NBSIR 75-936

THE NATIONAL ELECTROMAGNETIC MEASUREMENT SYSTEM

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National Bureau of Standards
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U.S. DEPARTMENT OF COMMERCE, Juanita M. Kreps, Secretary
Sidney Harman, Under Secretary
Jordan J. Baruch, Assistant Secretary for Science and Technology

NATIONAL BUREAU OF STANDARDS, Ernest Ambler, Acting Director

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THE NATIONAL ELECTROMAGNETIC MEASUREMENT SYSTEM

Robert A. Kamper
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EXECUTIVE SUMMARY

Electromagnetic technology is the practical exploitation of electromagnetic waves, propagating either in transmission lines or freely through the atmosphere, and occupying a very wide spectrum of frequencies. It has grown up within the limitations set by nature.

In the range of frequencies below a few hundred MHz components are cheap, most antennas are not very directional, and the background is noisy. This part of the spectrum is very heavily used by telecommunication systems, both for business and for pleasure. High performance brings no significant advantages to these systems, so accurate measurements of the characteristics of components are rarely called for. The FCC keeps order among the various users of the spectrum by assigning frequencies, which are checked routinely, and power levels, which are rarely enforced. Many electronic systems, such as computers and servo control systems, are unintentional transmitters and receivers of electromagnetic radiation in this part of the spectrum. Interference is therefore a severe problem, that calls for repeatable measurements of complex, fluctuating quantities, to be used a the basis for the assignment of responsibility for its resolution.

An extreme case of electromagnetic interference occurs when fields are strong enough to injure people. This is a real danger with radio and TV transmitters and leaking microwave ovens. Exposure to hazardous fields is regulated by OSHA, supported by measurements of the field levels in question.

Another aspect of electromagnetic waves in this part of the spectrum that is not yet fully exploited is their ability to penetrate to useful distances in rock, soil, concrete, water, etc., to probe structures of these materials to supply information for civil engineering, mining, or agriculture. This will require extensions in the formulation of electromagnetic theory and the acquisition of a base of data on the properties of materials, which are the subjects of research that is in progress now.

At frequencies in the range from about 300 MHz to 30 GHz we find a higher preponderance of more sophisticated systems. Here wavelengths are short enough that highly directional antennas are quite common. The background noise is low enough to enable systems to operate with very weak signals. This range of frequency is used by most of the radar systems on which modern navigation depends, both for ships and for airplanes. Improved systems such as discrete address microwave beacons are under development for air navigation. Microwave systems are under development for landing in conditions of poor visibility. The armed services use radar for the automatic guidance of terrain-following aircraft and of weapons, as well as for searching for the enemy. On the highways, the police use radar for speed control.

In addition to radar, this region of the spectrum is used for telecommunications. Most long-distance telephone traffic is carried by microwave beams between repeater stations in direct line of sight with each other. Satellite communications are a rapidly growing business. The driving force in the expansion of the telecommunications industry is the trend towards having distant computers communicate directly with one another. In addition to demanding large channel capacity, computers and the associated digital technology encourage a trend towards digital communication, and separating different messages in time rather than frequency. This also has advantages for transmitting the voice, in the efficiency of use of channel capacity and the quality of the transmission. This is generating a new demand for time-domain measurements. The electromagnetic systems that use this part of the spectrum tend to be expensive, but do repay their expense with very high performance if they are carefully designed and maintained. For this they require the support of accurate measurements.

The region of the spectrum from 30 GHz to 300 GHz is presently regarded mainly as an overflow for users of the crowded channels at lower frequency. Components become much more expensive and less efficient in this region, and the atmosphere has strong absorption bands. The most significant commercial system, under development in several countries, is for telecommunication at 90 GHz through oversize circular waveguides.

There is not much commercial activity at frequencies between 300 GHz and 100 THz. There is much scientific activity in the development of lasers, and the world's most accurate spectroscopy is done in this region. Surely commercial or military exploitation will follow, especially of the CO_2 laser, which can already be made to be cheap, efficient, and powerful. There is some activity with military funding to develop it into a weapon, and the most significant measurements to be made are of its beam profile and energy output.

The near infrared and visible parts of the spectrum are used for all the activities that the possession of eyesight has suggested to us, in addition to some that had to await the development of instruments. These include the remote sensing of temperature by radiometry, and all the possible applications of visible lasers, such as alignment and measurement of linear displacement, micromachining and surgery, holography, information processing (especially Fourier transformation), video disc recording, and automatic checking of groceries at the supermarket. Obviously, a very diverse collection of measurements must be made to support these activities, not the least important of which is the measurement of power and energy to regulate safety.

One newly developing optical technology that has much in common with the corresponding microwave techniques is telecommunication through optical fibers and the integrated electro-optical systems that will be used for transmitters and receivers. These will call for all the types of measurement that have been made on microwave systems, translated to a different region of the spectrum with different difficulties and conveniences.

In general, electromagnetic measurements do not attempt to attain the degree of accuracy that is possible for dc electrical measurements. Practical systems must be designed to tolerate variations of a few percent in circuit parameters due to instability of components and variations in operating conditions. Therefore measurements with uncertainty less than 0.1% are rarely called for.

Another striking feature of the electromagnetic scene is the high demand for measurements of dimensionless quantitites, such as attenuation, phase angle, reflection coefficient, and antenna gain. There are national standards and calibration services for many of these, but the trend is to replace them with self-calibration techniques.

Reference to the SI base units is tempered by the modest requirement for accuracy. The ohm can readily be independently realized in the form of a length of transmission line whose characteristic impedance can be calculated from its geometry. The amplitude of waves is determined by measuring power, voltage, current, electric, or magnetic field. The essential step in all these measurements is the conversion of the quantity to be measured to an equivalent dc quantity. Reference of the latter to the basic SI units is a trivial step at the level of accuracy required.

The foreseeable future challenges to the National Electromagnetic Measurement System will come from: heavier use of the "underdeveloped" parts of the spectrum, such as millimeter waves, and the infrared and visible, for communication; wider use of multimode transmission lines; the quest for optimum use of time division multiplexing and the consequent need for the precise characterization of the time-domain response of devices, systems, and materials; and the new forms of interference that all this activity will generate.

1. INTRODUCTION

Electromagnetic technology is the practical exploitation of electromagnetic waves, propagating either in transmission lines or freely through the atmosphere. These waves are useful over a very wide spectrum of frequencies, and this section will start with some general remarks about the characteristics of various regions of that spectrum. It will then continue with a survey of the most significant commercial, military, and scientific activities that use the various parts of the spectrum, speaking particularly to the nature and quality of physical measurements and standards that they require for support.

For practical purposes, two of the most important characteristics of the electromagnetic spectrum are the transparency of the atmosphere and the amount of background noise and their variation with frequency. These are illustrated in figure 1.

The atmosphere is essentially transparent at frequencies below about 1 GHz. In clear weather this transparency extends somewhat above 10 GHz, but the liquid water in falling rain begins to show significant absorption between 1 and 10 GHz. Between 10 GHz and 1 THz there are some very strong molecular absorption bands, separated by "windows" of moderate transparency. Between 1 THz and 10 THz the atmosphere is opaque, and so are most solid and liquid materials. This is the range of frequencies at which most molecules vibrate, absorbing radiation very strongly. At frequencies above 10 THz the molecular absorption bands become more widely separated again until we come to the prominent "window" through which we see visible light. Higher frequencies than this take us into ionizing radiation, which is discussed in R. S. Caswell's report on the National Measurement System for Ionizing Radiation (NBSIR 75-946).

At frequencies below about 100 MHz the world is very noisy, the sources being thunderstorms, the activity of the ionosphere and the galaxy, and the activities of man. In the range from a few hundred MHz to 10 GHz the background noise is much lower and is associated with localized sources such as the sun, the moon, and various radio stars. An antenna pointed at the regions of the sky in between these objects sees only the thermal noise from the cold background of the universe, at a temperature of about 3K. At higher frequencies where the atmosphere has appreciable absorption, the background noise corresponds to thermal noise at the temperature of the atmosphere, a few hundred K.

Electromagnetic technology has grown up within the limitations set by nature. In the range of frequencies below a few hundred MHz, components are cheap, most antennas are not very directional, and the background is noisy. This part of the spectrum is very heavily used by telecommunication systems, both for business and for pleasure. High performance brings no significant advantages to these systems, so accurate measurements of the characteristics of components are rarely called for. When they are required, the components in question are usually parts of microwave systems. The FCC keeps order among the various users of the spectrum by assigning frequencies, which are checked routinely, and power levels, which are rarely enforced. Many electronic systems, such as computers and servo control systems, are unintentional transmitters and receivers of electromagnetic radiation in this part of the spectrum. Interference is therefore a severe problem, that calls for repeatable measurements of fluctuating quantities, to be used as the basis both for agreement on the assignment of responsibility for its resolution and for changes in engineering design to reduce its effects.

The extreme case of electromagnetic interference occurs when fields are strong enough to injure people. This is a real danger with radio and TV transmitters and leaking microwave ovens. Exposure to hazardous fields is regulated by the Radiation Control for Health and Safety Act (PL90-602), and the Occupational Health and Safety Act (PL91-596), which require supporting measurements of the field levels in question.

Another aspect of electromagnetic waves in this part of the spectrum that is not yet fully exploited is their ability to penetrate to useful distances in rock, soil, concrete, water, etc. They may therefore be used to probe structures of these materials to supply information for civil engineering, agriculture, or mining. However, this will require extensions in the formulation of electromagnetic theory and the acquisition of a base of data on the properties of materials. These are the subjects of research that is in progress now.

At frequencies in the microwave range, from about 300 MHz to 30 GHz, we find a higher preponderance of more sophisticated systems. Here wavelengths are short enough that highly directional antennas are quite common. The background noise is low enough to enable systems to operate with very weak signals. This range of frequency is used by most of the radar systems on which modern navigation depends. Radar sets are carried

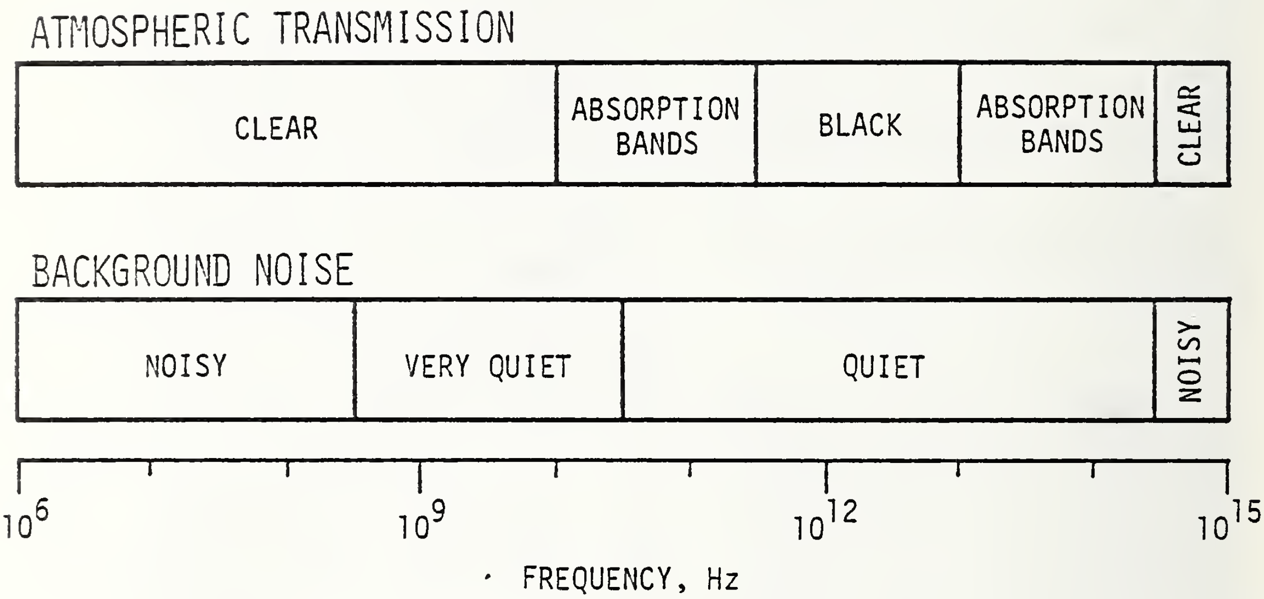

Figure 1. Spectral distribution of electromagnetic background noise and atmospheric transmission.

by ships and airplanes to give warning of potential collisions and severe weather. They are also placed at stations on the ground to determine the positions of aircraft to supply information for traffic control. More sophisticated microwave beacons are under development for air navigation. Microwave systems are under discussion and development for landing in conditions of poor visibility. The armed services use radar for the automatic guidance of terrain-following aircraft and of weapons, as well as for searching for the enemy. On the highways, the police use radar for enforcing the speed limit.

In addition to radar, the microwave region of the spectrum is used for telecommunications. Most long-distance telephone traffic is carried by microwave beams between repeater stations in direct line of sight with each other. Satellite communications are a rapidly growing business. The most common frequencies are 4 GHz and 6 GHz, and development work is in progress to use higher frequencies. One of the driving forces in the expansion of the telecommunications industry is the trend towards having distant computers communicate directly with one another. This enables large corporations to operate branch offices very efficiently, and specialized companies are being formed to serve this market. In addition to demanding large channel capacity, computers and associated digital technology encourage a trend towards digital communication, and separating different messages in time rather than frequency. This also has advantages for transmitting the voice, in the efficiency of use of channel capacity and the quality of the transmission. The trend towards digital communication is generating a new demand for time-domain measurements.

The major scientific uses of this part of the spectrum are in radio astronomy and molecular and solid state spectroscopy.

The electromagnetic systems that use the microwave part of the spectrum tend to be expensive, but the favorable natural conditions in which they operate enable them to repay their expense with very high performance if they are carefully designed and maintained. For example, satellite communication systems are very expensive to install. An orbiting satellite costs about $30 million, and is designed to last about 5 years, and the cost of a ground station varies in the range from $200 thousand to $5 million. Nonetheless, the channel capacity of the system can be large enough to offer communication services at very competitive prices. Furthermore, since the cost of transmission is independent of distance, the economics of long distance telecommunications are drastically altered. These systems call for accurate measurements of the electromagnetic characteristics of components, both during manufacture and acceptance and for routine maintenance.

The next region of the spectrum, from 30 GHz to 300 GHz, is presently regarded mainly as an overflow for users of the crowded channels at lower frequency. Components become much more expensive and less efficient in this region, and the atmosphere has strong absorption bands. These absorption bands are seen as an advantage for some military short-range systems that can use the attenuation of the atmosphere to avoid detection and interference from greater distances. The most significant commercial system, under development in several countries, is for telecommunication at 90 GHz through oversize circular waveguides, which minimize the effect of atmospheric attenuation.

There is not much commercial activity at frequencies between 300 GHz and 100 THz. There is much scientific activity in the development of lasers, and the world's most accurate spectroscopy is done in this region. Commercial or military exploitation are expected to follow, especially of the CO_2 laser, which can already be made to be cheap, efficient, and powerful. There is some activity with military funding to develop it into a weapon, and the most significant measurements to be made are of its beam profile and energy output.

The near infrared and visible parts of the spectrum are used for all the activities that the possession of eyesight has suggested to us, in addition to some that had to await the development of instruments. These include the remote sensing of temperature by radiometry, and all the possible applications of visible lasers, such as alignment and measurement of linear displacement, micromachining and surgery, holography, information processing (especially Fourier transformation), video disc recording, and automatic checking of groceries at the supermarket. Obviously, a very diverse collection of measurements must be made to support these activities, not the least important of which is the measurement of power and energy to regulate safety.

One newly developing optical technology that has much in common with the corresponding microwave techniques is telecommunication through optical fibers and the integrated electro-optical systems that will be used for transmitters and receivers. These will call for all the types of measurement that have been made on microwave systems, translated to a different region of the spectrum with different difficulties and conveniences.

2. STRUCTURE OF THE MEASUREMENT SYSTEM

2.1 Conceptual System

A complete description of an electromagnetic wave would have to specify the magnitudes of the three components each of electric and magnetic field, their distribution in space, and their variation with time. This is too much information either to obtain or to use for most practical purposes, so more specialized measures have been defined to convey more limited information about the wave and its interaction with devices and materials. Table 1 is a list of the electromagnetic quantities that are most commonly measured, and their units.

Table 1: Common Electromagnetic Quantities

Quantity	Unit
Electric field	Vm^{-1}
Electric Displacement	Asm^{-2}
Magnetic Field	Am^{-1}
Magnetic Flux Density	Vsm^{-2}
Voltage	V
Current	A
Power	W
Complex Impedance	Ω
Complex Admittance	Ω^{-1}
Components of the Complex Scattering Matrix	dimensionless
Impulse Response Function	dimensionless
Complex Reflection Coefficient	dimensionless
VSWR	dimensionless
Attenuation	dimensionless
Gain	dimensionless
Phase Shift	dimensionless
Q-Factor	dimensionless
Antenna Gain	dimensionless
Antenna Pattern	dimensionless
Efficiency	dimensionless
Noise Temperature	K
Noise Figure	dimensionless
Spectral Density	WHz^{-1}
Frequency*	Hz
Wavelength	m
Rise Time	s
Complex Relative Permittivity	dimensionless
Complex Relative Permeability	dimensionless
Dielectric Loss Tangent	dimensionless
Conductivity	$\Omega^{-1}m^{-1}$
Reflectivity	dimensionless

*Frequency is discussed in A. S. Risley's report on the National Measurement System for Time and Frequency (NBS Special Publication 445-1 (1976)).

It is obvious that there is a high degree of redundancy even in this list, even though it excludes many quantities that are only occasionally used.

In general, electromagnetic measurements do not attempt to attain the degree of accuracy that is possible for dc electrical measurements. The basic reason for this is that the reflections from connectors and bends in transmission lines, and variations in atmospheric conditions and the movement of reflecting objects, all cause variations of a few percent in the characteristics of parts of a system during normal use. With very few exceptions practical systems are designed to tolerate errors of comparable magnitude, so measurements with uncertainty less than 0.1% are rarely called for.

Another striking feature of the electromagnetic scene is the high demand for measurements of dimensionless quantitites, such as attenuation, phase angle, reflection coefficient, and antenna gain. These are the quantitites that determine the ability of a system to transmit electromagnetic energy. There are national reference standards and calibration services for many of these dimensionless quantities, but the trend is to replace them by self-calibration techniques.

The impedance of transmission lines and the amplitude of electromagnetic waves require reference to the basic units of the Systême International (SI). In practice, the ohm can be realized independently with sufficient accuracy in the form of a uniform transmission line whose characteristic impedance can be calculated from its linear dimensions and the permittivity of the dielectric (usually air). This is a convenient standard to which to refer the impedance at the ports of devices by measurements of reflection. The amplitudes of waves are determined by measuring power, voltage, current, electric field, or magnetic field, whichever is most convenient. The essential step in all these measurements is the conversion of the quantity to be measured to an equivalent dc quantity that can be compared directly with the realized SI electrical units. In practice, the final step of reference to the national electrical standards is trivial at the level of accuracy required. It is often left to the manufacturer of an instrument such as a digital voltmeter.

2.2 Basic Technical Infrastructure

2.2.1 Documentary Specification System

2.2.1.1 Standardization Institutions

In this section we consider voluntary specifications, or "paper standards," as distinct from physical standards and enforced regulations. These voluntary specifications cover topics such as definitions of technical terms and symbols, recommended test and measurement methods, and the performance, reliability, compatibility, and safety of products. They make a significant contribution to greasing the wheels of commerce.

The dominant international organization is the International Electrotechnical Commission (IEC). This draws its members from National Committees in each of the member countries. (The International Bureau of Weights and Measures (BIPM) keeps physical standards that have very little direct influence on electromagnetic measurements). In addition to the National Committees of the IEC, each country has a plethora of standardizing institutions that may or may not share members with one another and the IEC. One such institution of particular significance is the European Committee for Electrical Standardization (CENELEC), which speaks for all the members of the European Common Market.

In the United States, the institution with the greatest influence is the Department of Defense. It is the largest purchaser of electromagnetic equipment and the leader in developing the technology, so most commercial products are designed to conform with the Military Specifications (MIL-SPECs). Other significant standardizing institutions are: the Institute of Electrical and Electronics Engineers (IEEE); the Instrument Society of America (ISA); the Electronic Industries Association (EIA); the Society of Automotive Engineers (SAE); the Aerospace Industries Association of America (AIAA); the American Society for Testing and Materials (ASTM); and the American National Standards Institute (ANSI). There appears to be little formal coordination of these organizations, and activities seem to be taken up by one or another on the principle that "nature abhors a vacuum."

The National Bureau of Standards takes some part in writing specifications, usually in collaboration with one of the institutions listed in the previous paragraph, and especially when physical measurement methods must be specified. This activity is increasing at present. The regulatory agencies also write many specifications, which will be spoken to in section 2.4.4.

2.2.1.2 Survey of Documentary Standards

The various organizations listed in section 2.2.1.1 tend to emphasize somewhat different types of standards. These can be summarized as follows:

* MIL-SPECs are standards of performance and physical compatiblity of one device with another. They often specify testing methods, some of which need improvement.

* The professional societies, such as IEEE, SAE, and ISA, tend to write standards of terminology and engineering practice. These often include testing methods. They also write standards for physical compatibility.

* The trade associations, such as EIA and AIAA, emphasize those standards that are of mutual advantage to all the companies competing in their respective parts of the market.

* ASTM is concerned mainly with methods of testing materials. It does cover electromagnetic properties of materials and laser damage.

* ANSI covers a wide range of standardizing activities, including certifying products for quality, performance, and safety. It also attempts to coordinate the efforts of the other standardizing institutions, especially in the international arena.

2.2.2 Instrumentation System

2.2.2.1 Measurement Tools and Techniques

2.2.2.1.1 CW Transmission Line Systems

These comprise various active or passive components connected together by uniform transmission lines, which can be coaxial lines, strip lines, or singly connected waveguides. Until quite recently, it was almost universal practice to choose transmission lines that would support only a single mode of propagation at the operating frequency. The objectives of the measurements to be made are to determine the phase and amplitude of the electromagnetic waves traveling in either direction along the transmission lines, and the effect on these quantities of interaction with the components at the ends of the lines.

A great deal of useful information is conveyed by the n-dimensional scattering matrix that specifies the relationship between the waves passing into and out of the n ports of one of the components and the connecting waveguides. In their usual form, the coefficients of the scattering matrix are dimensionless quantities. They are measured by measuring the relative amplitude and phase of waves in different parts of the system.

The simplest way to compare amplitudes is to assume the linearity of a detector that converts each signal to dc that can be measured with a digital voltmeter. This is adequate if errors of a few percent and a somewhat restricted dynamic range can be tolerated. Greater accuracy and dynamic range are attained by using reference standard attenuators, or with a heterodyne system to convert both signals to a lower frequency at which they may be compared with a ratio transformer.

The measurement of phase angle requires more trouble and expense than almost any other quantity. The phase angle between the signal of interest and a coherent reference signal must be measured. This can be done by allowing the two signals to combine in an adjustable bridge and seeking a balance at which they cancel. A more elaborate way that is commonly used in automatic systems is to use mixers and a local oscillator to convert both signals down to an intermediate frequency that is low enough to permit the use of phase-sensitive detectors to compare phases directly. The most recent and sophisticated method employs the mathematics of scattering theory, recognizing that measurements of the amplitude of the signals at four properly chosen points in a transmission line network supplied with two coherent signals contain enough information to determine the relative phase and amplitude of the two signals. A simple calibration technique and a small computer to perform the necessary matrix manipulations comprise the remainder of a practical measuring system. This is known as a *6-port system*.

At the level of accuracy generally required for microwave measurements (0.1%), it is comparatively straightforward to make an independent realization of the ohm, in the form of a uniform coaxial transmission line whose characteristic impedance Z_0 may be calculated from the radii of the inner and outer conductors and the permittivity of the dielectric (usually air) between them. The impedance Z at the port of a component connected to this line is referred to Z_0 by measuring the complex reflection coefficient Γ, and using

$$Z = Z_0 \cdot (1+\Gamma)/(1-\Gamma).$$

When the characteristic impedance of the line is known, the amplitudes of electromagnetic waves can be referred to the SI units by measuring the power absorbed in an approximately matched (i.e., reflectionless) termination of a transmission line. The device commonly used is a bolometer, with which the heating effect of the absorbed wave is compared with that of a direct (or low frequency) current flowing through the same resistive element, thereby converting the measurement to one of dc (or low frequency) current and voltage. Corrections must be made for: residual reflections; absorption of some rf power in parts of the bolometer other than the intended resistive element; and differences between the spatial distributions of the heating effects of the dc and rf currents. Calibration of a bolometer consists of the evaluation of these corrections. It is interesting to note that although calorimetry is employed in the process, the results are expressed as dimensionless ratios. It is a dc calibration that carries the burden of the reference to the SI units. RF voltage is measured by a device that is similar to a bolometer but severely mismatched to the transmission line (it has a very high impedance).

These basic principles are applied in systems that fall in a wide range of sophistication, accuracy, and cost. There has been a constant evolution from simple bridge circuits that must be manually tuned up and balanced at each operating frequency, through self-balancing bridges, to fully automatic systems controlled by computers that electronically switch the frequency and other operating parameters, measure the transmission properties of the system both with and without the device under test inserted in it, and compute the desired scattering parameters of the device under test from the stored information obtained by these operations.

2.2.2.1.2 Antennas

At frequencies above about 1 GHz, antennas of moderate size have linear dimensions that encompass several wavelengths. The consequence of this is that the angular distribution of radiated power is usually very anisotropic, with distinct "lobes" of strong radiation and sensitive reception. This can be a nuisance or it can be exploited by the designer of a radar or communication system striving for high performance, but in either case it must be measured.

The quantity of interest is the distribution of radiated power and polarization in the "far-field," at distances greater than d^2/λ where emitted radiation can be regarded approximately as a plane wave. (d is the aperture of the antenna and λ is the wavelength.) Early methods of making these measurements required large antenna ranges. Although these are kept as clear as possible of obstructions, unwanted reflections from the ground, buildings, etc., still set a limit to attainable accuracy. Recently, techniques have been developed to use near-field scanning combined with a mathematical reconstruction of the far field. There is also a somewhat simpler extrapolation technique which can measure just the gain of the antenna in one direction. The workhorse of antenna standards is the "standard gain horn," a simple antenna with a calculable radiation pattern.

2.2.2.1.3 Noise

Noise sets the lower limit to the power level at which a radar or communication system can work. In the microwave range, where the background noise is very low and the atmosphere is transparent, the limiting noise is apt to be within the system itself. The ultimate lower limit is the thermal noise power $P(T)$, described by Nyquist's formula

$$P(T) = \int kTdf$$

where k is Boltzmann's constant, T is the absolute temperature, f is the frequency, and the limits of integration are set by the pass band of the system. The primary standards of noise are matched (reflectionless) terminations of transmission lines maintained at controlled temperature. These are often used as working reference standards also, together with gas discharge tubes, semiconductor diodes and radio stars. All these must be calibrated against a primary standard. The instrument used to compare a noise source with a reference standard is a radiometer. The most commonly used type is the Dicke radiometer, which simply switches the two sources rhythmically to a sensitive detector and records the component of the detected signal at the switching frequency with a synchronous detector. The weakness of this system is the switch, which may be eliminated by more sophisticated correlation techniques.

2.2.2.1.4 Time Domain

The current trend towards digital communication and time division multiplexing is increasing the importance of the characterization of waveforms in the time domain, which is at present a more primitive art than the corresponding measurements in the frequency domain. The traditional tool is the real-time oscilloscope, but it has limited speed and accuracy. Better performance can be obtained by sampling techniques, especially with repetitive waveforms. The basic tool for this is the sampling oscilloscope, that samples successive parts of the waveform from each repetition. A more sophisticated system digitizes the information in these samples, and stores and manipulates it in a computer. In combination with a suitable signal source, a system like this can be used to characterize the response and transfer functions of transmission line networks to impulsive signals. Such a system is known as a time domain network analyzer. Work is in progress to increase the operating range of these systems, particularly in the resolution of short pulses, and to develop the transducers required to make these measurement techniques accessible to optical pulses.

2.2.2.1.5 Field Strength

The most important reason to measure electromagnetic field strength is to control electromagnetic interference (EMI) and the exposure of people to hazardous fields. The fields to be measured are therefore usually random and impulsive in nature, and often in the near-field zones of their sources. The best measuring devices at microwave and radio frequencies are small dipole antennas, connected to receivers by lines that are designed to minimize the perturbation of the field to be measured. These instruments need to be calibrated in standard fields, which can be set up with standard antennas inside anechoic chambers at frequencies above 1 GHz. Below 1 GHz, the transverse electromagnetic (TEM) cell can be used. These facilities are also well adapted for investigating the effects that EMI and hazard probes are meant to guard against. A great deal of such testing is done in undamped screened enclosures, and is prone to large errors because of the presence of standing waves.

The instruments available at present lack the full dynamic range and frequency range, and particularly the speed of response, that is needed. Work is in progress to remedy this, and to develop probes for baseband impulse fields.

2.2.2.1.6 Lasers

The quantities that characterize a laser beam are: average power (long term); "instantaneous" power (averaged over a specified interval of time controlled by the measuring equipment); energy (in a pulse); frequency (or wavelength) spectrum; spatial beam profile; and temporal pulse shape. Measurement of frequency is included in A. S. Risley's companion report on the National Measurement System for Time and Frequency (NBS Special Publication 445-1, 1976). Of the other quantities, only power and energy are the subjects of an organized measurement system. The basic measurement tools are calorimeters that compare the energy received from a laser beam in a controlled interval of time with an equivalent amount of energy supplied electrically. Imperfections such as backscatter and differences between optical and electrical efficiency are usuallly calculated with some support by auxiliary measurements. Photodiode detectors (usually silicon) are used when short response time or sensitivity to low power levels are needed. They can be calibrated against calorimeters with the aid of a calculable attenuator consisting of a thin prism in which a laser beam suffers multiple internal reflections, dividing its energy according to Fresnel's formula.

2.2.2.2 The Instrumentation Industry

There is a healthy instrumentation industry that supplies the bulk of the equipment needed for testing and tuning up working electromagnetic systems. The most clearly "electromagnetic" part of the total market is that which covers microwave test and measuring instruments. This is projected to amount to $145 million in sales in the U.S. in 1976. Appendix B is a list of U.S. manufacturers of this equipment, categorized by the quantities it is intended to measure.

The giant among the customers of this industry is the Department of Defense, which develops and uses the most advanced radiofrequency and microwave systems. A large quantity of test and measuring equipment is needed for maintenance of these systems.

2.2.3 Reference Data

Very few reference data are used in electromagnetic measurements, and most of them are found in regular engineering and mathematical handbooks. Descriptions of techniques and methods are usually found in professional society journals and other publications of the same kind. NBS has published the first three volumes of a series of Metrology Guides, that give a systematic exposition of all available techniques for measuring a given quantity. There is a need for more of these, and also for a classic text summarizing the whole field of electromagnetic measurements, explaining the general principles and their application to specific problems. Ginzton's book "Microwave Measurements" filled this need in its time, but that was 20 years ago, and the field has matured considerably since then. A successor is needed.

2.2.4 Reference Material

There is at present no organized source of reference materials for electromagnetic measurements. It will be necessary to create one to support full use of remote electromagnetic sensing. The U.S. Department of Agriculture may well become the repository for the first certified reference materials for dielectric measurements.

2.2.5 Science and People

The dominant professional society in the field of electromagnetic measurements is the Institute for Electrical and Electronic Engineers (IEEE). It publishes journals (including IEEE Proceedings, IEEE Transactions on Microwave Theory and Technique, IEEE Transactions on Instrumentation and Measurement), writes standards of practice and performance, and sponsors professional meetings. The National Conference of Standards Laboratories (NCSL) also provides a forum for exchange of metrological philosophy and technique at its conference and in its Newsletter. Other societies with some interest in the field are the Instrument Society of America (ISA), and the U.S. National Committee of the International Scientific Radio Union (URSI). Both of these organizations sponsor conferences.

The most important conference devoted to electromagnetic measurements is the biennial Conference on Precision Electromagnetic Measurements. This conference is sponsored jointly by NBS, IEEE, and URSI. The Proceedings are published in the following December issue of the IEEE Transactions on Instrumentation and Measurement.

2.3 Table 2. Realized Measurement Capabilities

QUANTITIES	TYPE OF MEASUREMENT	RANGES Frequency	Dynamic	ACCURACY
Impedance	Resistance	30 kHz - 1 MHz	10^{-1} - 10^{6} ohms	0.2 - 15%
		1 - 250 MHz	20 - $5x10^{4}$ ohms	0.2 - 15
	Inductance	30 kHz - 10 MHz	10^{-8} - 1 henries	0.1 - 20%
	Capacitance 2 terminal	0.3 - 250 MHz	10^{-12} - 10^{-7} farads	0.1 - 20%
	(MIL SPEC)	1 MHz	10^{-12} - 10^{-7} farads	0.1 - 1%
	3 terminal	100 kHz - 1 MHz	10^{-14} - 10^{-7} farads	0.05 - 10%
	Q	1000 Hz - 10 MHz	10^{-2} - 10^{2}	2 - 5%
		1000 Hz - 250 MHz	10^{-2} - $>10^{3}$	2 - 100%
	Magnitude including (VSWR of 1 to 4)	0.1 - 8 GHz	20 - 200 ohms	0.1% - 10%
	Phase Angle	0.1 - 8 GHz	0 - 90°	0.1 - 10%
	Phase Shift	1 - 8 GHz	0 - $\pi/2$ radians	0.4% - 10%
	Coaxial Impedance	8 - 18 GHz	20 - 200 ohms	0.3% - 10%
	Coaxial Phase of Impedances	8 - 18 GHz	0 - 90°	0.3% - 10%
	Length of equivalent airlines	0.1 - 8 GHz	5 - 30 cm	0.005 cm - 0.1 cm
	Reflection Coefficient	2.6 - 40 GHz	0 - 0.2	1 - 10%
		40 - 100 GHz	0 - 0.2	1 - 10%
Attenuation	Insertion Loss	1 MHz - 18 GHz	0 - 100 dB	0.02 - 1 dB
		18 - 40 GHz	0 - 70 dB	0.2 - 1 dB
		40 - 100 GHz	0 - 60 dB	0.05 - 2 dB

Table 2, continued

QUANTITIES	TYPE OF MEASUREMENT	RANGES Frequency	RANGES Dynamic	ACCURACY
Phase	Shift	0.1 - 18 GHz	0 - 360°	0.1 - 3°
		18 - 100 GHz	0 - 360°	3°
	Delay	0.1 - 18 GHz	10^{-12} - 10^{-5} sec	0.5 - 1%
Power	Instantaneous, CW, Average, Effective Efficiency	Coax 10 MHz - 17 GHz	1 mW - 100 W	1 - 10%
			10^{-12} - 1 mW	5 - 20%
		Waveguide 2.6-40 GHz	1 mW - 1 W	.7 - 10%
		40-95 GHz	1 mW - 1 W	3 - 10%
	Peak Pulse	50 MHz - 18 GHz	0.1 mW - 10 kW	2 - 10%
Voltage	Instantaneous, CW, RMS, Average	30 kHz - 1 GHz	1 mV - 200 V	0.01 - 15%
		1 GHz - 2.5 GHz	1 mV - 20 V	1 - 15%
		30 kHz - 2.5 GHz	Below 1 mV	≈20%
Current	No Known Needs			
Noise	Noise Temperature [or in Excess Noise Ratio above 290 K where applicable]	Coax: 10 MHz - 18 GHz	77 K - 30,000 K	5 - 15%
		Waveguide: 1.5 GHz - 18 GHz	77 K - 30,000 K	
		and 18 GHz - 100 GHz	10,000 K - 30,000 K	10 - 25%
	Impulse Noise	Coax: 10 MHz - 18 GHz	0 - 120 dB above 1 μV/MHz	25 - 300%
		Waveguide: 18 GHz - 40 GHz	0 - 140 dB above 1 μV/MHz	25 - 300%
	Baseband Gaussian Noise	10 Hz - 1 GHz	- 120 dBW - 0 dBW	±0.2 dB
	Amplitude and Phase Noise	Carrier: 1 MHz - 18 GHz		
		Sideband Offset 10 Hz - 100 MHz	-165 dBc per Hz Resolution	±2 dB

Table 2, continued

QUANTITIES	TYPE OF MEASUREMENT	RANGES Frequency	RANGES Dynamic	ACCURACY
Waveform	Transition Time		10^{-11} s - 1 s	≈0 - 50%
	Pulse Amplitude		1 mV - 100 V	1 - 20%
EM Fields	Field Strength	10 Hz - 100 GHz	10^{-6} - 10^{4} Volt/meter	3 - 20%
	Antenna Gain	10 kHz - 100 GHz	0 - 60 dB	.25 - 2 dB
Laser Output	Power	28 THz	50 mW - 100 kW	5%
		280 THz - 750 THz	1 nW - 1 mW	5%
		280 THz - 750 THz	0.3 mW - 22 W	1%
	Energy	28 THz	15 J - 7 MJ	5%
		280 THz - 750 THz	10 mJ - 200 J	3%

2.4 Dissemination and Enforcement Network

2.4.1 Central Standard Authorities

The only central authority in this field for physical standards in the U.S. is the National Bureau of Standards (NBS), which maintains an Electromagnetics Division to provide standards and measurement services in electromagnetic quantities. Intercomparison of electromagnetic standards with other national laboratories does occur occasionally, but it plays a very minor role in maintaining statistical control of the measurement system. There is almost no interaction with BIPM connected with electromagnetic measurements. Although the SI electrical units are subject to frequent international intercomparisons, these have very little influence on the electromagnetic measurements that are referred to them because of the comparatively low level of accuracy that is called for.

The most sophisticated and highly organized part of the National Electromagnetic Measuring System is that which serves the Department of Defense and its industrial contractors. Control of errors is maintained there by requiring that all measurements must be traceable to physical standards kept at NBS. Army Regulation 750.25, Air Force Regulation 74-2, and Navy Regulation SEC NAV 4355.14 require that the standards for calibration of all military measuring instruments must be traceable to NBS. Similar requirements are imposed upon industrial defense contractors by the Military Specification MIL-C-45662A.

Professional societies such as the IEEE and the SAE do publish recommendations for measuring techniques, but the physical standards to support these all reside at NBS.

2.4.2 State and Local Offices of Weight, and Measures

State and local governments hold no formal electromagnetic standards. In California, there is some talk of offering the calibration services of private companies under a state license, but this is more likely to be done for quantities that are more directly subject to state regulation. It is conceivable that California and other State governments may take a more active interest in measurements of electromagnetic interference in the future.

2.4.3 Standards and Testing Laboratories and Services

There are many private and federal government laboratories that are capable of electromagnetic measurements and calibrations. Appendix C is a list of these laboratories taken from the 1976 Directory of Standards Laboratories, published by the National Conference of Standards Laboratories (NCSL), an organization of which many of the listed laboratories are members.

Many of these laboratories serve either the Department of Defense or defense contractors, and are therefore subject to the DoD regulations requiring traceability to NBS. At present, there is no formal mechanism for assuring the compatibility of measurements and calibrations made by the remainder of the laboratories on the list with national standards. In an attempt to remedy this deficiency, the Department of Commerce has announced a National Voluntary Laboratory Accreditation Program (see the Federal Register, 40FR20092-95 and 41FR8163-68). This program is intended to cover all laboratories that request accreditation, but it is in a very early stage of development. So far, one private company has applied for accreditation to measure microwave power and attenuation, and it will probably take at least two years to organize the necessary inspection, certification, and connection to national standards.

2.4.4 Regulatory Agencies

Most of the regulatory agencies that use electromagnetic measurements do so to control the effects of excessive radiation: either the direct hazard to people or interference with the functions of electronic control and communication systems.

The Radiation Control for Health and Safety Act of 1968 (PL 90-602) set limits to the electromagnetic field strength that may be radiated by electronic products. The classes of people most likely to be exposed to hazardous field strengths are the owners of leaking microwave ovens and people who work near radio and TV transmitters. The Bureau of Radiological Health (BRH) tests samples of the microwave ovens on the market for leaks, when they are new and also after many openings and closings of their doors. The Occupational Safety and Health Administration (OSHA, authorized by PL 91-596) inspects work places for hazards including those from electromagnetic radiation in places where they are likely to be found.

The safety of lasers is also controlled by BRH and OSHA. Following a standard published by ANSI (Z 136.1-1973), BRH classifies lasers into four classes that are defined according to the hazard of exposure to the direct beam that is accessible outside the case of the instrument. Class I lasers are regarded as perfectly safe under all conditions: one can stare directly into the beam with impunity. Class II is restricted to visible, continuous wave lasers that present a hazard similar to that of the sun: the direct beam is capable of damaging our eyes but we instinctively avert them before damage is inflicted. Class III includes lasers from which our instinct is not sufficient to protect our eyes from damage: the power is too great or the beam is pulsed or the radiation is not visible. Class IV lasers can burn the skin. The ANSI standard assigns boundaries to these classes according to wavelength, average power, or the energy and duration of pulses. BRH requires labelling of all commercial lasers to specify which class they belong to. OSHA is in the process of defining the safety precautions that industrial employers must provide for workers exposed to the various classes of lasers, and Executive Order 11807 will extend the OSHA regulation to the Federal Government.

The control of electromagnetic interference (EMI) by fields below the human hazard level is a much more diffuse responsibility that simply has not been properly organized yet. The Federal Communication Commission (FCC) issues licenses for transmitters, which can be revoked when a nuisance is proven. However, some of the sources of interference are perfectly legitimate users of the electromagnetic spectrum, and some are unintentional emitters from equipment such as internal combustion engines that are not regulated directly by the FCC. In Canada, the Radio Act was recently amended to cover emission of interference by such equipment. In a series of dockets (20654, 20718, and 20780) the FCC has announced its intention to follow suit in the U.S. At present, manufacturers of automobiles in the U.S. all observe a voluntary standard, SAE J-551d, but there are many other kinds of gasoline-powered machines that do not conform to it.

Motor vehicles can be victims of EMI as well as sources. The National Highway Transport Safety Administration recently set a standard for the braking performance of trucks and buses (FMVSS-121) that can be met only by using an electronic servo system to prevent locking and skidding of wheels. These devices proved to be susceptible to interference from Citizens' Band radio transmitters, and no doubt the regulation will need to be modified to specify a reasonable degree of immunity to this problem.

The principle of regulating the victim rather than the often inaccessible source of EMI is carried further in bills introduced into the Congress by Charles Vanick (HR 7052) and into the Senate by Barry Goldwater (S 3033). Among other provisions, these bills would require equipment such as TV sets to have filters to make them reasonably insensitive to the parts of the electromagnetic spectrum outside the bands they are designed to respond to. It is expected that Federal Drug Administration (FDA) will be required to set limits to the susceptibility to interference of acceptable medical electronic devices, such as heart pacemakers and diagnostic equipment.

The Federal Aviation Administration (FAA) maintains radio navigation aids such as airport radar, VOR, and ILS. It therefore needs to make the measurements necessary to keep these systems working with tolerable accuracy and also to conform to the OSHA regulations controlling the exposure of its employees to the fields generated by the associated transmitters. The U.S. Coast Guard has similar responsibilities for marine navigation aids such as LORAN-C.

Finally, if any gaps are left in the protection of the public from nuisance and hazard from electromagnetic radiation by these various regulatory agencies, the Environmental Protection Agency (EPA) stands ready to fill them. At present, it is engaged in a survey of background fields throughout the U. S.

Although all these agencies have legal responsibilities that require measuring very complex electromagnetic fields, the necessary techniques are not yet fully developed throughout the range in which they are needed. Work is in progress, at NBS and elsewhere, to remedy this deficiency.

2.5 Organizational Input-Output Transactions Matrix

2.5.1 Analysis of Suppliers and Users

The two essential components of an acceptable measurement system are: a set of measurement techniques, supported by available equipment and a complete understanding of sources of error; and a set of accessible reference standards to enable different people, measuring the same quantity by different techniques, to make sure that their results are consistent.

Electromagnetic measurement techniques are generally developed by metrology engineering laboratories (including the Electromagnetics Division of NBS), by universities, and by the manufacturers of instruments. They are passed on to the users by publications in professional journals (such as the IEEE Transactions on Instrumentation and Measurement and the IEEE Transactions on Microwave Theory and Technique), at professional conferences such as the Conference on Precision Electromagnetic Measurements, and by the detailed reporting that is usually required to fulfill development contracts. The major users at present are the Department of Defense, the aerospace industry, and the telecommunications industry. The transportation industry and the regulatory agencies are becoming significant users as they face growing problems of interference with electronic controls and radiation hazard to people. State and local government agencies are conspicuous by their absence from the electromagnetic scene.

2.5.2 Highlights re Major Users

The <u>Department of Defense</u> and the <u>Aerospace Industry</u> that supplies it use electromagnetic technology for surveillance, navigation, guidance of weapons and terrain-following aircraft, and communication. They have developed very sophisticated systems for these purposes, and these systems require the best available electromagnetic measurements to ensure the compatibility of components made by different manufacturers and to maintain performance after they are installed. Control of this part of the National Measurement System is maintained by requiring all calibrations of instruments to be traceable to standards at NBS. To make this possible the three armed services have a hierarchy of calibration laboratories. Laboratories at each level of this hierarchy receive transfer standards from laboratories at the next higher level. The top laboratories are the primary metrology centers at Newark, Ohio (Air Force); San Diego, California (Navy); Washington, D. C. (Navy); and Huntsville, Alabama (Army). These laboratories have their reference standards calibrated by NBS. The manufacturers supplying the equipment are left to find their own paths

DIRECT MEASUREMENTS TRANSACTIONS MATRIX FOR LASERS — SUPPLIERS / USERS	KNOWLEDGE COMMUNITY (Science, Education, Prof. Soc. & Publ.) 1	INTERNATIONAL METROLOGICAL ORGANIZATIONS 2	DOCUMENTARY STANDARDS ORGANIZATIONS 3	INSTRUMENTATION INDUSTRY (SIC Major Gp 38) 4	NBS 5	OTHER U.S. NATIONAL STANDARDS AUTHORITIES 6	STATE & LOCAL OFFICES OF WEIGHTS & MEASURES (OWM's) 7	STANDARDS & TESTING LABORATORIES AND SERVICES 8	REGULATORY AGENCIES (excl. OWM's) 9	DEPARTMENT OF DEFENSE (excl. Stds. Labs) 10	CIVILIAN FEDERAL GOVT AGENCIES (exc. Stds Labs & Reg. Ag.) 11	STATE & LOCAL GOV'T AGENCIES (exc. OWM's & Reg. Ag.) 12	INDUSTRIAL TRADE ASSOCIATIONS 13	AGRICULTURE, FORESTRY FISHING; MINING (SIC Div. A & B) 14	CONSTRUCTION (SIC Div. C) 15	FOOD/TEXTILE/LBR/PAPER/LEATHER/ETC. (SIC 20-26, 31) 16	CHEM/PETROL/RUBBER/STONE/CLAY/GLASS (SIC 28-30, 32) 17	PRIMARY & FAB. METAL PRODUCTS (SIC 33-34, 391) 18	MACHINERY EXCEPT ELECTRICAL (SIC Major Gp 35) 19	ELECTRIC AND ELECTRONIC EQPMT (SIC Major Gp 36) 20	TRANSPORTATION EQUIPMENT (SIC Major Gp 37) 21	TRANSPORTATION & PUBLIC UTILITIES (SIC Div. E) 22	TRADE/INS/FIN/REAL EST/PERS SVCS/PRINT (SIC F-H, bal I, 27) 23	HEALTH SERVICES (SIC Major Gp 80) 24	GENERAL PUBLIC 25
1 KNOWLEDGE COMMUNITY (Science, Education, Prof. Soc. & Publ.)	4 4	3	4 3	3 4	4 4				4 3	4 4	4 4		1		4 1		4 3	4 1	1	3 3	3	4 2	4 1	4 2	
2 INTERNATIONAL METROLOGICAL ORGANIZATIONS	1	1			1																				
3 DOCUMENTARY STANDARDIZATION ORGANIZATIONS	1		2	2	2				1	1	1	1	1		1	1	1	1		2	1	2	2	2	1
4 INSTRUMENTATION INDUSTRY (SIC Major Gp 38)	1	1	2	3	2			1	3	4	3	1	3		1	1	2	1	1	3	2	2	2	1	
5 NBS	4 3	4 2	4 3	4 2 4	4			2	4 4	4 4	4 4	1 3 1	1							4 2 4	4 2 3	3	3		
6 OTHER U.S. NATIONAL STANDARDS AUTHORITIES																									
7 STATE & LOCAL OFFICES OF WEIGHTS & MEASURES (OWM's)																									
8 STANDARDS & TESTING LABORATORIES AND SERVICES				1 R				2	1	2	1									1	1	1			
9 REGULATORY AGENCIES (excl. OWM's)	1		1 2 4	1 2 4	2			1	4 3	2 R	3 R	4 2	2		1 R	1 R	4 2 R	4 2 R	4 1 R	2 2 4 R	2 R	3 2 R	3 2 R	4 1 R	1 R
10 DEPARTMENT OF DEFENSE (excl. Stds. Labs)	4		1	3	3					4	2									4	2	2	2		
11 CIVILIAN FEDERAL GOV'T AGENCIES (excl. Stds. Labs & Reg. Ag.	3 3 2		3 2	3 3 2	3 3				2	3 2 2	3 3 2	1	1			1	1	3 1	1	3 3 2	1	3 1		3 2	
12 STATE & LOCAL GOVERNMENT AGENCIES (exc. OWM's & Reg. Ag.)				1 R	1 3 1 2 R				1			1 3 1 2	1		3 1 R	3 3 1 R	3 3 1 R	3 3 1 R		1 R		1 R	4 3 1 R	1 R	
13 INDUSTRIAL TRADE ASSOCIATIONS	1		1	1	1 R				4 3	1	1	1 3 1	1		1	1	1	1		1		1	1	1	
14 AGRICULTURE, FORESTRY FISHING; MINING (SIC Div. A & B)																									
15 CONSTRUCTION (SIC Div. C)	1		1	1 R	1 R				1	1			2		1					1 R					
16 FOOD/TOB/TEXTILE/APPAREL/LBR/FURN/PAPER/LEATHER (SIC 20-26, 31)			2	1 R	1 R				1		1		2			1				1 R					
17 CHEM/PETROL/RUBBER/PLASTICS/STONE/CLAY/GLASS (SIC 28-30, 32)	2		2	2 R	1 R				2	1	1		2				2			1 R					
18 PRIMARY & FAB. METAL PRODUCTS (SIC 33-34, 391)	1		2	1 R	1 R				1	1	1		2					1		1 R					
19 MACHINERY, EXCEPT ELECTRICAL (SIC Major Gp 35)			1	1 R															1	1 R					
20 ELECTRIC AND ELECTRONIC EQPMT (SIC Major Gp 36)	3		3	3 R	1			1	2	3	3		3		1	1	1	1	1	3	2	2	3		
21 TRANSPORTATION EQUIPMENT (SIC Major Gp 37)	3		1	2 R	1								2							2 R	2				
22 TRANSPORTATION & PUBLIC UTILITIES (SIC Div. E)	2		1	2 R	2				1	1	1		2							2 R		2			
23 TRADE/INS/FIN/REAL EST/PERS SVCS/PRINT-PUB (SIC F-H, bal. I, 27)	1		2	2 R	1 R				2	1	1	1 3 1	3							2 R			2		
24 HEALTH SERVICES (SIC Major Gp 80)	2		2	2 R	1 R				1	1	2	1 3 1	2							2 R			1	1	1
25 GENERAL PUBLIC					1 R				1 R		1 R	1 2 1 2 R								1 R			1 R	1 R	

KEY TO MATRIX ENTRIES

C - IMPORTANCE OF TRANSACTIONS
- 1 = Purely convenience
- 2 = Strongly desirable
- 3 = No real alternatives
- 4 = Essential

D - (IN)ADEQUACY OF SERVICES
- 0 = No improvements needed
- 1 = Could be improved
- 2 = Marginal
- 3 = Serious deficiencies
- 4 = Out of control

USERS

C	D
A	
B	R

B - RATE OF CHANGE
- N = Declining
- 0 = Stable
- 2 = Growing
- 4 = Growing explosively

A - MAGNITUDE OF TRANSACTIONS
- 0 = Trivial
- 1 = Minor
- 2 = Moderate
- 3 = Important
- 4 = Major

R = Flow of requirements info dominates

? = Unknown, X = Not studied, Blank = 0

Figure 2. Direct measurements transactions matrix for lasers.

Each matrix entry below is written as "C D / A / B R": corner values first, then the centre value (A), then the lower corners.

DIRECT MEASUREMENTS TRANSACTIONS MATRIX FOR ELECTROMAGNETICS — SUPPLIERS \ USERS	1 KNOWLEDGE COMMUNITY (Science, Education, Prof. Soc. & Publ.)	2 INTERNATIONAL METROLOGICAL ORGANIZATIONS	3 DOCUMENTARY STANDARDS ORGANIZATIONS	4 INSTRUMENTATION INDUSTRY (SIC Major Gp 38)	5 NBS	6 OTHER U.S. NATIONAL STANDARDS AUTHORITIES	7 STATE & LOCAL OFFICES OF WEIGHTS & MEASURES (OWM's)	8 STANDARDS & TESTING LABORATORIES AND SERVICES	9 REGULATORY AGENCIES (excl. OWM's)	10 DEPARTMENT OF DEFENSE (excl. Stds. Labs)	11 CIVILIAN FEDERAL GOVT AGENCIES (exc. Stds Labs & Reg. Ag.)	12 STATE & LOCAL GOV'T AGENCIES (exc. OWM's & Reg. Ag.)	13 INDUSTRIAL TRADE ASSOCIATIONS	14 AGRICULTURE, FORESTRY FISHING; MINING (SIC Div. A & B)	15 CONSTRUCTION (SIC Div. C)	16 FOOD/TEXTILE/LBR/PAPER/LEATHER/ETC. (SIC 20-26, 31)	17 CHEM/PETROL/RUBBER/STONE/CLAY/GLASS... (SIC 28-30, 32)	18 PRIMARY & FAB. METAL PRODUCTS (SIC 33-34, 391)	19 MACHINERY EXCEPT ELECTRICAL (SIC Major Gp 35)	20 ELECTRIC AND ELECTRONIC EQPMT (SIC Major Gp 36)	21 TRANSPORTATION EQUIPMENT (SIC Major Gp 37)	22 TRANSPORTATION & PUBLIC UTILITIES (SIC Div. E)	23 TRADE/INS/FIN/REAL EST/PERS SVCS/PRINT (SIC F-H, bal I, 27)	24 HEALTH SERVICES (SIC Major Gp 80)	25 GENERAL PUBLIC
1 KNOWLEDGE COMMUNITY (Science, Education, Prof. Soc. & Publ.)	3 2 / 4 / 2	2 2 / 3 / 2	4 2 / 4 / 2	3 1 / 3 / 2	3 / 4 / 2			3 / 2 / 2	3 1 / 3 / 2	3 1 / 4 / 2	3 1 / 4 / 1		3 2 / 3 / 2						1	3 1 / 4 / 1	3 1 / 4 / 1	3 2 / 4 / 2		1	1 1 / 1 / 1
2 INTERNATIONAL METROLOGICAL ORGANIZATIONS	2 2 / 2 / 2	1 / 3	1 / 1	2 2 / 1 / 1	2 2 / 2 / 1																				
3 DOCUMENTARY STANDARDIZATION ORGANIZATIONS	4 2 / 2 / 3	4 2 / 3 / 2	2 2 / 3 / 2	3 2 / 3 / 2	2 2 / 3 / 1			2 2 / 3 / 1	3 2 / 3 / 3	4 2 / 3 / 1	2 2 / 3 / 1		4 2 / 3 / 2						1	2 2 / 4 / 1	2 2 / 3 / 1	4 2 / 4 / 3	1	1	
4 INSTRUMENTATION INDUSTRY (SIC Major Gp 38)	2 2 / 3 / 2	3 2 / 2 / 1	3 2 / 3 / 2	4 2 / 4 / 1	4 2 / 4 / 2			3 2 / 4 / 2	3 2 / 3 / 2	3 1 / 4 / 2	3 2 / 4 / 1		2 2 / 2 / 1			1	1	1	2	3 2 / 4 / 2	3 2 / 4 / 2	3 2 / 4 / 3	2	1	1
5 NBS	3 2 / 4 / 2	3 2 / 3 / 1	2 2 / 2 / 1	3 2 / 4 / 1	3 1 / 4 / 1			3 2 / 4 / 1	3 2 / 2 / 1	1 / 3	3 2 / 3 / 1		2 2 / 1 / 1						1	3 2 / 3 / 1	3 2 / 3 / 1	4 3 / 3 / 3		1	
6 OTHER U.S. NATIONAL STANDARDS AUTHORITIES																									
7 STATE & LOCAL OFFICES OF WEIGHTS & MEASURES (OWM's)																									
8 STANDARDS & TESTING LABORATORIES AND SERVICES	2 2 / 2 / 2		3 2 / 3 / 2	3 2 / 4 / 2 R	3 1 / 4 / 2 R			3 1 / 4 / 1	3 2 / 3 / 1	4 2 / 4 / 2	3 1 / 3 / 1		2 1 / 2 / 1				1	1	1	3 1 / 4 / 1	2 2 / 4 / 1	3 2 / 3 / 1	1		
9 REGULATORY AGENCIES (excl. OWM's)	3 2 / 2 / 2		3 2 / 3 / 2	2 2 / 3 / 2 R	3 2 / 3 / 1 R			2 2 / 3 / 2 R	3 2 / 3 / 2	2 1 / 2 / 2 R	3 2 / 3 / 2 R		2 2 / 2 / 1 R			1 / R	1 / R	1 / R	1 / 2 R	3 2 / 4 / 2 R	3 2 / 4 / 2 R	3 2 / 4 / 2 R		2 / R	1 1 / 1 / R
10 DEPARTMENT OF DEFENSE (excl. Stds. Labs)	2 2 / 3 / 2		1 2 / 3 / 1	3 1 / 4 / 2 R	2 1 / 3 / 1 R			3 2 / 4 / 2 R	2 2 / 1 / 1	2 2 / 4 / 1	3 2 / 2		2 2 / 2 / 1						3 2 / 2 / 2 R	3 2 / 4 / 2 R	3 2 / 4 / 2 R	3 2 / 3 / 2 R			
11 CIVILIAN FEDERAL GOV'T AGENCIES (excl. Stds. Labs & Reg. Ag.)	2 2 / 3 / 1		2 2 / 3 / 1	2 2 / 4 / 2 R	2 2 / 3 / 1 R			2 2 / 4 / 2 R	2 2 / 3 / 1	3 2 / 2 / 2	3 1 / 4 / 1		3 2 / 2 / 2						1 / R	3 1 / 3 / 2 R	3 1 / 3 / 2 R	3 2 / 3 / 1 R			
12 STATE & LOCAL GOVERNMENT AGENCIES (exc. OWM's & Reg. Ag.)																									
13 INDUSTRIAL TRADE ASSOCIATIONS	2 2 / 2 / 1		2 2 / 3 / 2	3 2 / 3 / 2 R	2 2 / 2 / 2 R			1 1 / 2 / 1 R	2 2 / 3 / 2	2 2 / 2 / 2	1 1 / 1 / 1		2 2 / 3 / 1						1	2 2 / 3 / 1	2 2 / 3 / 1	2 2 / 3 / 1			
14 AGRICULTURE, FORESTRY FISHING; MINING (SIC Div. A & B)																									
15 CONSTRUCTION (SIC Div. C)																									
16 FOOD/TOB/TEXTILE/APPAREL/LBR/FURN/PAPER/LEATHER (SIC 20-26, 31)																1									
17 CHEM/PETROL/RUBBER/PLASTICS/STONE/CLAY/GLASS (SIC 28-30, 32)																	1								
18 PRIMARY & FAB. METAL PRODUCTS (SIC 33-34, 391)																		1							
19 MACHINERY, EXCEPT ELECTRICAL (SIC Major Gp 35)	1									1			1						2	1	1				
20 ELECTRIC AND ELECTRONIC EQPMT (SIC Major Gp 36)	2 2 / 3 / 2		1 1 / 3 / 1	3 2 / 4 / 3 R	2 1 / 3 / 1 R			2 2 / 4 / 3 R	2 2 / 2 / 2	3 2 / 4 / 2	2 1 / 4 / 2		3 2 / 3 / 2				1	1	2	3 2 / 4 / 3	3 2 / 4 / 3	2 2 / 4 / 2	2	1	1
21 TRANSPORTATION EQUIPMENT (SIC Major Gp 37)	3		2	3 2 / 4 / 2 R	3 / R			2 2 / 4 / 2 R	2	3 2 / 4 / 2	2 1 / 3 / 2		3 2 / 2 / 2							3 2 / 3 / 3	3 2 / 4 / 3	3			
22 TRANSPORTATION & PUBLIC UTILITIES (SIC Div. E)	2 2 / 3 / 2		2 1 / 3	3 2 / 4 / 2 R	2 2 / 3 / 2 R			3 2 / 4 / 2 R	3 2 / 4 / 2	3 2 / 3 / 3	2 2 / 3 / 2		1 1 / 2 / 1							3 2 / 3 / 3	3 2 / 3 / 3	3 2 / 4 / 3			
23 TRADE/INS/FIN/REAL EST/PERS SVCS/PRINT-PUB (SIC F-H, bal. I, 27)				1 / R																1 / R			2		1
24 HEALTH SERVICES (SIC Major Gp 80)	?			1 / R					1											1 / R				1	
25 GENERAL PUBLIC																							1 / R		1

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- 1 = Minor
- 2 = Moderate
- 3 = Important
- 4 = Major

R = Flow of requirements info dominates

? = Unknown, X = Not studied, Blank = 0

Figure 3. Direct measurements transactions matrix for electromagnetics.

for traceability to NBS. They do it partly by having their own reference standards calibrated at NBS and partly by buying calibrated test instruments from manufacturers who, in their turn, use reference standards calibrated at NBS.

The measurement system for high energy CO_2 lasers is now entirely controlled by the DoD. These devices are being developed for weapons, and early disagreements on measuring their performance led to the formation of an ad hoc committee among the armed services, which assigned to NBS the task of developing standard calorimeters to measure the energy delivered by these devices. At first the NBS calorimeters were taken to the testing ranges for evaluation by NBS personnel. When they had been established as a measuring system under good statistical control, they were transferred to the custody of Newark Air Force Station, where the service begun by NBS is being continued.

Commercial airlines and ships use electromagnetic aids to navigation that are generally derived from technology developed by the Department of Defense, but make lower demands on performance.

The Telecommunications Industry serves the home entertainment industry, emergency services, and common carriers of information such as telephone conversations and digital data. The first two of these make very low direct demands on measurement technique. They mostly use frequencies below about 200 MHz, so that performance is limited by background noise rather than the engineering of the equipment. However, these services are an important part of the electromagnetic interference problem, both as sources and as victims. The solution of this problem will require regulations based on sound measurement techniques. The common carriers operate at a much higher level of technical sophistication, and so demand good measurement techniques to maintain performance. They must respond to a rapidly growing demand for channel capacity as the direct communication of digitized information between computers is added to the already vigorous telephone traffic. To meet this demand, communication along wires has been supplemented by multiplexed communication along coaxial lines and line-of-sight terrestrial microwave links. Large numbers of microwave links via orbiting satellites are being added to these at present, and in the future fiber optic links will become important.

The giant among the common carriers is the American Telephone and Telegraph Company, which is almost completely self-sufficient in its measurement system, as it is in all its operations. Independent companies are appearing to take advantage of new types of traffic, such as the direct communication of data between computers, and new technology such as satellite communication. These companies must maintain close ties with the overall U.S. National Measurement System, because they buy their equipment from a variety of independent manufacturers.

The Regulatory Agencies depend heavily on measurements to set regulations and to enforce them. Their measurements must be able to survive challenges in court. They usually derive their measurement techniques from the sources described in section 2.5.1. They need national measurement standards maintained at NBS for independent proof of their accuracy.

3. IMPACT, STATUS AND TRENDS OF THE MEASUREMENT SYSTEM

3.1 Impact of Measurements

3.1.1 Functional

There are three fields in which electromagnetic measurements of high accuracy and reliability are required in order to make complex systems function. They are: military avionics; satellite communications; and remote sensing.

Since the time of World War II, the U.S. Department of Defense has been the world leader in the development of rf and microwave technologies applied to: early warning radar; side-looking radar; the guidance of terrain-following airplanes; the guidance of weapons; navigation; and telecommunication. Our national security and our national bargaining position in international affairs depend in no small measure on our leadership in these technologies. The systems that have been developed are very complex, and are assembled from components and sub-systems procured from a wide variety of manufacturers, both large and small, that comprise the U.S. aerospace/defense industry. All these components and sub-systems must be compatible with one another and must meet stringent specifications for performance. This can be accomplished only if the three armed services and the industry that serves them have a unified system of physical measurements for the quantities that specify operating characteristics and performance.

The formal mechanism for setting up such a system of measurement is to require all measurements made by the three armed services and their industrial contractors to be referred to standards that are traceable to the national standards maintained by NBS. A close cooperation between the electromagnetic measurement and standards program at NBS and the Department of Defense has existed since 1958 and has contributed significantly to the success of the technology it serves.

Satellite communications were developed during the '60s, by a combination of the Department of Defense and the National Aeronautics and Space Administration, followed in due course by the COMSAT Corporation, which was formed when the time was propitious for commercialization. This form of telecommunication depends on the reliable reception of very weak signals. This becomes very obvious as one contemplates the large dish antennas that are used. The highest performance is required of all components of the system, particularly the antennas. There is therefore a demand for accurate measurements, both for "tuning up" the system and for acceptance of components from their various manufacturers. One of the payloads that are planned for the NASA space shuttle is an orbiting standards platform, loaded with instruments to test satellite communication systems. This will be used to calibrate ground stations, which in turn can then measure the performance of flying satellites. The whole of a satellite communication system must be monitored constantly to maintain reliable performance.

Remote sensing with rf and microwave radiation is a technique that has been developing slowly and is still a long way from reaching its full potential. It depends on deducing variations in the dielectric properties of unseen objects by measuring the scattering of electromagnetic radiation, either in the form of short pulses or in the form of continuous radiation with variable frequency. The required information is obtained from quite small variations in the scattered radiation, and when dielectric anomalies are found, a connection must be established with variations in composition or structure before the information becomes useful. Good electromagnetic measurement technique is required, coupled with a data base to aid interpretation. The most important application of this technique will be to the detection and measurement of moisture in soil, concrete, grain, etc. It has also been applied to mapping rock strata (including coal seams), finding underground pipes and voids, detecting plastic land mines, and measuring the depth of glaciers and sea ice.

3.1.2 Economic

Of the three fields mentioned in the previous section, military avionics and satellite communications support large industries, the latter of which is growing at a rapid rate. If remote electromagnetic sensing fulfills its promise as an aid to water management in farming, its direct economic effect will be enormous. Another field that may develop a large economic significance in the next few years is the regulation of electromagnetic interference. Sales of the products of various industries will depend upon proving compliance with regulations that are in the process of being written now.

The total U.S. military procurement of electronic equipment was $14 billion in 1976, of which $4 billion was spent on avionics and missile guidance systems. In addition a large amount is spent on measurements to support maintenance of equipment that is already in use. The Air Force alone has about 160 field calibration centers (PMELS) to maintain its measuring instruments.

Satellite communication systems serve a market of about $1 billion per year, of which half is civilian and half is military. It is growing at the rate of 12% per year. In the period from 1975 through 1983, there are plans to launch 51 new satellites and build at least 2900 new commercial ground stations: 51 for the Intelsat system, 58 for U.S. domestic use, 200 for shipboard use as part of the MARISAT program, and 2500 in Brazil for a new communications network. The Intelsat ground stations cost about $5 million each, the MARISAT terminals will cost about $20K each, and the others range from $200K to $2M. Performance is at a premium, and contracts between satellite users and vendors usually have incentive clauses which pay 5 to 10% extra for radiated power exceeding an agreed minimum value and up to 35% for lifetime of performance up to specification. The measurements required to determine the payment of incentive bonuses are at the limit of attainable accuracy, and they control the vendors' profit margins. Measurements required just to optimize performance can become quite expensive. The antenna range to test Intelsat 4 cost $550K, and Intelsat 5 will require 10,000 times as many measurements as were needed by Intelsat 4.

The real economic promise of remote electromagnetic sensing is in water management in agriculture, a field in which it has yet to be proven and accepted. In particular, accurate methods are needed for measuring the moisture content of grain and the distribution of water in the soil, and electromagnetic techniques are under development for both of these. The annual grain harvest in the U.S. is about 10 billion bushels, and it sells for an average price of about $3 per bushel. This price is reduced by 1¢ for every ½% by which the water content exceeds 13% in wheat or 15% in corn, and the determination depends on sampling and using instruments with errors of about 2 or 3%. If the moisture in corn is allowed to exceed 18%, then moulds can grow and make it inedible. In 1970, 1% of the U.S. corn crop was affected this way. In 1975 it was 11%. It requires 10,000 Btu per bushel to dry grain from 20% to 13% moisture. An even greater problem in Western farming is the control of irrigation. Water itself is scarce. If too little is used the crop dies. If too much is used it washes out salts from the soil and concentrates them in places where a shallow water table encourages evaporation. Already 150,000 acres in Montana have been lost to agriculture because of this "saline seep," and another 10,000 acres per year are going. Electromagnetic measurements may not solve all the measurement problems associated with water management, but they appear to offer the best hope at present.

In October 1975, Canada passed an Amendment (SOR 75-629), to the Canadian Radio Act requiring the enforcement of much more restrictive laws governing the emission of electromagnetic radiation from all manner of devices, excluding legal transmissions for communications. The Act now stipulates that such devices will be equipped with EM noise suppression equipment by the manufacturer who, in turn, must maintain records of proof of testing, ensuring that such devices are compatible with the limits set by the Act. The Act covers equipment "generating electromagnetic noise" such as: spark ignition systems of vehicles and other devices equipped with internal combustion engines, electric motors, medical equipment, industrial sources, computers, welding equipment, process controls, etc. It also covers radiation conducted back into power transmission lines from equipment, especially television receivers. This far-reaching Act applies to a substantial U.S. export market, e.g., the internal combustion engine powered products market which in 1974 amounted to $3.6B.

In the U.S. the FCC is acutely aware of the growing EMI problem and is seriously considering further regulatory actions to meet the problem. Accordingly, the FCC plans to update regulations Parts 18 and 15; the former deals with industrial, scientific, and medical equipment while the latter deals with low-power intentional radiation (e.g., wireless intercoms), and with unintentional radiation (e.g., electronic and video games). To this end the FCC has looked at the amended Canadian Radio Act and has proposed changes to Part 15 (Docket 20780), and to Part 18 (Docket 20718), to include interference from broadband sources such as ignition systems (Docket 20654). The impact of FCC actions will be substantial, affecting the following products (1972 Department of Commerce data): motor vehicles - $39B, construction machinery - $3.8B, electric motors - $2.4B, farm machinery and equipment - $1.8B, electronic computing equipment - $4.6B, household appliances - $3.9B, industrial controls - $1.4B, etc.

The FCC prefers requiring U.S. manufacturers to make their products EMI proof; i.e., control the susceptibility of products to EM interference. Currently, FCC has no legal authority to require such; however, if the action of Senator Goldwater (S. 3033) and Congressman Vanik (H.R. 7052) succeeds in amending Section 302 of the Communications Act then the FCC may indeed make reasonable regulations governing: (1) the interference potential of devices that can cause harmful interference to communications, and (2) the use of protective components in audio and visual electronic equipment to reduce susceptibility. This would make the whole consumer electronics market ($7.5B in 1976) depend upon meeting regulations based on fairly sophisticated electromagnetic measurements.

The industrial part of the laser market was $384M in 1976, and is growing at the rate of 22% PA. The use of all these lasers will be controlled by OSHA regulations, based on the BRH classification.

3.1.3 Social

The most important direct social consequence of electromagnetic measurements is in the enforcement of safety regulations covering direct radiation hazard and, to a lesser extent, electromagnetic interference with control systems. It is a somewhat negative benefit: our lives are not threatened by the electromagnetic technology that serves us. The particular threats from which we are protected include microwave ovens, radar systems, TV and radio transmitters, and industrial rf equipment.

3.2 Status and Trends of the System

Most of the National Electromagnetic Measurement System is under good statistical control because the dominant user - The Department of Defense - has insisted on the traceability of all essential measurements to national standards. Adequate measurement and calibration services are available to support most of the electromagnetic equipment in use at present. The challenges for the future are: to support the maturing parts of the technology more efficiently; to develop measurement techniques and standards to support new technology that is being developed now and will become commercially important during the next few years; to develop a measurement base for the regulation of radiation hazard and interference without unnecessary restriction of electromagnetic activities; and to fully exploit the possibilities of remote electromagnetic measurement.

A trend of the recent past that is maturing now is the use of the mini-computer to improve the efficiency of the measurement process. Early microwave measurement systems depended for their accuracy on very accurately made components, whose residual errors were tuned out for each frequency with stub tuners. This is not necessary when a computer is available to perform manipulations of scattering matrices. Instead, the effects of imperfect components are measured using a set of check standards. The information is stored by the computer and automatically applied as a correction to subsequent measurements. With the aid of a programmable signal generator it becomes possible to repeat a set of measurements rapidly at many different frequencies without any retuning. Systems that use this principle are the Automatic Network Analyzer, that compares the phase and amplitude of incident and reflected waves at two measuring ports, and the more recently invented 6-port coupler, that uses interference between signals in different branches of a network to derive the same information from measurements of power only at four measuring ports.

Both these systems have the added advantage of allowing much greater flexibility in the choice of reference standards. In particular, they lend themselves very conveniently to self-calibration procedures that can eliminate the need for many of the reference standards for dimensionless ratios that are still used very heavily in electromagnetic metrology. As automatic systems take a more prominent part in metrology, the supporting organization of national standards and calibration services can become more compact than it is at present.

The computer has had a similarly profound influence on antenna measurements, where it can be used to transform measurements of the near field of an antenna, that are relatively easy to make, into a map of the far field, which is the region of greatest interest.

Of the developing technologies that will require new measurement techniques to support them, telecommunication will make the greatest foreseeable demands. The desire for direct communication at a very high bit rate between computers is causing a great increase in the demand for channel capacity. It is also leading a trend to use pulse code modulation to carry information instead of the familiar relatively narrowband modulation of a continuous carrier wave. It is coming to be recognized that this digital mode of communication also makes the most efficient use of channel capacity for audio and video information. Thus, many of the new systems will call for a much heavier emphasis on time domain measurements, which are generally in a more primitive state than the available techniques for frequency domain measurements.

Satellite communications systems will call for measurements at very low power levels, and for the accurate characterization of very large and elaborate antennas. The frequencies used are spreading into the millimeter wave region, limited only by the absorption of the atmosphere.

A new communication system that is essentially fully engineered but not yet deployed uses millimeter waves propagating in oversize circular waveguide. It has the characteristic that it offers a very high channel capacity for a cost that is competitive with other systems only if all the channels are used. The system does not have the flexibility to offer a lower capacity at a proportionately lower cost, so its future is uncertain in the face of competition from fiber-optic systems.

Other, mostly military, applications of millimeter waves are under development. The measurements they will require for support will differ from present-day microwave measurements in that there will probably be much more call to characterize transmission systems that will support multiple modes of propagation at the operating frequency. Inconvenient physical size will also limit the use of some of the techniques presently used for microwave measurements.

The future of optical fibers as a transmission medium appears to be more certain. They have the advantage that single fibers offer moderate channel capacity at moderate cost, but are very compact so that higher capacity can easily be achieved by cabling. This flexibility will permit the testing of many experimental systems and an orderly progression to greater complexity, without the barrier of having to design an expensive system with inadequate experience of the performance of components in the field. The technical problems of the manufacture of low-loss fibers, and sources, modulators and detectors with acceptable reliability, are being solved. Reasonable projections of the cost of fiber-optic systems look attractive. Therefore, it is reasonable to expect them to come into widespread use in the next few years. Experimental systems are already being installed for short-range communication within cities (e.g., cable TV links) and for transmitting control signals in aircraft. The present size of the market is small ($25M per year) but the rate of growth is 40% per year. The measurements and standards required to support fiber-optic communication systems will probably be similar to those required by microwave systems: power, scattering parameters of components, and dispersion of transmission lines. Measurements of the index profile of fibers will be important to the manufacturers, but system design and trade in components are more likely to depend on measurements of performance; i.e., dispersion and attenuation. These techniques and standards have yet to be developed.

Much work remains to be done in the development of definitions, standards, and measurement techniques for electromagnetic interference and radiation hazards, especially as regulations in the process of being written could cause unnecessary confusion and restriction of activities unless they are based on sound measurement techniques that allow a unique determination of compliance. Methods of measuring the interaction (both emission and susceptibility) of devices with interfering fields, and probes with which to measure ambient fields, all exist but need development to cover a wider range of frequency, field strength, and response time. This last is particularly important because of the random, impulsive nature of interfering fields. More work must also be done to define realizable measures of interfering fields that can accommodate their statistical fluctuations.

Finally, the full exploitation of remote electromagnetic measurements will require the compilation of a base of data on the dielectric properties of materials and their variation with physical condition. It will also require a systematic exploration of the limits of detectability and interpretation of dielectric anomalies in various conditions. This is a field that needs a theoretical framework on which to organize a lot of empirical observations.

4. SURVEY OF NBS SERVICES

All NBS electromagnetic measurement and calibration services, and the standards that support them, are developed and maintained by the Electromagnetics Division in Boulder, Colorado. The basic electrical standards, and electrical measurements that are not significantly affected by the dynamics of propagating waves, are the province of the Electricity Division, in Gaithersburg, Maryland.

4.1 The Past

The NBS Electromagnetics Division traces its origin to two primary sources. The first is the work within the National Bureau of Standards on radio communications, which began in 1904. The second is the Electronic Calibration Center, which was set up within the Bureau in 1957, in response to urgent needs arising within the Department of Defense.

On the radio side, the first work associated with the Bureau was under Dr. Louis W. Austin, a guest worker who was investigating, for the U.S. Navy, the practical application of radio-telegraphy. From 1908 to 1932, Dr. Austin headed the U.S. Naval Radiotelegraphic Laboratory at the Bureau. In 1911, the Bureau itself entered the radio field, when J. Howard Dellinger was assigned the problem of calibrating a "wavemeter." Soon thereafter, Dellinger became Head of a new Section in the Electrical Division called "Radio Measurements."

The Bureau was very active in the entire field of radio during both World Wars. It supported the development of commercial radio during the 1920's, and was closely connected with the establishment of the Federal Radio Commission, later renamed the Federal Communications Commission. War-time needs during World War II stimulated heavy Bureau involvement in radio propagation research and the formation at the Bureau of the Interservice Radio Propagation Laboratory. From 1925 to the end of World War II, the Bureau was engaged in studies of the ionosphere and in radio engineering projects, including aeronautical radio guidance systems, a blind landing system, the radiosonde, and early developments of the proximity fuse. With a single important exception (new precise frequency measurements), radio <u>standards</u> work went into an eclipse in that period.

Following World War II, the Radio Section (which included the Interservice Radio Propagation Laboratory) was renamed the Central Radio Propagation Laboratory (CRPL) and became the central agency of the nation for basic research in the propagation of radio waves. CRPL had division status and was organized into nine sections. Its operations included all the research and standards functions of the former Radio Section of the Bureau's Electrical Division. Research in the lower frequencies was extended into the ultrahigh frequency and microwave regions, for the new fields of television, FM broadcasting, and military and commercial radar. In 1954, CRPL moved to the new Bureau site at Boulder, Colorado, in order to find a more favorable radio environment than that existing in the Washington, D.C., area, and as a part of a general move to disperse Government facilities in response to the nuclear bomb threat.

After the move from the east coast, the Radio Standards Division was formed within CRPL. In 1961 it was separated from CRPL and became the Radio Standards Laboratory (RSL). In 1965, CRPL was transferred from NBS into the newly created Environmental Sciences Services Administration.

In 1962, RSL was divided into two Divisions - Radio Physics and Circuit Standards. In 1967, a third Division, Time and Frequency, was added, and the names of the existing Divisions were changed to Radio Standards Physics and Radio Standards Engineering, respectively. By this time all three Divisions were part of the NBS Institute for Basic Standards. In 1970, the name of the Radio Standards Engineering Division was changed to Electromagnetics, that of Radio Standards Physics to Quantum Electronics; and for the first time in sixty-six years, the Bureau had no organizational unit affiliated with it bearing the name "Radio."

Meanwhile, during the 1950's, the growing complication and sophistication of the electronic equipment used by the military was leading to increasing problems in connection with maintenance and repair and with the standards supporting the maintenance and repair test equipment. In 1951, the Air Force took initial steps in requesting that a new and large-scale facility be established in the Bureau to meet an increasing need for calibration of its electronic standards in order to obtain "traceability" to the national standards. Soon thereafter, the Army and Navy made similar requests. In 1957-58 these requests culminated in the establishment of the Electronic Calibration Center at the Boulder Laboratories. This facility was grafted onto the ongoing work of the Radio Standards Division.

While the basic mission of developing standards and measurement techniques for electromagnetic measurements continued, two significant changes occurred between 1968 and 1974. A new and major emphasis upon applied metrology began. For example, the Division's basic measurement expertise was applied to problems such as measuring the electromagnetic noise in coal mines so that the Bureau of Mines could obtain suitable communication equipment. The second change was that major work was begun on automated measurements. The Division had had several small efforts on automated measurements, but finally funds were accumulated and programs redirected so that a concentrated effort could begin.

Today automated measurement systems have arrived, and are expected to play a prominent part in the consolidation of the rf and microwave calibration services to improve their efficiency and rationalize their scope. Vigorous development is in progress to create measurement techniques and standards for: millimeter wave and fiber optic systems; complex antennas and other components of satellite communication systems; transient waveforms; electromagnetic interference; hazardous fields; and remote electromagnetic sensing. Responsibility for laser power and energy measurements was transferred to the Division in 1974, when the Quantum Electronics Division was abolished and its personnel divided between the Electromagnetics and Time and Frequency Divisions.

4.2 The Present-Scope of NBS Services

4.2.1 Description of NBS Services

The Electromagnetics Division of NBS has recently been drastically reorganized in response to a reordering of priorities. This description will speak to the Division in its new form. The new Electromagnetics Division is divided into five programs:

1. Guided Wave Metrology
2. Electromagnetic Sensing Metrology
3. Electromagnetic Interference/Radiation Hazards
4. Signal Waveform Metrology
5. Antenna Systems Metrology

The following five subsections will comprise brief descriptions of the services offered by these five programs.

4.2.1.1 Guided Wave Metrology

This program provides standards and measurement services for the basic quantities describing waveguide systems and continuous waves propagating through them: power, voltage, attenuation, dispersion, and reflection coefficient. At present, there is a comprehensive calibration service for transfer standards of these quantities, both in coaxial line and in the various standard waveguides at appropriate frequencies. The frequency ranges covered are from 30 kHz to 1 GHz for voltage, and roughly from 10 MHz to 65 GHz (with a gap from 40 GHz to 55 GHz) for the other quantities. These services are in process of being cut down to the minimum that is considered essential for maintaining the traceability of the National Electromagnetic Measurement System to standards maintained by NBS. This will be discussed in section 4.5.

In addition to these services, work is in progress to develop new standards and measurement techniques. These include the 6-port coupler, which is expected to play a prominent role in the rationalization of microwave measurements as well as providing the most promising approach to millimeter wave measurements. The Superconducting QUantum Interference Device (SQUID) is being developed as a way of measuring rf power at very low levels. Development of fiber optic standards and measurement techniques is beginning. Preliminary work is in progress on the measurement of power and dispersion in optical fibers.

4.2.1.2 Electromagnetic Sensing Metrology

This program develops the mathematical foundation for systematic use of remote sensing of dielectric anomalies, as well as a data base correlating the dielectric properties of materials with other physical properties. Much of the work is done in collaboration with other government agencies that need to use remote sensing techniques, so as to maintain the discipline of solving real problems while developing the basic tools. Work is in progress to develop electromagnetic measurement techniques for: moisture in grain (with the Department of Agriculture); the structure of coal layers above mines (with the Bureau of Mines); the structure of soil in potential landslide areas (with the Geological Survey and the Federal Highway Administration); the distribution of water in soil (with several Western State governments); and the progress of curing concrete (as part of a larger program in other parts of NBS). Measurements are being made of the dielectric properties of moon dust, to assist remote monitoring of the radiation temperature of the moon's surface. A system has been developed for the Army to use to detect plastic land mines. All these projects will expand the body of available technology to be applied to other problems as well as solving the problems of primary interest to the cooperating agencies.

4.2.1.3 Electromagnetic Interference/Radiation Hazards

This program develops techniques for measuring the strength of interfering fields over a wide range of frequency, time, and amplitude, and the emission of and response to these fields by devices to be tested. These techniques are then made available through workshops, seminars, and voluntary standard-setting committees. The goal is to cover the range of frequency from 10 kHz to 30 GHz, with response times down to 10^{-8} s, and at power densities from 10^{-10} W/cm^2 to 1 W/cm^2. The measuring devices under development include anechoic chambers (for frequencies above 1 GHz) and TEM cells and field synthesizers (for frequencies below 1 GHz) to measure emission and susceptibility and to calibrate field probes. Probes to measure various combinations of the components of electric and magnetic field are also under development. Part of the desired range is already covered, but much remains to be done before complete coverage will be available.

4.2.1.4 Signal Waveform Metrology

This program develops techniques and standards for measuring waveforms (both transient and repeating) in the time domain. Both optical (envelope) and electrical waveforms are being worked upon, and the ultimate goal is to attain a time resolution of 10^{-12} s. A calibration service is offered for the transition times of pulse generators and filters in the range above 10^{-11} s, and for the spectrum of impulse generators in the range 5 MHz to 6 GHz.

Measurement Assurance Programs are offered for laser power and energy in various ranges for HeNe, Nd-YAG, and CO_2 lasers.

4.2.1.5 Antenna Systems Metrology

This program develops techniques for measuring the performance of the large antennas used for satellite communication and advanced radar systems. It also maintains noise standards to test the performance of the associated receivers. Special measurement services are performed, including: determination of the radiation patterns of antennas by scanning the near field on a planar, cylindrical, or spherical surface (whichever is most appropriate); determination of the gain on axis by an extrapolation method; and determination of the performance of complete satellite ground stations using radio stars for reference. Also, a regular calibration service is offered for standard noise sources. This group provides consultation on antenna problems, such as the design of the proposed Orbiting Standards Platform and the testing of the Global Positioning System, and is developing new measurement techniques such as a system to test the response of small antennas to impulsive fields.

4.2.2 Users of NBS Services

The direct services provided by the NBS Electromagnetics Division may be divided into three categories: research and development of new standards and measurement techniques; special testing and measurement services; and calibration of transfer standards.

Research and development account for 50% of the total. Over 65% of this is performed for the various branches of the Department of Defense. Most of the remaining 35% is performed for other agencies of the Federal Government, mostly regulatory agencies.

Special testing and measurement services account for about 30%. Over 80% of this is for the Department of Defense, the remainder being also mainly for regulatory agencies of the Federal Government.

Calibration is the smallest category, accounting for less than 20% of the total. One half of this is done for the Department of Defense, almost exclusively for the four Metrology Centers of the armed services. Nearly all of the remainder is for defense contractors in private industry, in fulfillment of requirements for traceability to NBS.

4.2.3 Alternate Sources

The four large Metrology Centers of the Department of Defense, and the calibration laboratories of many large aerospace and instrument corporations, are all capable of performing electromagnetic measurements and calibrations under good statistical control although none offer so comprehensive a service as NBS. The maintenance of statistical control relies heavily on the concept of traceability to NBS, so there is no serious alternative to using NBS as the central reference point of the National Measurement System. However, a question that is open to debate is how wide a variety of transfer standards needs to be calibrated at NBS, and how far the users should carry the burden of converting quantities to be measured into a form that can be referred directly to the national standards. Negotiations are in progress to cut down the transfer standards calibrated by NBS for the Department of Defense to the minimum set that is essential to maintaining traceability. Similar discussions will be held with the aerospace industry, but the opportunity to bring about a significant reduction in calibrations there is less obvious.

Another method by which a large part of the load of routine calibrations can be moved away from NBS is by commercial laboratory accreditation. Accredited laboratories would offer calibration services that are inspected by NBS so as to give some degree of assurance of their quality. An invitation to interested organizations to seek accreditation was published in the Federal Register of February 25, 1976, pages 8163-8168. This document describes the procedures for setting up an accrediation program for any class of measurements. So far, there has been only one formal application for accreditation in electromagnetic measurements. Since the whole accreditation program is in its early stages of development, it will be at least two or three years before proper arrangements can be made.

4.2.4 Funding Sources for NBS Services

Section 4.2.2 describes the distribution of direct users of NBS services in electromagnetic measurements and standards. These users pay for the services they receive, and this accounts for 45% of the funding of the NBS Electromagnetics Division. The remaining 55% comes from direct appropriation for research and development in anticipation of future needs.

4.2.5 Mechanism for Supplying Services

The direct services were described in section 4.2.2. In addition, staff members of the NBS Electromagnetics Division are active in several voluntary standards committees, publish monographs on the techniques for particular types of measurement (e.g., Metrology Guides), publish papers in professional journals, organize workshops for the detailed discussion of various measurement problems, and occasionally organize conferences such as the Laser Damage Symposium and the Conference on Precision Electromagnetic Measurement.

4.3 Impact of NBS Services

4.3.1 Economic Impact of Major User Classes

The major users of NBS services in electromagnetic measurements are: the Department of Defense; the aerospace industry (serving defense, civil aviation, and satellite communication); and the federal regulatory agencies. The economic significance of these users was discussed in section 3.1.2 of this study.

To summarize, our national defense relies heavily on surveillance with sophisticated radar systems to give early warning of attack, and possession of airplanes and missiles with electromagnetic guidance systems, all of which need NBS services to support the measurements needed for acceptance and maintenance. Satellite communications need the most accurate available measurements for adjusting complex systems for optimum performance and to determine the payment of performance bonuses. The regulation of electromagnetic interference and radiation hazard could inhibit commerce significantly unless it is based on sound testing methods that determine compliance unambiguously.

4.3.2 Technological Impact of Services

The technological impact of NBS services is greatest when the technology they serve is in the early stages of being made to work. As technologies mature the support they receive from measurement services is more for maintenance than development, and the measurement services themselves should evolve so as to improve efficiency rather than accuracy.

Twenty years ago the NBS services in basic rf and microwave measurements made an essential contribution to the development of the military radar and guidance systems that are part of the defensive posture we enjoy today. As these systems have matured, so have the measurement services supporting them. The old manual measurement systems, which were capable of great accuracy but required much skilled labor, are being replaced by computer-controlled systems that are no more accurate but a great deal more efficient in their use of time, although the operators they require are if anything more skilled than before.

The rapidly developing electromagnetic technologies of today still include radar systems, using complex phased-array antennas, as well as satellite communications, remote electromagnetic sensing (of nearby objects), and electronic servo control of vehicles and processes.

Near-field scanning methods for measuring the radiation patterns of antennas have proven to be particularly useful with phased-array antennas, which are used for both radar and satellite communications. The near-field information itself is valuable in determining the adjustments required by individual elements of an array. The use of radio stars as standard noise sources also provides a valuable tool for testing the performance of complete satellite communications ground stations, that can be used when putting a new station into service.

Measurement services connected with electromagnetic interference can save a great deal of trouble if they are used to test and correct prototype servo control systems, before the design is "frozen" and becomes expensive to change. The major automobile manufacturers in the U.S. are now using NBS-designed TEM cells for this purpose, following unfortunate experiences with early electronic servo systems in automobiles, trucks, and buses.

4.3.3 Payoff from Changes in NBS Services

The automation and consolidation of the basic rf and microwave calibration services have already been discussed. The benefit to the users is that computer-controlled systems can give much better coverage of the effects of changing frequency and power level for the same cost. The benefit to NBS is that manpower can be taken from this work and used to develop the measurement services that are expected to be needed in the future.

The payoff from the development of measurement services for millimeter waves and fiber optic systems, and for fast transient waveforms, is obvious. These are the services that will be in demand in a few years time, and now is the time to develop them.

The most fundamental change in the form of NBS services is the adoption of Measurement Assurance Programs as a replacement for most of the calibration services. This change is in progress now and will take about two years to complete. A measurement assurance program is designed to test the user's overall measurement system. It makes maximum use of check standards (that do not require calibration at NBS) to maintain statistical control. The connection to national standards maintained at NBS is through a set of transfer standards that are sent to all the users in turn, at quite long intervals of time that are determined by the stability of the users' measurement systems as monitored by the check standards.

Measurement Assurance Programs require just as much highly skilled manpower as the calibration services did, but they are capable of keeping the National Measurement System in much tighter statistical control simply because they test the whole measurement process rather than allowing the responsibility of NBS to stop at the calibration of transfer standards.

4.4. Evaluation of NBS Program

The NBS program in electromagnetic metrology is reviewed by the NBS Executive Board at the annual Base Program Review, where priorities are assigned to the various programs throughout NBS. It is also reviewed annually by an Evaluation Panel organized by the National Academy of Science. This panel consists of nine experts in the field drawn from universities and private corporations.

In the Spring of 1976, the NBS Executive Board determined that the Electromagnetics Division (which employed about 130 people full time) was larger than was warranted by the priority of its work relative to other responsibilities of NBS. Consequently, the 10 programs in the Division were consolidated into 5, with the elimination of 31 positions. At the same time, the calibration services were reduced in scope so as to retain only those services that are essential to the maintenance of traceability of the National Electromagnetic Measurement System to NBS, as discussed earlier in this report. The Evaluation Panel generally approved of the reorganization with some reservations about parts of the program that were not completely settled at the time of its examination. Judgement about performance is reserved until the wounds from the reorganization have had a chance to heal.

Public reaction to the curtailment of calibration services, expressed in the professional journals, showed that the users of these services had been satisfied with them in the past and were uneasy about the possible consequences of reducing them and dissipating the resources that supported them. However, when questioned directly about the adequacy of the remaining services, most of the users (both in the DoD and in private industry) seemed to be willing to accept the changes. Only experience will tell if further adjustments will be necessary.

4.5 The Future

The status and trends of the National Electromagnetic Measurement System were discussed in section 3.2. NBS must respond to those trends, of which the most significant are:

1) the rapid expansion of satellite communications, both military and commercial, to form a world-wide system;

2) the rapid expansion of electro-optic technology, for applications ranging from control functions within an airplane to inter-city communications;

3) the full exploitation of electromagnetic remote sensing, particularly in agriculture;

4) increasing reliance on electronic servo control of industrial processes and vehicles;

5) worsening of the problem of electromagnetic interference, as a consequence of item (4) coupled with a proliferation of CB radios and the like, leading to stricter regulations;

6) increasing public exposure to non-ionizing radiation hazard, which may be accompanied by a lowering of the permissible exposure to a level nearer that which is used in Eastern Europe.

The response of NBS has been to reorganize the Electromagnetics Division into five programs:

1) Guided Wave Metrology
2) Electromagnetic Sensing Metrology
3) Electromagnetic Interference/Radiation Hazards
4) Signal Waveform Metrology
5) Antenna Systems Metrology

The scope of these five programs, and their relationship to the technological trends mentioned above, were discussed in section 4.2.

Overall, the development and dissemination of electromagnetic metrology is declining in priority as new calls are made on the limited resources of NBS to attend to matters that are regarded as more urgent. The Electromagnetics Division recently suffered a 25% reduction in staff. This was accompanied by a 50% reduction in the volume of calibrations. Services essential to maintaining statistical control of the National Electromagnetic Measurement System will be maintained, together with the basic standards that they require. Indeed, new services will continue to be developed to meet future needs, but with shrinking resources a strong sense of priorities must be exercised.

The only program that may experience significant expansion in the near future is the development of measurement techniques and standards for electromagnetic interference. As the urgency of this problem comes to be generally recognized, it may receive priority comparable with the other new tasks that are being assigned to NBS.

5. SUMMARY AND CONCLUSIONS

In the past, the National Electromagnetic Measurement System made an essential contribution to the development and maintenance of the military systems for early warning radar, side-looking radar, the guidance of terrain-following airplanes, the guidance of weapons, navigation, and telecommunications on which our defensive posture relies very heavily. As usual, commercial technology has followed the military lead, so that today six trends can be seen that will determine the development of electromagnetic measurements and standards in the next few years:

1) the rapid expansion of satellite communications into a world-wide system;

2) the rapid expansion of electro-optic technology, particularly fiber-optic communication systems;

3) the full exploitation of electromagnetic remote sensing, particularly in agriculture;

4) increasing reliance on electronic servo control of industrial processes and vehicles;

5) worsening of the problem of electromagnetic interference, leading to stricter regulation of both sources and victims;

6) increasing public exposure to non-ionizing radiation hazard.

In response to these trends, the NBS Electromagnetics Division is being reorganized into five programs:

1) Guided Wave Metrology, which provides the basic rf and microwave measurement and calibration services, and develops stanards and measurement techniques for millimeter wave systems and fiber optics;

2) Electromagnetic Sensing Metrology, which performs the research and development necessary to enable electromagnetic waves to be used for remote sensing and characterization of inaccessible dielectric anomalies;

3) Electromagnetic Interference/Radiation Hazards, which develops standards and measurement techniques to determine the emission and susceptibility of devices of and to interfering fields, and the strength of fields to which people and equipment are exposed;

4) Signal Waveform Metrology, which develops standards and measurement techniques to characterize transient and modulated waveforms, and systems designed to transmit them, in the time domain;

5) Antenna Systems Metrology, which develops measurement techniques and provides measurement services to characterize complex antennas and associated systems used for satellite communications.

This reorganization is a direct response to information collected for this study of the National Electromagnetic Measurement System.

APPENDIX A - METHODOLOGY OF THE STUDY (AND ACKNOWLEDGMENTS)

The first source of material for this study was an earlier description of the National Electromagnetic Measurement System by Francis X. Ries and Wilbur J. Anson (unpublished, July 25, 1975). In particular, the list of realized measurement capabilities (section 2.3), the history of NBS services (section 4.1), and the list of instrument manufactures (appendix B) were all taken directly from that report. Additional material was collected by Ramon C. Baird, Arthur J. Estin, Paul A. Hudson, and Charles K. S. Miller, by visiting representatives of eleven parts of the Department of Defense, three other agencies of the Federal Government, and fourteen private companies in the aerospace and telecommunications industries. A one-day meeting was held at NBS at which representatives of NBS and the four metrology centers of the Department of Defense discussed the future of the maintenance of traceability of electromagnetic measurements to NBS. Most of the material on laser measurements was contributed by Richard L. Smith. The two organizational input-output matrices were taken from a consistent set published by Raymond C. Sangster (NBSIR 75-943).

I thank all these people for their contributions to this report.

APPENDIX B - INSTRUMENT MANUFACTURERS

These lists were compiled from the 1973 "Electronic Engineers Master" (EEM). The data is presented to illustrate the large number of instrument manufacturers facilitating the measurement of the parameters supported by the Electromagnetics Division of NBS. The parameter breakdown is impedance, attenuation, phase shift, power, voltage, current, waveform, noise, EM fields, and materials properties.

WAVEFORM OF VOLTAGE, CURRENT & POWER

MEASUREMENT INSTRUMENTATION

1-Analyzers
2-Calibrators
3-Generators
4-Indicators
5-Oscilloscopes
6-Recorders

MANUFACTURERS

Active Control Instrumentation: 5
Accutronics, Inc.: 2
A. D. Data Sys., Inc.: 1
AIL, Div. Cutler-Hammer, Inc.: 1
Alden Elctrn. & Impulse Record Equip.: 1
American Astrionics: 6
American Elctrn. Labs., Inc.: 1, 5
American Time Products: 3
A. P. Circuit Corp.: 1
Applied Magnetics Corp.: 5
Applied Microwave Lab.: 3
AUL Instrs., Inc.: 1, 5
Austron, Inc.: 1
Automated Meas.: 5
B & F Instrs., Inc.: 5
B & K Instrs.: 1
Bafco, Inc.: 1
Baganoff Assocs., Inc.: 1
Ballantine Laboratories: 5, 6
Barry Resch. Corp.: 1
Beckman Instrs., (AISSD): 1, 5
Behlman Div., California Instrs.: 5
Bell & Howell Co.: 5, 6
Berkeley Nucleonics Corp.: 3
Bicron Elctrns., Co.: 3
Biocom, Inc.: 5
Biomation Corp.: 6
BLH Elctrns., Inc.: 5
Bowmar/ALI, Inc.: 1
Bowmar Instr., Corp.: 1
Calico Div., California Instrs. Co.: 5
California Instrs., Co.: 5
CELCO: 1
Chronetics, Inc.: 3
Chuo Electronics Co., Ltd.: 1, 3
Circon Corp.: 5
Clavier Corp.: 1, 5
Cober Elctrns., Inc.: 3
Collins Radio Co.: 1
Colorado Video, Inc.: 1
Comaltest: 3
Connor-Winfield Corp.: 3
Crown Int'l.: 1
Dacc Instr. Co., Inc.: 4
Damon Corp.: 1
Data Disc Inc.: 6
Data Dynamics Div.: 3
Disc Instruments, Inc.: 3
Dixson, Inc.: 5
Dranetz Engrg. Labs.: 1, 3, 4
Dumont Oscilloscope Labs., Inc.: 5
Dynair Elctrns. Inc.: 1
Dynascan Corp.: 5
Eastern Delta Corp.: 4
E G & G, Inc.: 3
E-H Resch. Labs., Inc.: 2, 5, 6
Electro/Data, Inc.: 1
Electro-Numerics: 4
Electro-Optical: 1, 5
Endevco: 6
Engdahl Enterprises: 6
Essential Elctrns. Corp.: 5
Esterline Angus Div.: 5
Exact Elctrns., Inc.: 3
E-Z Hook, Test Prods.: 5
Fairchild Electro-Metrics: 1
Federal Sci. Corp.: 1
Feedback, Inc.: 1
General Microwave Corp.: 3
General Radio Co.: 1, 3
Geo Space: 5
Gordon Alan Entprs.: 5
Gould, Inc.: 5, 6
Gralex Inds., Inc.: 3
Hallmark Standards, Inc.: 5
Harshaw Chem. Co.: 1
Heath Co.: 5
Hewlett-Packard: 1, 3, 5
Hickok Elect. Instr.: 5
Honeywell: 1, 5
Hughes Aircraft Co.: 1
ILC, Inc.: 3
Ind'l. Control Co.: 1
Infadex, Inc.: 5
Inter-Computer Elctrns.: 1
Interstate Elctrns. Corp.: 3
IRD Mechanalysis, Inc.: 1
ITI Electronics, Inc.: 5
James Elctrns., Inc.: 1
Jodon Engrg. Assocs.: 1
Kay Elemetrics: 1
Kenton Engrg. Corp.: 6
Kikusui Elctrns. Corp.: 2, 5
Kikusui Elctrns. Inc.: 5
Lab Electro-Acoustique: 1
Labgear, Ltd.: 1
Leader Instruments Corp.: 3, 5
Lecroy Resch. Sys. Corp.: 5, 6
London Co.: 1
Loral Elctrn. Sys.: 1
Magnetic Elctrns.: 3
Marconi Instrs.: 1
MB Elctrns/Textron Co.: 1
MCG Electronics Inc.: 4
Medistor Instr. Co.: 2
Meguro Denpa Sokki K.K.: 1
Meloy Laboratories: 2
Metra Instrs., Inc.: 5
MFE Corporation: 5
Micro Instr. Co.: 1, 4, 6
Micro-Tel Corp.: 1
Microwave Control Co.: 3
Miles Reproducer Co., Inc.: 6
Millen, James Mfg.: 5
Multimetric Industries.: 1
Nano Fast, Inc.: 2
Nelaon Ross Elctrns.: 1
Nicolet Instr., Corp.: 1
Northern Sci., Inc.: 1
Novatronics, Inc.: 1
Nuclear-Chicago: 1
Nuclear Data: 1
Nuclear Equip. Chem. Corp.: 1
Nuclear Meas. Corp.: 1
Optics Technology: 1
Packard Instrument Co., Inc.: 1
Panametrics, Inc.: 3
Philips Elctrn. Instrs.: 3, 5
Photron Instr. Co.: 5
Pioneer Magnetics: 1
Polarad Elctrn. Instrs.: 1
Precision Apparatus: 5
Precision Standards Corp.: 5
Princeton Applied Resch. Corp.: 1
Projects Unlimited, Inc.: 5
Quan-Tech: 1
Railway Comm.: 1
Raytheon Instrs.: 5
RCA Elctrns. Co.: 5
Rockland Sys. Corp.: 1
Rohde & Schwarz Sis.: 1
Schoeffel Instr. Corp.: 1
Scientific Measurements.: 3
Servo Corp. America: 1
Siemens Corp.: 1
Signal Analysis Inds. Corp.: 1
Signatron, Inc.: 1
Simpson Elec. Co.: 5
Simulation Prods. Div.: 1
Singer Instrumentation, Los Angeles, Oper.: 1, 3
Singer Instrumentation, Palo Alto Oper.: 1
Soltec Corp.: 1, 5
Spectra-Physics, Inc.: 1
Spectral Dynamics Corp.: 1
Spectran Elctrns.: 1
Spectrum Instrs., Inc.: 1
Sprengnether, W. F. Instr., Co., Inc.: 6
Stoddart Electro Sys.: 1
Systems Resch. Labs.: 1, 5
Systron-Donner Corp.: 1, 3
Systron-Donner Datapulse Div.: 1, 3
Systron-Donner Kruse Elctrns. Sub.: 1, 3
Systron-Donner Microwave Div.: 1, 3
Takeda Riken Industry Ltd.: 3
Tasker Inds.: 1
Technical Research & Mfg. Co.: 1
Tektronix, Inc.: 1, 2, 5
Teldyne Geotech:
Telonic Inds., Inc.: 5
Tennelek, Inc.: 1
Texscan Corp.: 1, 5
Transducer Controls Corp.: 1
Universal Ad-Yu Elctrns., Inc.: 1
Vanan Aerograph: 6
Varian Data Machines: 5
Vari-L Co., Inc.: 1
Vector Engrg.: 5
Vega Precision Labs.: 3
Velonex: 3
Vibration Instrs. Co.: 1
Viz Mfg. Co.: 5
Voiceprint Laboratories: 1
Voltex Co., Inc.: 5
Vu-data Corp.: 1, 5
Wandel & Goltermann: 1
Weston Instruments, Inc.: 1
Westronics, Inc.: 6
Wolff Industries: 5
Yewtec Corporation: 5
Zonic Tech. Labs.: 6
Zoomar, Inc.: 1

VOLTAGE

MEASUREMENT INSTRUMENTATION

1-Calibrators
2-Meters
3-Monitors
4-Standards

MANUFACTURERS

Active Control Instrumentation: 3
Airpax Elctrns.: 3
Allied Elctrns., Corp.: 3
American Aerospace Controls: 3
AMF Electrical Prods.: 3, 4
Amprobe Instr.: 3
Analogic: 1, 4
Analogic Co.: 1, 4
A.O.I.P.: 4
Astro Comm. Lab.: 2
AUL Instrs., Inc.: 4
Automatic Switch Co.: 3
Autronics Corp.: 3
B & K Instrs., Inc.: 2
Ballantine Laboratories: 1, 2, 4
Beckman Instrs., (AISSD): 4
Beckman Instrs.: 1, 4
Beede Electrical Instrs., Co., Inc.: 2
Bendix: 2
Betamite Electronic Devices: 3
Biddle, James G.: 4
Blonder-Tongue Labs., Inc.: 2
Boonton Elctrns.: 2
Bulova Watch Co., Servo Prods. Elctrns., Div.: 3
CALEX: 3
California Instrs., Co.: 2
CEA: 4
Chicago Condenser Corp.: 1
Coax Devices Inc.: 1
Collins, G. L. Corp.: 4
Compu-Systems Co.: 1
Computer Diode: 1, 4
Computer Test Corp.: 1
Conner-Winfield Corp.: 4
Constant Voltage Co.: 1
Controlotron Corp.: 3
Diversified Elctrns.: 3
Doric Sci. Corp.: 1, 3
Dranetz Engrg. Labs.: 3
Dynage: 4
Dynamic Controls Corp.: 3
Elcom Sys.: 2
Electrical Instr. Svc., Inc.: 1, 2, 4
Electro/Data, Inc.: 2
Electro-Mechanics Co.: 2
Electronic Dev. Corp.: 1, 4
Elctrns. Ltd.: 3
Elctrn. Navigation Inds., Inc.: 2
Electro-Optical Inds., Inc.: 1
Electro Sci. Inds.: 1, 4
Emergency Beacon Corp.: 2
Eppley Lab., Inc.: 4
Esterline Angus Div.: 3, 4
Fairchild Electro-Metrics: 2
Fluke, John Mfg., Co., Inc.: 1, 2, 4
General Microwave Corp.: 1, 2, 3, 4
General Radio Co.: 2
General Resistance, Inc.: 1, 4
Glentronics, Div. Sawyer Inds.: 4
Gralex Inds., Inc.: 3
Guideline Instrs., Inc.: 1, 4
Hallmark Standards, Inc.: 1, 2, 4
Heath Co.: 2
Hewlett-Packard: 1, 2, 4
HI-G: 3
Hiram Jones: 2
Holt Instr. Labs.: 1, 4
Honeywell: 2
Horex Elctrns., Inc.: 1
Hoyt Elec. Instr. Works: 2
Idalee Elctrns., Corp.: 1, 4
Ideal Precision Meter Co., Inc.: 2
Industrial Inventions, Inc.: 3
Ind'l. Test Equip.: 1, 4
Instrulab, Inc.: 4
Instrs. for Ind., Inc.: 2
International Rectifier: 4
ITT Jennings Eastern Regional Office: 2
ITT Jennings, Instr. & Systems: 2
ITT Jennings, Vacuum Elctrn. Prods.: 2
ISC Magnetics Div.: 3
Jerrold Electronics Corp.: 2
J-Omega Co.: 3
Julie Research Lab., Instruments Div.: 1, 4
Keithley Instrs., Inc.: 1
Kepco, Inc.: 1, 4
Kilovolt Corp.: 4
Kistler Instr., Co.: 1
Kratos: 2
Lab. Electro-Acoustique: 2
Leader Instruments Corp.: 2
LFE Corp.: 3
Logitek, Inc.: 3
Lorch-Adret Corp.: 1, 4
Mag-Con Engrg. Co.: 3
Marconi Instrs.: 2
MCG Electronics Inc.: 3
Medistor Instr., Co.: 1, 4
Megavolt, Inc.: 4
Meguro Denpa Sokki K.K.: 1
MFE Corporation: 3
Micro Instr., Co.: 2, 3
Microlab/FXR: 3
Millen, James Mfg.: 2
Monroe Elctrns., Inc.: 1, 4
Mura Corp.: 2
NES, Inc.: 3
NH Research, Inc.: 3, 4
North Atlantic Inds.: 4
North Hills Elctrns., Inc.: 1, 4
Ohio Semitronics: 3
Pacific Meas., Inc.: 2
PECO Corp.: 3
Pioneer Magnetics: 1
Polarad Elctrn. Instrs.: 2
Power Designs: 1, 4
Precision Standards Corp.: 1, 4
Princeton Applied Resch. Corp.: 2, 3
Quan-Tech: 2
Q.V.S., Inc.: 2
Radiation Devices Co.: 2
Railway Comm.: 2
RCA Elctrns. Comps.: 2
Reeve Elctrns., Inc.: 2
RFL Inds., Instr. Div.: 1, 4
Rohde & Schwarz Sis.: 2
Ross Engrg. Corp.: 1, 2
Rystl Elctrns. Corp.: 2
Sawyer Inds.: 4
Sensitive Research Instrs.: 2, 4
Shurite Meters: 2
Sigma Instrs., Inc.: 3
Simpson Elec. Co.: 1, 2, 4
Singer Instrumentation, Los Angeles Oper.: 2
Solar Elctrns. Co.: 2
Spectral Dynamics Corp. San Diego: 2
Spectrum Control, Inc.: 2
SRC Div.: 3
Stoddart Electro Sys.: 2
Struthers-Dunn, Inc.: 3
Systron-Donner Alpha Scientific Sub.: 1, 4
Systron-Donner Corp.: 1
Takeda Riken Industry Co., Ltd.: 4
Tektronix, Inc.: 1, 3
TRI-COM, Inc.: 1
Trio Labs, Inc.: 3
Triplett Elec. Instr., Co.: 2
United Sys. Corp.: 1
Velcnex: 4
Vidar Corp.: 3
Voltex Co., Inc.: 3
Wandel & Goltermann: 2
Weinschel Engrg. Co.: 4
Westberg Mfg. Co.: 2
Westinghouse Elec. Corp., Computer & Instr. Div.: 2, 3
Weston Instruments, Inc.: 1, 2, 4
Westronics, Inc.: 1, 3
Yewtec Corporation: 4

CURRENT

MEASUREMENT INSTRUMENTATION

1-Sources
2-Meters

MANUFACTURERS

A & D Electrical Inst.: 2
American Aerospace Controls: 1
Ballantine Laboratories: 1, 2
Computer Test Corp.: 1
Electrical Instr. Svc., Inc.: 1, 2
Electronic Dev. Corp.: 1
Ferranti Ltd.: 2
Fluke John Mfg. Co., Inc.: 1
General Resistance, Inc.: 1
Guideline Instrs., Inc.: 1
Hallmark Standards, Inc.: 2
Holt Instr. Labs.: 1
Ideal Precision Meter Co., Inc.: 2
Ind'l. Test Equipment: 1
Julie Research Lab., Instruments Div.: 1
Keithley Instrs., Inc.: 1, 2
LFE Corp.: 2
North Hills Elctrns., Inc.: 1
Q.V.S., Inc.: 2
RFL Inds., Instr. Div.: 1
Sensitive Research Instrs.: 2
Simpson Elec. Co.: 2
Sunshine Sci. Instrs., Inc.: 2
Systron-Donner Alpha Scientific Sub.: 1
Triplett Elec. Instr. Co.: 2
United Sys. Corp.: 1
Westinghouse Elec. Corp.: 2
Weston Instruments, Inc.: 2
Yewtec Corporation: 2

POWER

MEASUREMENT INSTRUMENTATION

1-Bridges
2-Calorimeters
3-Bolometers
4-Mounts
5-Monitors
6-Probes
7-Meters

MANUFACTURERS

Aircom, Inc.: 4, 6
American Elctrn. Labs., Inc.: 4
A.O.I.P.: 7
AVL Instrs., Inc.: 1
Aviel Electronics Inc.: 5
Ballantine Laboratories: 7
Bell, F. W., Inc.: 7
Bendix: 2, 5, 7
Biddle, James G.: 1
Bird Elctrn.: 1, 2, 5, 7
Boonton Elctrns.: 6, 7
Centralab, Elctrns.: 4
CES Elctrns.: 4, 6
Chemalloy Elctrns.: 2
Clarke Hess: 7
Coax Devices Inc.: 3, 4
Collins Radio Co.: 5
Comdil, Inc.: 7
Cubic Corp.: 7
Datalight Inc.: 5
Dittmore-Freimuth Corp.: 4, 6
Drake, R. L., Co.: 7
EG&G, Inc.: 1, 5
Electrical Instr. Svc., Inc.: 7
Electro Impulse, Inc.: 1, 2, 7
Elctrn. Navigation Inds., Inc.: 7
Electrophysics Corp.: 5
Emergency Beacon Corp.: 7
Esterline Angus Div.: 7
Fairchild Electro-Metrics: 7
Fannon Electric: 5
Ferranti Elec., Inc.:
Ferranti Ltd.: 7
Fluke, John Mfg. Co., Inc.: 7
Frequency Engrg. Labs.: 7
Gabriel Elctrns. Corp.: 4
Gamma Sci.: 5
General Elec.: 7
General Elec. Co., Elctrn. Comps.
Sis. Dept.: 7
General Microwave: 1, 2, 3, 4, 5, 6, 7
General Radio: 6, 7
Guide Inds., Inc.: 4, 5, 6, 7
Hadron Inc.: 5
Hallmark Standards, Inc.: 7
Halmar Elctrns., Inc.: 7
Heath Co.: 7
Hewlett-Packard: 1, 2, 4, 5, 6, 7
Hickok Elect. Instr.: 7
Honeywell, Apparatus Controls: 4
Hughes Aircraft Co.: 4, 5
Ind'l. Test Equip.: 7
Instrument Displays: 7
International Light: 5
ISC Magnetics Div.: 7
Jodon Engrg. Assocs.: 5
Kahl Scientific Instr. Corp.: 2
Kratos: 7
Larson Instr. Co., Inc.: 7
LFE Corp.: 7
Marconi Instrs.: 7
Maury Microwave Corp.: 3, 4, 5, 6,
MCS Corp.: 4, 6, 7
Microdot Inc.: 7
Microflect Co.: 4
Micro Instr. Co.: 7
Microlab/FXR: 2, 3, 4, 6, 7
Microwave Assocs., Inc.: 4
Microwave Labs. America: 4, 6
Microwave Sys. Co.: 4
Mobil Elctrns., Inc.: 7
Molectron Corp.: 5
Multi-Amp Corp.: 7
Narda Microwave Corp.: 1, 2, 3, 4, 6, 7
New-Tronics Corp.: 1, 7
NH Research, Inc.: 7
Ohio Semitronics: 7
Olektron Corp.: 1
Omega Labs., Inc.: 4, 6
OMNI Spectra: 3
Pace Div.: 1, 5
Pacific Meas., Inc.: 5, 7
Polarad Elctrn. Instrs.: 7
PRD Elctrns., Inc.: 1, 2, 3, 4, 5, 6, 7
Premier Microwave: 4, 6, 7
Quantronix Corp.: 5
Q.V.S., Inc.: 7
Radiation Int'l., Inc.: 6
Rafec Elctrns.: 5
Raytheon Co.: 2, 5
RCA Corp.: 7
Reeve Elctrns., Inc.: 2, 7
Republic Elctrn. Inds., Inc.: 7
RF Communications, Inc.: 7
RFL Inds.: 4
Rohde & Schwarz Sis.: 7
Scientific Columbus: 7
Scientific Educational Prods.: 7
Sensitive Research Instrs.: 7
Shigoto Inds.: 7
Simpson Elec. Co.: 7
Struthers Elctrns. Corp.: 3, 4, 5,
6, 7
Sunshine Sci. Instrs., Inc.: 7
Systron-Donner Corp.: 7
Systron-Donner Datapulse Div.: 7
Systron-Donner Kruse Elctrns. Div.: 7
Systron-Donner Microwave Div.: 7
Telonic Inds., Inc.: 5, 7
TRG Prods.: 2, 3
Triplett Elec. Instr. Co.: 7
TRW Instrs.: 5
Union Carbide: 5
United Detector Technology: 5
Varian Assocs.: 2
Varian Assocs. Electron Tube
& Device Group: 2
Vari-L Co., Inc.: 5, 7
Vector Industries: 4
Waveline, Inc.: 4, 6, 7
Weinschel Engrg. Co.: 1, 3, 4, 7
Western Reserve Elctrns.: 7
Westinghouse Elec. Corp.: 7
Weston Instruments, Inc.: 1, 7
Yewtec Corporation: 7

PHASE SHIFT

MEASUREMENT INSTRUMENTATION

1-Analyzers
2-Meters
3-Standards
4-Sources
5-Monitors
6-Loads
7-Load Stretchers

MANUFACTURERS

Aircom, Inc.: 6, 7
Alford Mfg. Co.: 2, 6, 7
American Elctrn. Labs., Inc.: 7
American Microwave Inds., Inc.: 7
AMF Electrical Prods.: 4
Arra Inc.: 7
Associated Resch.: 5
Austron, Inc.: 2, 3
Automated Meas.: 1
Automatic Switch Co.: 5
Baganoff Assocs., Inc.: 1
Basler Elec. Co.: 5
Bowmar/ALI, Inc.: 1
C & A Products, Inc.: 4
CES Elctrns. 6
Chesterfield Prods. Inc.: 2, 5
Clarke-Hess: 2
Coax Devices Inc.: 6, 7
Collins Radio Co.: 2
Columbia Elec. Mfg. Co.: 4
Computer Conversions Corp.: 2
Control Elctrns. Co., Inc.: 2
Dawe Instruments, Ltd.: 1, 2
Dittmore-Freimuth Corp.: 2
Diversified Elctrns.: 5
Dranetz Engrg. Labs.: 1, 2, 5
Dyna Technology Inc.: 4
Dytronics Co.: 1, 2, 3
E-H Resch. Labs., Inc.: 1
Electro-Pacific, Inc.: 4
Elgar Corp.: 4
Exact Elctrns., Inc.: 4
Federal Sci. Corp.: 1
Feedback, Inc.: 1, 2, 4
Fermont Div.: 4
Ferranti Ltd.: 7
Forney Inds., Inc.: 4
Frequency Engrg. Labs.: 1
General Elec.: 2
General Elec. Co., Elctrn. Comps.
Sis. Dept.: 2
General Equip. & Mfg.: 5
General Radio Co.: 7
Georator Corp.:
Gould, Inc.: 1
Guide Inds., Inc.: 7
Hewlett-Packard: 2, 4, 6
HI-G, Windsor Locks, Connecticut: 5
Ind'l. Test Equip.: 2, 3, 4
Ithaco, Inc.: 1, 2
Kato Engrg. Co.: 4
Katolight Corp.: 4
Kratos: 2
Krohn-Hite: 2
Logitek, Inc.: 5
Loral Elctrn. Sys.: 1
Lorch-Adret Corp.: 3, 4, 7
Maury Microwave Corp.: 6, 7
Meguro Denpa Sokki K.K.: 2
Micro Instr., Co.: 1
Microlab/FXR: 6, 7
Microwave Labs. America: 6
Multi-Amp Corp.: 1
Narda Microwave Corp.: 7
North Atlantic Inds.: 1, 2, 4
Nu-Devices: 1, 3, 5
Omega Labs., Inc.: 6, 7
OMNI Spectra: 7
ONAN Div.: 4
Opad Elec. Co., Inc.: 5
PRD Elctrns., Inc.: 2
Premier Microwave: 7
Princeton Applied Resch. Corp.: 2, 5
Quan-Tech.: 1, 2
Rantec Div.: 1, 3
RF Systems, Inc.: 6
RLC Elctrns., Inc.: 7
Rohde & Schwarz Sis.: 2, 7
Scientific-Atlanta, Inc.: 1, 2
Scientific Columbus: 2
Servo Corp. America: 1, 4
Siemens Corp.: 2
Signal Analysis Inds. Corp: 1
Singer Instrumentation, Los
Angeles Oper.: 1, 2, 5
Special Microwave Devices Oper.: 4
Spectral Dynamics Corp. San
Diego: 1, 2
Struthers Elctrns. Corp.: 7
Sunshine Sci. Instrs., Inc.: 1
Systron-Donner Datapulse Div.: 4, 6
Teledyne Inet: 4
Theta Instr. Corp.: 1, 2, 3, 4
Trio Labs, Inc.: 2
TRW/Globe Motors: 4
Universal Ad-Yu Elctrns.: 1, 2, 3, 4
Varo, Inc.: 4
Vernitron Corp.: 4
Vibration Instrs., Co.: 1, 2-5
Video Resch. Corp.: 2
Waveline, Inc.: 6, 7
Wavetec: 2, 4
Weinschel Engrg. Co.: 7
Westinghouse Elec. Corp.: 1, 2, 4
Weston Instruments, Inc.: 1, 2
Wiltron Co.: 2
Yewtec Corporation: 2
Zonic Tech. Labs.: 2, 5

MEASUREMENT INSTRUMENTATION

1-Attenuators
2-Calibrators
3-Comparators
4-Insertion Loss Meas. Systems
5-Meters

MANUFACTURERS

ADC Products: 1
Aerolite Electronics Corp.: 1
AIL Division, Cutler-Hammer Inc.: 1, 2, 5
Aircom Inc.: 1
Airtron: 1
Alford: 1, 3, 4
Allen-Bradley: 1
Allen Avionics: 1
Altec: 1
American, Aerospace Controls: 1
American Electrn. Labs, Inc.: 1
American Microwave Inds, Inc.: 1
Amphenol RF Division: 1
A.O.I.P. Paris, France: 1
Anzac Elctrns.: 1
Applied Research, Inc.: 1
Arenberg Ultrasonics Lab., Inc.: 1
Arra, Inc.: 1, 2
Artech Corp.: 1
AUL Instrs., Inc.: 1
Automation Dev.: 1
Automation Dynamics: 4
Ava Elctrns.: 1
Aviel Electronics Inc.: 1
Barth Elctrns, Inc.: 1
Bell P/A Products Corp.: 1
Bird Elctrn.: 1
Blonder-Tongue Labs., Inc.: 1, 4
Carter Mfg., Corp.: 1
Centralab Electrns.: 1
CES Elctrns.: 1
Cir-Q-Tel.: 1
Clarostat Mfg., Co, Inc.: 1
Coax Devices Inc.: 1
Comdel Inc.: 1
Computer Labs.: 1
Daico Inds, Inc.: 1
Damon Corp.: 1
Delta-Benco Ltd.: 1
Dittmore-Freimuth Corp.: 1
Edison Elctrns., Div.: 1, 5
E-H Research Labs., Inc.: 1
Elcom Sys.: 1
Elctrn. Navigation Inds., Inc.: 1
Electronautics: 1
Electro Impulse Inc.: 1
E & M Labs.: 1
FMC Technology Inc.: 1
Emerson & Cuming, Inc.: 4
Engelmann Microwave.: 1
Fairchild Sound Equip.: 1
Fifth Dimension: 1
FKS Comms., Inc.: 1
GAF Corp.: 1
General Microwave Corp.: 1, 3, 4, 5
General Radio Co.: 1, 4
General Resistance, Inc.: 1
Gotham Audio Corp.: 1
Guide Inds., Inc.: 1
Guideline Instrs., Inc.: 2
Hewlett-Packard: 1, 3, 4, 5
Honeywell: 1
Hope Elctrns.: 1
Hughes Aircraft Co.: 1
Ithaco, Inc.: 1
Jerrold Elctrns., Corp.: 1, 4
Jewell Electrical Instrs.: 1, 5
Kay Elemtrics: 1
Kilovac Corp.: 1
Lab Electro-Acoustique: 1
Lecroy Resch, Sys., Corp.: 1
Litton Inds.: 1
Larch-Adret Corp.: 1
Larch Elctrns., Corp.: 1
Marconi Instrs.: 1
Maury Microwave Corp.: 1, 2, 3, 4, 5
MCS Corp.: 1
Megura Denpa Sokki K.K.: 1
Merrimac Resch. & Dev., Inc.: 1
Metric Sys.: 1
Microlab/FXR: 1, 5
Micrometals: 1
Microtech: 1
Micro-Tel Corp.: 2
Microwave Assocs., Inc.: 1
Microwave Development Labs., Inc.: 1
Microwave Filter Co., Inc.: 1
Microwave Labs., America: 1
Mini-Circuits Lab.: 1
Mu-Del Elctrns.: 1
Narda Microwave Corp.: 1, 2, 3, 4, 5
Nurad, Inc.: 1
Ohmite Mfg., Co.: 1
Olektron Corp.: 1, 4
Omega Labs.: 1
Omni Spectra: 1
OPT Industries: 1
Pabst Engrg., Eqpt., Co. Inc.: 1
PRD Elctrns., Inc.: 1, 2, 5
Premier Microwave: 1
Pyrofilm Corp.: 1
Q.V.S. Inc.: 5
Radiation Int'l., Inc.: 1
Radio Resch., Co.: 1
Rafec Elctrns.: 1
Rantec Div.: 1
Raytheon Co.: 1
Re-el Circuits, Inc.: 1
Reeve Elctrns., Inc.: 1
Relcom: 1
RF Interonics: 1
RLC Elctrns., Inc.: 1
Rohde & Schwarz Sis.: 1, 4, 5
Scientific-Atlanta, Inc.: 1, 2
Sealectro Corp.: 1
Sennherser Elctrn., Corp.: 1
Shallco., Inc.: 1
Siemens Corp.: 1, 5
Sinclair Radio Labs.: 1
Singer Instrumentation: 1, 2, 4
Solar Elctrns., Co.: 4
Somerset Radiation Lab.: 1
Special Microwave Devices Oper.: 1
Stoddard Electro Sys.: 1
Struthers Elctrns., Corp.: 1, 3
Stromberg Carlson Corp.: 1
Systron-Donner Kruse Elctrns.: 1, 4
Systron-Donner Microwave Div.: 1
Takeda Riken Ind., Co., Ltd.: 5
Tech Labs., Inc.: 1
Technical Research & Mfg. Co.: 1
Teledyne Microwave: 1
Telonic Inds., Inc.: 1
Tennelec., Inc.: 1
Texscan Corp.: 1
Thompson-CSF Electron Tubes: 1
Transco Prods., Inc.: 1
TRG Products: 1
Trompeter Elctrns.: 1
Varian Assocs.: 1
Varian Assocs. Electron Tube & Device Group: 1
Vari-L Co., Inc.: 3, 4, 5
Vega Products: 1
Vishay Resistor Prod., Div.: 1
Wandel & Goltermann: 1, 4
Waters Mfg., Inc.: 1
Watkins Johnson Co.: 1
Waveline Inc.: 1
Wavetek Ihdiana., Inc.: 1
Weinschel Engrg., Co.: 1, 2, 3, 4, 5
Welwyn Elec., Ltd.: 1
Welwyn Int'l., Inc.: 1
Wiltron Co.: 1, 4
Winegard Co.: 1

NOISE

MEASUREMENT INSTRUMENTATION

1-Analyzers
2-Meters
3-Standards
4-Sources

MANUFACTURERS

- AIL Div. Cutler-Hammer, Inc.: 1, 3, 4
- A.P. Circuit Corp.: 1
- B & K Instrs., Inc.: 1, 4
- Bearing Inspection: 1
- Beede Electrical Instr. Co., Inc.: 2
- Bowmar/ALI, Inc.: 1
- Chesterfield Prods. Inc.: 1
- Collins Radio Company: 1
- Dawe Instruments, Ltd.: 1
- DuMont Electron Tubes: 4
- Dutrex Inds., Inc.: 4
- Edison Elctrns. Div.: 2, 4
- Elcom Sys.: 4
- Electro-Optical Inds., Inc.: 1
- Elcenco, Inc.: 1
- English Electric Valve Co., Ltd.: 4
- Fairchild Electro-Metrics: 1, 4
- Federal Sci. Corp.: 1
- Freed Transformer Co.: 2
- Frequency Engrg. Labs.: 1
- General Microwave Corp.: 1, 4
- General Radio Co.: 1, 2
- GTE Sylvania Inc.: 4
- Heath Co.: 2
- Hewlett-Packard: 1, 2, 4
- Honeywell: 1
- IRD Mechanalysis, Inc.: 1
- Int'l. Elctrns.: 4
- Int'l. Microwave: 2, 4
- Kay Elemetrics: 1, 4
- Lab Electro-Acoustique: 1,2
- London Co., Cleveland Ohio: 2
- Marconi Instrs., Englewood, N.J.: 2
- Maury Microwave Corp.: 3
- Metropolitan Supply Corp.: 4
- Micro Instr. Co.: 2
- Milletron, Inc.: 1
- Nelson Ross Elctrns.: 1
- Northeast Elctrns. Corp.: 2
- Polarad Elctrn. Instrs.: 1
- Princeton Applied Resch. Corp.: 1
- Quan-Tech.: 1, 2, 3, 4
- Rockland Sys. Corp.: 1
- Rohde & Schwarz Sis.: 1, 2
- Siemens Corp.: 1, 2, 4
- Signal Analysis Inds. Corp.: 1
- Signalite, Neptune, N.J.: 4
- Singer Instrumentation: 1
- Solatron Enterprises: 4
- Soltec Corp.: 2
- Spectral Dynamics Corp.: 1
- Sperry Elctrn. Tube: 4
- Sprengnether, W. F. Instr. Co.: 2, 4
- Thompson-CSF Electron Tubes: 4
- Thor Elctrns. Corp.: 4
- Tracor, Inc.: 1
- Varian Assocs.: 4
- Vibration Instrs. Co.: 1, 2
- Wandel & Goltermann: 2
- Warnecki Electron Tubes, Inc.: 4
- Waveline, Inc.: 4

EM FIELDS

MEASUREMENT INSTRUMENTATION

1-Measuring Equipment
2-Meters
3-Antenna Analyzers
4-Analyzers

MANUFACTURERS

- American Elctrn. Labs., Inc.: 1, 4
- Analytical Meas., Inc.: 1
- Bell, F. W., Inc.: 2
- Blonder-Tongue Labs., Inc.: 2
- Carco Electronics: 4
- Collins Radio Co.: 1
- Delta-Benco Ltd.: 2
- Dittmore-Freimuth Corp.: 2
- Dranetz Engrg. Labs.: 4
- Elcom Sys.: 2
- Electro-Mechanics Co.: 1, 2
- Fairchild Electro-Metrics: 1, 2
- GTE Sylvania Inc. Electrn. Sys. Co.: 4
- Hewlett-Packard.: 1
- Hiram Jones: 1
- Honeywell: 1, 2
- Hughes Aircraft Co.: 4
- Incal Service Corp.: 1
- Instrs. for Ind., Inc.: 1, 2
- Jerrold Elctrns. Corp.: 2
- Kahl Scientific Instr. Corp.: 2
- Labgear, Ltd.: 2
- LDJ Electronics: 2
- Leader Instruments Corp.: 2
- Loral Electrn. Sys.: 4
- Magnaflux Corp.: 2
- Micro-Tel. Corp.: 1
- Mobil Elctrns., Inc.: 2
- Monroe Elctrns., Inc.: 2
- Narda Microwave Corp.: 2
- Nelson Ross Elctrns.: 1, 4
- Ohio Semitronics: 1
- O. S. Walker Co.: 2
- Oxford Instr. Corp.: 2
- Polarad Elctrn. Instrs.: 1, 2, 4
- Rafec Elctrns.: 1
- Reeve Elctrns., Inc.: 2
- Rohde & Schwarz Sis.: 1, 2
- Scientific-Atlanta Inc.: 4
- Shurite Meters: 2
- Siemens Corp.: 1, 2
- Singer Instrumentation, Los Angeles Oper.: 1, 2
- Singer Instrumentation, Palo Alto Oper.: 2, 4
- Solar Elctrns. Co.: 1, 2
- Sprague Elec. Co.: 1
- Stoddart Electro Sys.: 1, 2
- Vari L Co., Inc.: 4
- Varian Assocs.: 2
- Velonex: 1
- Watkins Johnson Co.: 1, 4
- Weinschel Engrg. Co.: 4
- Wilkinson Elctrns.: 2
- Wiltron Co.: 4

MATERIAL PROPERTIES

MEASUREMENT INSTRUMENTATION

1-Analyzers
2-Meters

MANUFACTURERS

- Advanced Patent Technology, Inc.: 1
- A. P. Circuit Corp.: 1
- B & K Instrs., Inc.: 1
- Bell, F. W., Inc.: 1, 2
- Chesapeake Instr. Corp.: 1
- Computer Test Corp.: 1
- Electro-Mechanics Co.: 1
- Federal Sci. Corp.: 1
- General Radio Co.: 1
- Hallmark Standards, Inc.: 1
- High Voltage Engrg. Corp.: 1
- Ind'l. Control Co.: 1
- Irwin Labs., Inc.: 1
- ISC Magnetics Div.: 2
- Kinetic Tech., Inc.: 1
- Lab Electro-Acoustique: 1
- LDJ Electronics: 1, 2
- Magnaflux Corp.: 1
- Magnetic Analysis Corp.: 1
- Nelson Ross Elctrns.: 1
- NuSonics, Inc.: 1
- Oeco Corp.: 1
- Ohio Semitronics: 1
- O. S. Walker Co.: 1, 2
- Polarad Electrn. Instrs.: 1
- Quan-Tech: 1
- RFL Inds., Instr. Div.: 1
- Shur-Lok Corp.: 1
- Spectrum Instrs., Inc.: 1
- Stoddart Electrc Sys.: 1
- Sunshine Sci. Instrs., Inc.: 2
- Systron-Donner Alpha Sci-entific Sub.: 1
- Systron-Donner Corp.: 1
- Techsonics: 1
- Thomas & Skinner, Inc.: 1, 2
- Varian Assocs.: 1

APPENDIX C - LABORATORIES AND CAPABILITIES+

Private Laboratories

O Service To Parent Organization Only
F Calibration Services Available On A Fee Basis
N Calibration Services Available On A No Fee Basis

Laboratories	Zip	Availability
*HERMES ELECTRONICS LIMITED		O
*RAYTHEON COMPANY	01778	O
RCA	01801	O
*MICROWAVE ASSOCIATES, INC.	01803	O
*RAYTHEON COMPANY	01810	O
*UNIV. OF LOWELL RESEARCH FOUND	01854	F
*AVCO CORP.	01887	F
RAYTHEON COM	02062	F
*STONE + WEBSTER ENGINEERING CO	02107	O
*CHARLES STARK DRAPER LABORATOR	02139	O
ITEK CORP.	02173	O
*SANDERS ASSOCIATES, INC.	03060	F
EATH IRON WORKS CORP.	04530	O
*FRATT & WHITNEY AIRCRAFT	06108	O
*GENERAL DYNAMICS CORPORATION	06340	O
*PERKIN ELMER CORP.	06810	O
*CAPITAL MAGNETIC PRODUCTS	06906	O
RFL INDUSTRIES, INC.	07005	O
*ITT--AVIONICS DIVISION	07014	O
*LOCKHEED ELECTRONICS CO., INC.	07061	F
HONEYWELL INC.	07090	F
*WESTON INSTRUMENTS, INC.	07114	O
*SINGER COMPANY	07424	O
RCA	08057	O
*SWEETMAN CALIBRATION SERVICES	08109	F
RCA	08540	O
*RCA SOLID STATE DIVISION	08876	O
*ELECTRICAL TESTING LABORATORIE	10021	F
*ELECTRICAL INSTRUMENT SERVICE,	01550	F
*SPERRY GYROSCOPE	11020	O
*GRUMMAN AEROSPACE CORP.	11714	F
*GENERAL ELECTRIC COMPANY	13201	F
NIAGARA MOHAWK POWER CORP.	13202	O
SPERRY RAND CORP.	13501	O
*EASTMAN KODAK COMPANY	14650	O
*EASTMAN KODAK COMPANY	14650	O
*WESTINGHOUSE ELECTRIC COMPANY	15235	O
*AMP, INC.	17105	O
*GAGE LAB CORPORATION	19006	F
*CLIFTON PRECISION	19018	O

Private Laboratories

O Service To Parent Organization Only
F Calibration Services Available On A Fee Basis
N Calibration Services Available On A No Fee Basis

Laboratories	Zip	Availability
*GENERAL ELECTRIC	19101	O
*AMERICAN INSTRUMENT SERVICE, I	19123	F
HONEYWELL INC.	19406	F
*AMERICAN ELECTRONIC LABS., INC	19446	F
*COMSAT LABORATORIES	20734	O
*FAIRCHILD SPACE + ELECTRONICS	20767	F
*APPLIED PHYSICS LAB	20810	O
*AUTOMATION INDUSTRIES, INC.	20910	O
*WESTINGHOUSE ELECTRIC CORPORAT	21203	F
*KOPPERS CO., INC.	21203	O
MARTIN MARIETTA CORP.	21220	O
*E-SYSTEMS	22046	F
*HONEYWELL INC.	22151	F
*NEWPORT NEWS SHIPBUILDING	23607	F
*MARTINSBURG ELECTRONICS	25401	F
LOCKHEED AIRCRAFT CORP.	30063	O
SPERRY RAND CORP.	32601	F
HONEYWELL INC.	32803	F
*MARTIN MARIETTA AEROSPACE	32805	O
*HARRIS CORPORATION	32901	F
*RCA INTERNATIONAL SERVICE CORP	32925	O
FLORIDA STANDARDS LAB	33405	F
*HONEYWELL INC.	33733	O
*BATTELLE MEMORIAL INSTITUTE	43201	O
ROCKWELL INTERNATIONAL	43216	O
HONEYWELL INC.	44135	F
*NORTH ELECTRIC CO.	44833	O
HONEYWELL INC.	45324	F
AVCC CORP.	47374	F
HONEYWELL INC.	48024	F
*SSCO STANDARDS LABORATORY	48237	F
*ROCKWELL INTL. COLLINS RADIO G	52406	F
*SPERRY UNIVAC, DEFENSE SYSTEMS	55165	O
*MEDTRONIC, INC.	55432	O
*MOTOROLA, INC.	60172	O
*IIT RESEARCH INSTITUTE	60616	F
*WESTERN ELECTRIC COMPANY	60623	O
HONEYWELL INC.	60634	F
*MCDONNELL DOUGLAS CORP.	63166	F
*BEECH AIRCRAFT CORPORATION	67201	O

+Source: NCSL Directory of Standards Laboratories, 1976

Private Laboratories

O Service To Parent Organization Only
F Calibration Services Available On A Fee Basis
N Calibration Services Available On A No Fee Basis

Laboratories	Zip	Availability
*BEECH AIRCRAFT CORP.	67201	O
*BOEING COMPANY	67210	F
*ROCKWELL INTERNATIONAL - TULSA	74151	F
*TUCKER ELECTRONICS COMPANY	75040	F
COLLINS RADIO COMPANY	75080	F
GENERAL ELECTRIC COMPANY	75220	F
*LOCKHEED ELECTRONICS CO., INC.	77058	O
*TRACOR, INC.	78721	O
*RHODES-GROOS LABORATORIES	78724	F
*MASON + HANSILAS MASON CO.	79177	O
*HONEYWELL INC.	80217	F
HEWLETT PACKARD CO.	80537	F
*AEROJET NUCLEAR COMPANY	83401	O
SPERRY RAND CORP.	84116	O
*THICKOL CORP.	84302	O
HONEYWELL INC.	85017	F
*SANDIA LABS	87115	F
*LOCKHEED ELECTRONICS CO. INC.	88001	O
*EG+G INC.	89101	F
HONEYWELL INC.	90040	F
HUGHES AIRCRAFT COMPANY	90230	O
NORTHROP CORP.	90250	O
GENERAL ELECTRIC INSTRUMENTION	90301	F
*MCDONNELL DOUGLAS CORPORATION	90846	O
*CALIFORNIA INSTITUTE OF TECHNO	91103	O
*BELL + HOWELL ELECT. + INSTR.	91109	O
*TELEDYNE SYSTEMS CO.	91324	F
*LITTON GUIDANCE + CONTROL SYST	91364	O
CERTIFIED SERVICES	91406	F
*LOCKHEED-CALIFORNIA COMPANY	91520	F
*AEROJET ELECTROSYSTEMS COMPANY	91702	O
*GENERAL DYNAMICS/POMONA DIVISI	91766	F
*TELEDYNE RYAN AERONAUTICAL	92112	O
*GENERAL DYNAMICS CORPORATION	92138	F
*GENERAL DYNAMICS CORPORATION	92138	F
*CELESCO INDUSTRIES, INC.	92626	O
*BECKMAN INSTRUMENTS, INC.	92634	F
*MCDONNELL DOUGLAS ASTRONAUTICS	92647	F
*AERONUTRONIC-FORD CORPORATION	92663	O
*ROCKWELL INTERNATIONAL	92803	F
*DALMO VICTOR COMPANY	94002	F
*FAIRCHILD CAMERA AND INSTRUMEN	94042	O
HEWLETT PACKARD CO.	94043	F
*AMPEX CORPORATION	94063	O
*LOCKHEED MISSILES AND SPACE CO	94088	F

Private Laboratories

O Service To Parent Organization Only
F Calibration Services Available On A Fee Basis
N Calibration Services Available On A No Fee Basis

Laboratories	Zip	Availability
*WESTINGHOUSE ELECTRIC CORPORAT	94088	O
*VARIAN	94303	F
HEWLETT PACKARD CO.	94304	F
*HEWLETT PACKARD CO.	94304	F
*SYSTRON-DONNER	94518	O
HONEYWELL INC.	94545	F
HEWLETT PACKARD CO.	95050	F
*HONEYWELL INC.	95110	F
HEWLETT PACKARD CO.	95401	F
TELETEK ENTERPRISES, INC.	95670	F
*TEKTRONIX, INC.	97077	O
HONEYWELL INC.	98109	F
*BOEING COMPANY	98124	O

Government Laboratories

Laboratories	Zip	Availability
*DEPARTMENT OF NATIONAL DEFENCE		O
*NAVAL UNDERWATER SYSTEMS CENTE	02840	O
*PORTSMOUTH NAVAL SHIPYARD	03801	O
*U.S. ARMY ELECTRONICS COMMAND	07703	F
*NAVY EASTERN STDS LAB	20374	F
*DEPARTMENT OF DEFENSE	20755	O
*HARRY DIAMOND LABS, AMXDC-EDG-	20783	O
*NAVAL AIR REWORK FACILITY 370	23511	F
NORFOLK NAVAL SHIPYARD	23709	O
*L.S. MARINE CORPS	31704	O
TYPE II STANDARDS LABORATORY	32508	F
*NASA/IN-MSD-4	32899	O
*U.S. ARMY METRO + CALIB CENTER	35809	O
*NASA	35812	N
*TENNESSEE VALLEY AUTHORITY	37401	O
*AEROSPACE GUIDANCE + METROLOGY	43055	O
*NASA JOHNSON SPACE CENTER	77058	O
*NAVAL AIR REWORK FACILITY	94501	F
*U.S. BONNEVILLE POWER ADMIN.	98660	O

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15. SUPPLEMENTARY NOTES

16. ABSTRACT (*A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.*)

This report reviews the scientific, commercial, civil, and military activities that use electromagnetic measurements, and the measurement techniques and standards, and the institutions developing and using them, that have evolved to satisfy their needs. Through the early influence of the Department of Defense, this part of the National Measurement System is well coordinated, with NBS established as the central reference point. The measurement needs of lasers are included in the discussion.

17. KEY WORDS (*six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons*)

Electromagnetic quantities; laser; microwave; National Measurement System; radio measurements.

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