RADIO STANDARDS

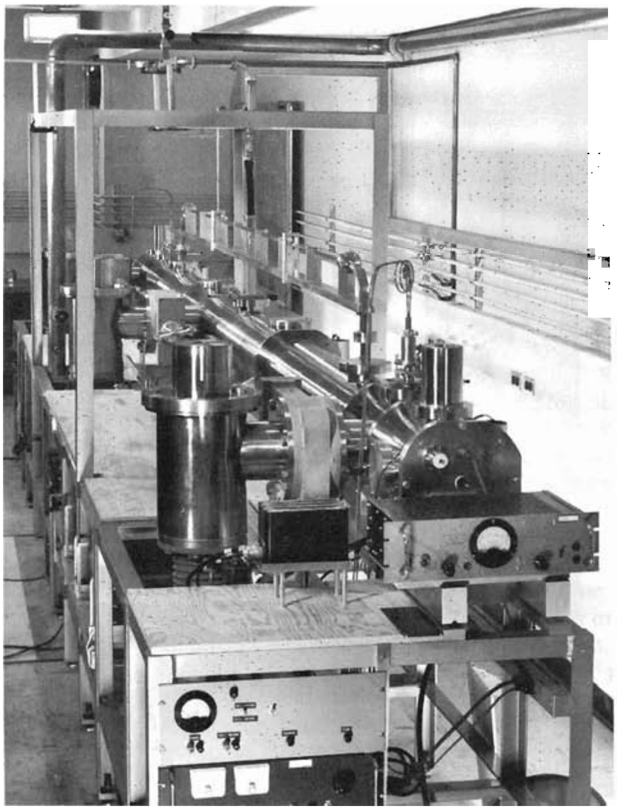
1954–1964

NBS WORK in radio standards began in 1911 with a frequency calibration made by J. Howard Dellinger. It was, as Dr. Dellinger said later, ". . . just a small offshoot of a number of electrical tasks one member of the Electrical Division was doing. . . ." By 1946 this effort had grown from one individual in the Electricity Division to two sections in the Central Radio Propagation Laboratory. With the move to Boulder in 1954 these two sections became the Radio Standards Division with an initial staff of about 50 people.

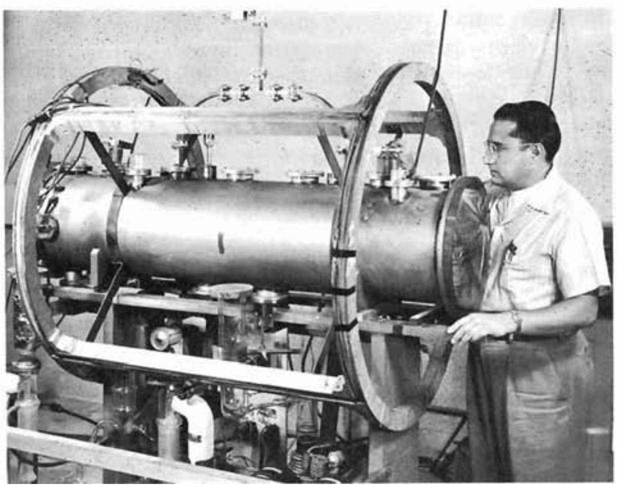
This modest beginning formed a strong nucleus for the work to follow. NBS had exhibited the world's first atomic clock in 1949. By 1950 the staff had developed the micropotentiometer for the measurement of small rf voltages up to 300 MHz. Also, by 1950 frequency calibrations extended to 30,000 MHz and other calibration services existed on a very limited scale. Development was under way in the areas of power, impedance, voltage, attenuation, field strength, noise, and the electromagnetic properties of materials.

Since 1954, NBS areas of research and development in radio standards have expanded to reflect both the work of the early 50's and also the newer needs of the electronics industry. Today the Radio Standards Laboratory is a leader in the development of frequency standards and their dissemination; it has excellent facilities for the measurement of both rf and microwave power; it has strong facilities in the other dominant areas of electromagnetic measurement; and its slender calibration efforts of the early 50's have grown into the Electronic Calibration Center which annually calibrates thousands of standards over a frequency range from zero to nearly 100 GHz.

The Laboratory also is heavily involved in studies using quantum physics as a basis for new radio standards; it has developed competence in the millimeter region and in plasma physics; it is a leader in the international comparison of radio standards; it is helping to train others in the newest techniques by offering workshops and courses in electromagnetic measurements; and it maintains close contact with both research and industry—with a particular desire to pinpoint and meet the needs of industry.



Left: A new cesium-beam frequency standard (NBS III), 18 feet long, is now being evaluated. Its length (about 8 feet longer than earlier models) should significantly increase the precision, since the spectral line width is about 45 Hz as compared with 110 Hz in the previous model. The new model can also be used with thallium. _Below:_ Henry Salazar is shown adjusting the experimental cesium-beam frequency standard shortly after it was moved from Washington to Boulder in 1954. With modifications, both internal and external, including removal of the open cylindrical frame (Helmholtz coils), the instrument is now the NBS I atomic frequency standard. With two additional standards in operation, NBS I has been further modified for research with thallium.



Early this summer the Electronic Calibration Center (ECC) completed its 20,000th calibration. The first, measurement of a high-frequency *Q* meter, was reported to the Navy on February 14, 1958. In these 6½ years, the program of the ECC has been greatly enlarged, the number of services increased, and the range of calibrations extended, both as to frequencies and as to the magnitude of the quantity being measured. A significant trend has occurred within the past year in the nature of the workload. Previously, the workload for the Department of Defense was approximately 50 percent greater than that for the public, but during the year the two have become about equal, with a continuing rise in calibrations being made for the public.

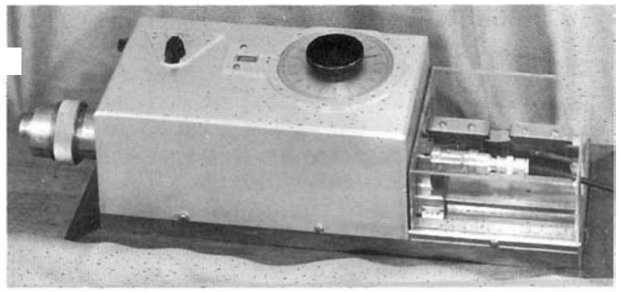
Frequency Standards

The most striking developments over the past decade have been in the area of frequency standards and their distribution. In 1957 cesium and ammonia beam spectrometers were operated for the first time in Boulder. Their precisions were 1 part in 10^9. In 1958 a second cesium beam apparatus was built and the original model was completely rebuilt. A comparison between the two was made over several months in 1959 and their frequencies agreed to an accuracy of about 1.5 parts in 10^{11} with a precision over several hours of 2 parts in 10^{12}. On January 1, 1960, the newest cesium beam became the device which provides the U.S. Frequency Standard (USFS).

Since 1960 the accuracy of the cesium beam standard has been refined to 1 part in 10^{11} and this is expected to be further improved by a new cesium beam which is about three meters long. There have also been interesting developments with thallium as an alternate frequency standard, and work is progressing on the development of a hydrogen maser.

Developments with atomic frequency standards raised the question of whether or not an atomic time scale could be maintained. Thus RSL began the development of an atomic time scale, capable of being synchronized or related to clocks at any remote location, and powered by an unfailing frequency source referenced to the U.S. Frequency Standard. Such a time scale was established in 1961. Later, by using a quartz-oscillator clock as a portable comparator, the scale was related to the time pulses of WWV, to the atomic time maintained by the Naval Observatory, to the time pulses of the Loran-C master station at Cape Fear, N.C., and to clocks at other laboratories.

The progress in the atomic measurement of time at NBS and other laboratories has led to consideration by the General Conference on Weights and Measures of defining the second in atomic instead of astronomical terms. It is probable that international agreement on the use of atomic standards for high-accuracy work will be reached this October in Paris.



Waveguide-below-cutoff attenuators serve as working standards in many of the measurement systems used in the Electronic Calibration Center.

As the atomic standards were refined, similar progress was made in the dissemination of the U.S. Frequency Standard. In 1954 the USFS was disseminated only via shortwave broadcast by WWV, near Washington, D.C., and by WWVH in Hawaii. Two years later the Laboratory began experimental transmissions at 60 kHz over WWVB in Boulder. This station radiated only 1½ W, but it proved that the lower frequency did offer much higher accuracy for those laboratories which could receive it.

Success with the 60-kHz transmission led to an experimental 20-kHz transmission in 1960 (theoretical studies had indicated that 60 kHz would be more stable over the continental United States but that 20 kHz offered greater stability for global transmission). The 20 kHz station, WWVL, radiated only 15 W, yet it was promptly picked up as far away as New Zealand. These experiments led to the construction in 1963 of more powerful transmitters and more efficient antennas at Fort Collins, Colo., for both WWVB and WWVL. WWVB now has a radiated power of about 2 kW and WWVL—still on an experimental basis—has a radiated power of about 500 W. The carrier signal of each station is phase locked to an atomically related time scale. This phase control of the low-frequency transmission means that clocks at remote locations, once synchronized, can maintain—to within a few microseconds—the accuracy of the U.S. Frequency Standard.

Radio Frequency Standards

For about four years after the move to Boulder major efforts in the areas of radio frequency and microwave standards were devoted to the development, construction, and installation of equipment in the Electronic Calibration Center. There had never been such a center before, and during these first few years several million dollars and about 50 percent of the staff's time were spent in equipping the center.

There were, however, many valuable developments in research. By 1956 a new AT (attenuator thermoelement) voltmeter demonstrated an improvement of more than an order of magnitude in both absolute accuracy and in calibration stability over the conventional vacuum-tube voltmeter. It also extended the range in both frequency and voltage.

In the field of impedance, a dramatic development was the achievement of a high-precision connector. Rather than having male or female elements, the terminals of this connector have flat faces, perpendicular to the axis, which allow the highest accuracy of the primary standard while giving the least loss of accuracy in transfer to calibrated instruments. This development made it possible to improve impedance measurements by about two orders of magnitude. At the same time it became possible to intercompare capacitors, inductors, and resistors (and therefore attenuators, power meters, and voltmeters) on the same mounts to detect possible calibration errors. This connector is now beginning to be used in industry and in other quantities of radio measurement.

By 1958 there existed a set of national primary power standards for use up to 300 MHz. These included the 0- to 100-mW thermistor bridge, the 1-mW to 10-W bolometer bridge, and the 200-mW to 20-W dry static calorimeter. The overall accuracy of 0.5 percent provided a marked improvement over previous accuracies and ranges.

A new development in the field of pulse radio frequency power—which formed the basis for a new calibration service—occurred in 1961. In this new method the power level of a selected portion of the pulse is compared with a known amount of CW power at approximately the same frequency.

At about this time the staff completed an international comparison of rf power (300 MHz) with Great Britain and later with Japan (400 MHz)—in both cases agreement was within the limits of experimental error. Thus for the first time it was known that the rf power measurements of all three countries are in close agreement.

The basis for a new calibration service has been provided during the past year by a noise power comparator which measures noise power from 10^{-18} to 10^{-21} W with a precision of at least 1 percent. This improvement in sensitivity and precision is achieved through the use of a two-channel radiometer developed by the staff. With refinements the comparator is expected eventually to achieve a precision of at least 0.02 percent.

View from top of one of the 400-ft towers which support antennas

Now nearing completion is an improved standard for calibrating rf attenuators which promises to provide an accuracy of 0.0001 dB per 10 dB in the near future. This standard is a self-calibrating, high-sensitivity insertion-ratio measuring system. It also has the ability to provide both the insertion phase angle and the insertion loss.

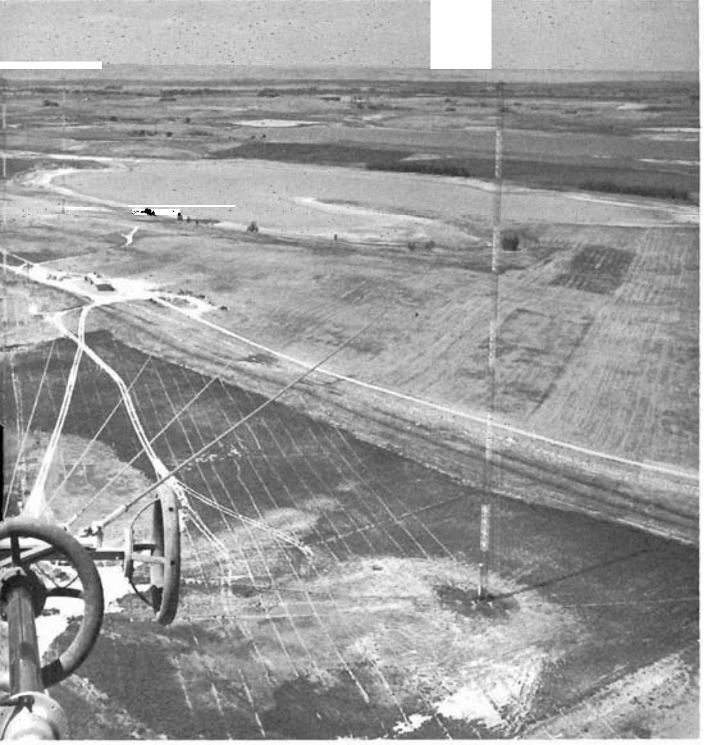
Microwave Standards

In 1954 only the attenuation and frequency standards were sufficiently advanced to justify the offering of a true calibration service in microwave measurements, although much valuable pioneering work had been done in the fields of microwave power, noise, attenuation, impedance, and frequency.

Within four years after the move, however, remarkable improvements in the accuracy of microwave power measurements had been achieved through the development of a self-balancing d-c bolometer bridge, a highly stable signal source, and the careful analysis and refinement of the NBS microcalorimeter. The 0.2 percent accuracy of these measurements raised NBS to world leadership in the field.

These developments also made possible the first international comparisons of microwave standards of any kind and, in 1957 and 1958, microwave power comparisons were made with Japan and the United Kingdom. All comparisons were within the limits of ex-

Construction details of the NBS microcalorimeter—the U.S. standard of microwave power—are explained to Dr. Wolfdietrich H. Schaffeld (*right*), head of the Microwave Physics Laboratory, Physikalisch Technische Bundesanstalt, Braunschweig, Germany. *Left to right:* Glenn Engen, Dr. George Schafer, and Dr. Schaffeld.



of the new 60- and 20-kHz transmitting stations at Fort Collins, Colo.

perimental error and, at 10 GHz, agreement was within 1.5 percent.

Microwave impedance standards and measurement techniques were brought to a high state of accuracy by 1959, when the tuned reflectometer was fully developed at NBS, and when both half-round inductive obstacles and quarter-wavelength short-circuit impedance standards were carefully evaluated. For the first time, impedance standards were available in which a high degree of confidence existed.

The following year two methods of measuring attenuation were reported—each capable of accuracies from within 0.0001 to within 0.06 dB over a range from 0.01 to 60 dB. One method employs differential power measurements by refined bolometric techniques, and the other is a modulated subcarrier system which lends itself to audio frequency techniques. In 1960 accuracies of these techniques exceeded the precision to which available attenuators could then be set and read.

A concerted effort on the development of microwave noise standards resulted, in 1962, in the establishment of a calibration service for WR 90 waveguide (8 to 12 GHz) standard noise sources. This was based on a hot load operating at approximately 1,000 °C and a thoroughly evaluated, sensitive radiometer for noise standard comparisons.

Work on microwave phase shift standards began in 1958, and the tunable reflectometer developed for impedance measurements was applied as a standard phase shifter. A modulated subcarrier technique was also developed as a sensitive method of measuring microwave phase shift. The basic theory of phase-shift measurements and standards has been developed by NBS during the past few years.

Present work in this area is concentrated on the development of microwave standards of field strength and high power where there are no existing NBS calibration services.

Extremely High Frequencies

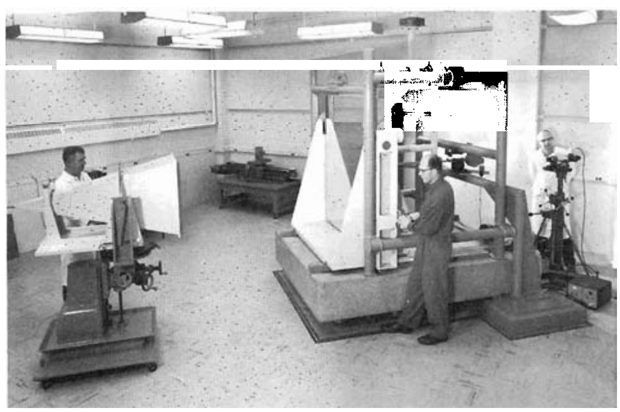
As early as 1952 NBS began conducting research at frequencies ranging from the shorter microwaves to millimeter waves to develop methods of generating, transmitting, and detecting energy in this region, and to explore applications of these frequencies to the measurement of significant physical quantities.

By 1956 a pilot-model microwave interferometer of the Michelson split-beam type had been built and operated at 6 mm as a first step in its development for measuring the velocity of light. The final version (which has a 2-ft sq horn and a 5-ft sq aluminum mirror) was in operation by 1962. The measurement has been delayed by diffraction effects that have required extensive mathematical analysis, but encouraging initial measurements reveal a standard deviation of a single measurement of about 0.2 to 0.3 km/sec. It is expected that this can be improved significantly for the final measurements.

A major achievement of the past ten years was the development of the Fabry-Perot interferometer designed to operate at millimeter wavelengths. The initial design of this interferometer began about 1957; by 1961 the instrument had been used to measure the length of millimeter waves to accuracies of better than 0.04 percent. In experiments with waves about 6 mm long, the resonant cavity attained Q values of around 100,000. The interferometer has been used to measure dielectric constants and loss tangents of materials in sheet form, and to make refractive index measurements on a variety of common gases to an accuracy of ± 1 part in 10^7.

The completely new type of resonator provided by the Fabry-Perot interferometer is now being applied in refractometers and spectrometers. During 1962 an absorption cell was built which uses a parallel-plate interferometer for the observation of Stark effects in molecular spectra. The Stark effect concerns the splitting of

Final tests are being conducted on the Michelson interferometer prior to measuring the speed of light at millimeter wavelengths.



spectral lines by the application of electric fields, and provides an unexploited possibility of measuring d-c and low-frequency voltages to high precision. The device has been tested at voltages up to 5000 V and has achieved short-term precisions of 1 or 2 parts in 10,000. It is now being refined with the expectation that the precision will be improved by one or two orders of magnitude.

Another application uses a miniature (2-in.) spherical-mirror Fabry-Perot resonator in a series of wavemeters covering the frequency range from 50 to 140 GHz. Experimental evaluation during the past year has shown that these have Q values many times that of commercial wavemeters and are easily read to three significant figures with no individual calibration curves required.

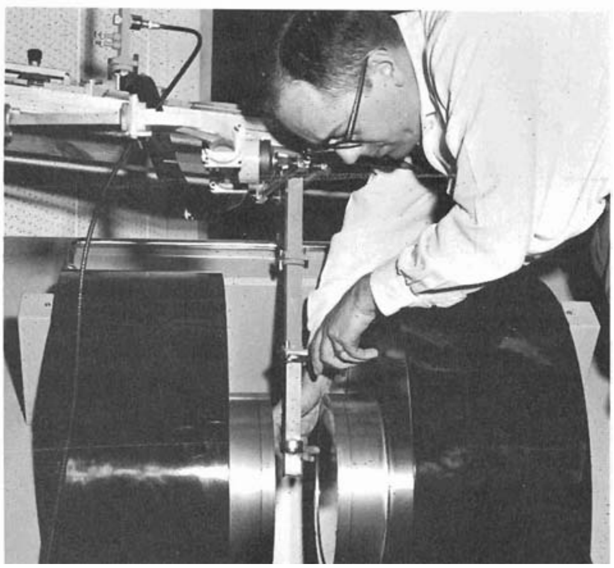
One of the newest programs in microwave physics is the development of an extremely wide-band absolute power standard based upon the pressure exerted by electromagnetic radiation on a perfect reflector. The standard is expected to cover the frequency range from 1 mm to visible light—10 octaves of the electromagnetic spectrum—in a single instrument.

Materials

A study which extended over much of the past ten years was a materials analysis program for the Bureau of Ships. Measurements were made on the magnetic characteristics, and on those parameters important to understanding material properties, of ferrimagnetic materials used in the radio and electronics industry. Tensor permeability studies, which were a part of this program, became possible when the staff developed an exact solution to a bimodal cavity which permitted the exact analysis of tensor permeability.

In 1958 the Department of Defense asked the Laboratory to establish facilities for the large-scale evaluation of materials, and for the complete investigation of certain classes of materials. These facilities now offer the unified program necessary for meaningful correlation and referencing of the electromagnetic constants of selected materials in the rf and microwave spectra.

Lawrence M. Matarrese places a waveguide cavity, containing a crystal specimen, between the poles of a magnet in studies of magnetic resonance. The objective is the establishment of standards and measurement techniques, based on a better understanding of the interaction of electromagnetic waves with matter.



Along with these developments there have been continuing advances in primary standards and basic research in both the magnetics and dielectrics areas. During the later 50's these studies led to continual improvements in specific instruments such as those used to study the magnetic and dielectric spectra of radio materials. By 1960 a permittimeter had been developed which makes it possible to measure complex rf permittivity or conductivity up to about 50 MHz without applying electrodes to the material. A microwave conductivity service was instituted as well.

During the early 60's a theoretical study of the complex tensor permeability led to a basic investigation of ferrimagnetic resonance (FMR)—especially of losses which may be related to spin waves. Two new and important methods were recently developed for studying the FMR loss versus coupling to the spin-wave spectrum.

Also during the early 60's the Laboratory began magnetic resonance studies to determine energy levels, crystalline fields, relaxation times, and transition probabilities in paramagnetic and antiferromagnetic crystals. An electron paramagnetic resonance spectrometer was built and is being used for the observation of interesting electron paramagnetic resonance spectra in materials such as iron-doped quartz, calcite containing manganese ions, amethyst and topaz, and a program to provide controlled specimens such as doped single crystals was also introduced.

Recently research has begun on antiferromagnetic resonance and the interaction of phonons and spins. Sizable single crystals of antiferromagnetic copper sulfate were produced and are being investigated. The phonon-spin interaction is studied using nuclear magnetic resonance as a diagnostic tool.

Radio Plasmas

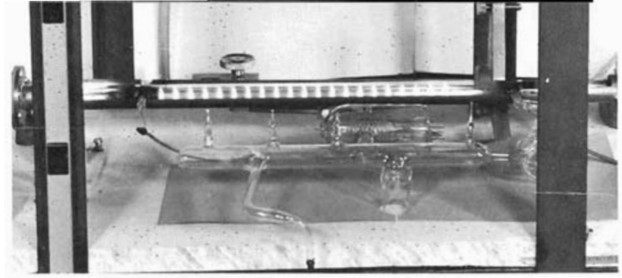
Since the interaction of radio waves and plasmas is a subject of much theoretical and practical interest, NBS began a study of radio plasmas in 1959. The goal is to develop precise measurement techniques and basic data on the fundamental properties of ionized gases.

A major initial project was the radio probing of a dense, highly magnetized, and bounded plasma by using the British thermonuclear machine ZETA. The early theory for this experiment indicated the possibility of accurate determination of the internal magnetic field, electron density, and electron temperature of extremely dense plasmas. Analysis of the ZETA data, however, revealed additional effects not explained by the early theory. A detailed solution for bounded plasmas has since been developed and is presently being checked.

During the past few years attention has been paid to the development of diagnostic methods based on microwave techniques and optical spectroscopy as well as to the development of stable and uniform plasmas.

Quantum Electronics

Since 1960 the Laboratory has become increasingly involved in research studies applying quantum physics to radio standards. The atomic frequency standards, the use of the Stark effect as a voltage standard, and the



Research on precise measurement techniques and basic data on the fundamental properties of radio plasmas is conducted at the Radio Standards Laboratory. Almost all laboratory plasmas (horizontal cylindrical tube, *center*) are nonuniform and exhibit structures as illustrated above. Such structures, caused by nonlinear flow mechanisms, must be better understood before they can be used effectively.

investigations of magnetic resonance have been mentioned. Other research in progress in this area includes the measurement of the velocity of gamma rays by means of the Mössbauer effect, the measurement of the fine-structure constant by determining the fine-structure separation in singly ionized helium, and a study of the various mechanisms of inducing blue fluorescence in anthracene with the red light of a "giant pulsed" ruby laser. In addition a small but significant research effort in optical laser phenomena has been established, which will serve as the basis of a possible future standards program for selected laser properties.

Theoretical Physics

A project which has been continuing for several years has been the preparation of a set of microwave spectral tables which are being published in five volumes. By providing an up-to-date catalog of information these tables will aid researchers in the identification and analysis of microwave spectra, with significant application to industrial chemical analysis and control.

During the late 50's, to meet the needs encountered in the microwave measurement of the velocity of light, the staff developed a general theory of diffraction in reflection and transmission systems. This provided an analytical tool for the original problems and also led to further theoretical work. One recent result permits electromagnetic field measurements with arbitrary probes.

About 1960 new perturbation formulas were developed and used to obtain approximate results in a variety of waveguide junctions. The formulas were applied in particular to make finite conductivity calculations for new impedance standards consisting of half-round obstacles in rectangular waveguide.

In 1962 a significant paper was presented which described some generalized variational principles for electromagnetic vibrations and applied these principles to the theory of waveguide junctions. During the same year calculations were completed on the bound state energies of an exponentially shielded Coulomb potential, that is, the Debye-Hückel potential in ionized gases. Recently a quantum statistical mechanical theory has been developed which may be the first fundamental and successful calculation of properties of a plasma model more realistic than the familiar electron-gas model; the expansions are carried to a higher order than they have been heretofore, and corrected lower-order terms are obtained.

Other Developments

The advances in the technical areas have been coupled with advances in the areas of administration, education, and communication. In 1962 the Radio Standards Division was reorganized as the Radio Standards Laboratory consisting of two technical divisions and a Laboratory office. This has provided the basis for expansion tailored to the needs of the electronics industry. A guideline for such expansion is being provided by a long-range planning committee which annually compares the present Laboratory capabilities with the needs of industry and—in view of these—outlines the program for the next five years. Provision of the physical facilities for expansion began in 1963 with the initial design of a new multi-million dollar building for the Radio Standards Laboratory. This design is now almost completed.

Contact with both industry and research is closely maintained through a series of measurement research conferences held in conjunction with the Aerospace Industries Association, through national conferences sponsored and hosted by the Laboratory, and through selected speakers who are invited to present lectures describing their measurement needs or new developments in their field. The biennial Conference on Precision Electromagnetic Measurements, which began in 1958, is now firmly established as a significant forum for the interchange of ideas. Although it is a national conference it has developed good international participation. This Conference has also led to the birth of the National Conference of Standards Laboratories and to a special committee representing both NBS and industry which has reduced the uncertainties of high-precision connectors by an order of magnitude.

There has been increasing contact with foreign laboratories. During the past year there was an exchange of U.S. and Soviet metrology delegations, and the Laboratory has since received a Soviet proposal for extensive high-frequency and microwave comparisons. Three European countries have expressed a desire to duplicate the NBS microwave power-measuring equipment.

The Laboratory has begun a strong education program for both industrial and research personnel by providing a microwave workshop in 1962 and a three-week course in electromagnetic measurement in 1963. Also, the publication rate of the Laboratory during the past few years has risen to a little more than one professional paper per week.

Since 1954 the size of the Laboratory staff has expanded from 50 to more than 300 people, the technical program has experienced a similar growth, and, in some respects, the present Laboratory facilities are the best in the world. Yet studies reveal a requirement for strong continued expansion if the Laboratory is to meet the real and expressed needs of the swiftly growing electronic industry. It is expected, therefore, that the next ten years will be a period of even more dramatic growth.