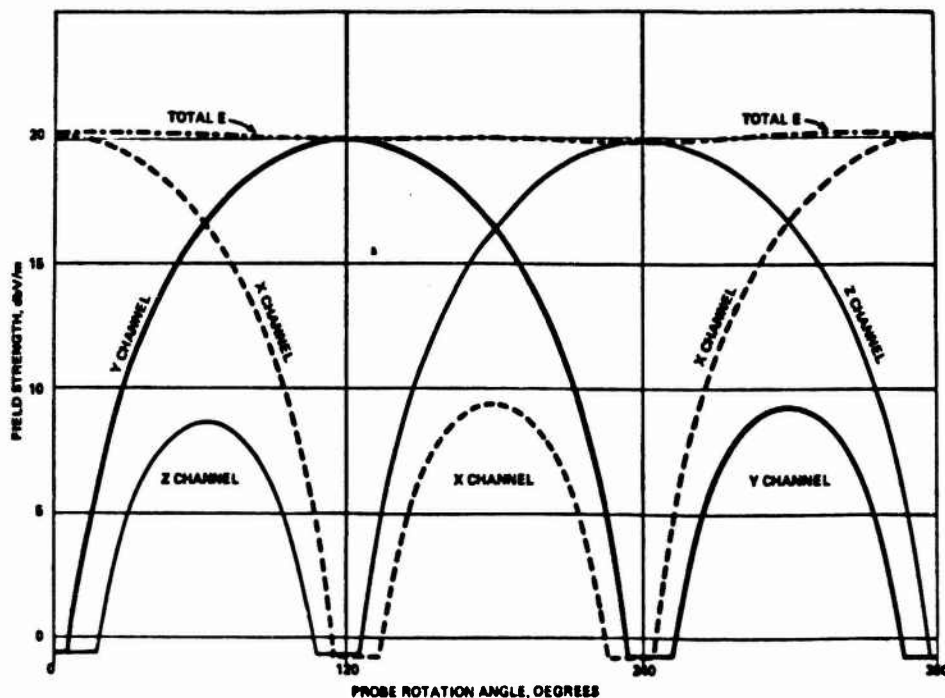


Figure 21. Response pattern of an EFM-5 antenna at 100 MHz and 10 V/m, with the probe handle at the analytic angle.

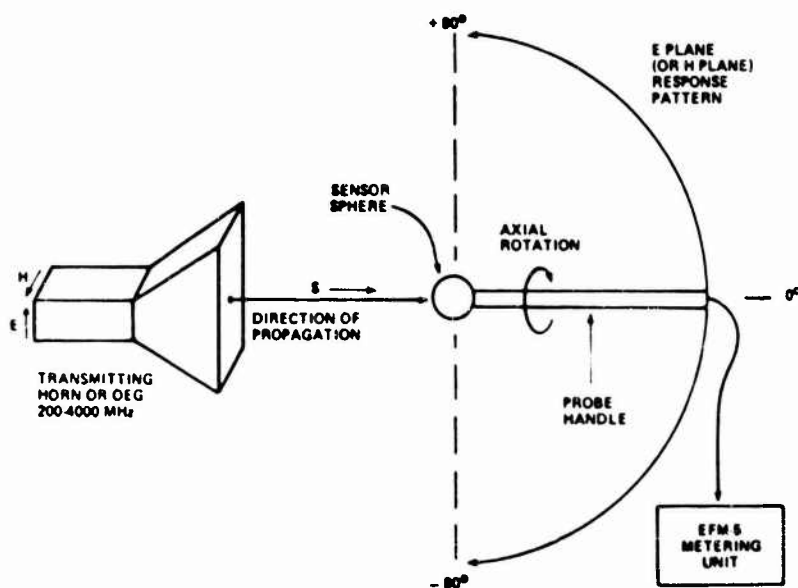


Figure 22. Instrumentation for measuring various response patterns of an rf radiation monitor.

This completes the initial calibration check point. The remainder of the calibration points are obtained in a similar manner. Selection of the proper calibrating chamber is determined mainly by the frequency, as explained in section 6.1. The desired calibration data generally consist of the maximum and minimum values from the X-Y recording. In some cases the average value of meter indication as a function of probe rotation angle is requested. It is then necessary to digitize the recorded curve and calculate the average.

The instrumentation for the 0.6 x 1 m TEM cell at NBS makes use of a 200 W linear amplifier, so it is possible to obtain field levels up to 50 dB V/m (about 300 V/m). A 1 kW rf amplifier is also available to generate fields exceeding 300 V/m. However, this large water-cooled amplifier is seldom used because it is not portable and operates only over the frequency range of 100 kHz to 200 MHz.

If higher field intensities are required at frequencies above 150 MHz, the smaller 0.2 x 0.3 m cell can be used. In this case the maximum achievable intensity with the 200 W amplifier is 60 dBV/m (1000 V/m). It could be noted that the small TEM cell has greater uncertainty in its calculated field values than the larger cell. However, a decrease in uncertainty can be achieved by using the EFM-5 as a transfer probe. The procedure is described as follows. The indication on the EFM-5 dial at a calculated field level of 40 dBV/m in the large cell is noted. The probe is then "transferred" to the small cell and the transmitter power is decreased and adjusted to obtain the same "noted" response. In this manner a more accurate field intensity is obtained than that produced by relying only on the voltmeter setting, because the 0.2 x 0.3 m cell is physically so small that the presence of the probe dipoles causes a slight enhancement of the electric field.

Calibrations at frequencies above 200 MHz are generally made in the anechoic chamber. Producing any desired intensity up to about 200 V/m (10 mW/cm^2) at any given frequency is described in section 6.1 c. The accuracy of the standard field at any location in the anechoic chamber can be verified, at each frequency used, by means of a small transfer probe which is flat vs frequency across the band being checked. A probe used for this purpose at NBS consists of a calibrated dipole of 2-cm length. For each check of the standard field value, the EFM-5 probe is removed from the field point and the transfer probe is placed at the same location in the chamber.

An estimate of the overall calibration uncertainty is given as follows:

- (1) The largest source of error in an EFM-5 calibration is uncertainty of the standard field value in the TEM cell or anechoic chamber. The greatest uncertainty in the TEM cell is due to field enhancement caused by the probe, especially when using the 0.2 x 0.3 m cell. The greatest possible error in the anechoic chamber is due to uncertainty in gain value of the various transmitting antennas. The estimated maximum error is ± 0.5 dB, which occurs at the close distances required to produce a strong radiated field (200 V/m or higher) in the anechoic chamber.
- (2) Other sources of calibration error are uncertainty in the magnitude of multipath reflections within the anechoic chamber, or perturbation of the field in the TEM cell by the probe leads, etc. These possible errors are estimated to be less than

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- (3) Other sources of calibration uncertainty are associated with antenna alignment, measurement of antenna separation distance or TEM cell plate spacing, and NBS calibrations of the various instruments used. These include voltmeters, directional couplers, and incident and reflected power monitors. The overall error due to these latter sources is estimated to be less than ± 0.3 dB.
 - (4) A possible source of calibration error is drift from "zero" indication of the meter, especially if the ambient temperature is changing or if the meter has not been turned on for a sufficient length of time.

The overall worst-case uncertainty of the calibration is the simple sum of those listed above, or ± 1 dB.

6.3 Measurement of Antenna Isotropy and Other Performance Tests

Figure 22 is a sketch of the instrumentation used to produce an EM field in the anechoic chamber for evaluating various response patterns of an rf monitor. Such patterns of an isotropic probe may be measured for several angular configurations [28,29]. For example, six types of amplitude-vs-angle patterns can be identified, as follows:

- (1) E-plane response pattern, -90° to 90° . This pattern is obtained if the rotation angle of the probe handle is fixed (no axial rotation) and the horn is oriented as shown in figure 22. The probe handle and dielectric support are rotated around the semicircle from -90° to $+90^\circ$, as indicated, while the probe sensor remains at a fixed location and distance with respect to the radiating horn.
- (2) H-plane response pattern, -90° to $+90^\circ$. This pattern is obtained in the same manner as the E-plane pattern except that the transmitting horn has been rotated 90° around its propagation axis. In other words, the E and H vectors have been interchanged.
- (3) Axial rotation of the probe on an axis through the center of the handle, 0° to 360° .
 - (a) Probe handle oriented parallel to the direction of energy propagation, S , where $S = E \times H =$ Poynting vector. In this case the probe sensor is pointing toward the center of the radiating aperture during the axial rotation of the probe.
 - (b) Probe handle oriented parallel to the E vector. In this case the probe handle is oriented at either $+90^\circ$ or -90° in figure 22, during the axial rotation.
 - (c) Probe handle oriented parallel to the H vector. This pattern is obtained in the same manner as (3b) above except that the transmitting horn has been rotated 90° around its propagation axis.

- (d) Probe handle oriented at the analytic angle, as defined and discussed in the previous section.

Response patterns have been recorded for the EFM-5 probe for several of the above configurations, over the frequency range of 100 kHz to 4 GHz. The pattern obtained with the probe handle fixed at the analytic angle is the most critical test of probe isotropy. If an rf monitor has switches for reading the three field sensors individually, the test can be used to analyze the overall probe quality, as discussed in section 6.2. This is the origin of the term "analytic angle." The pattern obtained in (3d) above is the easiest method to demonstrate experimentally whether a probe is truly isotropic. From past experience in evaluating the response vs orientation angle of rf radiation monitors, it is known that an isotropic response will be achieved if: (a) the three dipoles have separate "maximum" responses which are equal in amplitude but displaced 120° from each other on the X-Y recording, and (b) the three "minimum" responses in the recording have zero amplitude, or are at least 30 dB below the maximum value. Note that the three dipoles in each EFM-5 prototype antenna have been adjusted for equal response at a frequency of 100 MHz and a field level of 10 V/m. It is assumed here that accurate signal processing has been achieved in obtaining the Hermitian magnitude of the three orthogonal signal components.

The electronic circuitry of NBS radiation monitors has been improved and the newer EFM-5 has a more balanced input. This was done to provide as much rejection to the common-mode input signals as possible. A common-mode rejection ratio (CMRR) of 50 dB or better is obtained for common-mode frequencies up to 1 kHz. The susceptibility of the measuring dipoles to common-mode voltage on the transmission line is a function of the electrical symmetry or balance of the dipole with respect to the transmission line or any nearby ground plane. If perfect symmetry exists, there will be complete common-mode rejection.

One method to obtain an indication of dipole unbalance is to place the probe in a vertical electric field produced above a large metal ground plane at an outdoor field site. The probe handle is mounted on an antenna rotator/positioner and oriented at the analytic angle. A given dipole is aligned vertically to measure the vertical field component. If an antenna unbalance exists, the rf voltage appearing across the dipole gap will be the vector sum of the desired (differential) field-induced voltage and any common-mode voltage caused by the transmission line. If the probe is then rotated axially through 120° from its previous position, the dipole will be orthogonal to the E field but the common-mode voltage will remain the same. This prevents the meter indication from dropping to zero, indicating poor CMRR. Performance tests have been conducted on two EFM-5 monitors at a few frequencies, but additional systematic tests are planned to check antenna balance and CMRR.

Any electrical coupling between the plastic transmission line and a measuring dipole can be demonstrated by a method similar to that described in the previous paragraph for checking dipole unbalance. For this test the dipole is aligned parallel to the vertical field vector and the EFM-5 meter indication is noted. The position occupied by the transmission line is then changed radically. Any change in indicated field strength is due

to interaction of the line with the EM field being measured.

It is planned to make further performance tests at NBS of the EFM-5 instrument, for example to determine the magnitude of the CMRR at several frequencies and to measure the effects of ambient temperature, especially over the range of 15° to 25°C. The latter tests will be made at various frequencies and probe orientations with respect to the E field. Another planned test is to determine the amount of case leakage vs signal level and frequency. These tests will include the effect of ambient temperature on the sensitivity of the detector diodes in the probe and on the varistor shaping curve. However, sufficient field tests have already been made to ensure adequate performance of the radiation monitor.

7. PARTS LISTS AND COMPLETE SCHEMATIC DIAGRAMS

TABLE 3
PARTS LIST FOR THE PREAMPLIFIER BOARD

<u>Description</u>	<u>Quantity</u>
Resistor, 9.09 k Ω	3
Resistor, 22.1 k Ω	6
Resistor, 51.1 k Ω	6
Resistor, 100 k Ω	3
Resistor, 10 M Ω	6
Potentiometer, 500 k Ω	3
Capacitor, 10 μ F, 25 V, Tant.	2
Diode, type 1N4143	15
Amplifier, IC, type 3527 BM	6
Amplifier, IC, type 3627 BM	3
Switch, type HI 201	1
Socket, PTFE, 8-pin	9
Socket, OIP, 16-pin	1
Circuit board, two-sided	1
Test point terminals	4

TABLE 4
PARTS LIST FOR THE SHAPING BOARD

<u>Description</u>	<u>Quantity</u>
Resistor, 10 k Ω	12
Resistor, 20 k Ω	3
Resistor, 100 k Ω	5
Resistor 10 M Ω	4
Resistor 22.1 M Ω	1
Potentiometer, one turn, 1 k Ω	1
Potentiometer, one-turn, 10 k Ω	1
Potentiometer, one-turn, 100 k Ω	6
Potentiometer, one-turn, 1 M Ω	1
Potentiometer 20-turn, 20 k Ω	3
Potentiometer, 20-turn, 100 k Ω	4
Varistor, type 432BNR-101	3
Capacitor, 39 pF	1
Capacitor, 10 μ F	2
Diode, type 1N4153	10
Amplifier, IC, type OP20	3
Amplifier, IC, type 3527BM	1
Switch, type AD 7502	3
Socket, PTFE, 8-pin	4
Socket, DIP, 16-pin	3
Plug, OIP, 8-pin	6
Connector terminal	7
Circuit board, two-sided	1
Test point terminals	5

TABLE 5
PARTS LIST FOR THE LOGARITHM BOARD

<u>Description</u>	<u>Quantity</u>	<u>Description</u>	<u>Quantity</u>
Resistor, 182 Ω	2	Capacitor, 500 pF	2
Resistor, 511 Ω	1	Capacitor, 0.01 μ F	1
Resistor, 1.82 k Ω	1	Capacitor, 0.033 μ F	1
Resistor, 2 k Ω	1	Capacitor, 0.1 μ F	2
Resistor, 6.19 k Ω	1	Capacitor, 0.33 μ F	1
Resistor, 20 k Ω	2	Capacitor, 1 μ F	2
Resistor, 43.2 k Ω	1	Capacitor, 10 μ F	1
Resistor, 51.1 k Ω	1	Diode, type HP 2800	2
Resistor, 56.2 k Ω	1	Diode, type 1N4153	4
Resistor, 90.9 k Ω	1	Amplifier, IC, type TL061	2
Resistor, 100 k Ω	2	Amplifier, IC, type TL084	2
Resistor, 200 k Ω	1	Transistor, type 2N3904	1
Resistor, 1 M Ω	1	Transistor, type 2N5245	1
Resistor, 2.21 M Ω	1	Logarithm module, type TP4357	1
Resistor, 4.75 M Ω	3	Switch, type H15042	1
Resistor, 10 M Ω	7	Switch, type H1201	1
Resistor, 15 M Ω	2	Socket, DIP, 8-pin	2
Resistor, 22.1 M Ω	2	Socket, DIP, 14-pin	2
Potentiometer, one-turn, 100 k Ω	3	Socket, DIP, 16-pin	2
Potentiometer, 20-turn, 500 Ω	1	Socket, for logarithm module	1
Potentiometer, 20-turn, 10 k Ω	2	Circuit board, two-sided	1
Potentiometer, 20-turn, 20 k Ω	1	Test point terminals	3
Potentiometer, 20-turn, 1 M Ω	1		

TABLE 6
PARTS LIST FOR THE POWER SUPPLY
AND ON/OFF/CHARGE SWITCH

<u>Description</u>	<u>Quantity</u>
Resistor, 100 Ω	2
Resistor, 1 k Ω	1
Resistor, 2.2 k Ω	1
Resistor, 4.7 k Ω	2
Resistor, 1 k μ	1
Potentiometer, 1 M Ω	1
Capacitor, 0.01 μ F	3
Capacitor, 1 μ F	3
Diode, type 1N4004	2
Diode, type 1N4153	1
Diode, Zener, type 1N5232	2
Diode, light emitting, type HP 5082-4484	1
Transistor, type 2N4919	1
Transistor, type 2N4922	1
Operational amplifier, IC, type 741	1
Voltage regulator, + 15 volt, type 7815	1
Voltage regulator, - 15 volt, type 7915	1
Voltage regulator, + 5 volt, type 7805	1
Power supply module, $\pm$ 15 volt DC, 150 mA	1
Power cord, 115V AC	1
Chassis plug, 115V AC	1
Fuse holder and fuse, 3/4 amp	1
Switch, wafer, 6 pole-triple throw	1
Circuit board	1
Battery, Ni Cd, rechargeable, size AA	3

TABLE 7
ADDITIONAL PARTS FOR THE EFM-5
RADIATION MONITOR

<u>Description</u>	<u>Quantity</u>
Probe unit (see section 4.2)	1
Resistive transmission line (see section 4.3)	1
Case, metal	1
Front panel	1
Resistor, 511 Ω	1
Resistor, 500 k Ω	2
Potentiometer, 100 k Ω	1
Meter, 200 μ A, with modified dial	1
Switch, wafer, triple pole- 4 throw	1
Switch, wafer, triple pole- triple throw	1
Switch, wafer, 4 pole - 4 throw	1
Switch, toggle, single pole- double throw	1
Switch, push type, double pole- double throw	1
Socket, chassis type, 9 pin	1

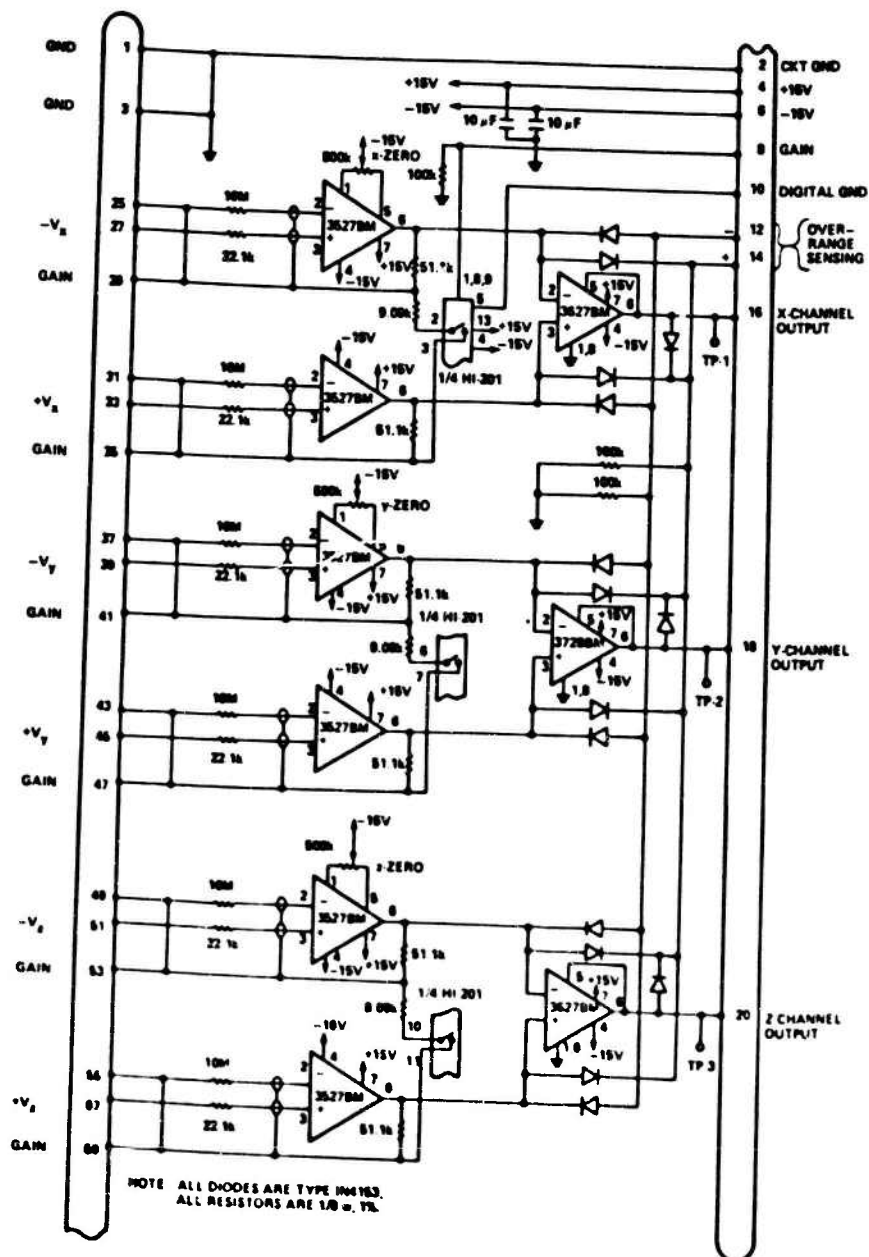


Figure 23. Schematic diagram of the preamplifier board.

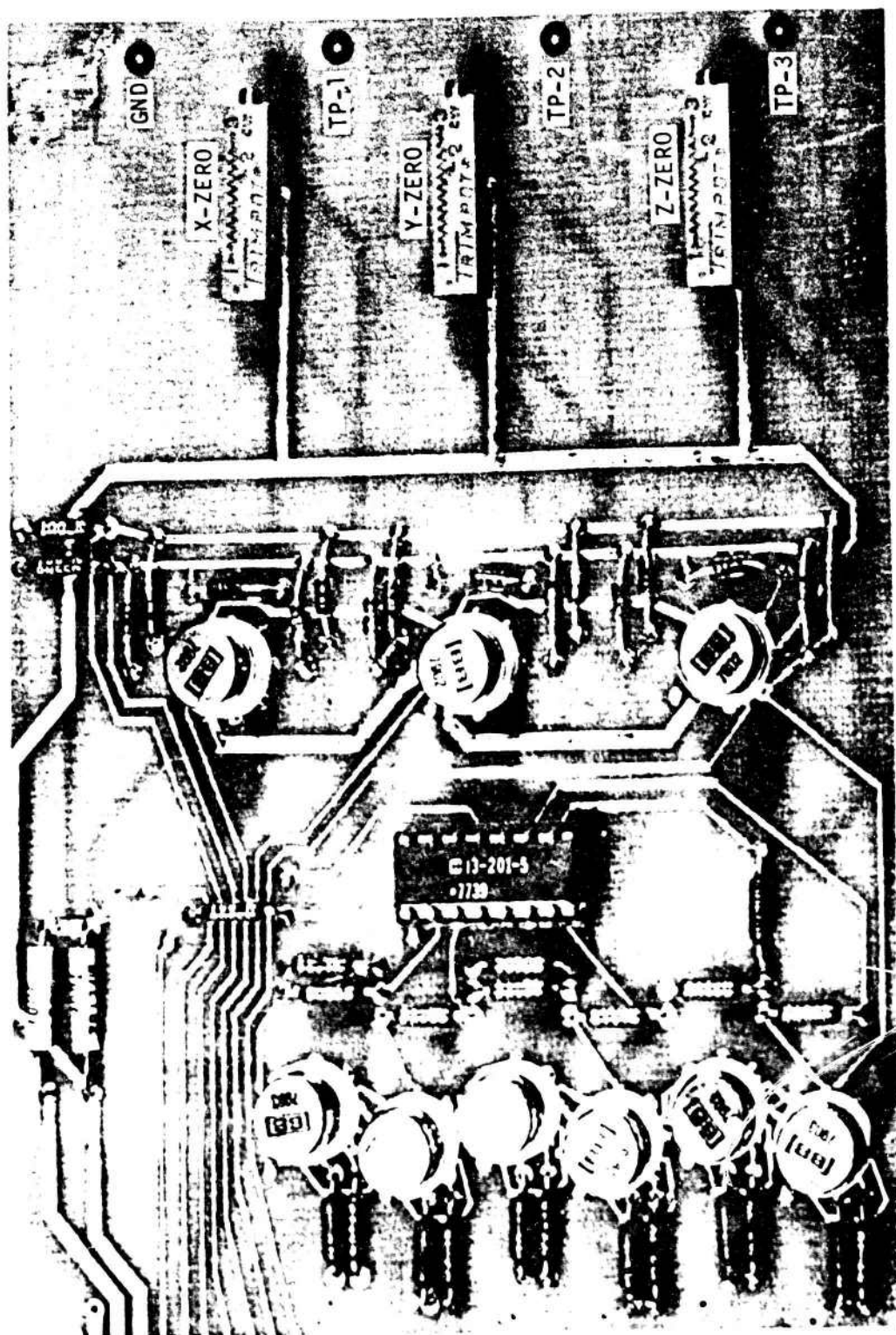


Figure 24. Photograph of the preamplifier board showing the zeroing controls and test points.

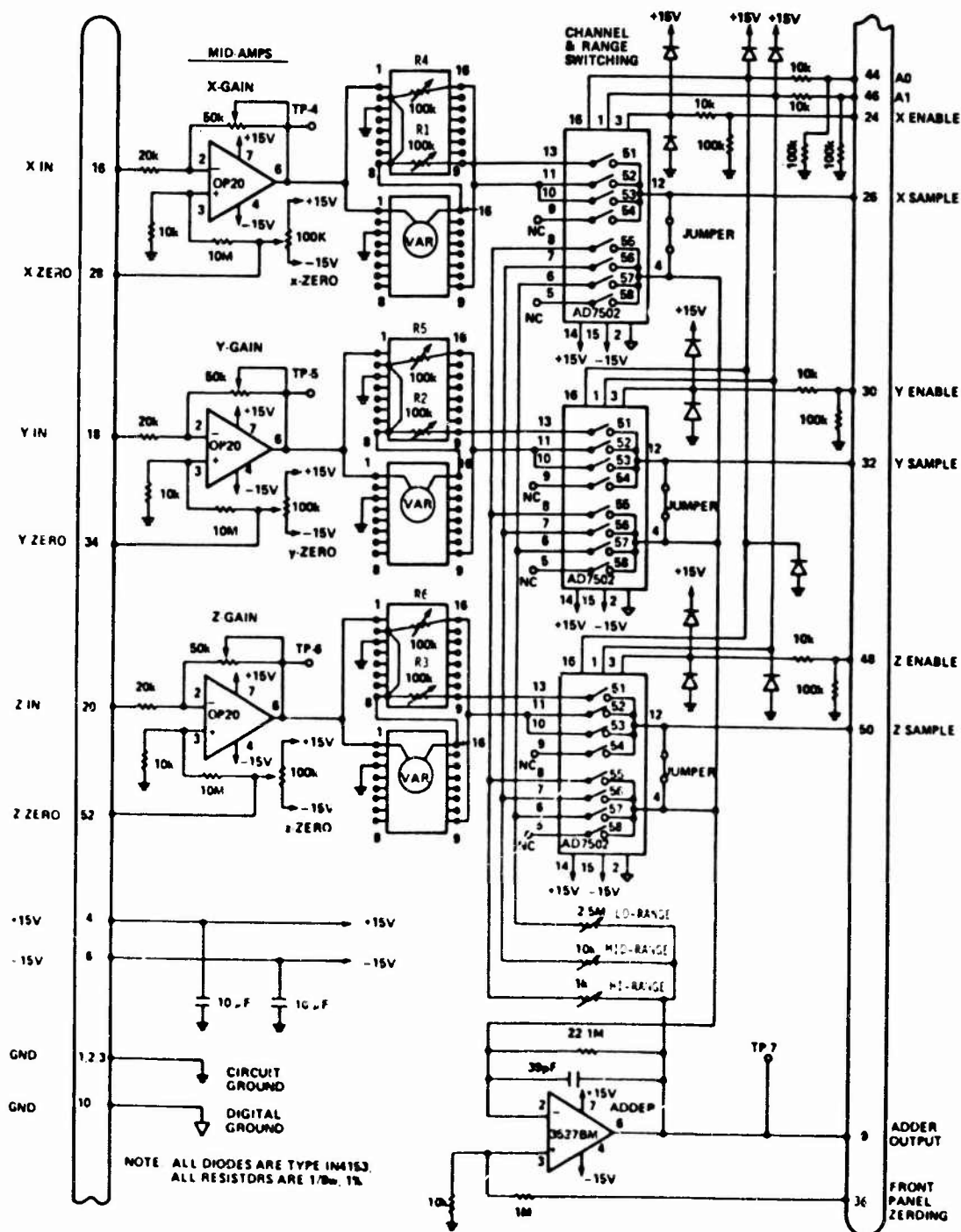


Figure 25. Schematic diagram of the shaping board.

ADDER GAIN

LO RANGE MID RANGE HI RANGE

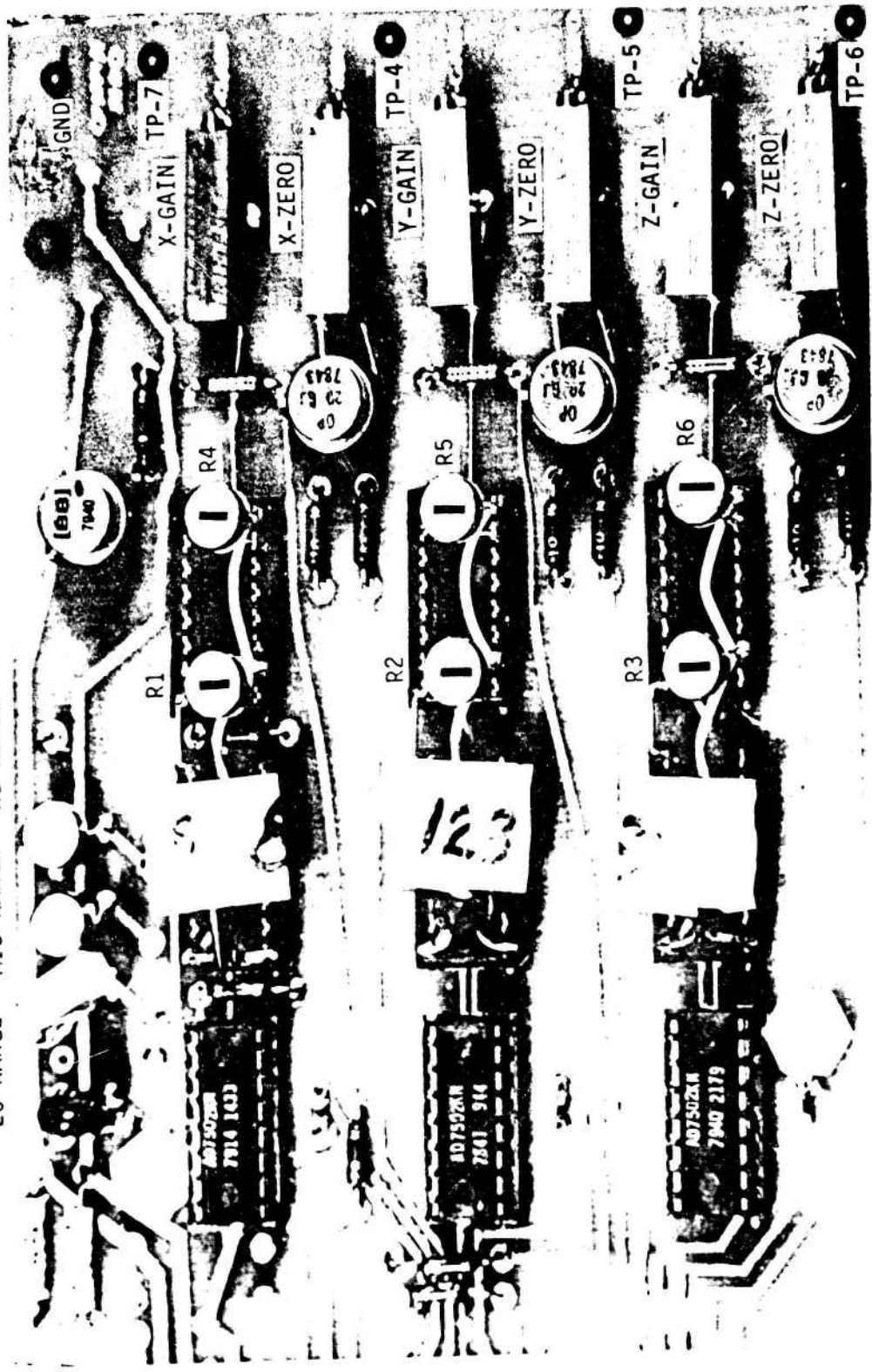


Figure 26. Photograph of the shaping board showing the zeroing and alignment controls and the test points.

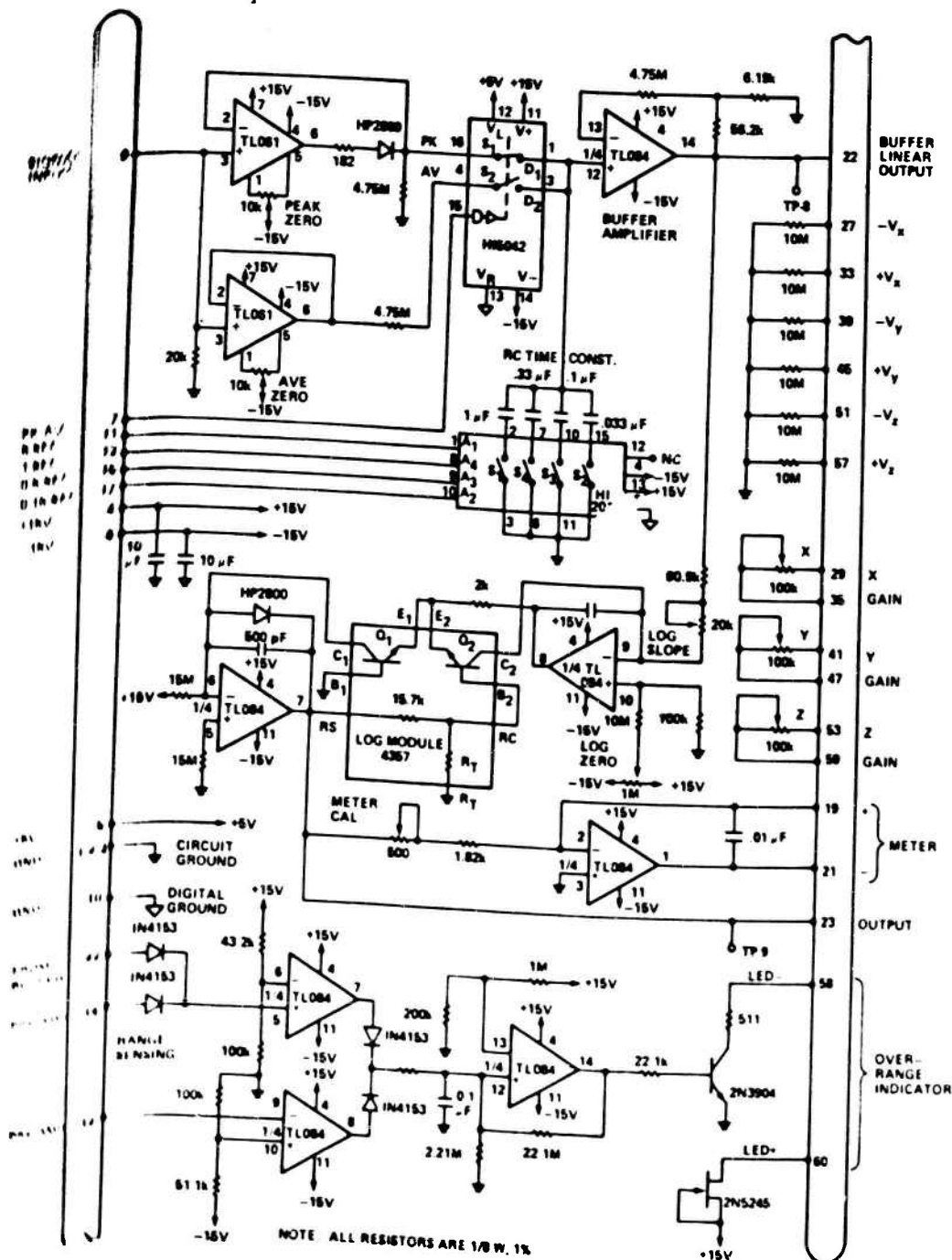


Figure 27. Schematic diagram of the logarithm board.

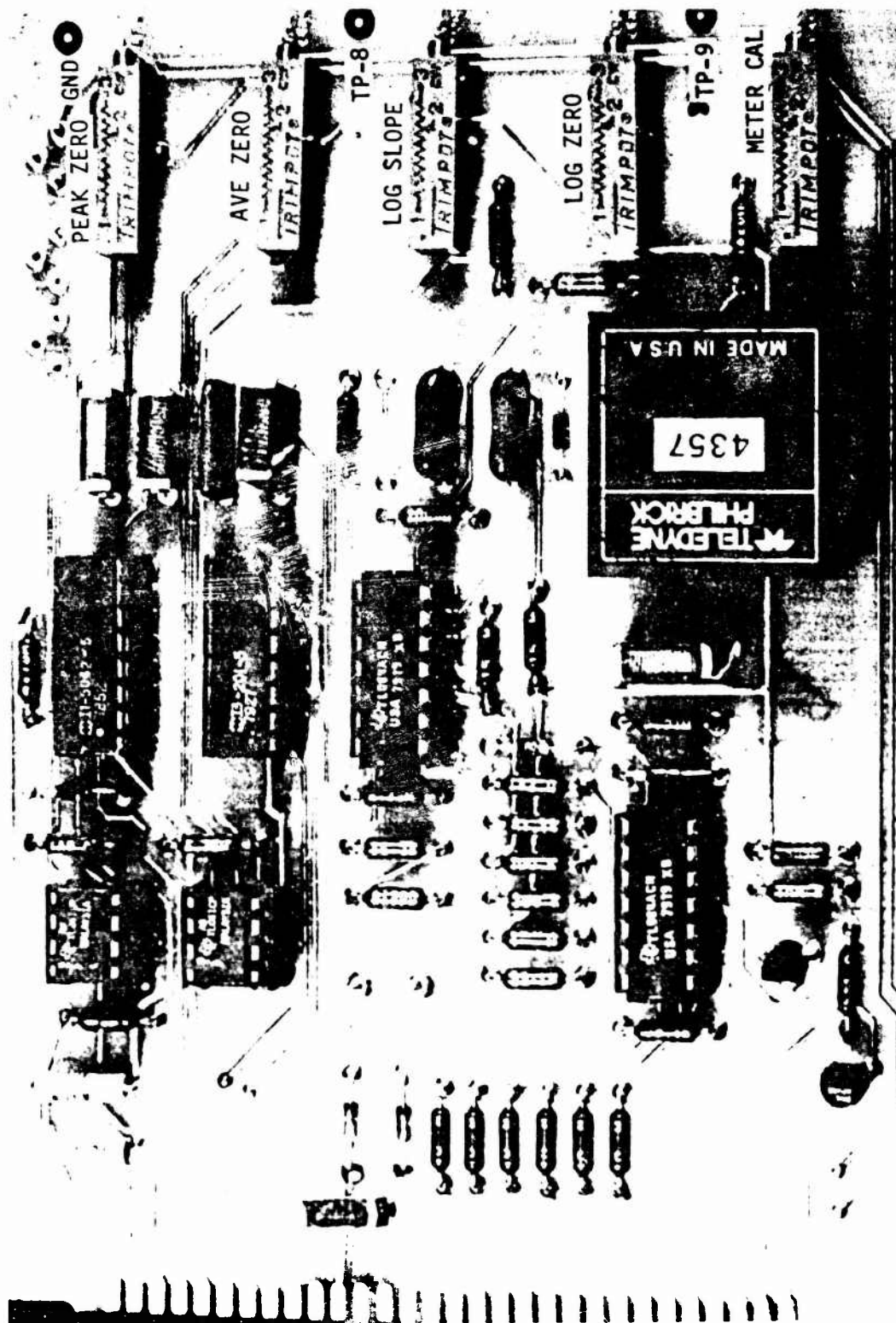


Figure 28. Photograph of the logarithm board showing the zeroing and alignment controls and the test points.

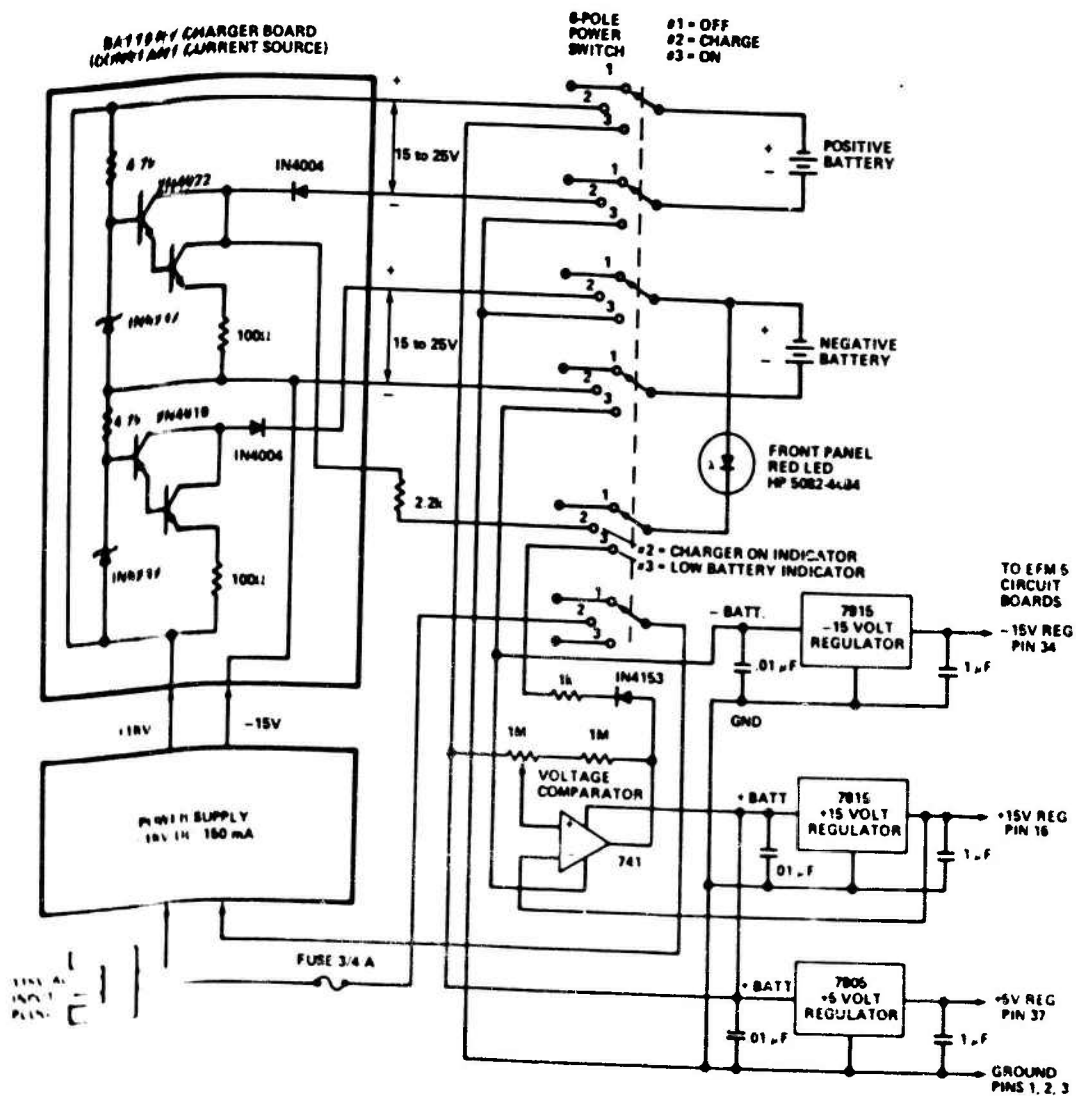
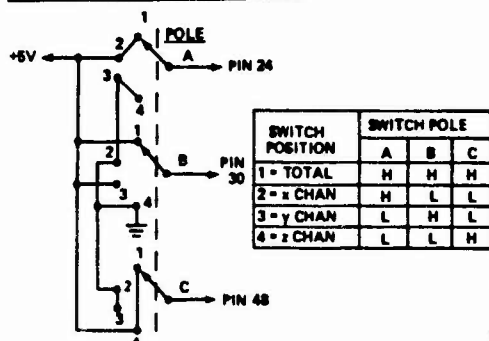
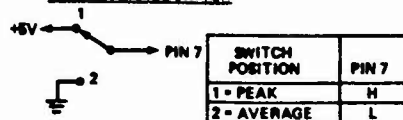


FIGURE 20. Schematic diagram of the power supply circuitry and power switch.

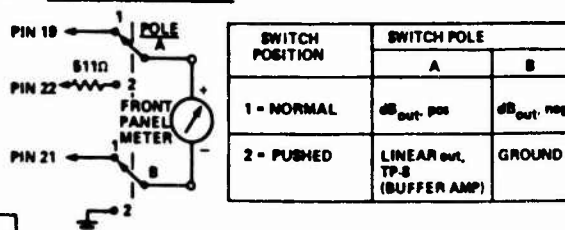
ANTENNA CHANNEL SELECTOR SWITCH



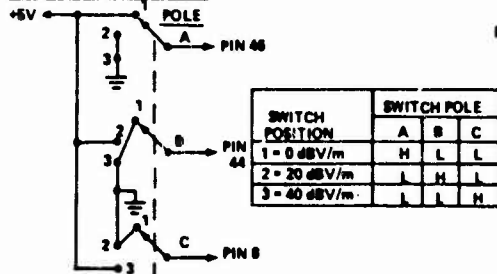
PEAK/AVERAGE SWITCH



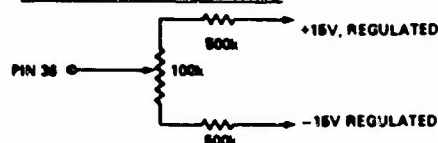
PUSH-TO-ZERO SWITCH



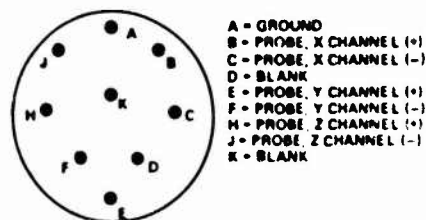
RANGE SELECTOR SWITCH



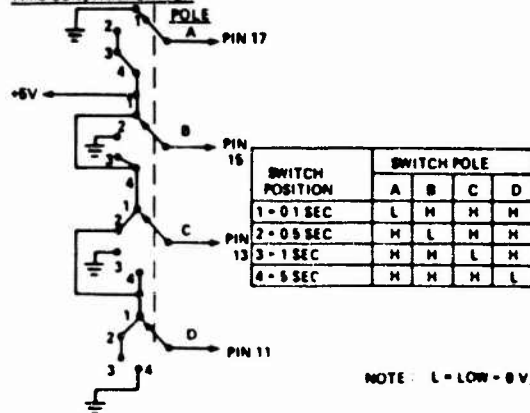
FRONT PANEL ZEROING CONTROL



FRONT PANEL SOCKET FOR THE PROBE CABLE



TIME CONSTANT SWITCH



NOTE: L = LOW - 0 V, H = HIGH - +5 VOLTS, REGULATED

Figure 30. Schematic diagrams of the other front panel controls and components.

8. ALIGNMENT AND ADJUSTMENT PROCEDURE

This section describes the procedure for making the (initial) adjustments of the internal potentiometers in the EFM-5 metering unit. In addition to op-amp zeroing, gain-setting controls, and logarithm circuit adjustments, a "shaping" operation is performed in order to produce the correct meter indication as a function of field intensity. This non-linear processing is required for field strength levels above 10 V/m. The frequency chosen at NBS to perform the signal shaping is 100 MHz. As mentioned previously, the standard field setup is accurate and convenient at this frequency and the EFM-5 response curve is essentially flat. In essence, the shaping procedure involves an iterative adjustment of the non-linear adder circuitry, for each channel, to achieve an optimum overall readout accuracy. That is, potentiometers are set to achieve minimum error in indicated field strength over the total measurement range of 1 to 1000 V/m.

The first stage in the shaping procedure (and also in a calibration of the radiation monitor) is to "zero" all the op-amps in the metering unit. The probe antenna must be in a zero-field (shielded) environment for this step, for example within a TEM cell or anechoic chamber. The basic alignment procedure then involves adjustment of the receiving gain controls and shaping controls until the meter indicates the correct field strength value, for each of the three dipoles in the isotropic antenna. The shaping adjustments are made with the EFM-5 probe inserted in the standard electric field of a TEM cell, using the instrumentation shown in figure 14 and described in section 6.1. For an rf power of 200 W, a 0.6 x 1 m TEM cell will produce field intensities up to about 50 dBV/m (316 V/m), and a 0.2 x 0.3 m cell will produce fields up to 60 dBV/m (1000 V/m).

There are three removable electronic circuit boards in the metering unit. They have been designated in this report as: (a) preamplifier board, (b) shaping board, and (c) logarithm board. Figures 24, 26 and 28 give photographs of these three main boards showing the internal alignment potentiometers and voltage test points. The following procedure is used to make the amplitude/shaping adjustments within the metering unit, producing a meter indication which is proportional to the RSS value of the measured E field as expressed in dB above 1 V/m. NOTE: Refer to figure 11 for a sketch of the EFM-5 front panel.

- (a) Mechanical zero. With the OFF/CHARGE/ON power switch in the OFF position, check the mechanical zero of the meter movement. If required, adjust the screw located on the meter housing to obtain a zero dBV/m indication.
- (b) Battery check. With the power switch in the ON position and no 115 V cord plugged into the back panel, check the battery voltage. If the warning LED located above the power switch does not glow, it indicates that the battery voltage is sufficient for proper operation of the EFM-5 radiation monitor. Do not leave the power switch in the ON position when the instrument is not in use because the battery life is only about seven hours. (NOTE: If the batteries are discharged, there may not be enough potential to light the LED.)

(c) Preliminary setting of the front panel switches and controls.

- (1) Power switch in the OFF position.
- (2) Field intensity RANGE selector switch in the + 0 dBV/m step, corresponding to the maximum sensitivity range of 0 to 20 dBV/m (1 to 10 V/m).
- (3) PEAK/AVE switch in the AVE position.
- (4) ANTENNA channel-selector switch in the TOTAL position.
- (5) TIME CONSTANT switch in the 0.1 SEC position.

(d) TEM cell setup for zeroing the EFM-5 and producing standard fields.

- (1) Mount the EFM-5 probe in the 0.6 x 1 m TEM cell at the analytic angle, with the sensor sphere located as shown in figure 14. Connect the probe to the metering unit via the flexible resistance line.
- (2) Insert a low-pass filter having a cutoff frequency between 100 and 175 MHz between the rf source and the TEM cell.
- (3) Turn the EFM-5 power switch to the ON position.
- (4) Turn on the rf source at a frequency of 100 MHz. Increase the cell voltage to obtain an indication on the EFM-5, recalling that 3 volts corresponds to a field strength of 10 V/m = 20 dBV/m. Note: if this metering unit has not been aligned previously, it may be necessary to do steps (e) and (f) before completing step (d).
- (5) Turn the ANTENNA switch to the X-channel position.
- (6) Set the antenna rotator and X-Y plotter to an angle of 0°.
- (7) Rotate the probe axially to align the X-channel dipole parallel to the E field, that is, to obtain a maximum EFM-5 indication.
- (8) Set the field strength to zero (TEM cell voltage = zero) and turn off the EFM-5.

(e) Zeroing the op-amps on the preamplifier board. (See figures 23 and 24).

- (1) Connect an external high-impedance dc voltmeter between test point number 1 (TP-1) on the pre-amp board and circuit ground. This permits measurement of the X-channel pre-amp output.

- (2) Turn the ANTENNA switch to the X position.
- (3) Turn the power switch to the ON position.

NOTE: for accurate zeroing, the instrument should be turned ON for at least 15 minutes before final adjustment of the zeroing potentiometers.

- (4) Adjust the X-ZERO potentiometer on the pre-amp board for minimum indication on the voltmeter. The indication should be within ± 1 mV of zero (0 ± 1 mV).
- (5) Turn the ANTENNA switch to the Y position.
- (6) Connect the external voltmeter to TP-2 for measurement of the Y-channel pre-amp output.
- (7) Adjust the Y-ZERO potentiometer to obtain a voltmeter indication of 0 ± 1 mV.

- (8) Turn the ANTENNA switch to the Z position.
 - (9) Connect the voltmeter to TP-3 for measurement of the Z-channel pre-amp output, and adjust the Z-ZERO potentiometer to obtain 0 ± 1 mV.
- (f) Zeroing the op-amps on the shaping board. (See figures 25 and 26).
- (1) If this metering unit has not been aligned previously, insert an extender board between the shaping board and back plane of the metering unit. Set all six varistor potentiometers to approximately their center positions. These are the 100 k Ω potentiometers (R1 through R6) shown near the center of each figure.
 - (2) Connect the voltmeter to TP-4 (X-channel mid-amp output).
 - (3) Adjust the X-ZERO potentiometer to obtain a voltmeter indication of 0 ± 1 mV.
 - (4) Connect the voltmeter to TP-5 (Y-channel output) and adjust the Y-ZERO potentiometer for 0 ± 1 mV.
 - (5) Connect the voltmeter to TP-6 (Z-channel output) and adjust the Z-ZERO potentiometer for 0 ± 1 mV.
 - (6) Turn the front panel ANTENNA switch to the TOTAL position.
 - (7) Connect the voltmeter to TP-7 (adder output). Adjust the front panel ZERO control with a screwdriver for 0 ± 1 mV on the voltmeter.
- (g) Alignment of the shaping board. (See figures 25 and 26).
- (1) Turn the ANTENNA switch to the X position.
 - (2) Connect the voltmeter to TP-7 and adjust the front panel ZERO control for 0 ± 1 mV on the voltmeter.
 - (3) At a frequency of 100 MHz, set the field strength in the TEM cell to 20 dBV/m.
 - (4) Check to insure that the probe is positioned at the analytic angle and rotated axially for maximum response at a rotator angle of 0° .
 - (5) Connect the voltmeter to TP-4 and adjust the X-GAIN potentiometer for approximately -300 mV indication.
 - (6) Set the field strength to 10 dBV/m.
 - (7) Connect the voltmeter to TP-7 and adjust the adder LO-RANGE gain potentiometer for 100 ± 5 mV.
 - (8) Turn the RANGE switch to the 20 dBV/m step.
 - (9) Set the field strength to 30 dBV/m.
 - (10) Adjust the adder MID-RANGE gain potentiometer for 100 ± 5 mV.
 - (11) Set the field strength to 40 dBV/m.
 - (12) Adjust the R1 potentiometer for 1 volt ± 50 mV.
 - (13) Repeat steps (6) through (12), if required, until the voltmeter readings are within the specified values.

NOTE: this completes the X-channel shaping and alignment for the lower two field-strength ranges.

- of
- (14) Set the field strength to zero.
 - (15) Turn the RANGE switch to the 0 dBV/m step.
 - (16) Turn the ANTENNA switch to the Y position.
 - (17) With the voltmeter connected to TP-7, adjust the front panel ZERO control for 0 ± 1 mV indication.
 - (18) Set the field strength to 20 dBV/m.
 - (19) Rotate the probe axially to align the Y-axis dipole with the E field, that is, to produce a maximum indication on the voltmeter. This should occur at an angle of 120° on the antenna rotator.
 - (20) Set the field strength to 10 dBV/m.
 - (21) Adjust the Y-GAIN potentiometer for 100 ± 5 mV.
 - (22) Turn the RANGE switch to the 20 dBV/m step.
 - (23) Set the field strength to 40 dBV/m.
 - (24) Adjust the R2 potentiometer for $1V \pm 50$ mV.
 - (25) Set the field strength to 10 dBV/m and turn the RANGE switch to the 0 dBV/m step.
 - (26) Repeat steps (21) through (24) until the voltmeter readings are within the above specified values.

NOTE: this completes the Y-channel shaping and alignment for the lower two ranges.

- (27) Set the field strength to zero.
- (28) Turn the RANGE switch to the 0 dBV/m step.
- (29) Turn the ANTENNA switch to the Z position.
- (30) Adjust the front panel ZERO control for 0 ± 1 mV.
- (31) Set the field strength to 20 dBV/m.
- (32) Rotate the probe axially to align the Z-axis dipole with the E field. The maximum voltmeter indication should occur at an angle of 240° on the antenna rotator.
- (33) Set the field strength to 10 dBV/m.
- (34) Adjust the Z-GAIN potentiometer for 100 ± 5 mV.
- (35) Turn the RANGE switch to the 20 dBV/m step.
- (36) Set the field strength to 40 dBV/m.
- (37) Adjust the R3 potentiometer for $1 V \pm 50$ mV.
- (38) Set the field strength to 10 dBV/m and turn the RANGE switch to the 0 dBV/m step.
- (39) Repeat steps (34) through (37) until the voltmeter readings are within the above specified values.

NOTE: this completes the shaping and alignment of all three channels for the lower two ranges.

- (40) Set the field strength to zero.
- (41) Turn the RANGE switch to the 0 dBV/m step.
- (42) Turn the ANTENNA switch to the X position.

- (43) Adjust the front panel ZERO control for 0 ± 1 mV.
- (44) Set the field strength to 20 dBV/m.
- (45) Rotate the probe axially for a maximum voltmeter indication near an angle of 0° on the antenna rotator. Note the voltmeter indication at TP-7. Move the EFM-5 probe from the 0.6×1 m TEM cell to the small 0.2×0.3 m cell. Adjust the field strength to obtain the previously noted voltmeter indication at TP-7. The field strength in the small TEM cell is now 10 V/m.
- (46) Turn the RANGE switch to the 40 dBV/m step.
- (47) Set the field strength to 40 dBV/m.
- (48) Adjust the adder HI-RANGE gain potentiometer for 10 ± 1 mV.
- (49) Set the field strength to 60 dBV/m.
- (50) Adjust the R4 gain potentiometer for $1 \text{ V} \pm 50 \text{ mV}$.
- (51) Repeat steps (47) through (50) until the voltmeter readings are within the above specified values.
- NOTE: This completes the X-channel shaping and alignment for the upper range.
- (52) Turn the ANTENNA switch to the Y position.
- (53) Turn the probe axially for a maximum voltmeter indication, near 120° on the antenna rotator.
- (54) If the field strength is not 60 dBV/m, set it to this value.
- (55) Adjust the R5 gain potentiometer for $1 \text{ V} \pm 50 \text{ mV}$.
- (56) Set the field strength to 40 dBV/m.
- (57) Check the voltmeter indication. If necessary, readjust the R5 potentiometer for 10 ± 1 mV.
- (58) Repeat steps (54) through (57) until the voltmeter readings are within the above specified values.
- NOTE: This completes the Y-channel shaping and alignment for the upper range.
- (59) Turn the ANTENNA switch to the Z position.
- (60) Turn the probe axially for a maximum voltmeter indication, near 240° on the antenna rotator.
- (61) Set the field strength to 60 dBV/m.
- (62) Adjust the R6 potentiometer for $1 \text{ V} \pm 50 \text{ mV}$.
- (63) Set the field strength to 40 dBV/m.
- (64) Check the voltmeter indication. If necessary, readjust the R6 potentiometer for 10 ± 1 mV.
- (65) Repeat steps (61) through (64) until the voltmeter readings are within the above specified values.
- (66) Set the field strength to zero and the RANGE switch to the 0 dBV/m step.
- (67) Turn the ANTENNA switch to the TOTAL position.
- (68) Adjust the front panel ZERO control for 0 ± 1 mV.
- (69) Turn the power switch to the OFF position.
- (70) Remove the extender board and insert the shaping board into the back plane of the metering unit.

NOTE: This completes the shaping and alignment of the three channels for the three field strength ranges. The procedure should result in the following indications on the external voltmeter:

<u>Electric field strength</u>		<u>EFM-5 range</u>	<u>Voltage at</u>
<u>V/m</u>	<u>dBV/m</u>	<u>dBV/m</u>	<u>TP-7</u>
1	0	0	10 ± 1 mV
3.16	10	0	100 ± 5 mV
10	20	0	1V ± 50 mV
10	20	20	10 ± 1 mV
31.6	30	20	100 ± 5 mV
100	40	20	1V ± 50 mV
100	40	40	10 ± 1 mV
316	50	40	100 ± 5 mV
1000	60	40	1V ± 50 mV

(h) Adjustment of the logarithm board. (See figures 27 and 28).

- (1) With the power switch in the OFF position, insert an extender board between the logarithm board and the back plane of the metering unit.
- (2) Turn the RANGE switch to the 0 dBV/m step.
- (3) Connect the voltmeter between the output of the buffer amplifier (TP-8) and circuit ground on the logarithm board.
- (4) With the field strength set to zero, turn the power switch to the ON position.
- (5) With the PEAK/AVE switch in the AVE position, adjust the AVE-ZERO potentiometer for 0 ± 10 mV.
- (6) Set the PEAK/AVE switch to the PEAK position.
- (7) Adjust the PEAK-ZERO potentiometer for 20 ± 10 mV, that is, +10 to +30 mV.
- (8) Set the PEAK/AVE switch to the AVE position.
- (9) Connect the voltmeter to TP-9.
- (10) Set the field strength to 0 dBV/m (1 V/m).
- (11) Adjust the LOG-ZERO potentiometer for 0 ± 1 mV.
- (12) Set the field strength to 20 dBV/m.
- (13) Adjust the LOG-SLOPE potentiometer for $2V \pm 1$ mV.
- (14) Repeat steps (10) to (13) until the voltmeter readings are within the above specified values.
- (15) Set the field strength to 20 dBV/m.
- (16) Adjust the METER-CAL potentiometer for a 20 dBV/m indication on the front panel meter.
- (17) Set the field strength to zero.
- (18) Depress the PUSH TO ZERO button on the front panel and adjust the ZERO control for 0 dBV/m indication on the front panel meter.

- (19) Repeat steps (18) through (20) until the front panel indications at 0 dBV/m and 20 dBV/m are correct visually.
- (20) Turn the power switch to the OFF position.
- (21) Remove the extender board and insert the logarithm board into the back plane of the metering unit.

NOTE: This completes the alignment and adjustment of the EFM-5 radiation monitor.

9. SUMMARY AND CONCLUSIONS

This project was sponsored jointly by the U.S. Army and the National Bureau of Standards. It is part of a continuing program to design rf radiation monitors for making accurate surveys of complex fields. The work involves both theoretical and experimental aspects of quantifying EM fields, including the fabrication and calibration of prototype instruments. The immediate goal was to develop an improved isotropic E-field monitor having a flat response from 600 kHz to 1000 MHz.

The measuring range of the NBS-developed EFM-5 instrument is 0 to 60 dBV/m (1 to 1000 V/m). This is equivalent to a plane-wave power density range of 0.000265 to 2.4 mW/cm^2 . The frequency range for a response within $\pm 1 \text{ dB}$ is 0.3 to 900 MHz on the present instrument, and for $\pm 2 \text{ dB}$ response it is 0.2 to 1000 MHz. However, the monitor is sensitive to all frequencies from 100 kHz to 4 GHz, with greatest response at the antenna self resonant frequency of 2.46 GHz.

The relatively strong fields of primary interest in this project generally occur close to a transmitting antenna or reflecting surface and are likely to have a complicated field structure. Therefore the only practical way to make quick field-intensity surveys is with an isotropic probe, that is, an antenna system which is omnidirectional in a three dimensional sense. The antenna of the EFM-5 consists of three mutually-orthogonal dipoles, each 6 cm long by 2 mm wide. This sensor size is small enough to resolve the spatial fine structure of complex fields, with minimum perturbation to the field being measured. Due to orthogonality of the dipoles, there is no mutual coupling of the fields produced by the dipole currents.

The EFM-5 radiation monitor measures the total electric-field magnitude (Total E), which is defined as the root-mean-square (RMS) value of three perpendicular field components at the measurement point. This permits easy and accurate measurement of either plane waves in the far zone or a complex field structure in the near zone. The monitor can be used to measure either the relatively weak ambient field pollution of distant broadcasting stations, or the more intense leakage fields of industrial curing chambers and plastic sealers. The instrument is rugged in construction and battery powered for portable operation.

Previous radiation monitors designed at NBS have demonstrated the feasibility and accuracy of a crossed dipole type of rf sensor. The EFM-5 antenna is embedded in a spherical sphere 10 cm in diameter so as to measure close to leakage sources, similar to commercial microwave hazards meters. However, the EFM-5 can also measure the relatively-

weak lower-frequency fields normally measured with large self-resonant dipoles and tunable receivers. Thus the capabilities of the NBS and commercial instruments are somewhat different. For example, the commercial monitors are generally more useful for measuring the time-average level of high-power microwave radars, while the EFM-5 is better suited to measure lower-frequency non-pulsed signals.

The EFM-5 incorporates other features not commercially available, such as a front panel switch to select measurement of either a single E-field component or the RSS value. The EFM-5 also provides a choice of measuring either the time-average signal level or using a peaking circuit to measure the peak value, with four selectable time constants. It is thus possible to measure the peak amplitude of modulated signals - within the 0.3 millisecond risetime of the measurement system. The NBS-designed probe uses Schottky beam-lead diodes as the rf detectors. This type was chosen because they are small, stable, have a high back resistance, high breakdown voltage (70 V), high sensitivity, and low temperature dependence. Many commercially available monitors employ thermocouple sensors with a long response time and therefore cannot display rapid variations in modulated fields.

The EFM-5 field strength monitor consists of three units. The first is the isotropic probe having three dipoles, three diode detectors, and three high-resistance plastic twinleads. All are embedded in a 10 cm diameter sphere, which sets the minimum measurement distance at 5 cm (2 inches). The second part is a six-conductor transmission line, also made of partially conducting plastic. This flexible line is 1 to 3 m long. Most commercial rf monitors use short-handled probes which make them more susceptible to perturbation by the operator when the probe is hand held. The EFM-5 includes an extension handle to further reduce the operator perturbation when desired. The third part, the metering unit, contains the electronic circuitry, panel controls, batteries and readout meter. The detected dc voltages from the dipoles are conveyed to high-impedance instrumentation amplifiers. The high input impedance prevents excessive voltage drop on the plastic transmission lines.

The three detected voltages from the probe are processed electronically (shaped) and summed to produce a single dc voltage which is proportional to the total magnitude of the electric field. This is defined by the equation

$$(\text{TOTAL } E) = \sqrt{E_x^2 + E_y^2 + E_z^2}. \quad (2)$$

This is a scalar quantity which relates well to the potential for causing rf interference or possible hazard to personnel. Thus the EFM-5 readout indication includes the overall effect of all E-field components in the EM wave, of all possible polarizations and arrival directions, for all frequencies within the passband of the antenna/filter combination. The meter indication on the EFM-5 is linearly proportional to the field magnitude expressed in units of dB above 1 V/m (dBV/m).

The heating of a lossy dielectric material is proportional to the square of the Total E as defined above. However, it is generally assumed that the potential for rf interference is proportional to the first power of Total E. The power density of an EM field, $\vec{E} \times \vec{H}$, is a vector quantity relating to power flow in a given direction and it does not necessarily

correlate with the possibility of an rf hazard, especially for the type of reactive fields usually encountered in the near zone of rf sources.

Each EFM-5 monitor is calibrated by immersing the probe in a standard field (known magnitude) in the NBS laboratories. These CW calibrations are described in section 6 of this report. A radiation monitor can be calibrated over the frequency range of 100 kHz to 4 GHz with an uncertainty less than ± 0.5 dB. The calibrations are performed as a function of signal frequency, field amplitude, polarization, and orientation angle of the probe with respect to the EM field.

There is still no general agreement among scientists as to the optimum field parameter to quantify for identifying the hazard potential of rf radiation. To our knowledge, there is no meter available for sensing power density. Rather, all presently available instruments respond to either the electric or magnetic field alone. In spite of this, it is common practice for manufacturers to mark the meter dial in mW/cm^2 , a power density unit. However, most of the good radiation monitors employ isotropic antennas, so the indication is essentially independent of field polarization, direction of power flow, or orientation angle of the probe. If a comparison with power density units is desired, it should be remembered that a correct conversion is possible only if the field being measured is planar in nature, such as the far zone of a transmitter. If far-field conditions apply, the following relation may be used:

$$\text{Power Density in } \mu\text{W}/\text{cm}^2 = \frac{(\text{Electric Field in V/m})^2}{3.77} \quad (15)$$

At the present time there is no public health protection standard for the radiofrequency spectrum. The Bureau of Radiological Health of the Food and Drug Administration maintains a product performance standard for microwave ovens. There is also a voluntary standard for occupational health and safety of $10 \text{ mW}/\text{cm}^2$ that was written by the American National Standards Institute (ANSI); this standard is currently undergoing revision and review. The Occupational Safety and Health Administration (OSHA) used the ANSI standard in writing an OSHA occupational regulation; this regulation is only advisory in nature. The National Institute of Occupational Safety and Health (NIOSH) has a draft document for consideration as a regulation for occupational health and safety.

The EFM-5 developed at NBS is a prototype instrument and is not available commercially. However, one manufacturer has begun production of this type of meter, and this document is intended to provide sufficient information so that further commercialization is possible. The EFM-5 is capable of measuring rf fields under more general conditions than a conventional FIM, but it has greater sensitivity than the usual hazard meter. A few applications for this type of monitor are summarized as follows:

- (1) Making ambient field surveys of lower-level rf pollution caused by AM, FM, TV, CB and other broadcasting services.
- (2) Measuring possible hazards at frequencies between 100 kHz and 4 GHz caused by diathermy equipment, industrial rf heaters, plastic sealers, and in the near zone

of transmitting antennas.

- (3) Checking the EM field environment in sensitive areas containing electroexplosive devices or flammable fluids.
- (4) Checking sites having instruments which are susceptible to rf interference or have degraded operation when exposed to EM radiation.
- (5) Plotting transmitter antenna patterns and monitoring the tuning to obtain maximum radiated power or optimum pattern.

New technologies employing laser diodes, single-mode fiber-optic guides, and integrated-circuit optical components may eventually provide the answer to the search for an EMI antenna with huge bandwidth and good sensitivity [30]. Research is now in progress at NBS with this aim. However, in the meantime the EFM-5 is a convenient tool for measuring either hazards or the weaker fields which represent an rf "smog" that is becoming of greater concern to health scientists and electronics users. It is an example of the next generation of FIM's for searching and quantifying leakage fields or rf pollution.

A prototype version of the EFM-5 has been supplied to and tested by the EPA, NIOSH and other interested agencies. Extensive field tests have demonstrated the measurement accuracy and simplicity of operation of this NBS meter, and the absence of perturbing effects from the transmission lines. It is believed that this type of rf monitor will evolve, be recognized by industry, and find widespread use in the future.

10. RECOMMENDATIONS

The results achieved in this NBS program for development of rf radiation monitors have been encouraging. Although the project resulted in a near-zone, isotropic, electric-field monitor with significant improvements, there are still certain areas of investigation that would be beneficial to pursue.

First, we recommend a follow-on program in which the existing EFM-5 instrument is more thoroughly evaluated. For example, the temperature characteristics of the rf sensor and varistor shaping circuit should be tested. As discussed in section 4 of this report, the Si detector diodes in the probe are somewhat sensitive to temperature changes, with increased response at higher temperature. To a lesser extent, the resistance of the Si C varistors in the metering unit is a function of temperature, with decreased resistance at higher temperature. Additional calibrations should therefore be performed to measure the effect of ambient temperature on the indicated field strength, especially over the 15° to 35°C range. It would then be possible to design temperature compensation for the detector and adder circuitry, using thermistors or other compensating components.

It is also recommended that the magnitude of the instrument common-mode rejection be tested. Such performance checks have been conducted on two EFM-5 units at a few frequencies, but systematic measurements should be made to check the antenna balance and

CMRR of the dipole/preamplifier system. Another recommended test is to determine quantitatively the amount of case leakage vs field level at various frequencies throughout the 100 kHz to 4 GHz range. There is a possible need for special EMI shielding and gasketing of the metal case to prevent penetration of strong EM fields into the electronic circuitry of the metering unit.

Additional development work should be done to extend the frequency range of flat response. A small increase in usable frequency could be obtained by using shorter dipoles in place of the 5 cm dipoles, perhaps 3 cm or 2 cm long. However, this approach would not overcome the increased response at the natural resonant frequency of the dipoles. Therefore, it would be preferable to develop a resistively loaded antenna in place of the metal dipoles now used. Results of probe research at NBS indicate that dipoles with a pickup that is essentially independent of frequency, exhibiting very little increase in response at resonance, could be adapted for use with this rf monitor [31].

The concept of measuring the E-field total magnitude with an isotropic probe and plastic transmission lines has been verified. In view of the advantages gained by using this type of "isolated" sensor, it would be desirable to continue the research effort. Additional types of electronic components and circuitry should be tested, including integrated-circuit memories or digital techniques to obtain a more repeatable design of the shaping (non linear) process. It would then be possible to simplify the alignment procedure and some of the circuitry.

Another worthwhile investigation would be to develop a radiation monitor for the measurement of magnetic field intensity. While the EFM-5 meter was designed solely for measuring electric fields, the principles and much of the instrumentation could be used (with appropriate modifications) for the measurement of magnetic fields. It is thus recommended that an H-field version of the present EFM-5 be fabricated and tested. The antenna geometry would be changed to that of three small orthogonal loops instead of short dipoles, and the amplifier gain would be increased to maintain an equivalent measurement sensitivity.

If it is desired to make a more complete characterization of an EM field, means should be devised to measure both the E and H fields simultaneously. If possible, the time-phase angle between E and H should be determined with an electrically-isolated sensor. This report makes no attempt to cover that investigation. However, NBS personnel have analyzed possible approaches and have made preliminary evaluations of new types of antennas that promise to define and quantify near-zone electromagnetic fields more completely than is possible at the present time.

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10. SUPPLEMENTARY NOTES ☐ Document describes a computer program; SF-105, FiPS Software Summary, is attached.			
11. ABSTRACT (A 200-word or less factual summary of most significant information, if document includes a significant bibliography or literature survey, mention it here) A broadband rf radiation monitor was developed at NBS for the frequency range of 200 kHz to 1000 MHz. The isotropic antenna unit consists of three mutually-orthogonal dipoles, each 5 cm long by 2 mm wide. The receiver described in this paper has an accurate measurement range of 1 to 1000 V/m. The readout indication is in terms of the Hermitian or "total" magnitude of the electric (E) field strength, which is equal to the root-sum-square value of three perpendicular E-field components at the measurement point. Previous radiation monitors designed at NBS have demonstrated the accuracy of a crossed-dipole sensor for measuring the total E-field magnitude of complicated electromagnetic fields. Several prototype units of an advanced instrument have been fabricated and tested. This instrument, the EFM-5 Electric Field Monitor, has nearly perfect isotropy over a 60 dB dynamic range. The dial readout units are dB above 1 V/m (dBV/m) and V/m. Three ranges cover 0 to 60 dBV/m (1 to 1000 V/m). The electronic circuitry of the EFM-5 obtains the total magnitude of all field polarizations and all signals in the entire frequency band. The sensor response is isotropic; that is, there is no preferred field polarization or preferred direction of arrival of the incoming wave. Therefore this probe is well suited for measuring the near field of an emitter, including regions of multiple reflection, standing waves, etc. The EFM-5 can be used to monitor either the weak plane-wave fields in the far zone of a transmitting antenna, or the complicated fields only 5 cm from an rf leakage source. The special features, electronic design, physical construction, and calibration are described in this paper.			
12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons) Electromagnetic field; electronic instrument design; field intensity meter; field strength measurement; isotropic antenna; radio frequency radiation; receiver calibration.			
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