The U.S. basis of electromagnetic measurements

Whenever technology outstrips our ability to measure, the result is poor reliability, overdesign, and delays. Here is how a radio standard evolves, and how NBS is striving to shorten the standards time lag

John M. Richardson, James F. Brockman *National Bureau of Standards*

The undersigned believe that the following material, describing the national basis of electromagnetic measurements, deserves the thoughtful consideration of all members of the IEEE, and we have recommended that it be brought to their attention through this publication.

The size and importance of the electrical and electronics industry is clear to all members of the IEEE without the need of statistics. What may not be so clear is that this whole industry must rest on a uniform base of accurate and precise measurement if it is to achieve in practice the results which physicists and engineers find possible in principle. That base can only be provided by the National Bureau of Standards. However, the provision of a uniform base of measurement is costly in manpower, laboratory space, equipment, and time because of the great scope of electromagnetic quantities in kind, frequency, magnitude, and accuracy.

There is a strong indication, from some of the material presented, that the provision of that base has not kept pace with the growth of the industry. We believe that the National Bureau of Standards is making strong efforts to discharge the task assigned to it by Congress, but we also believe that the importance and magnitude of the problem call for understanding and support from outside NBS. It is from this standpoint that we recommend to members of the profession the reading of this article.

A. A. Oliner, Chairman	*E. C. Jordan*
S. A. Bowhill	*R. Kompfner*
W. Gordy	*W. A. Lewis*
E. L. Hahn	*N. F. Ramsey*
E. W. Houghton	*J. C. Simons, Jr.*

Members, National Academy of Sciences–National Research Council Advisory Panel to the Radio Standards Laboratory of the National Bureau of Standards.

In 1911, J. V. L. Hogan, one of the founders of the IRE, asked the National Bureau of Standards to calibrate a wavemeter. The job was given to a young employee, J. Howard Dellinger, who, 50 years later, described the event as follows:

"I was working in the Inductance and Capacity Section, in part of a room in the South Building. I was taking a course in Maxwell and had been intensively studying high-frequency phenomena. So this job was handed to me. It had to be in the Inductance and Capacity Section, for how else could you make a frequency standard at radio frequencies than by setting up a resonating *LC* circuit? I had to improvise such a circuit which generated the current, and the crystal rectifier to detect resonance, all without vitiating the value of frequency calculated from the *L* and the *C*."

Thus was the first radio calibration made by the National Bureau of Standards. Apparently the work was satisfactory since Dellinger later became chief of the NBS Central Radio Propagation Laboratory and was elected president of IRE.

From one man, the Bureau's effort in radio standards has grown to a staff of 300 people, who form the Radio Standards Laboratory. The Laboratory's purpose is to provide the central basis for electromagnetic measurements in the United States and to assure their international coordination. Thus it provides the measurement foundation for the electronics industry—an industry that has multiplied about 35 times during the past 25 years while the gross national product has increased only by a factor of six.

Pressure from the research frontiers

Electronics' first big leap forward came with the widespread use of radar during World War II. NBS felt the impact through a request from the Joint Chiefs of Staff dated April 26, 1944:

"The Joint Communications Board has decided that there is a need by our Armed Forces for primary radio frequency standards for frequencies between 1,550 and 11,000 megacycles per second. These standards are necessary for the proper calibration of secondary standards by which the radio equipment of our Armed Forces can be calibrated in the field. No primary standards of frequency determination for use in the radio spectrum between 1,550 and 11,000 megacycles per second are now known to be available. . . ."

The need was clear-cut, the reasons behind it were well defined, and the need could be considered with little concern for large simultaneous improvements in other quantities. This was probably the last time that major measurement needs in the field could be so clearly and succinctly summarized.

Since 1944, electronics has enjoyed spectacular growth in both size and scope. Its importance in new, extreme, and complex environments means continual pressure for extending the useful range of electromagnetic energy. This in turn means continual and substantial pressure for improving the art of radio measurement—to higher frequencies, to different magnitudes (both high and low), and always with greater accuracies.

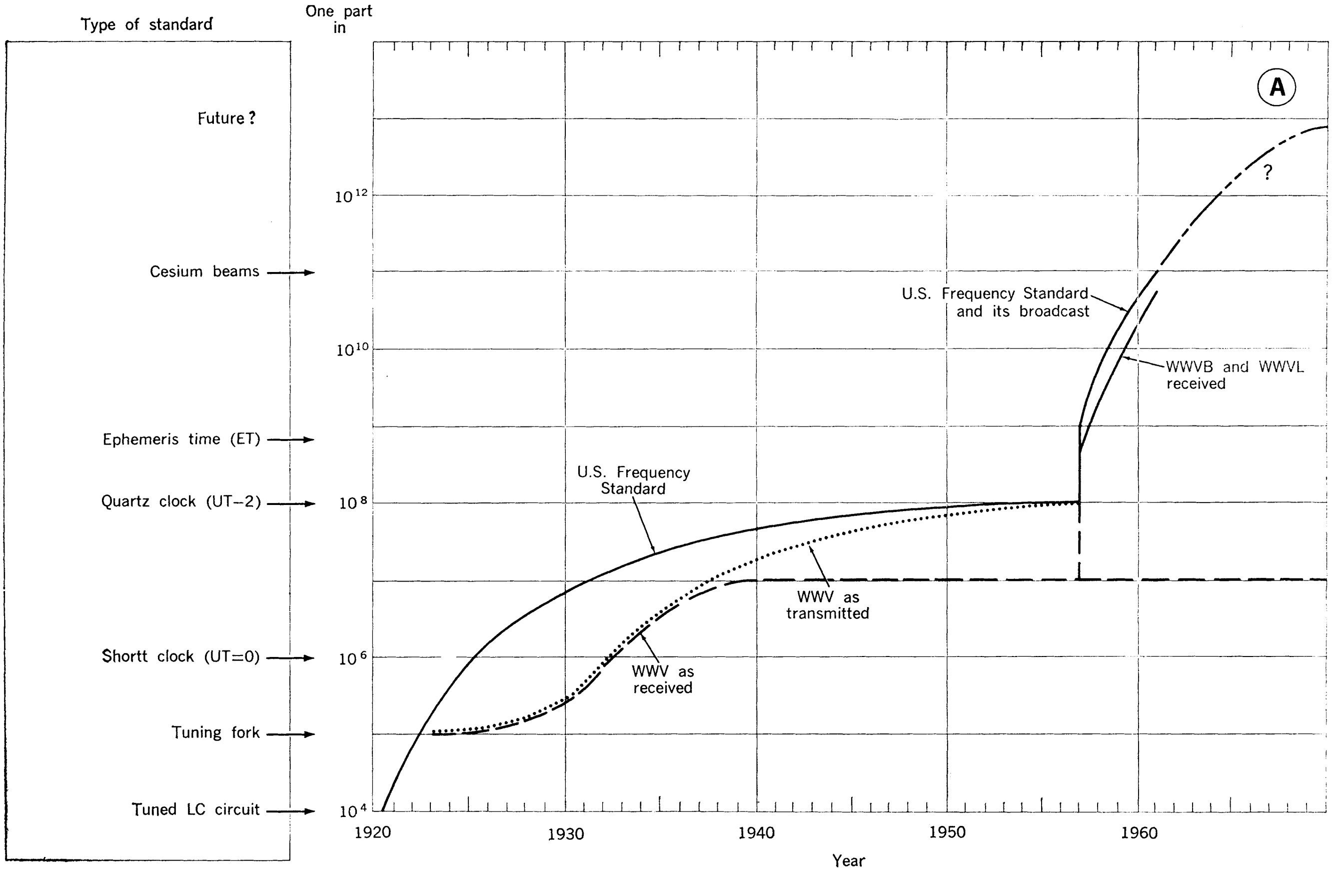
This pressure for the extension of radio measurements is augmented by the swift application of new discoveries. It is well known that the lag time between the discovery and application of major developments is swiftly decreasing; over 50 years for electric power generation, about 4 years for the transistor, about 19 months for the laser. A consequence of this acceleration is that new standards are desired barely moments after discovery.

Effects of a measurement gap

With the need for better standards, more standards, and the rapid development of standards, it is not surprising that technology sometimes outstrips the science of radio measurement. It should also come as no surprise that this lack of measurement creates spectacular problems. Usually, however, these problems are not recognized as being the result of inadequate measurement, for standards of measurement tend to remain hidden in the background.

Since 1960, NBS has been meeting with members of the Aerospace Industries Association to compare industry's measurement needs with the services offered by NBS. This has helped define the needs more precisely and has provided some measure of their relative urgency. The meetings have also uncovered many specific illustrations of how industry is affected when a standard of measurement does not exist—when there is a measurement gap. Some of the effects are:

- Disagreement between contractor and subcontractor as to whether a product meets specifications.
- Poor reliability.
- Excessive time required to produce equipment by trial and error since, if the component characteristics are unknown, it is impossible to predict performance accurately.
- Need to overdesign to be sure the product will do the job.
- Schedule delays caused by inacceptable components and systems.
- Duplication of effort.



The dramatic quality of our national defense and space programs, and the fact that most unsatisfied customers of the Radio Standards Laboratory are tied to these programs, may create the feeling that improved electromagnetic standards need only concern those whose work is related to the defense and space efforts. It should be apparent, however, that better measurement in these areas affects the entire national economy.

The National Aeronautics and Space Administration has estimated that about 90 per cent of space systems failures are electronic; it seems reasonable to assume that a portion of these are due to inadequate measurement.

While visiting our laboratory last year, H. L. Balderston of the Boeing Aircraft Corp. referred to the early (1952–1954) flights of the Bomarc missile which occurred before the Department of Defense was insisting that weapons systems be tested by instruments whose calibration was directly traceable to the U.S. standards at NBS. None of the first six test flights was completely successful. The next missile, thoroughly tested with measurement traceability, was the first Bomarc that accomplished all flight test objectives and marked the turning point in a successful flight test program.

Obviously it is important to both industry and the taxpayers that the expense of these programs be kept at a minimum by the very best measurements we are able to provide. And experience shows that meeting the extreme demands of advanced technologies often provides the ability to meet similar needs as they develop in such fields as telephone, radio, television, electric power, and industrial process control.

Fig. 1. Evolution of a national standard. Improvements in the accuracy of the U.S. national frequency standard (A). New cesium beam standard (also usable with thallium) was built and is now being evaluated by the NBS Radio Standards Laboratory (B). Its 18-foot length should reduce spectral line width to about 45 cycles as compared with 110 cycles in the previous 10-foot model, and should increase precision significantly. Improved frequency stability of WWV due to control by low-frequency broadcasts from WWVB and WWVL (C)

Major users

Verification of cosmological theories
Fundamental relativistic experiments
Deep space research and development
National and international frequency standards

National coordination of standards laboratories
Aerospace research and development laboratories

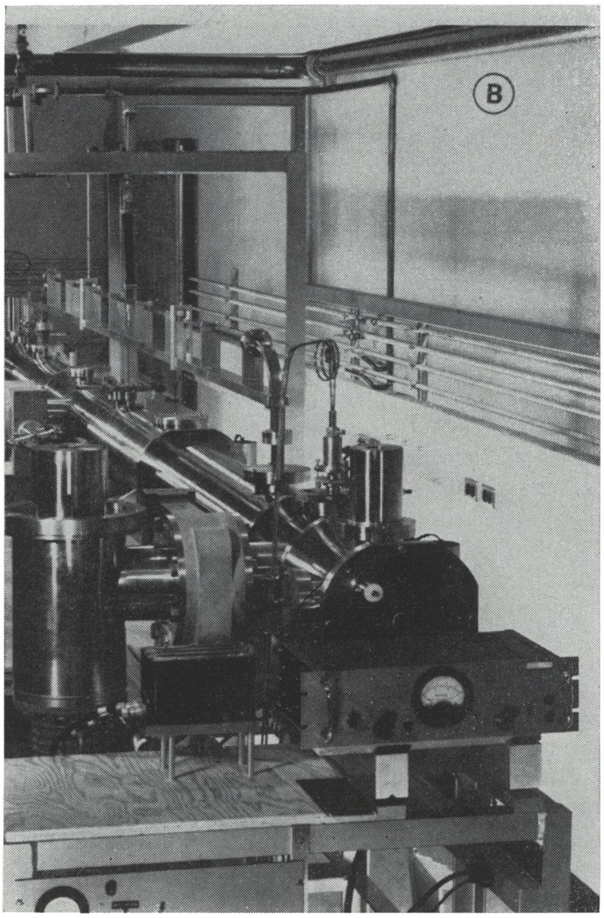
Aerospace operations (doppler tracking)
Research laboratories
Instrument manufacturers
Space navigation, velocity of light experiments

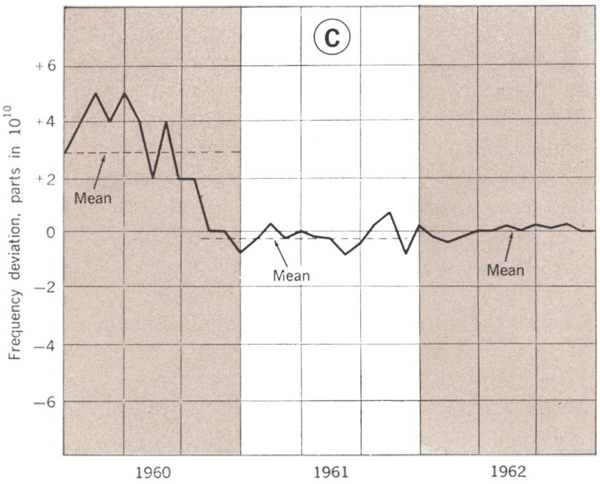
Optical satellite tracking
Air navigation, astronomy

Radio and TV servicing
Automatically controlled clocks

Radio and TV broadcasting, radio communications
Radio amateurs, telephoto, facsimile

Surface transportation
Power companies, telephone companies





How a national standard is developed

The pressure for new and more accurate standards of electromagnetic measurement means that the Radio Standards Laboratory is continually faced with requests for crash development. This pressure provides an exciting stimulus, but it has forced the staff to concentrate on developing calibration services at the expense of national standards of measurement.

A standard of measurement grows from fundamental research. It evolves through theoretical work that applies the fundamental principle to a particular measurement problem. It matures as the instrumentation and procedures that provide a standard, and finally a calibration service, are developed and evaluated.

Development of a national standard is illustrated by the evolution of the United States Frequency Standard, presently obtained from cesium atomic beams. The fundamental research on which these machines are founded was done by Rabi and his associates about 1940. NBS published early research results of the development of an atomic frequency standard in 1949, and the first machine began reliable operation in 1957. But this machine was not accepted as a standard until a second one was completed and independently evaluated.

The independent testing of each machine, together with a comparison of their frequencies over a period of three years, establishes our confidence in the quoted accuracy with respect to the idealized atomic transition frequency (about 1 part in 10^{11}) and precision (about 2 parts in 10^{13} for a 12-hour averaging time). What these machines mean in the evolution of the U.S. Frequency Standards is shown in Fig. 1(A).

Now the staff is evaluating a new cesium beam, Fig. 1(B), which is longer and therefore should be more precise. They have also developed thallium beams to evaluate their potential as frequency standards, and are exploring the possibility of using lasers.

During development of the cesium beams, the staff was also concerned with making the frequency standard available to others. The instabilities of high-frequency propagation require averaging the signals from station WWV for a period of up to 30 days to achieve a precision of 1 part in 10^{10} (the usual, quickly attainable precision is only about 1 part in 10^{7}), and reliable reception is limited to a few thousand miles. In 1959, several major organizations, including NASA, requested much higher accuracies over most of the globe.

The Laboratory began an experimental broadcast at 60 kc/s, WWVB, in 1956. Although the radiated power was only 2 watts, this did meet the needs of some specialized users by offering higher precision over shorter measuring periods. For precise measurement, however, 60-kc/s transmission is effectively limited to the continental United States.

In April 1960, the Laboratory began broadcasting with another experimental station, WWVL, at 20 kc/s. WWVL was located in the mountains near Boulder, Colorado. With a radiated power of only 15 watts, it was received as far away as New Zealand and verified predictions of the NBS Central Radio Propagation Laboratory that 20 kc/s was suitable for stable global transmissions. Since 1961, WWVL and WWVB have been controlling WWV in Maryland and WWVH in Hawaii. The improvement this provided in the frequency control of WWV can be seen in Fig. 1(C).

In 1963, both the 60- and 20-kc/s stations began broadcasting with larger antennas and more powerful transmitters from a new site near Fort Collins, Colorado. The radiated power was increased to about 1 kW for WWVL and to about 7 kW for WWVB. The 60-kc/s transmission includes time signals that will offer a precision ranging from a ten-thousandth to a millionth of a second (depending on distance from the transmitter) which is 10 to 1000 times more stable than the signals from WWV. The WWVL 20-kc/s transmission is being used to extend experimental studies required to provide accurate time signals, clock synchronization, and frequency transmission with very narrow band signals over much of the globe.

Besides the creation and dissemination of standards, another major responsibility of the Radio Standards Laboratory is the international comparison of standards. In the area of frequency standards, this responsibility has been met by comparisons made through propagation data among the Bureau standards, four commercial cesium standards in the United States and one in France, the British standard at the National Physical Laboratory, the Canadian standard at the National Research Council, and the Swiss standard at Neuchâtel.

The performance of these various standards has led to international consideration of redefining the unit of time in terms of an atomic transition. The ephemeris second, the presently accepted astronomically based unit, is now recognized as inadequate for precision measurement, and a change to a definition of the second based on atomic properties will probably follow. The choice of a particular atom and a particular transition, the experimental conditions under which this transition is observed, and the assignment of a particular frequency to this transition, will be based on scientific results of the next few years.

The standard of frequency is unique in two ways: the unit of frequency is directly related to the unit defined for one of the six basic physical quantities (length, mass, time, current, temperature, and luminous intensity) in terms of which the units for all other physical quantities are defined; and it is the one standard disseminated by broadcast.

Usually, the chain of derivation extending from a basic physical quantity is quite lengthy and complex and requires meticulous care in analysis and, usually, dissemination is accomplished through the calibration of interlaboratory standards by the NBS Electronic Calibration Center. Otherwise, the various steps in the development of the atomic frequency standards are representative of the evolution of each national standard of measurement.

Dimensionality of radio measurements

Even those working in electronics seldom realize the number of national standards involved in electromagnetic measurements. Figure 2 illustrates three "dimensions" of this work. The front plane shows the variety of standards required to measure power at various frequencies and magnitudes. Succeeding planes show the various quantities of electromagnetic measurement—each requiring an entirely new family of standards.

One must imagine a fourth dimension to this graph to indicate the various activities required in the development of each standard—research, development, and distribution. Finally, a fifth dimension is involved in that the equipment sometimes must operate in a variety of tem-

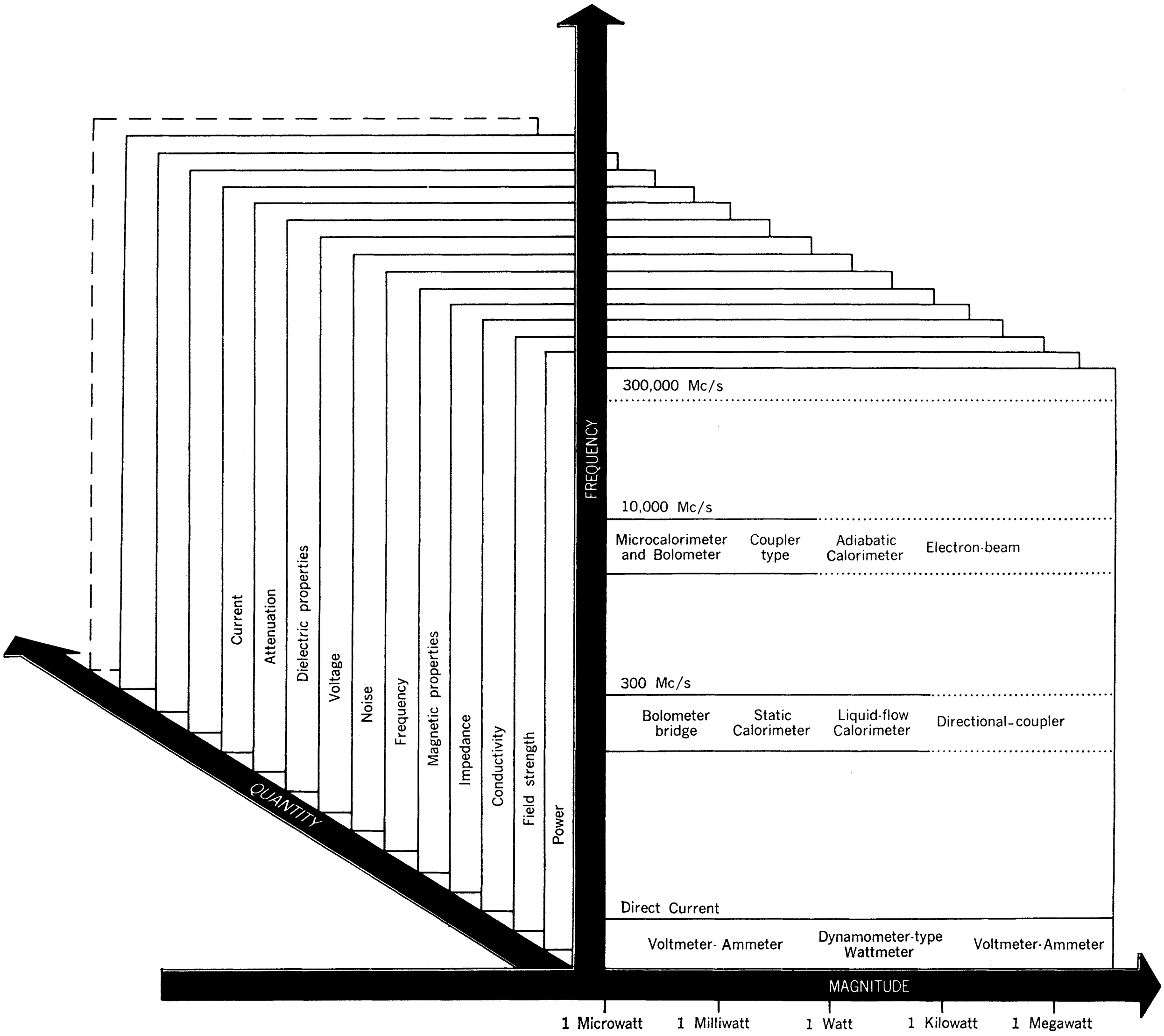


Fig. 2. Three "dimensions" of electromagnetic measurement. Each quantity represented by a plane (power, field strength, etc.) requires a new family of standards

peratures, applied fields, or other environmental parameters.

The scope of this multidimensional space is obviously so big that the Laboratory cannot hope to fill the entire volume. We therefore do our best to recognize key anchor points, and upon these to erect a network to span the various areas to a suitable degree.

Suppose, for example, that we decide that power shall be standardized only at an anchor point near one milliwatt. By standardizing attenuation for all ranges, any value of power can be referred to the one-milliwatt level with a standard attenuator. Thus the need for power standards at all other levels is eliminated.

The general areas of research and engineering at the Radio Standards Laboratory are the development and distribution of frequency standards; studies in the areas of radio and microwave materials, radio plasmas, and microwave physics; the development of high-frequency and microwave standards; and the development and calibration work of the Electronic Calibration Center. A look at work under way and at some of the services available gives an idea of the present status of radio measurement.

Studying basic materials

Materials research at the Laboratory is designed to acquire an understanding of the magnetic (primarily ferrimagnetic), dielectric, and conductive behavior of materials at radio and microwave frequencies, in terms of the atomic constitution and structure of matter. For example, magnetic resonance studies are being conducted to determine the magnetic energy levels, relaxation times, and transition probabilities in paramagnetic and antiferromagnetic crystals.

Specific tools and techniques are developed, such as the RF permittimeter which makes dielectric measurements without electrodes, thus avoiding dielectric and electrode interaction problems and errors.

Probing radio plasmas

Plasma physics is of great interest to the Laboratory because of the potential use of radio methods to characterize plasmas and the potential use of plasmas as radio devices. Measurement of plasma mechanisms is complicated by the number of parameters and variables involved, and by the fact that the numerical values of these quantities cover five to ten orders of magnitude in experimental plasmas.

Because of these problems, the prevalent theories apply to rather idealized plasmas, and often it is impossible to realize physically the assumptions that are used in the theory. Research at the Laboratory is presently limited to phenomena that are associated with the macroscopic properties of plasmas generated in the laboratory, and the goal is reasonably accurate measurement of plasma parameters, variables, and mechanisms.

Exploring millimeter waves

In microwave physics the staff is concerned with the generation, detection, transmission, and measurement of millimeter- and submillimeter-wave power.

Useful devices in industry are already operating at wavelengths as short as one millimeter. Thus, sooner or later the Laboratory is sure to be called upon to make numerous measurements and to provide standards of virtually every quantity that has been of interest at longer wavelengths, especially power, attenuation, and *Q*. Presently the Laboratory has no measurement facilities below 3 millimeters, but we hope during the next few years to have equipment working at wavelengths as short as 0.5 millimeter.

This group is also adapting the Fabry-Perot resonator for use in refractometers, wavemeters, and resonators for masers; is in the final stages of measuring the velocity of light at millimeter wavelengths with a Michelson interferometer, and is using the Stark effect—the splitting of spectral lines by the application of electric fields—to measure dc and low-frequency voltages with very high precision.

Creating microwave and HF standards

In the sections concerned with the creation and evaluation of microwave and high-frequency standards, research is usually aimed directly at a specific measurement application. Two of the basic measurement tools of industry invented by these groups are the RF micropotentiometers for providing accurately known microvoltages at radio frequencies, Fig. 3, and an improved bolometer bridge for measuring microwave power.

Among the national standards and measurement techniques the staff has developed in recent years are systems for measuring attenuation differences up to 120 dB in the 1–300 Mc/s frequency range with an accuracy of ±0.002 to ±0.05 dB; and in the 0–50 dB range, at 10 Gc/s, with an accuracy of ±0.0001 to ±0.06 dB. These high accuracies are possible at present only as attenuation differences in a system. Measurements on attenuators that must be inserted into the measurement system are more limited in accuracy due to mismatch errors. Reflection coefficients of 0.1 are measured to an accuracy of 1 part in 1000. These are the best values currently available, and are higher than the accuracies offered on a regular calibration basis.

Providing calibration services

NBS working standards for quantities in the high-frequency and microwave regions are established and maintained in the Electronic Calibration Center. Here the Laboratory provides those calibration services which are in sufficient demand to justify the development of instrumentation. Special calibrations not available through the Center can sometimes be arranged, but these

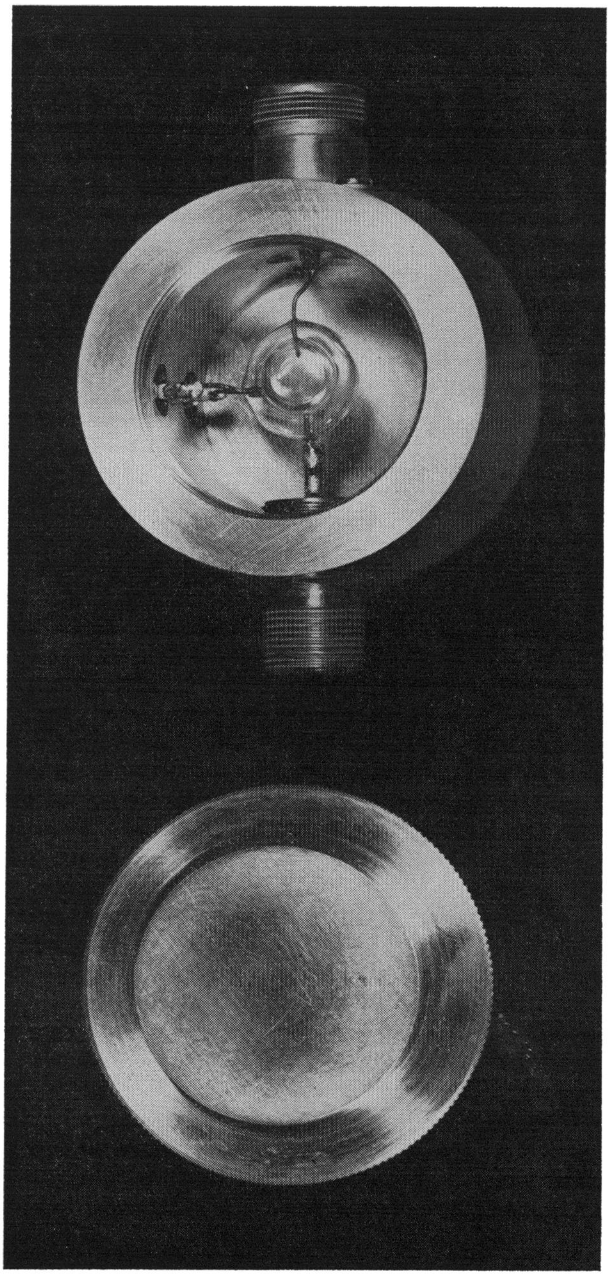


Fig. 3. Micropotentiometer operates on a simple principle a known current is fed into a known very low resistance (one or more milliohms), and the potential drop across the resistance gives a voltage that can be precisely calibrated. Primary purpose is to provide accurate microvolts for checking standard-voltage generators or for use directly as a standard-voltage generator at all frequencies to 1 Gc/s

may require time-consuming research and thus be quite expensive.

The Electricity Division of NBS, in Washington, D.C. is primarily responsible for standards and calibrations in the low-frequency region (below about 30 kc/s), but the Center also provides the low-frequency calibrations that are in greatest demand.

About half the Center's work load is devoted to the design and construction of the special instrumentation required to perform calibrations at optimum accuracies on a routine basis. It is interesting to note what routine means in this context. Since the Center calibrates interlaboratory standards for the nation's top standards laboratories in terms of the national standards, it is obvious that its shop-level calibrations carry a profound responsibility.

At high frequencies (30 kc/s to 300 Mc/s), the Center is equipped to calibrate standards of voltage, power, impedance, attenuation, and field strength. These standards are at present limited to those designed for continuous-wave measurements and those having coaxial terminals. For most quantities, calibration services are offered at the fixed frequencies of 30, 100, and 300 kc/s; and at 1, 3, 10, 30, 100, and 300 Mc/s. Continuous-frequency coverage is provided where feasible, but such calibration equipment is usually less stable and less accurate than that used at the fixed frequencies.

Microwave calibration facilities are being provided at the Center for the measurement of power, impedence, frequency, attenuation, and noise power. The initial goal is to cover the frequency range from 300 to 40 000 Mc/s for all quantities. For one quantity—the frequency of cavity wavemeters—the Center provides a calibration service to 75 000 Mc/s.

Examples of developments in this area include an improved measurement system for microwave impedance (reflection coefficient) calibrations based on reflectometer principles, and an improved microwave radiometer for use in measuring the noise temperatures of microwave sources.

The calibration workload of the Center, see Fig. 4, shows a dip in man-hours during 1962. This is largely attributable to a more efficient calibration program adopted by the Navy which reduces the number of standards sent to NBS for calibration. The upturn during 1963 is the result of some of the new services being offered by the Center.

Measurement needs of the future

To assist in planning for the future, the Radio Standards Laboratory staff has prepared a set of accuracy charts that summarize the state of the art, including existing national standards and calibration services, its five-year goals in national standards and calibrations, and the approximate present measurement needs of industry.

One example of such a chart is Fig. 5 showing microwave power standards in waveguide systems. It shows that at X band (8.2–12.4 Gc/s) a national standard exists in the neighborhood of 10^{-3} to 10^{-2} watt, to an accuracy of one part in 1000, and that this exceeds most of the present needs at this magnitude and frequency. At lower powers there is a continuing loss of accuracy until it is no better than 10 per cent at 1 microwatt. There is also a loss

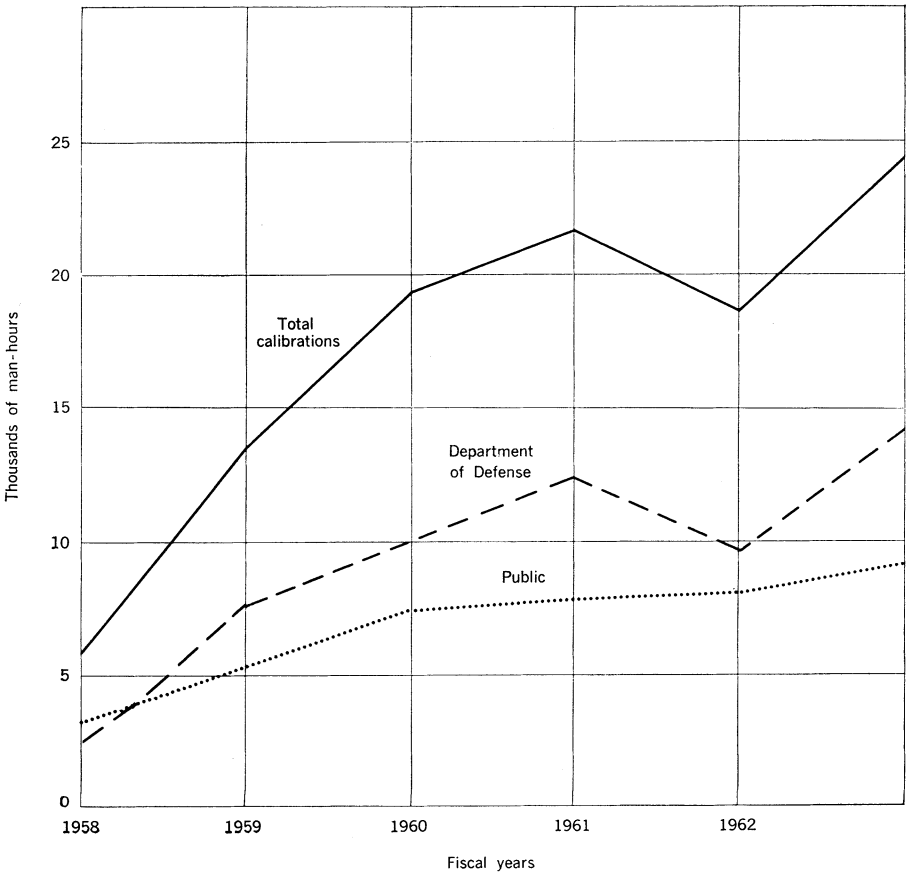


Fig. 4. Calibration man-hours, by fiscal year, of the NBS Electronic Calibration Center. The dips and upturns evident in some of the curves are explained in the text

of accuracy in other frequency bands, and there is no national standard above 10 milliwatts. In this same area, measurements are being made by industry at levels of 1000 or 100 000 watts to accuracies of from 1 to 10 per cent.

The laboratory's five-year objective is to fill in some of these gaps at selected frequencies and at selected power levels, but at somewhat lower accuracies.

Of course, such charts are merely guide lines and are subject to constant review as we continue to receive feedback from industry on present and future requirements. For example, we recently learned of a development program for high-power millimeter-wave tubes that is being undertaken by manufacturers on both coasts. They are in great need of a national standard of millimeter-wave power for rather high peak powers. It takes time for such a development to be incorporated into our program, and we appreciate having as much feedback as possible, as early as possible, and that it be specific and realistic.

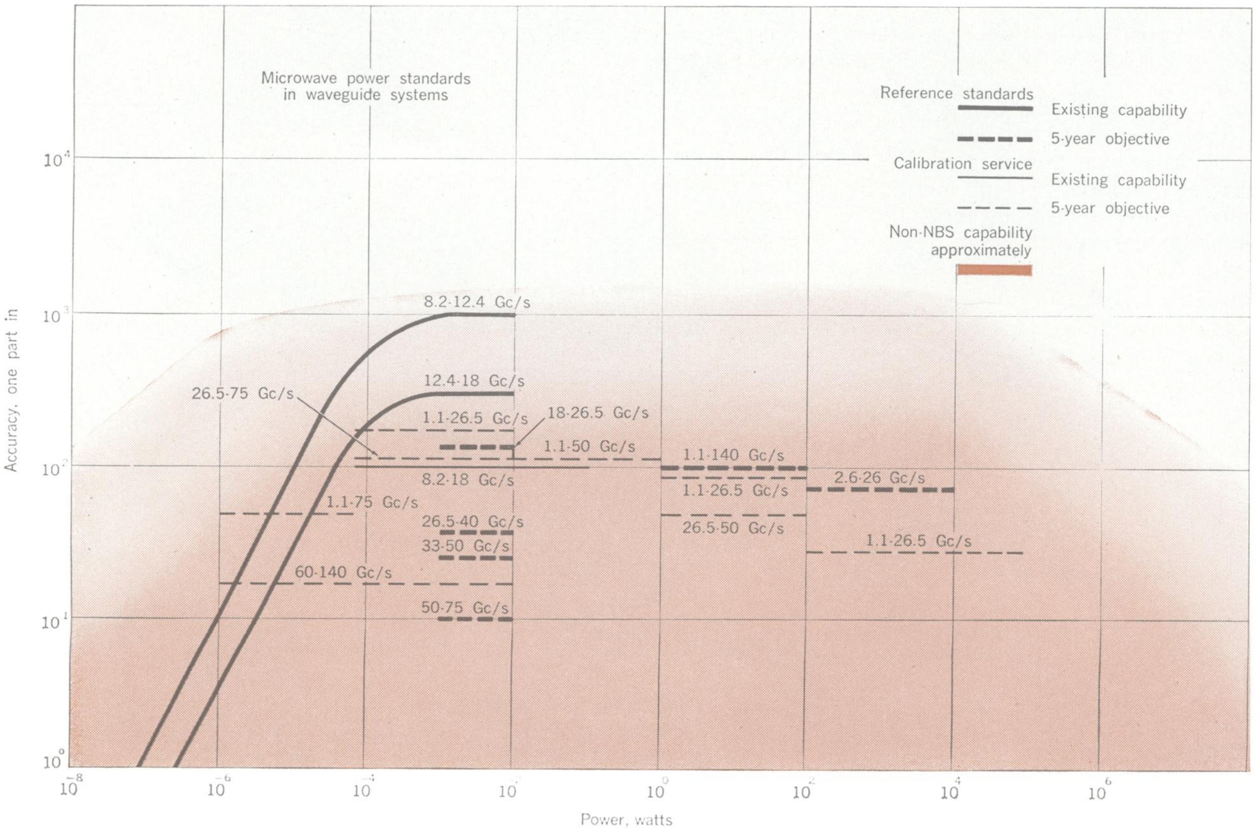
There are other examples which indicate future needs being created by technological advance. NASA is going to extremely narrow-band operation to reduce the transmitter and transponder power required for tracking and communication with deep-space vehicles. Bandwidths of $1/10$ c/s at 10^{10} c/s will be in use shortly. Assuming that an automatic frequency control system would be used, for searching and locking, the signal must be maintained at this stability for at least the AFC time constant, which in turn must be large compared to the reciprocal of the system bandwidth. The frequency stability implied in this requirement is of the order of one part in 10^{13} per second. It is fairly clear that NASA will be forced to hydrogen masers to control such signals, and that therefore we should be considering the performance standards of hydrogen masers.

Measurement of the phase of radio and microwave signals is becoming more and more important. Phase measurement has wide application in the electronic scanning of fixed directional antenna arrays and is essential to the ranging of missiles and space vehicles. Linear phase characteristics are essential to communication systems that transmit high information rates.

During August 1962, the Inter-Range Instrumentation Group determined that there is a need for global synchronization of time to the order of microseconds. The maintenance of time to microsecond accuracy over a typically desired interval of one day requires frequency stability to parts in 10^{11}. Here we have to determine whether it is appropriate for NBS to undertake full global distribution of time and frequency and, if so, the Laboratory must determine feasible ways of accomplishing the objective. One method which should be carefully considered is standard frequency broadcasts from satellites.

Most likely, the whole burden of national standards for lasers as communications devices will fall upon the Radio Standards Laboratory and the NBS Central Radio Propagation Laboratory. The latter is undertaking preliminary experiments with a commercial continuous-wave He-Ne laser and is proposing a substantial study of the propagation of laser beams. The Radio Standards Laboratory must provide the measurement standards for

Fig. 5. Accuracy sheet shows existing and proposed national standards and calibration services, and the present measurement needs of industry



lasers as, for example, measurements of the elements of the third-order tensor giving the nonlinear electric polarization of a material resulting from the application of two intense electric fields.

Other laser standards that are likely to be required, and which we are preparing to investigate, are power, spectral purity, directivity, quantum efficiency of mixers and harmonic generators, power dissipating ability, mode determination, modulation, and noise level. During the next five years, the staff plans to consider the use of double heterodyning systems for measuring attenuation, power, or other quantities at laser frequencies, and laser control by lower frequencies through phase or frequency lock.

The effect of quantum electronics upon radio science has grown until now it overshadows almost all of our future planning. In many projects it is the dominant area of study. For example, a group in materials research is working to establish material constants and characteristics that will provide energy level information for solid-state microwave and millimeter-wave applications. Development has begun on an antiferromagnetic resonance spectrometer, and preliminary antiferromagnetic resonance measurements are being made on systems with low Néel temperatures such as $CuSO_4$ and $CoSO_4$ (anhydrous). During the next few years, the group expects to extend these measurements to many more systems such as the double fluorides KMF_3 (M = Mn, Fe, Co, or Ni) and MnTe, MnSe, and MnSb—including those with higher Néel temperatures.

In the area of nonlinear dielectrics, the Laboratory is beginning the development of a measurement technology to determine the material characteristics of ferro, ferri, and antiferroelectrics under a variety of control parameters. Classes of materials must be investigated for special characteristics such as domain structure and relaxation processes, and the investigations and measurement technology must be extended to optical frequencies. Special needs in this area include knowledge of materials sensitive to thermal environments, development of synthesized specimens of controlled structure and composition, and development of optical measurement equipment.

A goal that underlies all of this work is to increase the accuracy and reproducibility provided by our present macroscopic standards by developing standards (such as the atomic beams) based on atomic or molecular phenomena. Therefore we are increasing our studies into the possibility of deriving electromagnetic standards from such phenomena as the Zeeman effect, the Stark effect, Larmor precession, electron–proton resonance, and nuclear magnetic resonance.

Closing the measurement gap

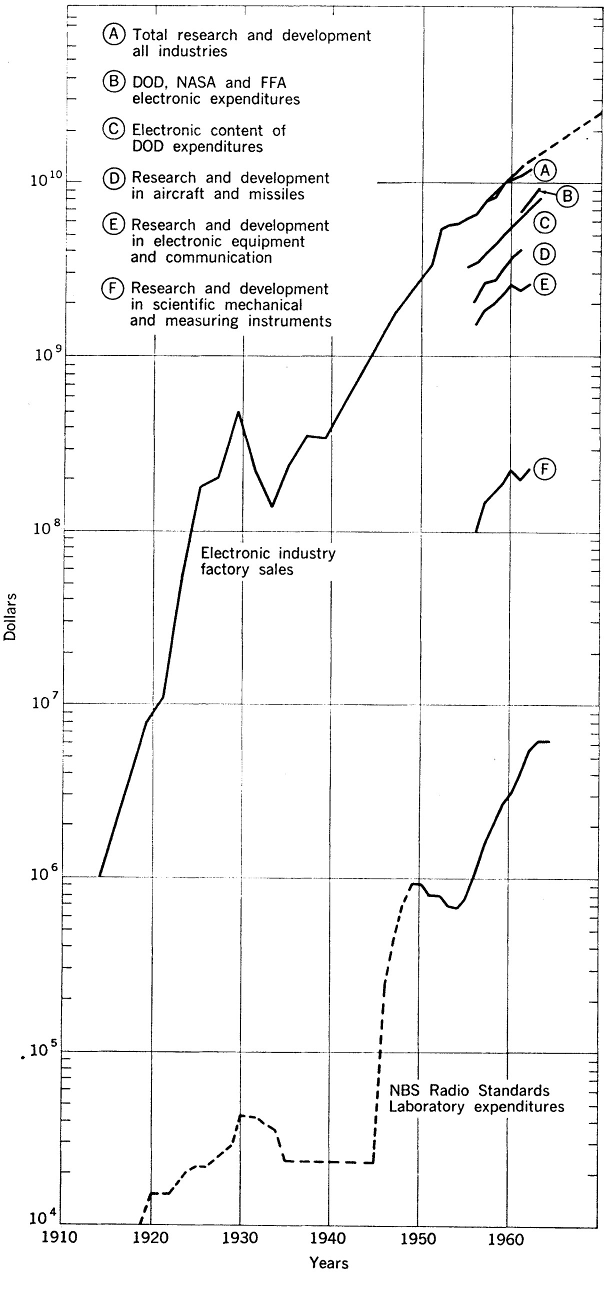
In considering which steps can best help the Radio Standards Laboratory meet its responsibilities, the most obvious is one of selection: the weeding out of measurement needs that can be met by commercial laboratories, and the careful assignment of priority to the work that remains. This is being done, and already a substantial portion of proposed work has been eliminated.

Another possible step is to substitute precision for accuracy. Consider, for example, the cycle of events that has occurred in evolving the length standard. At first the standard of length was to be one ten-millionth of the quadrant of the meridian passing through Paris. Conceptually, this was very satisfying, but in practice it was inconvenient to use. Therefore an arbitrary standard, the meter bar, was adopted because it could be used with much higher precision.

Next the meter bar as a standard was replaced by the wavelength of krypton, at a temperature of the triple point of nitrogen. This is conceptually much more satisfying than the arbitrary meter. It now appears possible that by going to an oscillating laser we will have a standard of length that is much more precise than the krypton wavelength, but its unperturbed value may not be known with such absolute certainty. We might then arbitrarily adopt a laser oscillating under specified conditions as a more convenient standard than the krypton lamp.

The Laboratory is in a similar position with respect to Q factor. We have a bank of standard coils with which

Fig. 6. Financial support for radio standards. Annual sales of the electronic industry and annual expenditures of the Radio Standards Laboratory. (See the Appendix)

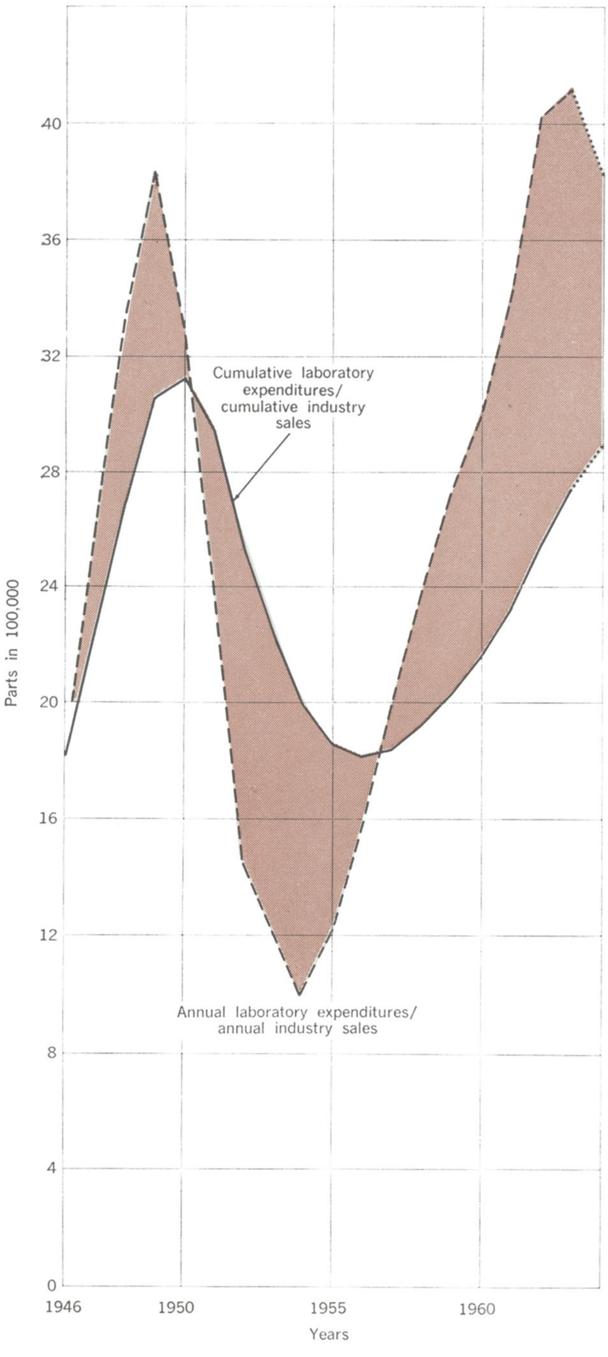


other unknown coils can be compared more precisely than their Q factor can be stated in terms of the ratio of energy stored to power dissipated per cycle.

Thus where precision exists with respect to existing arbitrary apparatus, we might quote the results of NBS tests with respect to the "standard of X" as maintained at NBS with, for example, a precision of comparison of perhaps one part in 10^4 and with an accuracy with respect to the international standards of perhaps one part in 10^2.

This would be analogous to the present situation for frequency in which an unknown frequency source can be compared to the national standard of frequency with a precision of one part in 10^{12}, but the accuracy of the national standard of frequency with respect to the internationally accepted standard of time is only one part in 10^9. This anomalous situation occurs because the internationally accepted standard of time (based on astronomical units) is very imprecise, although by definition it is infinitely accurate.

Fig. 7. Ratios of annual and cumulative expenditures of the Radio Standards Laboratory to annual and cumulative industry sales. (See the Appendix)



However, the substitution of precision for accuracy and the careful selection of priority do not strike at the heart of the problem, and the program of fundamental development which remains is sobering.

The main curves in Fig. 6 show (1) the annual factory sales of the electronic industry and (2) the annual expenditures of the NBS Radio Standards Laboratory—expenditures which provide the national basis of measurement for this industry. The secondary curves, identified on the figure, show expenditures in related areas.

Figure 7 gives (1) the ratio, since 1946, of the cumulative expenditures of the Radio Standards Laboratory to the cumulative factory sales of the electronics industry, and (2) the ratio of the annual expenditures of the Radio Standards Laboratory to the annual industry sales.

It is clear that there was a period of relatively low support for radio standards, and that in recent years this support has increased. The cumulative effect of the drop in support is seen in the curve which shows cumulative expenditures of the Laboratory relative to industry sales. This curve, which falls below the one showing the relative yearly ratios, indicates the possibility of a backlog of unmet demands.

To explore this situation, the Radio Standards Laboratory has analyzed current needs reported to the Laboratory and has estimated the effort it will take to meet these needs at a rapid but realistic rate of development. The needs in question were made as specific as possible by asking each company or organization involved to define the reason (application) for a reported need, and to estimate the required accuracy at particular points of magnitude and frequency.

These studies indicate a requirement for a significant enlargement in the program of the Radio Standards Laboratory if the very real and expressed needs of the industry are to be met in a realistically determined length of time. Significant enlargement means increases of the order of 30 per cent per year for several years.

This would be a challenge to any organization; it is a particular challenge to a government laboratory devoted to scientific research, whose basic product is knowledge or applied science in which advancement is recorded in the movement of a decimal point.

APPENDIX

Sources of information for Figs. 6 and 7 are the Electronic Industries Association and the National Science Foundation. The estimate that factory sales of the electronic industry will total \$25 billion by 1970 is from R. R. Dockson, "The Electronics Industry and the Dynamic Los Angeles Metropolitan Area," *Growth Pattern Study No. 4*, of the Union Bank, Los Angeles, 1962. The early expenditures of the Radio Standards Laboratory are shown dashed (Fig. 6) since it is difficult to isolate the work in radio standards from other radio research being conducted by NBS at that time. The Laboratory expenditures are expressed in fiscal years while all of the other values are in calendar years; the six-month offset between fiscal and calendar values is ignored. The 1964 figure for the Laboratory is an estimate as of September 1, 1963.