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PLANNING GUIDANCE FOR FUTURE EMI MEASUREMENT INSTRUMENTATION

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U.S. Department of Commerce
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Planning Guidance for Future EMI Measurement Instrumentation

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The environment in which electronic apparatus of all types must function is becoming increasingly hostile because of a burgeoning electronic technology. This increases the potential for electromagnetic interference (EMI), and places new demands upon those organizations who are responsible for measuring EMI. This report (a) reviews the electrical quantities that are used to describe and evaluate EMI, (b) discusses current EMI measurement principles, (c) attempts to identify future EMI measurement requirements for the post 1985-1990 time period, (d) identifies certain expected new instrumentation opportunities, and (e) suggests action to meet the future needs for measurement instrumentation.

Key words: electromagnetic interference; electromagnetic environment; EMI instrumentation; EMI measurments; future EMI requirements; planning guidance.

1. INTRODUCTION

1.1 Background

The Electromagnetic Engineering Office (EMEO) USACEEIA, Fort Huachuca, Arizona, has asked the Electromagnetic Fields Division, National Bureau of Standards (NBS), Boulder, Colorado, to study the future prospects of electromagnetic interference (EMI), and provide planning guidance to EMEO for measurement instrumentation that will help them meet their mission tasks in the post 1985-1990 time period. The study was to be focused upon the anticipated character of EMI in the future electromagnetic environment, and upon the instrument specifications that will provide EMEO with the needed measurement capability to solve both the new and continuing electromagnetic compatibility (EMC) problems. Emphasis was to be placed upon new technologies that offer new approaches to instrument design that improve upon presently available equipment.

1.2 Problem Statement

One of the tasks of the EMEO is to perform certain electromagnetic interference (EMI) measurements that require the use of manportable electronic equipment. Although EMEO has other tasks and capabilities, this planning guidance addresses only those requiring manportable equipment.

The principal types of EMI measurements for which capabilities are required are the following:

1. Spectrum occupancy
2. Path loss
3. Ambient noise
4. Electromagnetic pulse hazards
5. General EMC "trouble shooting."

The manportable equipment that EMEO currently has in their inventory to make these measurements is inadequate in several ways:

1. It is heavy and bulky. This makes it difficult to transport, assemble, and disassemble by only a few men; many men are required.

2. It requires manual adjustment of operating controls, and much manual processing of measurement data. Very little automation or built-in processing is employed.

3. It is designed for laboratory or well-sheltered environments. It is not designed for adverse field conditions.

4. The ranges of measurement parameters are insufficient for some present requirements, and future requirements will be even less adequately met.

Items 1 and 2 above cause the use of this equipment to be very manpower intensive. More men are required than if it were lighter, smaller, more automated, and simpler to operate. One result is that measurement missions are very expensive, especially when they require air transportation to remote regions of the world. Also, reaction time is slower, and the time required to gather data is longer, adding to the cost. Furthermore, insufficient data is sometimes taken because of the slowness with which it can be gathered and processed. Item 3 results in poor performance reliability, and creates the need for spares that aggravates the transportation and cost problems. Item 4 also results in insufficient data, and makes it impossible to adequately survey or evaluate the EMC conditions in a given field situation.

1.3 Purpose

The purpose of this report is to provide planning guidance to EMEO so that they may prepare themselves to meet their EMI measurement requirements in the post 1985-1990 time period. To do this, we have endeavored to:

a. Identify the relevant EMI quantities to be measured by EMEO.

b. Review the adequacies and inadequacies of presently-used EMI measurement techniques and instruments.

c. Review the anticipated measurement requirements that will exist in the post 1985-1990 time period.

d. Review the present and anticipated new measurement technologies that can be employed to meet EMEO's mission requirements.

e. Recommend technical solutions and a possible course of action that will help EMEO meet its future mission requirements.

1.4 Limitations

This report is limited to those topics which EMEO personnel, in conversations with NBS personnel, have identified as being relevant to their mission. It is not intended as a comprehensive review or assessment of the larger field of EMI metrology, nor does it address the measurement requirements of agencies, either civilian or military, other than EMEO.

The EMI measurands discussed in section 2 are only a sub-set of a somewhat larger group of EMI measurands. Furthermore, these discussions, along with the discussions in section 3, are slanted in directions that relate to the particular ways which EMEO normally encounters those quantities.

The recommendations in section 6 are based upon the findings reported in sections 4 and 5. Those findings are the result of a modest and limited search for information, and are not to be considered to be exhaustive. However, we believe they are representative, and any further search is unlikely to significantly alter the picture that has been assembled here.

2. EMI MEASURANDS

2.1 Introduction

A measurand is a physical or electrical quantity, property, or condition that is to be measured (IEEE Std. 100-1977, p. 410). EMI measurands depict properties of interference waveforms that are needed by the EMC engineer to solve compatibility problems. They fall into two broad categories, each of which is further divided into two additional categories (see figure 1). The first two categories are (1) circuit quantities and (2) field quantities.

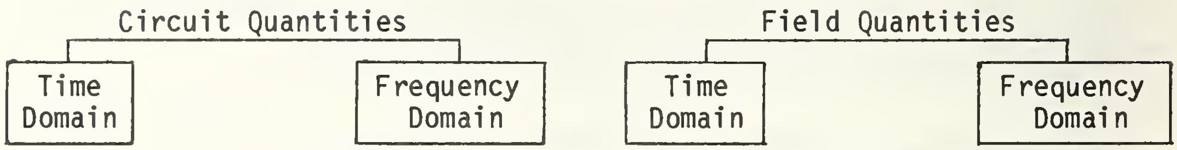

Figure 1. Categories of EMI Measurands

The second two categories are (3) time domain quantities and (4) frequency domain quantities. The first two categories are related through some sort of transducer transfer characteristic such as antenna factor or coupling coefficient (see figure 2). The relationship between the second two categories is expressed by a suitable mathematical transform pair, most commonly the Fourier transform and its inverse.

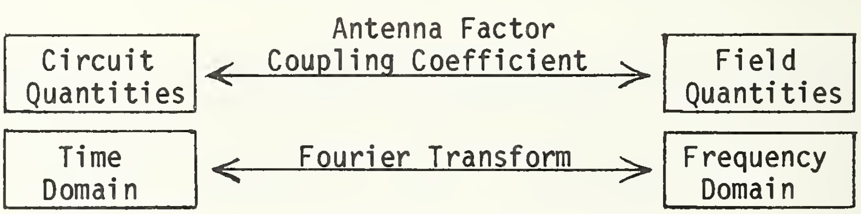

Figure 2. Relationships between quantities

Table 1 is a list of the basic measurands and their basic electrical units that are in common use by EMC engineers. In practice, the units are often modified by scaling factors; for example, volts per meter per hertz becomes microvolts per meter per megahertz. Also, engineers commonly express certain of the quantities as a decibel ratio relative to a reference value; for example, microvolts per meter per megahertz becomes decibels above one microvolt per meter per megahertz, abbreviated dBμV/mHz.

Table 1. EMI Measurands and Units

I. Circuit Quantities

A. Time Domain

Measurand	Units
a. Amplitude	volts, amperes
b. Power	watts

B. Frequency Domain

Measurand	Units
a. Frequency	hertz
b. Bandwidth	hertz
c. Spectrum amplitude	volts per hertz
d. Power density	watts per hertz

II. Field Quantities

A. Time Domain

Measurand	Units
a. Field strength	volts per meter; amperes per meter
b. Power flux density	watts per square meter
c. Energy density	joules per cubic meter

B. Frequency Domain

Measurand	Units
a. Frequency	hertz
b. Bandwidth	hertz
c. Broadband field strength	volts per meter per hertz amperes per meter per hertz
d. Broadband power flux density	watts per square meter per hertz

2.2 Circuit Quantities, Time Domain

2.2.1 Amplitude

The amplitude of an arbitrary electrical waveform in the time domain is subject to a variety of definitions. These are discussed below.

Technically, the single term amplitude applies only to a sinusoidal waveform. For a sinusoidal voltage waveform, $v_s(t)$, where

$$v_s(t) = V\sin\,(2\pi ft + \phi), \qquad (1)$$

the various quantities are defined as follows:

$v_s(t)$ = instantaneous voltage at time t

V = amplitude

f = frequency

ϕ = phase angle at $t = 0$.

By the addition of modifiers, other amplitudes are defined that apply to both sinusoidal and non-sinusoidal periodic waveforms, $v_p(t)$. These are:

a. Instantaneous amplitude, $v_i(t)$: the voltage value of a waveform at any specified time instant.

b. Average amplitude, v_{avg}:

$$v_{avg} = \frac{1}{T} \int_0^T v_p(t)\,dt, \qquad (2)$$

where T = period.

c. RMS amplitude, v_{rms}:

$$v_{rms} = [\frac{1}{T} \int_0^T v_p^2(t)dt]^{1/2}. \quad (3)$$

Note that the rms and average amplitudes are defined in terms of one full period, T, and do not vary with time.

d. Peak amplitude, V_p: the maximum (positive or negative) instantaneous amplitude that occurs in an observation time interval.

e. Quasi-peak amplitude, V_q: the output voltage from a rectifier network that has specified charge and discharge time constants. (See the appropriate ANSI and CISPR standards for the values of these constants.)

Note that the peak and quasi-peak amplitudes may depend upon the observation time interval.

For a sinusoidal waveform, the average amplitude is zero by the above definition. Therefore it is redefined to be the average over T/2, in which case it is 0.6366 V. The rms amplitude is 0.7071 V. The peak amplitude is synonymous with its simple amplitude, V. The quasi-peak amplitude may vary with frequency and observation time.

If the voltage waveform is not periodic, only the following amplitude definitions strictly apply:

a. Instantaneous amplitude
b. Peak amplitude
c. Quasi-peak amplitude

Average and rms amplitudes are not defined for non-periodic waveforms because they may vary with the observation (integration) time interval. However, an electrical instrument that is designed to measure the true rms and true average amplitudes of an arbitrary periodic waveform may give useful information about non-periodic waveforms, at least for the duration of the measurement time interval.

If the waveform is a current instead of a voltage as used in the above discussion, the same definitions apply with current replacing voltage. EMI instruments are more commonly designed to measure voltage amplitude than current amplitude. The discussions in this report use voltage amplitude for illustration purposes only.

2.2.2 Power

The power of an arbitrary electrical waveform in the time domain is also subject to a variety of definitions. In general, power is the time rate of transferring or transforming energy (IEEE Std. 100-1977, p. 510). Of the various specific types of power, the following are of principal value to the EMC engineer:

a. Instantaneous real power, $P_i(t)$: the power dissipated in a resistive termination at any specified time instant.

b. Average real power, P_{avg}:

$$P_{avg} = \frac{1}{T} \int_0^T P_i(t)\, dt, \tag{4}$$

where T is the period over which the power is averaged.

c. Peak real power, P_p: the maximum instantaneous real power that occurs in an observation time interval.

d. Available power, P_{avl}: the maximum average real power that can be transferred from a port to a termination which is adjusted for this condition.

Note 1. These definitions deal with real power as distinct from reactive power, which is normally of little interest to the EMC engineer as a circuit measurand.

Note 2. These definitions apply to any arbitrary waveform. However, if the waveform is non-stationary, average real power may vary with the observation time interval.

2.3 Circuit Quantities, Frequency Domain

2.3.1 Frequency

The frequency of a periodic waveform is the number of periods per unit time. For a non-sinusoidal periodic waveform, frequency refers to its fundamental component, unless otherwise stated. For a non-periodic waveform, frequency refers to the sinusoidal components into which the waveform may be analyzed.

2.3.2 Bandwidth

As an EMI measurand, bandwidth refers to signal bandwidth. It is the least frequency interval outside of which the power spectrum of the time-varying quantity is everywhere less than some specified fraction of its value at a reference frequency (IEEE Std. 100-1977, p. 52). Unless otherwise stated, the reference frequency is that at which the spectrum has its maximum value.

2.3.3 Spectrum Amplitude

Mathematically, spectrum amplitude, S(f), is twice the magnitude of the Fourier transform, V(f), of an arbitrary time-domain waveform, v(t). That is,

$$S(f) = 2|V(f)|, \qquad (5)$$

where

$$V(f) = \int_{-\infty}^{\infty} v(t)e^{-j2\pi ft}dt. \qquad (6)$$

Conceptually, spectrum amplitude is the value of the spectrum of a signal at any specified frequency.

There is a dualism between instantaneous amplitude (in the time domain) and spectrum amplitude (in the frequency domain). The distribution of instantaneous amplitudes of a signal in the time domain is called its (amplitude) waveform. The distribution of spectrum amplitudes of a signal in the frequency domain is called its (amplitude) spectrum. Thus, instantaneous amplitude, $v_i(t)$, and spectrum amplitude, $S(f)$, are equivalent quantities for describing the amplitude of a signal. However, note that because of the transformation defined by eq. (6), spectrum amplitude has (for example) the units of volt-seconds or volts per hertz in contrast to the units of instantaneous amplitude which is simply volts.

By definition, spectrum amplitude does not vary with time (see eqs. (5) and (6)). However, because of the finite time required to measure spectrum amplitude, its measured value may vary with time, particularly for non-periodic or very long-period waveforms.

2.3.4 Power Density

Mathematically, the frequency domain power density (power per unit bandwidth), $P(f)$, of a waveform, $v(t)$, is defined from the energy density, $E(f)$. The total energy, E_t, in joules, is given by the equations

$$E_t = \frac{1}{R} \int_{-\infty}^{\infty} v^2(t)dt = \frac{1}{R} \int_{-\infty}^{\infty} |S(f)|^2 \, df, \qquad (7)$$

where $S(f)$ is the spectrum amplitude of $v(t)$, and R is the circuit resistance. The energy density (energy per unit bandwidth), $E(f)$, is given by the equation

$$E(f) = \frac{|S(f)|^2}{R}, \qquad (8)$$

where the integration of eq. (7) is over a one-hertz bandwidth at frequency f. Power density is given by the equation

$$P(f) = \frac{E(f)}{\Delta T} = \frac{|S(f)|^2}{R\Delta T}, \tag{9}$$

where ΔT is the time interval during which the energy is transferred or transformed.

Conceptually, power density is the power in the spectrum of a signal at any specified frequency. It has the dimensional units of watts per hertz.

2.4 Field Quantities, Time Domain

2.4.1 Field Strength

Field strength is the magnitude of the electric (or magnetic) field vector of an electromagnetic field at a point in space.

The dimensional units of field strength are volts per meter or amperes per meter. The discussion of amplitude in section 2.2.1 above applies also to field strength.

2.4.2 Power Flux Density

The power flux density, P, of an electromagnetic field is the value of the Poynting vector at a point in space. It is the rate of energy flow per unit area at the point. For a plane wave in free space, P is given by the equation

$$\vec{P} = \vec{E} \times \vec{H} \tag{10}$$

where

E = electric field strength

H = magnetic field strength.

P, E, and H are vector quantities, and P is the cross product of E and H.

For a sinusoidal field, the instantaneous power flux density, P_i, is given by the equation

$$P_i = \left(\frac{\varepsilon_o}{\mu_o}\right)^{1/2} E_o^2 \sin^2 (\omega t - \phi) \tag{11}$$

where

E_o = amplitude of the electric field

ε_o = permittivity of free space

μ_o = permeability of free space.

The average power flux density, P_{avg}, is

$$P_{avg} = 1/2 \left(\frac{\varepsilon_o}{\mu_o}\right)^{1/2} E_o^2 = 1/2 \left(\frac{\mu_o}{\varepsilon_o}\right)^{1/2} H_o^2, \tag{12}$$

and the peak power flux density, P_p, is

$$P_p = \left(\frac{\varepsilon_o}{\mu_o}\right)^{1/2} E_o^2 = \left(\frac{\mu_o}{\varepsilon_o}\right)^{1/2} H_o^2. \tag{13}$$

P has the dimensional units of watts per square meter.

2.4.3 Energy Density

The energy density, W, at a point in an electromagnetic field is the sum of the electric energy density and magnetic energy density. For a plane wave in free space, W is given by the equations

$$W = \tfrac{1}{2}\varepsilon_o E^2 + \tfrac{1}{2}\mu_o H^2 \qquad (14)$$
$$= \varepsilon_o E^2 = \mu_o H^2$$

The dimensional units of W are joules per cubic meter.

For a non-planar wave, and for fields in an inhomogeneous lossy dielectric medium, the energy density may be difficult to calculate or measure.

2.5 Field Quantities, Frequency Domain

2.5.1 Frequency

The frequency of a periodic waveform is the number of periods per unit time. For a non-sinusoidal periodic waveform, frequency refers to its fundamental component, unless otherwise stated. For a non-periodic waveform, frequency refers to the sinusoidal components into which the waveform may be analyzed.

2.5.2 Bandwidth

As an EMI measurand, bandwidth refers to signal bandwidth. It is the least frequency interval outside of which the power spectrum of the time-varying quantity is everywhere less than some specified fraction of its value at a reference frequency (IEEE Std. 100-1977, p. 52). Unless otherwise stated, the reference frequency is that at which the spectrum has its maximum value.

2.5.3 Broadband Field Strength

Mathematically, broadband field strength is twice the magnitude of the Fourier transform of the electric or magnetic field vector of an electromagnetic field at a point in space. Conceptually, it is the value of the spectrum of the field strength of a signal at any specified frequency. The dimensional units of broadband field strength are volts per meter per hertz.

The discussion in section 2.3.3 about the dualism between instantaneous amplitude (in this case, field strength) and spectrum amplitude (in this case, broadband field strength) also applies here.

2.5.4 Broadband Power Flux Density

Mathematically, the frequency domain power flux density (power per unit area per unit bandwidth), P(f), is defined from the frequency domain energy density, W(f). The total energy density, W_t, in joules per square meter, is given by the equations

$$W_t = \left(\frac{\varepsilon_o}{\mu_o}\right)^{1/2} \int_{-\infty}^{\infty} e^2(t)dt = \left(\frac{\varepsilon_o}{\mu_o}\right)^{1/2} \int_{-\infty}^{\infty} |E(f)|^2 \, df \qquad (15)$$

where e(t) is the electric-field strength and E(f) is the Fourier transform of e(t). The energy density per unit bandwidth, W(f), is given by the equation

$$W(f) = \left(\frac{\varepsilon_o}{\mu_o}\right)^{1/2} |E(f)|^2 \qquad (16)$$

where the integration of eq. (15) is over a one-hertz bandwidth at frequency f. Power density is given by the equation

$$P(f) = \frac{W(f)}{\Delta T} = \left(\frac{\varepsilon_0}{\mu_0}\right)^{1/2} \frac{|E(f)|^2}{\Delta T} \qquad (17)$$

where ΔT is the time interval during which the energy is transferred or transformed.

Conceptually, broadband power flux density is the power per unit area in the spectrum of a signal at any specified frequency. It has the dimensional units of watts per square meter per hertz.

2.6 Generalized Approach

There has been an increased recognition of the need for a statistical approach to the solutions of many electromagnetic inteference problems. This trend reflects the realization that the noise source and the environment are often best described in statistical terms.

Basically, the electromagnetic interference problems may be considered to consist of three major parts: namely, the source, the environment, and the receiver. A recent approach is to characterize each of these three parts in terms of the so-called mutual coherence function. For example, the noise source may be described by the correlation function in time and space or in terms of the temporal and angular spectra.

Similarly, the electromagnetic environment from source to the observation point may be characterized by a general time-varying and dispersive transfer function. Then the correlation function for the received signal may be expressed in terms of these coherence function and the specific receiver characteristics.

Furthermore, the field strength appearing at a given point in space and time can also be expressed as a sum of the coherent (average) field strength and the incoherent (fluctuating) field strength. The average field may be obtained by measuring the average in-phase and quadrature components of the field. The variance of the fluctuation yields a measure of the incoherent field. Theoretical models for calculating these component fields are also possible.

Detailed studies of time, space, frequency and angular characteristics of the mutual coherence functions and of the component fields should give a good picture of the electromagnetic interference problem.

3. MEASUREMENT PRINCIPLES

3.1 Background

Historically, the two basic instruments for measuring electromagnetic interference have been the field intensity meter (FIM) and the spectrum analyzer (SA). They are augmented by a variety of antennas, probes, couplers, recorders, printers, and controllers to perform a wide range of measurements.

Both the FIM and SA are two-port devices that respond to an electromagnetic signal and deliver certain information about the signal in one form or another. The basic distinction between the two is that the FIM is considered to be an instrument that processes information in the time domain, whereas the SA is considered to process information in the frequency domain. Actually, both instruments function in the time domain only, but the SA is arranged to analyze the time domain information in terms of its spectral equivalent representation.

Functionally, both the FIM and SA are "radio receivers" in that they (1) "receive" an electromagnetic signal either from a circuit by direct connection or from a field by inductive/capacitive coupling, (2) process a replica of the signal through various filters, amplifiers, limiters, rectifiers, etc., and (3) deliver one (or more) output signal(s) to a transducer such as a voltmeter, loudspeaker, CRT, pen recorder, tape recorder, etc., which either displays it in real time, stores it for later use, or processes it further into still other forms. In fact, the early FIM's were closely similar to the communications receivers of their day.

Operationally, the essential difference between the FIM and the SA has been (1) in the method used to tune the instrument to the desired reception frequency, and (2) in the display format which the output transducer employs. Historically, FIM's were tuned manually by the operator, whereas SA's were electronically tuned; the output format for FIM's was a quantity that ran in real time, whereas for SA's the quantity was expressed as a function of reception frequency. Modern methods of tuning and control have largely removed the first distinction, and the second distinction has become irrelevant as FIM's are fitted with X-Y plotters whose X-axis is related to reception frequency, and SA's can be operated in an oscilloscopic mode.

The purpose of this background review is to point out that the FIM and the SA represent two essentially different approaches to signal measurement and analysis, but through the use of modern technology they have both evolved to the point where either instrument can be used to obtain both time domain and frequency domain information about the signal.

In addition to the FIM and SA, a third approach is widely used in which the signal is processed by a wideband or untuned instrument. This has the advantage of operating simplicity, but may sacrifice sensitivity and measurement accuracy.

3.2 Basic Techniques, Circuit Quantities

3.2.1 Amplitude

When an FIM or an SA is used to measure amplitude, it is operating as a narrowband tuned voltmeter. To measure voltage amplitude in a circuit, the instrument is connected through a suitable cable and voltage probe to the point at which the voltage is to be measured. The ordinary principles of voltage measurement apply. To measure current amplitude, the instrument still operates as a tuned voltmeter, and the current being measured is converted to a voltage either by the use of a transducer such as a current probe or by passing it through a calibrated resistor. Again, the ordinary principles of current measurement apply.

The five types of amplitude discussed in section 2.2.1 are measured as follows:

a. Instantaneous amplitude: This cannot be measured with an FIM or SA because these instruments do not respond rapidly enough to radiofrequency waveforms. Instead, an oscilloscope must be used.

b. Average amplitude: This is measured by designing the detector network in the FIM or SA in one of three ways. One is to use a linear rectifier circuit in which the component values are selected to produce a dc voltage that is proportional (or equal) to the average value of a sinusoidal voltage. A second way is to use a square-law rectifier circuit, again selecting component values to produce a dc voltage proportional to the average value of a sinusoidal voltage. The third method is to sample the voltage waveform and compute the average value by means of a programmed electronic computer built into the FIM or SA.

The first two methods give accurate results for sinusoidal voltages, but may not be accurate for non-sinusoidal waveforms. The third method gives the best accuracy for arbitrary waveforms as long as the sampling rate is fast enough to provide a faithful representation of the waveform to the electronic computer.

c. RMS amplitude: This is measured by designing the detector network in one of the three ways discussed in b above except that the component values and the computer program are selected to produce an output voltage that is proportional to the rms amplitude of the waveform. A linear rectifier will give accurate results only for sinusoidal voltages. The square-law rectifier and the sampling technique will give accurate results for arbitrary waveforms that fall within the amplitude and frequency ranges over which these characteristics hold.

d. Peak amplitude: This is measured by designing the detector network to have a short (e.g., a few microseconds) charge time constant and a very long (e.g., many seconds) discharge time constant. Alternatively, an oscilloscope with a very long persistence phosphor CRT may be used.

e. Quasi-peak amplitude: This is measured by designing the detector network to have a specified charge time constant and a specified discharge time constant. These time constants differ between American standards (ANSI) and European standards (CISPR), and also vary with frequency range. Refer to those standards for specific values.

Insofar as the FIM and SA are narrowband tuned voltmeters, their predetection voltage waveform, r(t), is the result of frequency filtering. Mathematically, this instantaneous waveform is the convolution of the input voltage waveform, $v_i(t)$, and the impulse response function, h(t), of the cascade of networks preceding the detector. See eq. (18).

$$r(t) = v_i(t) * h(t) \tag{18}$$

Thus, the detector output is proportional to the amplitude (average, rms, etc., whichever) of the filtered waveform, which is not necessarily the same as the input waveform to the FIM or SA. If the bandwidth of the input waveform is small (narrowband signal) compared with that of the predetection circuit bandwidth, the predetection waveform will be essentially the same as the input waveform and the detector output will represent the total input waveform. However, if the input waveform bandwidth is large (broadband signal) compared with the predetection bandwidth, the predetection waveform will differ from the input waveform and the detector output will represent only a part of the input waveform; specifically, that part that lies in the bandpass of the tuned circuits. Thus, the resulting measured value of amplitude depends upon the relative bandwidths of the input waveform and the predetection filters. For a sinusoidal input waveform, this bandwidth effect does not produce a measurement error; for non-sinusoidal wideband signals (noise, impulsive, modulated, etc.), an error may occur if the bandwidth factor is not taken into account.

In the spectrum analyzer, tuning over a range of frequencies is achieved rapidly and repeatedly (if desired), and the output display has the form of voltage (or current) amplitude as a function of frequency. The trace is, point-by-point, the amplitude of the predetection filtered waveform which, except for a sinusoidal waveform, has a certain bandwidth and therefore is subject to the variations cited in the previous paragraph. It is necessary to select the correct combination of SA bandwidth and tuning (sweep) rate in order to get an accurate measure of waveform amplitude.

A word of caution is needed concerning the SA output display. Although the output appears to be in terms of amplitude as a function of frequency, it is not a frequency-domain display in the sense of the spectrum amplitude discussed in section 2.3.3 The dimensional unit of the SA output is volts (or amperes), whereas the dimensional units of spectrum amplitude are volt-seconds or volts per hertz. The former quantity is analogous to the Fourier components of a periodic waveform; the latter quantity requires the infinite summation (i.e., integration; see eq. (6)) of the product of $v_i(t)$ and an eternal exponential function of time. If the measured waveform is periodic, the shape of the SA output display function and the shape of the spectrum amplitude function are closely similar. But they represent distinctly different quantities. To repeat, the SA output display is a time-domain measurement, but arranged to show this quantity (amplitude) as a function of the frequency to which the SA is tuned.

The technique for measuring spectrum amplitude, a frequency-domain measurement, involves the fast Fourier transform (FFT) and is discussed in section 3.2.4.

In order to prevent the distortion of input waveform by predetection filtering and its accompanying effects on the measured amplitude, a very broadband (untuned) voltmeter is used. Because of its smaller sensitivity, such a technique is used principally when the waveform amplitude is large (e.g., high-level and/or hazard-level signals).

3.2.2 Power

The power transferred by a waveform is not normally measured directly; that is, an electromagnetic wattmeter is not used. Instead, it is computed from data obtained from the measurement of waveform amplitude and circuit impedance. Amplitude is measured by the techniques discussed in section 3.2.1.; impedance is measured by conventional techniques. Power is computed by well-established formulas. In some instances, the scale on the output meter of an amplitude-measuring instrument is calibrated in units of power, in which case a specific circuit impedance is assumed (e.g., 50 ohms).

3.2.3 Frequency and Bandwidth

The frequency and bandwidth of a waveform are measured with either an FIM or an SA which are used as a calibrated frequency meter. The individual sinusoidal components of a complex periodic waveform are measured using narrow bandpass filter networks in the FIM or SA for best resolution. Nonperiodic random waveforms and very broadband waveforms (e.g., pulse trains, etc.) are best measured with an SA. Bandwidth is usually specified in terms of the half-power (-3 dB) frequencies of the waveform's spectrum.

3.2.4 Spectrum Amplitude

Spectrum amplitude is measured in either of two ways. The first is more suited to field conditions, whereas the second is normally limited to the laboratory because of the instruments required.

The first technique uses the FIM or SA as a transfer standard. A test signal whose spectrum amplitude is known is used to calibrate the FIM or SA. The test signal waveform is a pulse train in which the width of each pulse is very short, e.g., 10 ns or less. The repetition rate varies from 60 pps to over 1 Mpps, depending upon the design of the generator. For very short pulse widths (<0.5 ns), the spectrum amplitude is constant with frequency to within ±5 dB from dc to over 1 GHz.

In this technique, the assumption is made that the response of the FIM or SA to arbitrary broadband EMI waveforms is the same as their response to the test signal. That is, if the FIM or SA measures the same (time-domain) amplitude within a given bandwidth when two different broadband signals are applied, then the two signals must have the same (frequency-domain) spectrum amplitude. Strictly speaking, the spectrum amplitude of an arbitrary waveform depends upon its instantaneous amplitude. For example, the spectrum amplitude of a rectangular pulse differs from that of a cosine-squared pulse of the same amplitude and pulse width. Correspondingly, the FIM or SA response likewise depends upon the input waveform's instantaneous amplitude. In practice, many of the broadband EMI waveforms encountered are enough similar to the test signal that this technique is useful. However, it is not highly accurate, with typical measurement errors between 6 dB and 40 dB, depending upon circumstances.

Bear in mind that, although the FIM or SA is calibrated in terms of a frequency-domain quantity (spectrum amplitude, in units of dBμV/MHz), the connection between the two domains, metrologically speaking, is the assumption stated in the previous paragraph.

The second technique for measuring spectrum amplitude is as follows:

a. The signal waveform, v(t), is recorded by sampling techniques, and waveform data is stored in computer memory.

b. Spectrum amplitude is computed by an electronic computer using the fast Fourier transform algorithm based on eqs. (5) and (6).

This technique is capable of high accuracy (approximately 1 dB or less), but requires laboratory-quality instrumentation.

3.2.5 Power Density

Power density (frequency domain) is not measured directly, but is computed from spectrum amplitude and circuit impedance using eq. (9). In some instances, the scale of the output meter of a FIM is calibrated in units of power density (e.g., dBm/MHz), in which case a specific circuit impedance is assumed (e.g., 50 ohms).

3.3 Basic Techniques, Field Quantities

3.3.1 Field Strength

Field strength is measured by transforming the electromagnetic field energy into circuit energy by means of a suitable transducer, such as an antenna or probe, and measuring the circuit amplitude by the techniques discussed in section 3.2.1. The antenna or probe may be of various types: rod antenna, dipole antenna, horn antenna, loop antenna, directional antenna arrays of various designs, or combinations of these.

The measurement of E-field strength using a traveling-wave linear antenna is based on the following formula:

$$v_e(t) = k l_e E(t), \qquad (19)$$

where

$v_e(t)$ = instantaneous voltage at antenna output port

k = antenna factor (dimensionless ratio)

l_e = effective antenna length

$E(t)$ = E-field strength (volts per meter)

Factors k and l_e, or their product, are measured by a calibration procedure. For other types of antennas, the coefficient of E(t) in eq. (19) may take a different algebraic form, but the basic concept remains.

Similarly, H-field strength measurement is based upon the general equation

$$v_h(t) = A\, H(t) \tag{20}$$

where H(t) is the H-field strength and A is a constant found by calibration of the loop antenna or probe.

An FIM or SA is then used to measure the amplitude of $v_e(t)$ or $v_h(t)$.

3.3.2 Power Flux Density

Power flux density is determined by calculation using eqs. (11), (12), or (13). Although in principle the Poynting vector can be measured directly, such as with a combined E-field and H-field antenna structure or a Hall-effect device, this approach has not been developed into a practical technique.

In some instances, the scale of the output meter of an FIM is calibrated in units of power flux density (e.g., dBm/m^2). This is more commonly found on high-level, broadband meters such as EM hazard meters.

3.3.3 Energy Density

Energy density is determined by calculation using eq. (14). As with power flux density, practical instrumentation has not been developed to measure energy density directly. Likewise, the output meter scale of some FIM's has been calibrated to read in units of energy density (e.g., J/m^2).

3.3.4 Broadband Field Strength

Broadband field strength is measured by the same techniques discussed in sections 3.2.1 and 3.2.4.

3.3.5 Broadband Power Flux Density

Broadband power flux density is measured by the same techniques discussed in sections 3.2.2 and 3.2.4, using eq. (17) of section 2.5.4.

3.4 General Evaluation of Present Measurement Techniques

The measurement techniques discussed above have evolved during approximately 40 years of EMI measurement experience. As new instrumentation and measurement technology have been developed, they have been incorporated in EMI instrumentation. But there has always been a lag between available technology and its deployment.

Present-day commercial instrumentation represents, for the most part, technology that was state-of-the-art in the early 1970's. Generally, it has the following characteristics that become limitations in the context of this report:

a. The equipment is not capable of instantaneous wideband operation. It is based upon frequency-sweeping techniques that require a finite time to gather data over a large frequency range.

b. The equipment is not capable of storing large amounts of data within its own internal memory banks. Data is normally transferred to accessory storage units either promptly or with a small time delay.

c. The equipment is not capable of performing complicated data processing with its own internal computer system so as to directly provide output information in its desired final form. Data is normally processed outside the FIM or SA, for example, to obtain amplitude and time statistics of EMI waveforms.

d. The equipment is not capable of directly measuring certain EMI measurands such as involve the energy or power associated with EMI waveforms. They must be computed from amplitude data. Phase information is notably lacking.

e. The equipment is not capable of making accurate measurements of frequency-domain quantities. Because by necessity we exist and operate in real time, a transformation of some sort is required to describe the signal in the frequency domain. Present techniques for implementing this transformation produce only approximations to the whole truth.

f. The equipment is not capable of making entirely satisfactory measurements of electromagnetic fields without disturbing the very fields being probed. In many cases, this disturbance is unacceptably great; only in a few cases have special techniques (optical fibers, high-resistance lines) been employed to reduce this problem.

These shortcomings must be removed in order to improve upon the basic measurement techniques that are presently available.

4. MEASUREMENT REQUIREMENTS

4.1 Introduction

To determine what measurement instrumentation will be needed in the post 1985-1990 time period requires some knowledge or forecasting of the measurements that will be required to be made. This section contains a summary of new requirements as determined from a survey of literature and knowledgeable persons. In addition to new requirements, most if not all of the present requirements will most likely continue to exist in this time period.

Two basic sources supplied the information in this section: (1) technical literature, and (2) knowledgeable persons. The process called literature search was used to access printed material. Sources consulted include the following:

1. Computer accessed data bases:
   a. Science Abstracts from the Institution of Electrical Engineers (INSPEC)

b. Smithsonian Science Information Exchange (SSIE)

c. National Telecommunication Information Service (NTIS)

d. Defense Documentation Center (DDC)

e. Comprehensive Dissertations Index (CDI)

2. Professional journals:

a. Proceedings of the IEEE

b. IEEE Transactions on Aerospace and Electronic Systems

c. IEEE Transactions on Communications

d. IEEE Transactions on Computers

e. IEEE Transactions on Electron Devices

f. IEEE Transactions on Instrumentation and Measurement

g. IEEE Transactions on Microwave Theory and Techniques

3. Technical Journals:

a. Electrical Communications

b. Electro-Optical Systems Design

c. Electronic Design (ED)

d. Electronic Design News (EDN)

e. Electronics Letters

f. Electronics Magazine

g. Electronic Warfare/Defense Electronics

h. IEEE Spectrum

i. Microwave Journal

j. Microwave System News (MSN)

k. Microwaves

l. Science

m. Science News

n. Systems (Stelsels) (So. Africa)

4. Special/miscellaneous publications

   a. "A Forecast of Space Technology, 1980-2000", NASA

   b. Advanced Space Systems Concepts and their Orbital Support Needs (1980-2000), The Aerospace Corporation, April 1976

   c. Air Force Aero Propulsion Laboratory Technology Plan, FY 77-81

   d. Air Force Materials Laboratory Research and Technology Plan, FY 77

   e. Air Force Systems Command Research Planning Guide, May 1975

   f. Final Acts of the World Administrative Radio Conference, Geneva, 1979

   g. International Conference on Communications (ICC) Conference Records (recent years)

   h. International EMC Symposium Records (recent years)

   i. National Aerospace Electronics Conference (NAECON) Records (recent years)

   j. Newsweek Magazine

   k. Technology Tomorrow

Knowledgeable persons contacted during 1979-1980 included the following:

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4.2 General Summary of Findings

The picture that has emerged from the information gathering task is the following.

The future EMI problems are not going to be of a different basic type than those at present. The post 1985-1990 era will be characterized by technological evolution rather than revolution. No radically new breakthroughs will occur that will significantly alter what we know at the present time.

Future EMI problems will be different in magnitude and scope, however, because of:

a. The proliferation of electronic devices in every facet of our society.

b. Increased ease with which super-high power levels can be generated, particularly at microwave and millimeter wave frequencies.

c. Increased speed of digital electronics, going into the gigabit/second range.

d. Wider use of geostationary satellites for varieties of applications.

e. Employment of spread-spectrum methods of communication and target detection, using new formats such as Walsh or other nonorthogonal functions.

f. Decreased integrated circuit size, resulting in increased circuit density, reduced operating and breakdown voltages, and faster operating speeds (greater bandwidths).

Metrologically, these factors will require the following new capabilities in EMI instrumentation:

a. Smaller size, weight, and power demands so as to make it easier and less costly to respond to an increasing demand for measurements.

b. Dynamic measurement ranges from at least -130 dBm to over +30 dBm.

c. Frequency coverage to 140 GHz or higher.

d. Measurement bandwidths to 1 GHz or greater.

e. Instantaneous frequency measurement capability covering large sections of the spectrum.

4.3 Specific New Requirements

In this section we discuss the new systems and those trends in present systems that our literature searches and personal interviews indicated as likely causes of EMI through the years 1985-2000. Classified systems of the future have not been included in this document.

4.3.1 Packet Radio

First a few words of introduction about packet switching, a technique developed for rapid and efficient communication throughout a hard-wired computer network. Digital data is sent from one network point (a computer, terminal, data bank, etc.) to another in packets containing up to several thousand bits. As the packet traverses the network, microprocessors at successive intersections receive information on network traffic. Dispatching circuits at each intersection read the packet's destination code and send the packet, link by link throughout the network, over the shortest-time route.

Packet radio (PR) is a wireless form of a packet switching network. That is, packets of computer data are broadcast from point to point on their journey through the network. There are some experimental PR systems, though transceiver cost will not be low enough for a practical system until the mid-1980's. Then PR should become increasingly competitive with (and ultimately more economical than) hard-wired systems for distributing low to moderate volumes of local computer data traffic.

The primary use of PR will be for computer data transmission according to the needs of users wishing to access data bases, manipulate files, run programs, or write and execute programs on remote computers. While the high throughput and low delay of hard-wired computer networks are maintained, a significant new aspect of a PR network is its accessibility to users at mobile terminals. An individual PR may serve as a repeater, or the portal between the network and a user, or it may broadcast information from a control station. This station uses a packet's routing and control information to decide the shortest-time route to the packet's destination.

A practical packet radio should have a frequency within the range from 300 MHz - 30 GHz. Above this, absorptive and scattering losses attenuate the signals. Below 300 MHz, multipath reception produces time discrepancies of milliseconds which limit the signal data rate. An experimental PR network in the San Francisco area operates within a band from 1710-1850 MHz.

The bandwidths of a PR network will depend in part on whether or not the system uses spread-spectrum transmissions. Without spread-spectrum, the data rate of a system will determine the bandwidth. The data rate in turn is arrived at from the number of bits per packet and the number of packets that can be sent each second. A system sending 2000-bit packets with a transit delay of 0.1 second from source to destination will have a data rate of several hundred kilobits per second, and thus a least bandwidth of several hundred kilohertz. In practice, this system would have a bandwidth of a few megahertz. As in a hard-wired packet switching network, each packet tells each PR transceiver to set its bandwidth to accommodate the transmission of that packet over the next link of the network. Successive packets may require different bandwidths.

The various types of spread-spectrum systems may have bandwidths ranging from tens to hundreds of megahertz. In the previous system operating from 1710-1850 MHz, the center frequency of successive packets takes predetermined hops within the 140 MHz range. By this technique, called "frequency hopping", the bandwidth of the system becomes, in effect, the entire 140 Mhz.

4.3.2 Spread-Spectrum Systems

A spread-spectrum system is a means for distributing the power spectrum of a signal over a much broader frequency range than that of the original signal. The extremely large bandwidths of some spread-spectrum techniques provide communications and data transmissions with multiple access, greater security, and high resistance to jamming.

A hybrid spread-spectrum and time-division-multiple-access (TDMA) system is employed by the military services in their Joint Tactical Information Distribution System (JTIDS), intended to become the major tactical communications network sometime during the 1980's. The system will have thousands of users and comprise transceivers on aircraft, ships, vehicles, manpacks, and perhaps smaller missiles. No communications center will be needed because all users will talk to all others on a common channel.

Some other military uses for spread-spectrum techniques are in satellite communications (tens of gigahertz), air-to-ground data links (12-18 GHz band), packet radio (mobile communications in mid- to upper-UHF), and a Position Location Reporting System (low UHF). The high anti-jamming and interference rejection capability of spread-spectrum systems also make them attractive for commercial and space versions of these military applications.

Spread-spectrum radars will appear during the next 10 years. They will operate at lower power than present radars because they will share spectrum space with telecommunications systems.

The bandwidth of a spread-spectrum system may be so large (e.g., 50 kHz expanded to 40 MHz) that the signal power density is below atmospheric noise and can be extracted only with sophisticated detectors and a knowledge of the modulation code. Such low signal flux allows many users to share a single band, a situation that may require specialized and highly sensitive receivers for those who monitor EMI conditions.

Spread-spectrum and TDMA systems will be employed in all bands from HF to SHF. The greater directivity of antennas at these frequencies may lead to high power densities even though the transmitted power spectrum will have lower density than in conventional transmissions. Spread-spectrum systems being studied are so many and varied that we cannot yet predict the type of EMI problems (if any) they may create. The National Telecommunications and Information Administration (NTIA) has made no estimate of the probable impact of spread-spectrum techniques because no such systems have been submitted for NTIA evaluation.

Spread-spectrum systems require standardization. The Electromagnetic Compatibility Analysis Center (ECAC) is working on the question of which quantities to standardize and the measurement methods to characterize them. A group at Ft. Monmouth is studying the properties of spread-spectrum signal propagation, and has funded the Institute for Telecommunications Sciences of NTIA to develop techniques for measuring these properties.

Most EMI receivers, while broadbanded, must be tuned. Monitoring the multiple frequencies and broad spectral range of a spread-spectrum system with such a receiver would be tedious and inefficient. A preferred approach may be with a receiver of wide instantaneous bandwidth which would receive all frequencies present over a short time interval.

Some spread-spectrum transmitters drive the antenna with Walsh-function current waveforms rather than a modulated sinewave carrier. Because Walsh waveforms can be likened to irregular square waves (switching from (+) to (-) polarity), the transmitted electromagnetic field is pulses (almost spikes) in the same sequence as the switching times of the Walsh waveform. If two different sets of such signals (pulses) are being received, the receiver must be gated to accept the desired pulse series and reject the other. This is a different technique than tuning the receiver to be resonant to a sinusoidal EM carrier wave. Thus, receivers to sense Walsh waveform transmissions will have different features than conventional receivers.

An example of a spread-spectrum system would be one used to eliminate a central high-power transmitter by replacing it with several low-power units located throughout the original central transmitter's broadcast range. A mobile unit would then communicate with the central station through the nearest low-power transceiver. Because each local transceiver has its own frequency, the total system requires as many different frequencies as there are local send-and-receive stations. Thus, in replacing a single-frequency high-power source with several low-power sources, each at a different frequency, a spread-spectrum system such as this may both relieve and aggravate different aspects of an EMI environment.

4.3.3 Solar Power Satellite

The solar power satellite (SPS) system would comprise 60 geostationary satellites, each about the size of Manhattan Island and each delivering a 5 GW, 2.45 GHz beam to its own receiving antenna within the United States. The frequency is conventional, but the manner of power delivery may create biological hazards and broadcast interference.

Sites for receiving antennas will be about 8 km in diameter. However, the beam pattern and atmospheric scattering will distribute the beam power over an area several times larger. The second harmonic (4.9 GHz) of the beam will contain about 16 MW, and the fourth (9.8 GHz) about 500 W. Even the fifth harmonic (12.25 GHz) may have upwards of 50 W. This range from 2.5-12 GHz has so many occupants that future satellite systems are being designed for the 30 GHz region. Thus, the stray harmonic power from SPS beams may give rise to significant EMI problems.

As of the completion of this report (September 1981) the future of the SPS system is greatly in doubt. It has been reported, although no printed confirmation is in hand, that the National Academy of Sciences has completed a report indicating the SPS is not a viable alternative and should not be pursued further. In any event, if the SPS were approved, its completion would require about 30 years from the date on which its deployment was begun. Solar power from satellites is thus a concept of enormous magnitude and complexity, but whose present uncertainty makes its attendant problems of little immediate (the next 10-20 years) concern.

4.3.4 Higher Power

While solar power satellites and their high power microwave beams may not get beyond their present conceptual stage, the gyrotron is a high power continuous wave (cw) microwave oscillator being actively developed at several laboratories here and abroad. The U.S. Naval Research Laboratory has tested a gyrotron traveling wave tube which produces 10 kW at 35 GHz. Refinements may boost the power to 200 kW and give a 7% bandwidth. NRL is also building a 240 GHz gyrotron. Varian Associates report obtaining 13 kW peak pulsed power from a 5 GHz TWT gyrotron, and expect to scale their device to 94 GHz. Some Russian organizations are also developing gyrotrons, and have made sales offers to several U.S. companies.

Gyrotrons may find use in radar and communications, and as power sources for fusion reactors. They may also be employed in electronic countermeasures systems, and in target illuminators for passive imaging systems. High power beams would be useful in millimeter wave communications (30-300 GHz) where rain and atmospheric pollutants can severely attenuate transmitted beams. As with the solar power satellite, power transmission by microwave beam is more concept than accomplishment. Beamed power technology would require that special antennas be designed for tight beams and minimal sidebands.

4.3.5 Communications Satellites

By the year 2000, as much as one-quarter of all long-distance voice communications and one-half of all data and video traffic may be carried by satellite, according to two studies done for the National Aeronautics and Space Administration (NASA). This growth will saturate the present satellite bands at 4-6 GHz and 11-14 GHz by the early 1990s, and is leading NASA to develop satellite communications systems at 20-30 GHz.

Domestic satellites will increase their message-carrying capacity by using high-speed satellite-switched time division multiple access systems. Message capacity may also be increased by multiple-spot beams in which the satellite beam is a bundle of separate beams at several frequencies, each frequency being shared by several of the component beams. Those beams at a given frequency each carry different information. Multiple spot beams are expected to reduce interference between the satellite and other sources through the use of narrower beams and improved sidelobe control.

A proposal to relieve anticipated orbital congestion involves a satellite called an Orbiting Antenna Farm. This large, multi-purpose satellite would operate over a broad frequency range and assume the duties of several smaller satellites.

A number of other uses are being proposed for satellite communications.

- The Navy will use radar satellites for monitoring ocean surface conditions.

- Other Navy satellite systems may operate at 20, 40, and 45 GHz.

- Digital satellite systems may be used for local distribution of business data.

- NASA is considering a satellite system with as many as 25 units, each with a beam whose shape is controlled from a ground station.

- Another military satellite will be for video link processing in which a TV picture is sent from an Airborne Warning and Control System satellite to a ground station for processing.

4.3.6 Higher Frequencies

Because the present bands for microwave uses are filling, the next ten years will see the adoption of new frequencies up to about 100 GHz with clustering around 30, 60, 90 GHz. Today's test and measurement equipment does not exceed 40 GHz.

The Navy is designing passive devices to detect radar signals in the 40-60 GHz range, and is considering satellite-based radar at 95 GHz to monitor ocean surface conditions as an indicator of local weather.

Having been squeezed from the 4-6 GHz band into 12-18 GHz, the users of satellite systems see continued crowding forcing them into the 30 GHz region and above. Military satellites are presently in the 7-8 GHz range though designers expect to enter the 20-40 GHz range over the next ten years. Operation of new military satellites above 40 GHz will come nearer 2000 AD.

In the near future, some earth communications systems (that is, not via satellite) will operate at 20 GHz or higher between ground-based antennas and receivers.

The Army is considering communications systems at frequencies up to 300 GHz though the latter frequency probably won't be seen until after the turn of the century. More immediate plans are for systems at 60 and 90 GHz.

The gyrotron, a high-power traveling-wave tube oscillator/amplifier, attracted some interest in the late 1950s but was then shelved. Now some manufacturers and laboratories are looking closely at the gyrotron's potential for high power at high frequencies. The Naval Research Laboratory (NRL) has tested a gyrotron at 35 GHz and 10 kW, and anticipates going to 200 kW. NRL has built a 35 GHz gyrotron that gave 100 kW cw, and is building another to operate at 240 GHz. A 30-month contract to Hughes Aircraft Co. should produce a 10 kW gyrotron at 94 GHz.

Presently the primary application of gyrotrons is expected to be microwave heating of plasmas in fusion reactors (18-120 GHz). There is also speculation that mm waves (30-300 GHz) will propagate through the plasma of a nuclear explosion and thus allow contingency comunications through the blast's fireball and turbulence.

A more mundane application may be that of the USAF which is considering gyrotrons for use in radar and communications.

Soviet engineers have designed gyrotrons for which Russia is willing to sell the rights. A pulsed model yields 1 MW at 100 GHz with 100 ps pulse width. Another gives 1 kW at 330 GHz cw.

So we see the immediate intent to convert many commercial and military systems to frequencies approaching 40 GHz, with serious thought being given to employing the 50-100 GHz range within the next decade. Millimeter waves up to 300 GHz are foreseen in more speculative applications. Furthermore, these systems will be capable of higher-power operation than has heretofore been possible.

4.3.7 Proliferation

In this section, we have discussed some of the devices, systems, and trends that the technical community sees as new or continuing sources of EMI over the next two decades. However, another and more pervasive aspect of EMI is the phenomenon of proliferation. Advances in solid state technology are bringing an enormous and growing array of electronic devices into our domestic lives as well as into technology and commerce. Seminal among these advances are very large scale and high speed integrated circuits which, while providing more powerful and compact means of measurement and control, are also heavy contributors to the proliferation of the electronic circuit in our society.

Antennas are radiators and their radiation properties are well known. Other devices also radiate but their fields are not evaluated and may not even be anticipated. Such devices as personal computers, automotive electronics, banking systems, cable and closed-circuit TV, and two-way communications often have poorly known and controlled EM emissions as well as high susceptibility to such emissions. A present concern is that stray fields from these devices and systems can and do degrade the performance of nearby instruments. A greater concern is that EMI will be increasingly deleterious as proliferation continues.

EMI can be controlled by minimizing the EM radiation emitted by a device and reducing its radiation susceptibility. Neither approach is practical to carry to the point of certainty. Therefore, an essential part of any EMI program is a monitoring system which measures the emissions from a given device and evaluates the EM environment in which the device is to operate. Clearly, the capabilities of such a measurement system must keep pace with electronic proliferation.

4.3.8 Renewed Emphasis on HF Communication

The realization that communication satellites are vulnerable to enemy attack has led to a reassessment of the role of high frequencies (3 - 30 MHz in military communications. Improved equipment in terms of size, portability, power output, and reliability, plus the relative attack proof nature of the ionosphere have led to a renewed interest in maintaining a strong military communications capability in the 3-30 MHz range. Also, new techniques, using "chirp sounders" which can evaluate the optimum frequency for any communications path from one end of the circuit, combined with burst communication systems (AN/TSC-99), have greatly increased the reliability of HF circuits. The very presence of higher power transmitters co-located with other vulnerable systems should ultimately mean increased EMEO tasking in this frequency range.

4.3.9 Summary of Consequences of Anticipated EMI Sources

The preceding discussion of technologies likely to aggravate EMI problems over the next two decades reveals nothing dramatically new compared with the technologies of today. Instead, upcoming EMI aggravations are primarily today's but evolved to higher powers and frequencies. Satellite communications and radar are likely to be operating at several tens of gigahertz, and the developers of the gyrotron talk about tens of kilowatts of cw power at up to 240 GHz.

Gyrotron cw power from 10-200 kW would be from 26-29 dB higher than an aircraft radar (typically about 40 kW peak pulse power) with an average cw power of 25 W. Air surveillance radar (425-550 kW peak pulse power) has an average cw power of about 400 W, and is the highest power unit at most FAA airport installations. The 10-200 kW gyrotrons would be 14-27 dB higher than the ASR average power. If such high rf-power sources as gyrotrons should find use in aircraft and airport radar systems, the 20-30 dB increase in their radiated power flux density could be of concern to the EMI engineer.

The field strengths and power flux densities near a transmitting antenna driven by a gyrotron would be an extreme, though not new, biological hazard. Today's large radar and microwave transmitters produce power flux densities that are equally hazardous (biological effects ranging from "rare" to "well done" have similar consequences in an EMI context). Rather than these high field intensities, the major EMI concern related to higher power sources is the greater distance at which the source can commit electromagnetic mischief. Even so, this greater pervasiveness just boosts the EMI power level at locations remote from an antenna. A more provocative change in the EMI environment is the appearance of frequencies higher than those which our present monitoring systems deal with. That is, the advent of higher frequencies rather than higher powers is more likely to require the redesign of EMI monitoring instruments.

Because packet radio and spread-spectrum systems scatter broadband electromagnetic energy into the environment, they are further reason for designing an EMI system with a wideband receiver.

5. NEW INSTRUMENTATION OPPORTUNITIES

5.1 Introduction

Advancing technology has provided new and improved devices and techniques that can be exploited by the EMI metrologist. These include the following:

a. Instantaneous frequency measurement (IFM) techniques.

b. General improvements in solid-state devices through the development of amorphous semiconductor technology.

c. Faster (gigabits/second) digital circuits to permit faster realtime data processing, thus permitting more types of information to be extracted simultaneously from a given set of input data.

d. Improvements in optical fibers and in opto-electronic devices.

e. Increased memory storage size and access speed resulting from the further development of magnetic bubble technology.

f. Vastly greater application of time-domain metrology (as contrasted with the present domination of frequency-domain metrology).

This section contains a brief discussion of these developments.

5.2 Instantaneous Frequency Measurement Receivers

The IFM receiver uses a comparatively recent circuit development to access large portions of the spectrum instantaneously. Most often an IFM will give a digital display of the frequency being received. Present IFM's usually have octave bandwidths or cover bands typically used in military applications: 2-4 GHz, 4-8 GHz, 8-12 GHz, 12-18 GHz. Several IFM's in parallel can cover a 0.5-18 GHz range with 100 percent intercept probability for any signal exceeding the detection threshold. However, relative to a superheterodyne receiver the IFM has lower sensitivity due to the noise admitted by its wide bandwidth.

One manufacturer has combined digital IFM (DIFM) and superhet designs in one system which appears to successfully combine the strong points of both receiver technologies. The system monitors a 0.5-18 GHz spectrum with high sensitivity, fast signal acquisition, high probability of intercept, and accurate measurement of signal parameters.

Another manufacturer has reduced the volume of its digital IFM receivers from about 16400 cm^3 to 1058 cm^3 (1000 in^3 to 64 in^3). These receivers cover the same bands as those mentioned above, and also the L (1-2 GHz) band.

This presently developing IFM and integrated IFM-superhet receiver technology looks promising for EMI applications. To those interested, a spokesperson for one manufacturer advises that "systems engineers should make an effort to determine what DIFM receivers manufacturers have built, are now building or plan to develop an IR&D programs."

In addition to these IFM circuit developments, new broadband antennas and probes are becoming available. By resistive loading techniques, bandwidths greater than 1 GHz with a linear phase response are possible. This permits the accurate reception of broadband signals without serious waveform distortion.

5.3 VLSI and VHSIC

Two of the newest developments in solid state and integrated circuit electronics are pertinent to our inquiry into a smaller and more powerful EMI measurement system: very large scale integration (VLSI) and very high speed integrated circuits (VHSIC). The first help decrease circuit and component sizes, as it has already done for the shrinking IFM two paragraphs before; and the second increases the speed of such circuit functions as computation and signal processing. Between the two of them, VLSI and VHSIC are providing smaller but more powerful devices for measurement and control. Thus, they are giving electronic technology and its systems designers greater capability for producing a compact, portable EMI metrology system which can do more things faster.

By the greater use of CMOS technology, significant savings in power requirements can be made. Reductions as great as 90 percent as compared with TTL technology are possible. This can lighten the weight and reduce the size of EMI instrumentation.

5.4 Fiber Optics

Fiber optics is another technology of high promise and rapid growth. Optical communications (the primary fiber-optic application) has greater bandwidth (and greater information-carrying capacity) because optical frequencies are much higher than those of carrier waves in conventional communications by broadcast or wire. The optical fibers themselves are dielectric "light pipes" and so are believed to be neither sources of nor susceptible to electromagnetic interference. With respect to EMI, fiber optics is thus a very clean communications technology which will reduce EMI problems as it replaces signal transmissions over wires.

Optical fibers are useful as leads which perturb an electromagnetic environment as little as possible. They, therefore, could be of value as the link between a probe and the rest of an EMI monitoring system.

5.5 Magnetic Bubble Memories

Since the 1967 discovery of magnetic bubble phenomena, bubble devices have been steadily developed but only recently have received serious notice in the marketplace. Now, magnetic bubble memories are filling the gap between the short access time and high storage cost random access memories, and the high access time and low storage cost moving surface memory devices (drum, tape, disc). The appeal of bubble memories has increased with the appearance of several commercial sources for bubble-memory test equipment.

A notable feature of bubble memories is their nonvolatility (ability to retain stored information with power off). Thus, bubble devices are suited to portable systems because additional battery packs are not needed for stand-by power. In some military systems, bubble devices have contributed to extremely small size and low weight, high untended reliability, and very low power.

Though VLSI is keeping semiconductor devices at the top of the market, bubble chips are also compatible with and will benefit from VLSI. The future of bubble technology is very promising, for these chips have not only memory but also switching and logic capabilities. They are modular and offer large data bandwidths through chips in parallel. The primary initial application for bubble memory will be in fast auxiliary memories and in fixed-media mass storage in microcomputers.

5.6 Time Domain Metrology

The availability of higher-speed integrated circuits and switching devices and the development of large computers and efficient software have made time-domain measurements competitive with classic frequency-domain measurements. With Josephson junction devices, it is now possible to sample at picosecond rates with the promise of femtosecond rates in the forseeable future. Fast computers with large computational capability make it feasible to transform time-domain data to frequency-domain information (e.g., by FFT algorithms) when this is desired. However, engineers are now learning to "think" in terms of time-domain processes, even for the faster signals having frequencies in the gigahertz range.

6. CONCLUSIONS

6.1 Purpose

The purpose of this section is to apply the information presented in sections 1 - 5 to the mission of EMEO. The specific mission tasks of EMEO will be compared to the new requirements and possible advances in technology to see where impacts may occur. Lastly, some of the driving forces of the marketplace will be examined as they affect the availability of measurement equipment suited to the mission of EMEO.

6.2 Specific EMEO Tasking

In par. 1.2 the broad areas of EMI measurements in which EMEO engages were enumerated. However, these can be more narrowly defined in an operational way by examining the specific task areas of EMEO involving EMI measurements.

a. SHF DSCS. This involves performing general spectrum occupation surveys of a contemplated satellite ground station site for the Defense Satellite Communications System. Occasionally measurements to estimate ERP from a satellite are made.

b. UHF SAT. This is similar to (a) above but involves different measurements and equipment.

c. EMRH. These measurements usually of high level fields, are made to estimate the EMR environment to which sensitive military equipment will be exposed.

d. ATC. Generalized interference (EMI) problems with military air traffic control communications.

e. LOS. Measurement of path loss and fading on direct path UHF and microwave links.

f. EMC. Generalized EMC/EMI measurement problems not specifically in one of the other categories.

g. N.T. New tasking which will arise as more complex electronic equipment involving new technology is deployed by the Army.

6.3 Impact of New Requirements

In section 4 the technological areas of possible new requirements were discussed. These are numbered, in the list which follows, for use in table A. This table, by means of coded symbols explained below, indicates the task area of impact.

1. Packet Radio
2. Spread Spectrum
3. Solar Power Satellites
4. Higher Power
5. New Communications Satellites
6. Higher Frequencies
7. Proliferation of Sources
8. Renewed Interest in HF

	Technological Area								
Impact Area	1	2	3	4	5	6	7	8	Σ Score
SHF DSCS	+	+	++	+	+	++	+	-	8+
UHF SAT	0	+	+	+	-	-	+	-	1+
EMRH	0	0	++	++	-	0	+	++	6+
ATC	0	+	0	+	0	0	+	0	3+
LOS	++	+	0	0	-	+	+	-	3+
EMC	+	+	++	++	0	+	++	++	11+
NT	++	++	0	+	+	+	+	+	9+
Σ Score	6+	7+	7+	8+	1-	4+	8+	2+	

Legend
- ++ high impact
- \+ moderate impact
- 0 little change
- \- reduced impact because new technology is superseding

Table A. Impact of New Requirements/Technology on EMEO Tasking.

6.4 Impact of New Technological Advances on EMEO Measurement Techniques and Equipment

In section 5, new areas of instrumentation opportunities were discussed. They are enumerated below with one or two additional allied categories added from other sections of the report. The impact of these advances in EMI measurement technology are then compared with the different EMEO task areas in table B using the same symbology as in table A.

I. Instantaneous Frequency Measurement Receiver
II. VLSI and VHSIC
III. Fiber Optics
IV. Magnetic Bubble Memories
V. Time Domain Metrology
VI. Generalized Techniques for Describing the EMI Environment
VII. New Antenna Designs

	Instrumentation Technological Area							
Impact Area	I	II	III	IV	V	VI	VII	Σ Score
SHF DSCS	++	0	0	0	+	+	0	4+
UHF SAT	+	0	0	0	+	+	0	3+
EMRH	0	0	-	+	++	++	++	6+
ATC	+	+	0	0	+	+	+	5+
LOS	0	+	0	++	0	0	0	3+
EMC	+	++	-	++	++	++	+	9+
NT	+	+	+	+	++	+	+	8+
Σ Score	6+	5+	1-	6+	9+	8+	5+	

Legend
++ high impact
\+ moderate impact
0 little change
\- reduced impact because new technology is superseding.

Table B. Impact of New Technological Advances on EMEO Measurement Techniques and Equipment.

6.5 Observations

Looking at table A, it can be seen that the major EMEO areas impacted are SHF DSCS, EMRH, general EMC measurements, and unknown new tasks. By looking at the sums across the bottom it can be seen which technological areas will cause the most effect, namely, higher power and proliferation of sources, although a few other areas are close behind.

Turning to table B, we see that the areas of measurement capability impacted by new technology (a positive score means an increased capability) are EMRH, generalized EMC measurements, and unknown new tasking. Likewise referring to the bottom sums, the advances in time domain metrology and generalized techniques for describing the EMI environment should impact the measurement process the most, although again, several other areas will also have a major effect.

Note that the high scores in generalized EMI measurements would seem to indicate that EMEO will have a need in this area and that there should be adequate measurement technological advances available to meet this need. However, before this assumption can be made the forces which control the availability of equipment for this marketplace must be examined.

6.6 Driving Forces in the Marketplace

Since EMEO is largely constrained to obtaining equipment that is commercially available, off the shelf, (or modifications thereof), it is necessary to see what are the driving forces that control the development, and hence the availability, of such equipment. This is assuming that no substantial funds are available from Military Research and Development Commands to support specific developments.

The three main forces or needs in the marketplace that have influenced the development of EMI/field strength measuring equipment over the past twenty years are:

1. Compliance testing to MIL STD 461 mandated by government contract requirements.
2. Specialized needs of the security agencies of the government such as ASA, CIA, etc.
3. Commercial measurement needs to satisfy FCC type acceptance testing and field strength survey requirements for broadcast stations.

Obviously, there is some overlap in the requirements of these various areas of the user community, but definite segments of the electronics market can be identified with these areas.

To these three areas can be added a fourth category called "modern spectrum analyzers." Early equipment of this type was often considered inadequate for general EMI field measurements because of lack of sensitivity and susceptibility to overloading with strong signals. However, recent improvements in these parameters, the addition of phase lock loops to give accurate frequency information, and the incorporation of a microprocessor to control and handle data, have made these instruments more useful. Unfortunately, they are generally not designed for rugged field use, and do not have shielding adequate to operate in strong ambient fields.

Table C examines these categories of equipment from the standpoint of market share, size and weight, ruggedness, shielding, general quality, flexibility and usefulness to EMEO measurement needs, willingness of the manufacturers to produce small quantities of specialized measurement equipment modified to a user's need, and accuracy of frequency and amplitude measurement. The share of the marketplace estimates were arrived at by talking with the marketing representatives of several manufacturers. Although they show general trends no particular accuracy is claimed for the numbers given. The estimates of the other performance parameters are those of the authors, although they have been discussed with other engineers involved in EMI measurements.

TYPE OF EQUIPMENT	1	2	3	4	5	6	7	8
FIMs - designed for MIL STD 461 testing	55%	P	E	E	F G**	P	P	E
Specialized EMR security equipment	25%	G	G	G	F	F +	E	P
FCC compliance and misc. commercial field measurement equipment	15%	F	F	F	P	P	P	G
Modern spectrum analyzers	5% *	P	?	P	G**	P	G	E

Notes: *, % of EMI market only
**, particulary when used with external computers.
+, at a high cost, usually

Code:
1. % of marketplace (estimate) in dollars
2. Small size and weight
3. Ruggedness
4. Shielding
5. Flexibility
6. Willingness of manufacturer to modify.
7. Accuracy of frequency measurement.
8. Accuracy of amplitude measurement.

E = excellent
G = good
F = fair
P = poor

Table C. EMI Equipment Analysis.

As can be seen in table C, no one category of equipment scores high in all desired qualities, and few, if any, manufacturers are willing to produce small quantities of custom equipment at a reasonable price. Although technological forecasting is difficult, it is likely that the primary driving force in the marketplace, i.e., MIL STD 461 testing requirements, will remain dominant for the next several years. Thus it would appear that equipment expressly tailored to the needs of EMEO is not likely to be forthcoming without being specifically developed with R&D funds.

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10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, 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)*

The environment in which electronic apparatus of all types must function is becoming increasingly hostile because of a burgeoning electronic technology. This increases the potential for electromagnetic interference (EMI), and places new demands upon those organizations who are responsible for measuring EMI. This report (a) reviews the electrical quantities that are used to describe and evaluate EMI, (b) discusses current EMI measurement principles, (c) attempts to identify future EMI measurement requirements for the post 1985-1990 time period, (d) identifies certain expected new instrumentation opportunities, and (e) suggests action to meet the future needs for measurement instrumentation.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

Electromagnetic interference; electromagnetic environment; EMI instrumentation; EMI measurements; future EMI requirements; planning guidance.

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