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Review of developments occurring within the United States in the fields of Radio Measurement Methods and Standards during the triennium 1960 through 1962.

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1. Atomic Frequency and Time Interval Standards

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Probably the most noteworthy accomplishment in the period 1960–61–62 has been the development of the hydrogen maser. The HCN maser may also have application as a frequency standard, but no serious attempt to evaluate its usefulness to this purpose has been made. A thallium beam is finally under critical test as a frequency standard. Considerable technological development of cesium beams, ammonia masers, and optically pumped gas cells has taken place. Commercial rubidium gas cells of excellent quality are now available, together with much improved new models of commercial cesium beam standards. Techniques have been developed for synchronizing and comparing widely separated clocks by propagated signals. It is now possible to compare atomic frequency standards using VLF transmissions to about 2 parts in 10^{11} over large distances.

1.2. Atomic Beam Standards

The hydrogen atomic beam maser has been shown to have an interaction time the order of 1 sec, from which is inferred a spectral line width of about 1 c/s. This is the narrowest line employed in any of the present-day frequency standards. The extreme narrowness of the line reduces very substantially the effects of "frequency pulling" by the resonant cavity on the emission frequency. As a consequence of the large number of collisions taking place within the decay time, there is practically no first-order Doppler shift. Two hydrogen masers at Harvard have demonstrated a relative stability of 1 part in 10^{12} over a 12-hr period. A frequency shift of about 1 part in 10^{11} exists as a result of interaction with the wall coatings. There is hope of eliminating this shift to a large extent [Goldenberg, Kleppner, and Ramsey, 1960; Goldenberg, Kleppner, and Ramsey, 1961; Kleppner, Goldenberg, and Ramsey, 1962 a and b; Ramsey and Kleppner, 1962; Vessot and Peters, 1962]. Although hydrogen is much more sensitive to a magnetic field than is thallium or even cesium, its narrow line width will allow the field to be reduced to a very low level. However, it remains to be determined just how low this field may be reduced. Intensity may suffer drastically at the desirable field level as a result of "Majorana flop."

NBS has made preliminary measurements on a thallium beam, obtaining precisions of 5 parts in 10^{13} in a given day. However, the day-to-day frequency measurements show a standard deviation of the mean of 4 parts in 10^{12}. This scatter in the day-to-day measurements has been found to be attributable to the rather poor construction of the microwave structure exciting the transition. From the present data it is inferred that significantly higher accuracy can be obtained with thallium as opposed to cesium if a suitable microwave structure is used.

The United States Frequency Standard (USFS) and its alternate have undergone rather extensive tests through the past 4 years at NBS. Their accuracy is about 1 part in 10^{11} and precision of about 2 parts in 10^{13} for 12-hr averaging times. χ^2 tests demonstrate a gaussian distribution of the data. Manual and servo measurements of frequency agree to the precision of measurement ($\pm 2\times 10^{-12}$) over a period of 1 year [Mockler, Beehler, and Snider, 1960; Mockler, 1961; Beehler, Atkinson, Heim, and Snider, 1962].

1.3. Optically Pumped Standards

Extensive development and analysis of frequency standards employing optical pumping techniques have yielded a rubidium gas cell standard with a drift rate of about 1 part in 10^{11} per month, and a temperature coefficient of 1 part in 10^{11} per °C. [Carpenter, Beaty, Bender, Saito, and Stone, 1960].

Investigation of alkali metal gas cells employing buffer gases show a shift in frequency when the intensity of the exciting resonance light is varied. High buffer gas pressures reduce this shift considerably [Arditi and Carver, 1961; Arditi, 1961]. Arditi and Carver have measured the hyperfine structure (hfs) separation as a function of the buffer gas pressure, temperature, and intensity of the pump light source. The rubidium hyperfine structure separation has been measured to ± 3 c/s ($\nu_0=$ 6,834,682,614) by Penselin et al. [Penselin, Moran, and Cohen, 1961].

Tests on a commercial rubidium gas cell standard give the following results (where σ denotes the standard deviation of frequency):

$\sigma=2.5$ parts in 10^{12} for a 10-hr run with 24-min averaging times;
$\sigma=2$ parts in 10^{11} for a 10-min run and 1/4-sec averaging times;
$\sigma=4.5$ parts in 10^{11} for a run of 160 days [Packard, 1962].

1.4. Molecular Beam Masers

Marcuse has successfully operated an HCN maser at 88.6 Gc/s [Marcuse, 1961; Marcuse, 1962]. An effort is being made to observe the $(J=2, K=1)\rightarrow(J=1, K=1)$ transition in ND_3 at 618 Gc/s [Derr, Gallagher, and Lichtenstein, 1961].

The ammonia maser has been employed as a stable signal source in order to spectrum-analyze frequency-multiplied signals from crystal oscillators and stabilized klystrons. The purpose of the experiments was to determine the short time stability of these signal sources and to appraise their usefulness in the excitation of cesium beam standards. This ammonia maser spectrum analyzer has a band width of about 3 c/s at 24,000 Mc/s [Barnes and Heim, 1961; Barnes and Mockler, 1960].

Barnes et al., have developed an $N^{14}H_3$ maser resettable to 3×10^{-11} [Barnes, Allan, and Wainwright, 1962]. A substantial improvement is expected if $N^{15}H_3$ is used. In their device a correction signal is obtained by Zeeman modulating which is used to continuously servo the cavity to the NH_3 resonance frequency. The maser signal stabilizes a frequency multiplier chain and imparts to it a stability of about $\pm 4\times 10^{-12}$ for periods the order of 1 hr.

1.5. Atomic Time

The Naval Observatory and the National Physical Laboratory determinded the frequency of the hyperfine structure separation in cesium in terms of Ephemeris Time. This frequency is 9,192,631,770$\pm$20 c/s [Markovitz, 1962].

NBS has established a separate atomic time scale based solely on the United States Frequency Standard, assuming the hfs separation in cesium to be 9,192,631,770.00 . . . c/s for purposes of research regarding the redefinition of the second in terms of an atomic transition. NBS atomic time has been assigned to WWV time pulses beginning in October 1957. These assignments have been compared to similar assignments of time by the Naval Observatory according to their A.1 scale. Analysis of the data between October 1957 and August 1962 shows that the NBS and A.1 scales are diverging at an average rate of 2×10^{-11} sec/sec [Newman, Fey, and Atkinson, 1963]. Although the rates of the two clock systems agree very well, the actual time when the two systems were chosen to be in coincidence (Jan. 1, 1958) has an uncertainty of about ± 1 msec. It is intended that the Loran-C system will be used to synchronize the NBS clocks with A.1 time to 1 μsec. The total delay time has not yet been determined.

1.6. Frequency and Time Interval Comparisons

The two cesium beam United States Frequency Standards (USFS) were compared throughout the period 1960–61–62. Their frequency difference is 1.6 part in 10^{11}. This difference remained constant within this time period to ± 2 parts in 10^{12} even though the machines were partially disassembled and moved to another laboratory, *C* field structures and shielding were changed, and frequency multipliers, deflecting magnets, and rf structures were changed.

Almost daily comparison of the United States Frequency Standards with the commercial beam and gas cell secondary standards at NBS demonstrate the newer models of these devices to be commonly stable within ± 2 parts in 10^{12} from day to day. A vast amount of this data has not yet been critically analyzed.

Atomic frequency standards in different parts of the world can now be best compared by monitoring the following VLF frequency stabilized transmissions: NBA (Canal Zone, 18 kc/s), GBR (England, 16 kc/s), WWVB (near Boulder, Colo., 60 kc/s), and

WWVL (near Boulder, Colo., 20 kc/s). NBS assigns corrections to these transmissions with respect to the United States Frequency Standard; the Naval Observatory assigns corrections to NBA and GBR according to the A.1 system; and the European nations assign corrections according to their own atomic standards based on the frequency 9,192,631,770 c/s for cesium. WWVB and WWVL are of low power and do not have the coverage of NBA and GBR.

Analysis of the data covering the period September 1960 to February 1961 for eight atomic frequency standards located at NBS, NRL, Naval Observatory, Cruft, NRC, NPL, CNET, and Neuchâtel shows a maximum divergence of 8 parts in 10^{10} and a minimum divergence of 3 parts in 10^{10}. More typically, the mean difference between standards was 1 to 2 parts in 10^{10} with fluctuations from month to month of the same order [Richardson, Beehler, Mockler, and Fey, 1961].

Data from November 30, 1959, to June 30, 1960, gave a difference between the United States Frequency Standards and the NPL standard as -6 parts in 10^{11} for one propagation link and $+1.2$ parts in 10^{10} for another propagation link. Comparison via a single propagated signal could not be made at the time. More recent and more direct comparisons show much better agreement. Data over the past 1½ yrs have not yet been completely analyzed.

Simultaneous phase measurements made at Cambridge, Mass., and Banbury, England, on the propagated signals from GBR were made in order to resolve the observed fluctuations into a contribution caused on the propagation path and a contribution produced by fluctuations in the oscillators. The fluctuations in transmission time were about 2 μsec. The corresponding contribution to the error of transatlantic frequency measurement is 2 parts in 10^{11} for a measurement time of 24 hr [Pierce, 1960].

Reder et al., studied the problem of synchronizing clocks separated by large distances by physically transporting atomic clocks and maintaining synchronization via VLF transmissions. Their conclusions were that clocks anywhere on the surface of the earth could be synchronized to 5 μsec or better [Reder and Winkler, 1960; Winkler and Reder, 1960; Reder, Brown, Winkler, and Bichart, 1961].

The Loran-C navigational system operating on a basic frequency of 100 kc/s has been demonstrated to be capable of synchronizing clocks separated by large distances to 1 μsec [Doherty, Hefley, and Linfield, 1960]. Delay times have evidently not been determined except by the measured two-way propagation time. It is inferred that frequency may be compared by such a system with a precision of 1 part in 10^{12} in 1 day and to 1 part in 10^{13} in about 10 days [Markowitz, 1962]. NBS and the Naval Observatory are cooperating in the development of the Loran-C system to provide time synchronization with the highest possible precision.

Joint experiments for time synchronization were performed by the Naval Observatory and the National Physical Laboratory, using the Telstar satellite, in August 1962. It was concluded that clocks at these two locations could be synchronized to about 1 μsec. It is believed that this could be improved to 0.1 μsec, in which case a frequency comparison to 1 part in 10^{13} could be accomplished in 10 days. Distances to the satellite determined by celestial mechanics and distances given by the travel time of the signal multiplied by the volocity of light agree to about 1 km, indicating that the delay time can be calculated to about 3 μsec. This might very well be improved with better range data.

Time signals from a clock in the navigational satellite Transit are being monitored by the Naval Observatory. The accuracy of measurements is now about 100 μsec.

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2. RF and Microwave Power Measurements

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Several contributions in the field of radiofrequency and microwave power measurement have been made since the last General Assembly. Both advances in existing techniques and entirely new approaches can be listed. These contributions fall naturally into the general categories of bolometric, calorimetric, and miscellaneous techniques. They are presented in this order.

Recently developed commercial bolometer bridges offer higher accuracies than have been available previously. Temperature-compensated and temperature-controlled mounts are now available from several manufacturers to cover the spectrum from 10 Mc/s to 40 Gc/s. Temperature coefficients of 2 μw/° C and resolutions of 0.5 μw are typical. Both manual and self-balancing types [Pramann, 1961] are represented.

Studies of superconducting and carbon disk bolometers at liquid helium temperatures continue [Lalevic, 1960 and 1961]. Such devices have possible applications in power measurement to 10^{-15} w.

A self-balancing d-c bridge for low-level power measurement was described [Reisener and Birx, 1962]. Alternate pulses of the unknown rf and d-c are applied to the bolometer. An a-c amplifier and synchronous detector comprise a null detector to give a sensitivity of 3×10^{-10} w.

An improved technique for determining bolometer mount efficiency by impedance measurements was developed at the National Bureau of Standards [Engen, 1961]. An accuracy of ±0.5 percent is possible. The theory was verified by comparison with calorimetric methods, and a limit can now be set on the magnitude of the d-c–rf substitution error. An analysis of a previously unrecognized source of substitution error in dual-element coaxial bolometer mounts was investigated and reported [Engen, 1962].

An adaption of the impedance method has allowed better measurement accuracy in the 1-mm region. The use of bolometric methods was extended to the measurement of low-pulse power at wavelengths less than 1 mm [Miller, Szente, and Mallory, 1963].

The introduction of thermoelectric power detectors using semiconductor materials is an innovation in the microwave field. Two such devices are now commercially available from one manufacturer under the trade names of "Bolomistor" and "Calorimistor." The "Bolomistor" is essentially a lead telluride thermocouple mounted in a standard crystal case. A 50-db range of square-law response is claimed. Time constant is about 1 μsec. The "Calorimistor" is an in-line microwave wattmeter with an insertion loss of 0.1 db and a maximum power rating of 250 w.

Investigations of the application of thin-film thermocouples has resulted in the development of another microwave power-measuring device of the thermoelectric type [Hopfer, Riederman, and Nadler, 1962]. It is expected that these units will also be available commercially in the near future.

A temperature-compensating accessory unit for use with the National Bureau of Standards self-balancing d-c bolometer bridge was developed. It affords about three orders of magnitude reduction in the effect of mount temperature fluctuations and may be used with unselected barretters or thermistors.

Advances have been made in commercially available dry calorimeters to improve the response time, and a simple, in-line calorimeter for monitoring high average levels was developed [Brady, 1962]. A flow type calorimeter with a limit of error of ±1 percent $+0.1$ w from 30 to 1000 w is now commercially available [Vinding, 1961].

A new 12.4 to 18.0 Gc/s microcalorimeter has been completed at the National Bureau of Standards and is now in use for routine calibrations. The new microcalorimeter is similar in design to the original 8.2 to 12.4 Gc/s model [Engen, 1959] with some refinements added.

A novel method of measuring peak pulse power density was reported at the 1962 International Conference on Precision Electromagnetic Measurements [White, 1962]. The system consists of an energy-absorbing surface coupled mechanically to an elastic wave sensor and an indicator. Thermal expansion produces an elastic wave much more efficiently than radiation pressure.

Two similar systems for the measurement of microwave pulse power by means of sampling techniques were reported at the 1962 ICPEM. One system [Denney, Mavis, and Still, 1962] uses a coherent detector to compare sample levels from unknown and standard sources. The other system [Hudson, Ecklund, and Ondreika, 1962] utilizes a fast solid-state coaxial switch to perform the sampling. Accuracies of $\pm$ 3 percent are possible, and the two systems together cover the range from -60 dbm to 70 dbm.

A method of power measurement depending on the acceleration experienced by electrons in a beam traversing an evacuated waveguide is still under development at the National Bureau of Standards. Errors due to the spread in energies of emitted electrons are larger than anticipated, but may be solved by audio substitution methods. Development of a high-power stirred-water calorimeter for the 8.2 to 12.4 Gc/s band continues at the National Bureau of Standards.

Two methods of evaluating the efficiency of waveguide-to-coaxial adaptors have been developed theoretically at the National Bureau of Standards. This approach may permit the use of waveguide bolometer mounts to calibrate coaxial power standards, and offers a solution to the difficulty in evaluating coaxial bolometer mount efficiencies directly.

The international intercomparison of microwave power standards has been extended to lower frequencies as recommended by the XIIIth General Assembly. At a frequency of 300 Mc/s, the United States and the United Kingdom standards were found to agree within 0.5 percent [NBS Tech. News Bull. **46** 40, Mar. 1962]. In a comparison with Japan at 400 Mc/s, a nominal difference of 2 percent was observed.

Some progress has also been realized in resolving the 1 to 2 percent difference which existed between the U.S. and U.K. X-band standards at the time of the last General Assembly. Additional measurements are planned for this frequency region.

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3. Standards and Measurements of Attenuation, Impedance, and Phase Shift

Period Covered: September 1960–December 1962

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3.1. Attenuation Standards and Measurements

Standards

At the lower frequencies, particularly in the audiofrequency range, the inductive voltage divider or ratio transformer serves as an accurate standard. The voltage ratios are so close to their nominal values that the problem of calibrating this type of standard has been a challenging one. Refined equipment developed in 1960 permitted the 10 to 1 ratio to be determined to $\pm 4 \times 10^{-9}$ with a 50 percent confidence interval [Cutkosky and Shields, 1960]. By 1962, refined methods of calibrating inductive voltage dividers or ratio transformers had been developed having a routine measurement accuracy within ± 0.0000002 in voltage ratio [Zapf, 1962].

At higher frequencies, especially at 30 Mc/s, the below cutoff waveguide piston attenuator continued to be used as a standard although ways were devised to avoid the loss in dynamic range caused by the 20 to 30 db residual loss of this type of standard. In one case, a high-powered, water-cooled launching coil was designed to excite the correct mode in the standard attenuator [Allred and Cook, 1960].

At microwave frequencies, both audio and IF substitution techniques permitted use of the above types of attenuation standards, but above approximately 2.6 Gc/s, serious consideration was given to the rotary vane type of attenuator as a standard. The use of this type of attenuator as a calculable standard still awaits complete evaluation of all sources of error, but some progress was made in the investigation of certain types of errors. An analysis of error caused by imperfect knowledge of the angular position of the vane was described. Experimental confirmation of the analysis was obtained using an attenuator which had been modified to greatly increase the resolution [Larson, 1962].

A refined rotary vane type of attenuator was constructed in another attempt to analyze and reduce errors from various sources. An accuracy of 0.02 db per 10 db was estimated for this attenuator [James, 1962].

Measurements

The calibration of a resistive voltage divider at d-c, which is used in turn to calibrate other voltage dividers, was described [Morgan and Riley, 1960]. The divider could then be used for part-per-million ratio measurements.

Ratiometric measurements using ratio transformers at audiofrequencies were briefly summarized [Widenor and Hermon, 1962].

An accurate loss and phase shift measuring apparatus was developed for the range 10–300 kc/s. Estimated error limit for insertion loss measurements is ± 0.002 db. Mercury relays operating at 13 c/s facilitate rapid comparison of the unknown with the carbon film standard attenuator [Elliott, 1962].

Operating in the frequency range 5 to 250 Mc/s, another loss and phase shift measuring apparatus was developed. It also employs rapid switching and heterodyned all signals to 1 Mc/s, the operating frequency of the carbon film attenuation standard. The estimated error limit is ± 0.1 db [Leed and Kummer, 1961].

Refinements and applications of known techniques continued at the higher frequencies, resulting in wider ranges and increased accuracies, the total error in the range from 130 to 140 db estimated to be ± 0.068 db [Allred and Cook, 1960]. The parallel IF substitution technique was again used at microwave frequencies to avoid the loss in dynamic range of attenuation measurements normally caused by the 20 to 30 db residual loss of below-cutoff waveguide piston attenuators [Weinschel, 1961].

Another so-called "self-calibration" technique was developed and applied to the checking of a below-cutoff waveguide piston attenuator, obtaining good agreement with the calculated attenuation rate [Peck, 1962].

A modulated subcarrier technique for measuring microwave attenuation was developed [Schafer and Bowman, 1962]. This technique has the advantage of requiring only one microwave source (no local oscillator required) while retaining the large dynamic range of the IF substitution technique. In addition, it permits the use of relatively inexpensive inductive voltage divider or ratio transformer types of attenuation standards. A further advantage is that the phase shift of the attenuator under test may be determined with the same system and at the same time that the attenuation measurement is made. The resolution is high (0.0001 db at 0.01

db), and the accuracy is comparable with both d-c and IF substitution systems of the highest quality.

Routine calibrations of coaxial attenuators at the National Bureau of Standards are performed over the frequency range 0.3 to 5.6 Gc/s, and attenuators in rectangular waveguide systems are calibrated from 2.6 to 26.5 Gc/s, using IF substitution techniques. The conservatively estimated limits of error are for fixed pads, coaxial: ±0.2 db or 1 percent of the attenuation in decibels, whichever is greater; and rectangular waveguide: ±0.1 db or 1 percent of the attenuation in decibels, whichever is greater. For incremental attenuation measurements on variable attenuators, the corresponding limits are coaxial: ±0.1 db or 1 percent of the attenuation change in decibels, whichever is greater; and rectangular waveguide: ±0.05 db or 0.5 percent of the attenuation change in decibels, whichever is greater [Larson, 1961].

The attenuation of circular waveguide was measured at 33 to 90 Gc/s by a shuttle-pulse technique in which the pulse made 20 to 30 round trips in the waveguide before being detected. An ingenious circuit permitted the same oscillator to serve as signal source and local oscillator for the receiver [King and Mandeville, 1961].

At millimeter waves, conventional techniques for measuring attenuation at lower frequencies are applicable, and rapid comparison switching offers some advantages [Chasek, 1962].

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3.2. Impedance Standards and Measurements

Standards

The NBS Unit of Resistance was reevaluated by comparison with an improved computable cross capacitor of the Thompson-Lampard type. The NBS unit of resistance was determined to be 1.0000023 ohms ±2.1 parts per million. An angular frequency of $\omega = 10{,}000$ was used in the comparisons [Cutkosky, 1961].

At audiofrequencies, the calibration of inductance standards was described [Zapf, 1961].

The mutual inductance analog of the generalized Thompson-Lampard theorem was developed, and the advantages of an eight-wire cage were discussed [Page, 1962].

The development of coaxial line capacitance standards was continued [Jones, 1962; Selby, 1962].

At microwave frequencies, the design and construction of quarter-wavelength short-circuit reflection coefficient standards for coaxial line were described [Beatty and Anson, 1962].

Coaxial Connectors and Waveguide Joints

In connection with impedance measurements in coaxial systems, some very significant work was done in the design and development of high precision coaxial connectors. Connectors were produced for coaxial line of IDOC=0.5625 in., and ODIC=0.2442 in., which had a VSWR of less than 1.003 over the frequency range from 0 to 8 Gc/s [Sanderson, 1962]. This represents perhaps an order of magnitude decrease in the reflections from coaxial connectors operating over this frequency range. It is expected that this development will help usher in a period of advances in the state of the art in microwave measurements in coaxial systems.

The importance of coaxial connectors in VSWR measurements was well illustrated in a comprehensive summary article [Sweet and Lebowitz, 1961].

A technique to measure small reflections from coaxial connector pairs with a slotted line was developed [Sanderson, 1961]. In this method, a response curve for the slotted line was first obtained using a tuned load. Then a half-wavelength section of air line was inserted between the slotted line and the load and another response curve was obtained. Subtraction of one response curve from the other gave a standing wave pattern essentially free from effects of line and probe coupling irregularities, and indicative of the reflection from the connectors. The technique gave both magnitude and phase information and was useful in the above development of high-precision coaxial connectors.

A variation on the width of the minimum technique for slotted line measurement of VSWR was developed [Nunn, 1961]. Although both this technique and the one described immediately above were called substitution methods, they had little in common, and differed both in what was substituted, and the way in which it was substituted.

Leakage from coaxial cables and connectors was analyzed and studied experimentally. The leakage energy was confined by a triaxial line and load, resonated to yield maximum output. The method is valid to measure relative leakage, but since leakage depends to some extent on the state of things external to the transmission line, it is difficult to determine a realistic value for absolute leakage [Zorzy and Muehlberger, 1961].

A sensitive method using a tuned, single-directional coupler and sliding terminations was developed to measure reflections and losses from waveguide joints [Beatty, Engen, and Anson, 1960]. Measurements were made of the reflection from deliberately misalined joints in rectangular waveguide, comparing with calculated curves. The method is also applicable to coaxial connectors and has been used to check the above high-precision coaxial connectors, obtaining close agreement with the substitution method [Jickling, 1962].

The reflection from the junction of two rectangular waveguides, one having square inside corners, and the other having rounded or filleted inside corners, was investigated analytically and experimentally [Anson, Beatty, Kerns, and Grandy, 1962].

The use of short pulses to detect reflections from discontinuities on transmission lines received further attention. Use was made of a sampling oscilloscope and a pulse generator having a rise time of 0.5 nanosecond [Halverson, 1961].

The measurement of small reflections in rectangular waveguide systems, especially at waveguide joints was discussed, with special emphasis on the use of a hybrid junction and sliding termination. The residual equivalent return loss was defined and uncertainties in its measurement were discussed [Pomeroy, 1962].

Impedance Measurement Techniques

An improved technique for establishing resistance ratios for the precise comparison of standard resistors was described [Pailthorp and Riley, 1962]. The audiofrequency ratio transformer bridge for standardization of inductors and capacitors made possible fuller utilization of the accuracy of certified standards [Hillhouse and Kline, 1960]. The application of series resonance techniques to the ratio transformer bridge resulted in a resonance capacitance-to-inductance transfer accuracy better than 50 ppm [Hillhouse, 1961].

A further description of tuned reflectometer techniques with information useful in error analysis was given [Anson, 1961]. A method was developed for measuring the impedance of a load that varies with time, provided that the variation can be repeated periodically, at an audio rate for example. Basically, the familiar width of minimum method was used to measure the VSWR with a slotted line [Iizuka, 1962]. A sweep voltage was used to measure changes in capacitances of varactor diodes [Jasinski, 1962]. Another bridge was developed for the visual display of complex reflection coefficient [Strandberg, 1961].

A conductance analyzer was developed for use in the analysis of nonlinear devices [Conn, 1962].

A routine calibration service for reflection coefficient magnitude or VSWR standards was offered by NBS, Boulder, Colo., for WR–90 (X-band) rectangular waveguide systems. The limits of error in the measurement of reflection coefficients having magnitudes from 0.025 to 0.1 are ± 1.5 percent, and from 0.1 to 1.0, ± 1 percent, conservatively estimated [Larson, 1961].

Conventional microwave bridge techniques for impedance measurement have been found applicable at a frequency of 150 Gc/s [Thaxter, 1962].

A bridge was developed to measure the mutual impedance between antennas. It is especially helpful with large planar arrays [Rupp, 1962].

Impedance Measurements Associated with Networks

The transformation of impedances by lossless networks continued to receive attention [Dawirs, 1961]. The precision measurement of microwave networks was summarized and methods of measuring arbitrary linear 2-ports were given [Altschuler, 1961]. The measurement of active and nonreciprocal 2-ports using an interference bridge was described. Using slotted lines, circular loci of reflection coefficients were obtained from point-by-point measurements. All four of the scattering coefficients of a 2-port can be obtained by this technique [Altschuler, 1961].

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3.3. Phase Shift Standards and Measurements

Standards

A continuously variable phase shifter using L-C pi sections was developed at NBS for operation at 400 c/s. The error limit was estimated to be 0.01 deg, and the upper frequency limit for this type of phase shifter was estimated to be approximately 20 kc/s [Park and Cones, 1960].

A phase-measuring set operating from 10 to 300 kc/s heterodynes all signals to a lower frequency at which phase detection is based upon measurement of time interval corresponding to displacement of sine wave zero crossings by the unknown [Elliott, 1962]. An accuracy of ± 0.02 deg is estimated.

Spirally wound delay lines can be used as continuously variable phase shifters between 100 kc/s and 15 Mc/s [Yu, 1961].

A phase-measuring set operating from 5 to 250 Mc/s heterodynes all signals to 1 Mc/s, where the phase standard used is a continuously variable four-quadrant sine capacitor of high quality and permanence [Leed and Kummer, 1961].

At microwave frequencies, the terminated slotted line continues to be a convenient standard of phase shift where high accuracy is not required [Zacharias, 1961].

Phase discriminators employing waveguide hybrid junctions are used to measure phase difference between two signals [Cohn and Oltman, 1961].

The error analysis was completed for a standard phase shifter consisting of the combination of sliding short-circuit in a uniform section of rectangular waveguide connected to a tuned, single directional coupler reflectometer [Schafer and Beatty, 1960].

Measurements

At frequencies from 0.2 to 20 kc/s, phase difference was measured with transistor flip-flop circuit [Woodbury, 1961].

The phase-measuring sets previously mentioned cover frequency ranges from 10 to 300 kc/s [Elliott, 1962] and 5 to 250 Mc/s [Leed and Kummer, 1961].

A review and bibliography of phase-measuring technique was given [Sparks, 1961]. This was a valuable contribution, since a detailed treatment of this subject is lacking in most microwave textbooks and the technical papers on the subject are widely distributed in the literature.

A variety of phase-measurement techniques were developed for use at microwave frequencies. A measurement system using hybrid tees with no moving parts or variable phase shifters has no ambiguities throughout 360 deg [Kaiser, Smith, Pepper, and Little, 1962]. Swept-frequency phase-shift measurement techniques using hybrid tee circuits [Cohn, 1962] and spaced probes in a slotted line [Lacy, 1961] formed the basis for commercially available apparatus. A modulated subcarrier technique for measuring microwave phase shift, permitted high resolution and accuracy with independence from the relative levels of the two signals compared [Schafer, 1960]. An extension of a conventional method permitted measurement of differential phase shift of traveling-wave tube amplifiers or electrically variable phase shifters [Israelsen and Haegele, 1962].

The phase variation along a narrow pulse generated by a high-power traveling-wave tube was determined by a two-channel system and suppressed carrier technique [Sparks, 1962]. Delay at millimeter wavelengths was measured to 0.2 μsec [Chasek, 1962].

The mismatch errors in a number of basic phase-measuring methods were analyzed [Schafer, 1960].

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4. Pulsed and CW Sinusoidal Voltage and Current Measurements

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This report appears to be the first URSI measurement report dealing with pulsed voltages and currents; it seems therefore advisable to state briefly the applications, parameters, and ranges involved. Pulsed voltages, pulsed currents, and pulsed power are quantities widely applied in the field of radio-electronics for many years. Their importance is on a par with continuous wave (CW) amplitude modulation techniques in transmitting intelligence via electromagnetic media and exceeds CW in applications requiring signal levels in the megawatt range. These pulsed quantities are used, for example, in radar tracking and trajectography with angular precision of fractions of milliradians at distances up to 1500 mi, navigation, radar astronomy, digital meters, telemetry, pulsed light sources, television, telephony, telegraphy, digital counters, electronic computers, particle accelerator circuitry, measurements in nuclear physics, microwave relay systems, time domain reflectometry, ignition applications, x-ray equipment, carrier pulses, etc.

Pulsed voltages may be subdivided into three general classes: (a) "direct pulses," for example, pulses consisting of a positive unit step function and a delayed negative unit step function, forming a rectangular voltage pulse; (b) rf pulses consisting of groups of sinusoidal waves unmodulated or modulated in various ways; and (c) pulses obtained by demodulating the rf pulses. The parameters to be measured in the "direct" pulses are the same as for the demodulated pulses; however, measurement conditions may be different in the two cases. The rf-pulse parameters of interest are generally different from those of the other two classes.

The following parameters and approximate ranges seem presently of interest in measuring pulses:

Amplitude average peak and along the pulse: 10^{-6} to 5×10^{5} v.

Attenuation: 10^{-2} to 10^{2} db, to measure attenuations of such devices as screened rooms, radomes, guides, switches, etc.

Time intervals: 10^{-10} to 10^{-1} sec. These are needed to determine rise time, decay time, pulse duration (width), pulse spacing, pulse duty factor, computer memory time, network time response, and component (diode, switch, transistor, magnetic core, etc.) response.

Current amplitude: milliamperes to kiloamperes.

Center or carrier frequency of pulsed rf: to 100 Gc/s.

Bandwidth of circuits and amplitude spectra of pulses: to about 5 Gc/s.

Phase spectra and phase variations, e.g., along a narrow rf pulse: 0 to 2 $n\pi (n=1, 2, 3, \ldots)$.

"Jitter" (instability) of amplitude, frequency, time, and phase: over a range down to an order of magnitude lower than the low limits indicated above for the corresponding quantities.

Other parameter terms such as "overshoot," "undershoot," "droop," "ripple," and "zero reference" have been used, and still others may appear in recent publications. These will be defined when necessary.

The reader is referred to existing standards (IRE Standards, 1955) and prevalent methods of measurement. This review will be limited to progress reported in salient publications during the approximate period of 1960 to 1962.

4.1. Pulsed Voltage and Current

4.1.1. Low-Voltage Amplitudes

The predominant tool in the measurement of pulsed voltage and pulsed current characteristics is the cathode ray oscilloscope (CRO), as it was in the past, because it displays the waveform and affords the most convenient and practical way of measuring and monitoring the pulse parameters. The CRO and associated techniques have been undergoing continuous improvement to meet the needs of nanosecond-width pulses with rise times below a nanosecond. Lewis and Wells brought the subject up to date [Lewis and Wells, 1959] in analyzing how CRO traveling wave deflection systems advanced the state of the art; the effective cutoff frequency, f_c (defined as the frequency at which the deflection suffers a 3-db loss), was about 2000 Mc/s at a screen spot diameter of 0.04 mm, a deflection sensitivity of about 0.03 v per spot width, maximum writing speed of "10 to the 11th power" spot widths per second and maximum signal of about 5 v. Less practical oscilloscopes for direct display of the waveform were developed with bandwidths up to 10 Gc/s [Lewis and Wells, 1959]. An up-to-date account is given also of the sampling technique [Carlson, Krakauer, Magleby, Monnier, VanDuzer, and Woodbury, 1959] for f_c of about 300 Mc/s. A useful survey of most practical display traveling wave oscilloscopes (TWO) was prepared [Noel and Susskind, 1961]. It discusses basic deflection structures of various systems, and points out the major shortcomings of the sampling technique; these are its limited application to recurrent pulses and to maximum peak voltage values of the order of 1 v in order to avoid amplitude distortion; the cutoff frequency is given at about 1 Gc/s for the practical sampling systems and about 2 Gc/s for the practical TWO's with direct display.

A modified sampling technique to measure fractional nanosecond pulse characteristics was developed [Gaddy, 1960]. Conceding that the TWO and previous sampling techniques are capable of measuring pulses with rise times of 300 to 400 psec (picosecond= 10^{-12} sec), the paper claims considerably wider effective bandwidths with this system for approximately trapezoidal pulses. This technique, under the name of "pulse comparison technique," employs conventional CRO's. The unknown pulse is fed into two parallel identical channels, one of which has a variable delay line. The outputs of the two channels are added in a coincidence "tee" circuit consisting of a crystal diode, capacitor, and resistor coaxially assembled. The variable delay line allows a continuous relative time shifting of an identical pulse with respect to the original pulse, and the amplitude output of the coincidence circuit versus time delay is observed on an oscilloscope and plotted. The time delays corresponding to changes of slopes of this plot yield the rise, duration, and decay time intervals of the unknown pulse. The comparison system bandwidth is said to be limited only by that of the coincidence circuit and not by the width of the sampling pulse; the bandwidth of the comparison system is stated to be at least 4 Gc/s. Experimental results show measurements of rise time of the order of 300 psec at agreement with theoretical values and degree of confidence of about 30 percent. The same values measured with a TWO were of the order of 500 psec; the difference is ascribed to pulse distortion by the delay cables of the TWO and the bandwidth limitation of its deflection structure. The following drawbacks of the technique are indicated by the author: (a) as described, it is useful only for trapezoidal shape pulses; it can be applied to other shapes but these shapes as well as the shapes of the output curves must be known in advance; (b) the estimated bandwidth of the comparison system had a rise time limitation of the order of 100 psec; (c) the system does not furnish a display of the pulse that is being measured; and (d) point-by-point measurements must be taken with great care.

A useful summary of practical problems associated with nanosecond pulse measurement was presented [Winnigstad, 1961]. The need for a standard source of pulses and for sinusoidal voltages over a frequency range to a few gigacycles that is constant to better than $+0.025$ db was emphasized. Novel-design peak voltmeters were noted in two cases for relatively wide pulses [Lang, 1961; Mackenzie, 1960].

4.1.2. High-Voltage Amplitudes

There appear to be no publications in the current periodicals during the last 3 years on the subject of measuring megawatt pulses with rise times and durations of the order of a nanosecond or bandwidth requirement in the gigacycle range. Yet progress has been apparently made. Thus, for example [Varian Associates, 1962], a present capability is indicated of over 10 Mw peak at frequencies up to 300 Mc/s and over 2 Mw up to 10 Gc/s; bandwidths up to 3 Gc/s are indicated. Another source [Edson, 1960] indicates a current capability of about 50 Mw and a 1967 projected 125 Mw level to 2 Gc/s; the corresponding levels at 10 Gc/s are 10 Mw and 50 Mw.

From the standpoint of need, potential overall reliability, and wide frequency and dynamic ranges, the CRO seems still the most promising tool. Unfortunately, no progress has been reported beyond that of some years ago [Hergenrother and Rudenberg, 1953] when a 100-kv pulse CRO was described. The reader may be interested in frequency dependence of electric strength of various electrical insulation at frequencies to 100 Mc/s [Frisco, 1961]. Data are given for 31 different classes of materials; pulse applications at microwave frequencies are discussed and speculated upon. The results reported [Park and Cones, 1962] on spark gap flashover measurement may also be of interest. Linearly rising chopped impulses with peak voltages up to 300 kv and times to sparkover from 0.03 to 50 μsec were measured employing a specially constructed divider and a cold cathode CRO. The results are intended for direct application to single impulses rather than to repetitious pulse problems. However, Gould [1959] has indicated the possibility of application of such results in the 10- to 100-nsec range.

4.1.3. Frequency, Bandwidth, and Time Intervals

An improvement in resolving the line structure of microwave pulse spectra is claimed [Koontz, 1962] with a new spectrum analyzer employing coherent frequency conversion. Ability to inspect the "fine grain" structure of circuit outputs is important in order to detect and measure the noise and spurious modulation introduced by these circuits. A coherent converter translates a stable low frequency up to a microwave frequency which is used as the input into the circuit under test; the output spectrum is then reconverted down to the low frequency, using the same conversion chain; as a result, transfer oscillator instabilities are cancelled and the pulse spectrum, transferred to a low-frequency base, can be properly resolved by available filter design methods; the interline frequency spaces can then be conveniently studied. Such an analyzer was constructed with a 2 c/s (3-db) bandwidth filter. The most prominent causes of interline modulation in several UHF and *L*-band amplifiers tested were found to be power-line frequency modulation, mechanical vibration of cavity resonators, and instability of pulse repetition-frequency sources. An analytical discussion, block diagrams and experimental illustrations are included.

Time interval measurements requiring resolutions of the order of 500 psec were developed [Innes and Kerns, 1961]. The paper describes a pulsed light source used to stimulate scintillation from nuclear events. The light pulses were about 2 nsec long, had a rise time of the order of 0.1 to 0.6 nsec and 3000 v in amplitude into 50 ohms. The light pulse shape was measured by a sampling technique with a specially gated phototube; the grid of this tube was activated with pulse widths less than 0.7 nsec at the base. Nomograms to correct rise-time measurements obtained with CRO's having their own rise times commensurate with the unknown were published [Ransil, 1961]; these cover a range down to 1 nsec and lower. It was of interest to note that the commercially available high-speed scopes listed in that paper showed a range of 0.2 to 40 nsec rise times; one had a rise time of 350 and another 200 psec without resorting to the sampling technique. A circuit to automatically measure the rate of time displacement of pulses was described [Whatley, 1962]; it has been used to measure drift rates for changes of 50 to 500 nsec at repetition rates of 1000 to 2000 ppsec. The growing need of time resolutions of the order of 10 psec and better seems well illustrated in advanced carrier-pulse development work [Dietrich and Sharpless, 1961–62] where displays with 10 psec at clearly discernible variations per unit horizontal scale were used.

4.1.4. Phase and Frequency Jitter (Instability of Parameters)

An improvement of a technique used in previous years was developed [Sparks, 1962] to measure phase variations along narrow rf microwave pulses caused by tube parameter variations or general instabilities. A two-channel arrangement, balanced modulator, and homodyne detector are combined in a system to translate the phase information to a high intermediate frequency, e.g., 24 Mc/s, tuned for a 10-Mc/s bandwidth. The output is observed on a CRO. For a pulse width of 1 μsec there were approximately four cycles of IF displayed. For no relative phase shift, the amplitudes of all four cycles were zero. In the presence of phase shift its magnitude was measured by adjusting a calibrated phase shifter in one of the channels and nulling the output amplitude as the phase was tracked across the width of the pulse. The repeatability of measurement on low and medium power TWT's was less than 1 deg; an overall accuracy of 0.1 deg was predicted if a precision phase shifter was used and further refinement of the system made. A technique and experimental setup to measure phase differences between individual pulses of a pulsed signal were described [Holman and Shields, 1961]. Phase differences up to 180 deg were measured as a pulse to pulse rms deviation without a frequency reference from a signal source. A useful error analysis of a standard phase shifter was published [Schafer and Beatty, 1960]; it relates tuning errors of an adjustable-short-circuit three-arm standard phase shifter to detector output changes and treats errors of the order of 0.04 to 0.1 deg at 8 to 12 Gc/s.

Time jitter is a difficulty associated particularly with gaseous discharge switches. Time jitters of the order of 2 nsec in 250 nsec and higher were encountered in switching kilovolt levels [Theophanix, 1960]. Apparently no measurement difficulties were encountered in this case employing a CRO.

4.1.5. Pulsed Current

No progress was reported in measuring current pulses despite the apparent wide range requirements reaching peak values of 22,000 amp. A commercial clamp-on device was put on the market to measure current pulses over a range of 1 ma to 1 amp, and frequency range of about 25 c to 20 Mc/s, with claimed calibration stability of 1 percent.

4.2. Sinusoidal CW Voltages and Currents

The only published progress in these quantities during the time in question is an improvement in the accuracy of rf voltages of 1 to 200 v at frequencies to 30 Mc/s from a previous 1 percent to 0.1 percent [Hermach and Williams, 1960]. Despite the evidence of the need for voltage measurements based, among other things, on spectral analysis requirements, no descriptions of sources of rf voltages to 5 or 10 Gc/s and no methods for their measurement were found in the usual technical publications. Commercial voltage generators to 10 Gc/s with microvolt to volt levels have been announced.

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5. Radio Noise Measurement Methods and Standards

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The full impact of the application and utilization of low-noise receivers such as the maser and the parametric amplifier was felt during the past two years. First, the tendency toward expressing the noise performance of a receiver in terms of a temperature rather than in terms of a noise figure gathered momentum. Second, the accurate evaluation of the noise performance of low-noise receivers demanded more precision in the calibration of noise generators. Third, the use of cold loads at liquid gas temperatures for noise measurements became practical. Some of these and other developments were highlighted at two important sessions devoted entirely to the subject.

The first of these sessions occurred during a week-long symposium sponsored jointly by Canada, the United Kingdom, and the United States on the Application of Low-Noise Receivers to Radar and Allied Equipment held at Lincoln Laboratory, MIT, Lexington, Mass., Oct. 24 through 28, 1960. The Proceedings were published in three volumes by Lincoln Laboratory, edited by Dr. James W. Meyer and Dr. Robert E. Rader. Dr. Hermann A. Haus was the chairman of the session which was devoted to Noise Measurements.

The second session was held at the 1961 PGMTT National Symposium sponsored by the Institute of Radio Engineers Professional Group on Microwave

Theory and Techniques in Washington, D.C., May 17, 1961. This afternoon session was entitled "System and Receiver Noise Performance Clinic," and Dr. Hermann A. Haus was the Moderator. The Symposium Digest was published by the IRE.

The reason for the trend toward the use of an effective input noise temperature T_E [Haus, 1960a; Adler, 1961], rather than noise figure, appears to be threefold [Meyer and Rader, 1960]. (1) There have been too many different definitions of noise figure published [Weber, 1960]. (2) In low-noise receivers it is easier to use T_E than F, i.e., it is simpler to distinguish between 10° and 15° than it is to distinguish between 1.035 and 1.052. (3) In multichannel receivers, T_E and its measurements are definite, whereas F depends upon the nature of the signals, i.e., whether the signal lies in one or more channels. There are those who think F should be abandoned [Weber, 1960]. Although at least two new definitions of T_E [Haus, 1960b; Adler, 1961] have been proposed recently, the definition which describes a directly measurable and unambiguous quantity may be the one which survives the rigors of general acceptance. This one [Adler, 1961] is convenient to use to express the total output noise power thus:

$$N_0 = G_1 k B_1 (T_{g1} + T_e) + G_2 k B_2 (T_{g2} + T_e) + \dots + G_n k B_n (T_{gn} + T_e) \qquad (1)$$

where $G_n B_n$ and T_{gn} represent the gains, bandwidths and generator noise temperatures at the nth response or channel of the receiver, and T_E is readily measurable with a hot and cold load, thus:

$$T_e = \frac{T_{g(\mathrm{hot})} - Y T_{g(\mathrm{cold})}}{Y-1}. \qquad (2)$$

More precise calibration of noise sources has been achieved and maintained as a calibration service by the National Bureau of Standards at X-band using a heated waveguide load as a standard for comparison in a radiometer setup [Estine, 1960; Wells, 1962]. In their latest version the uncertainties give a total error of only 0.07 db in the excess noise ratio of a suitable unknown noise source. Preliminary results [Estine, 1960] on the Bendix TD–11 had indicated an excess noise ratio of the tube in mount of 15.9 db. Subsequent improvements in the technique led to results [Wells, 1962] more nearly in agreement with the calculated electron temperature, around 10,900°, which with the tube in mount results in an excess noise ratio of 15.55 db [Lee, 1962]. The agreement between calculated electron temperature and noise temperature was somewhat closer than that observed by Bekefi and Brown [1961], whose measurements on helium, neon, and hydrogen indicated a noise temperature somewhat less than the calculated electron temperature.

Using the NBS calibration service, Lee and Olson at Bendix obtained calibrations on several X-band tubes and then, using these as standards, calibrated a number of their other tubes in different frequency ranges and published the results [Lee, 1962]. In general, the agreement between calculated electron temperature and noise temperature was good.

Associated with the demand for greater precision in measuring low noise receivers, cold loads were employed [Grimm, 1960; Macpherson, 1962; De Grasse and Scovil, 1960; De Grasse, Ohm, Hogg, and Scovil, 1959a; Stelzried, 1961]. Here the physical temperature of the loads could be measured quite precisely and used to determine the noise figure. The ensuing calibration of argon gas discharge noise sources often led to values of excess noise temperatures which were higher than those quoted in the past by the manufacturers and indeed were closer to the values obtained from electron temperature calculations and subsequent calibrations [Ohm, 1961; De Grasse, Ohm, Hogg, and Scovil, 1959b].

Automatic noise figure meters were developed, in which the noise figure is read directly on a meter [Kuhn and Negrete, 1961; Bruck, 1960; Chenette and Van Der Ziel, 1962]. Pulsed operation presented some problems.

The pitfalls of noise figure measurement were enumerated in an amusing article on noisemanship by J. C. Green [1961].

A low-frequency noise source using two ganged potentiometers at different temperatures was devised and described by A. C. Macpherson [1962].

Theoretical studies of noise and its measurement were presented. The uncertainty principle was applied to prove that a finite minimum effective input noise temperature existed; a linear noiseless amplifier is impossible [Heffner, 1962; Siegman, 1961]. The effect of mismatch of the source impedance was derived in terms of measurable quantities [Haus, 1960b]. A résumé of various definitions of noise factor and other noise performance rating schemes was presented [Enslow, 1961]. Definition of temperature sensitivity including negative conductance devices was proposed [Fisher, 1962]. Standards on methods of measuring noise were published by the IRE [Haus, 1960a; Esperson, 1962].

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6. Measurements at Millimeter and Submillimeter Wavelengths

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The development of measurement techniques in the millimeter and submillimeter range has been accelerated by improvements in sources and the development of transmission systems including conventional dominant mode waveguide, TE_{01} mode circular waveguide, oversized rectangular waveguide, and free-space transmission systems with and without beam-guiding techniques.

Devices and Techniques in Dominant Mode Waveguide

The design of most standard components such as slotted lines, wavemeters, and attenuators has been extended to the 1.5 to 2 millimeter range. They are all characterized by close tolerances and precision fabrication methods. New developments include a standing-wave indicator using a fixed detector and a phase shifter and an impedance meter which measures the modulus and argument of the reflection coefficient by using the principle of the rotary attenuator [Bertan, 1960].

A Y circulator has been constructed with good performance at 140 Gc/s and a ferrite phase-shifter with a full 360° phase shift and a low loss (less than 0.45 db) has been developed for use at 35 Gc/s [Thaxter and Heller, 1960; McCarter and Landry, 1961].

A yttrium-iron-garnet resonator with Q values of several thousand has been developed for use at 35 and 70 Gc/s [Douthett and Kaufman, 1961].

Microwave type bolometers have been developed for use in the 0.25 to 2 mm range. They employ a horn-fed rectangular waveguide followed by a waveguide to coaxial line transition in which the bolometer is mounted. Sensitivities of the order of 10^{-11}w have been obtained [Byrne and Coor, 1963].

A ferrite isolator and variable attenuator has been designed for use at 50 to 60 Gc/s. As an attenuator the minimum loss is 1 db and the maximum loss 30 db over the band [Barnes, 1961].

A relatively conventional attenuator for 60 Gc/s use has been developed with a VSWR less than 1.1, a minimum attenuation of 0.2 db and a 10-w power dissipation [Wolfert, 1963].

6.1. Devices and Techniques in Free-Space Transmission

The development of free-space transmission techniques has led to the development of the free-space equivalent of many devices such as attenuators, hybrids, directional couplers, wavemeters, and standing wave indicators [Fellers, 1962].

Fabry-Perot interferometers have been developed with accuracies of 0.04 percent and Q values of 100,000 [Culshaw, 1960]. Recent developments of resonators have resulted in Q values of 300,000 at 0.1 mm [Culshaw, 1961; Culshaw, 1962].

Further developments of the Michelson Interferometer have produced a device using Fresnel zone plates with resulting high accuracy. This device has been used to measure dielectric constant and loss tangent at 140 and 210 Gc/s [Sobel, Wentworth, and Wiltse, 1961].

An arrangement of two dielectric prisms with adjustable spacing permits the adjustment of the fraction of energy which is passed through the prisms. This arrangement has found application as a half-silvered mirror, a hybrid junction, an adjustable attenuator, and an adjustable bidirectional coupler. The device is capable of theoretical calibration and has many measurement applications in interferometers, reflectometers, and the like [Fellers, 1962; Raker and Valenzuela, 1962].

An application of a quasi-optical directional coupler (dielectric sheet), to detector impedance measurement has produced usable results at 1 mm [Miller, Szente, and Mallory, 1963].

6.2. Devices and Techniques in Oversized Waveguide

The use of oversized waveguide for reduced attenuation has resulted in the development of a number of measuring devices.

The prism arrangement used in free space has been employed in oversized rectangular waveguide to produce a directional coupler, variable attenuator, and a variable phase-shifter. Coupling ratios of 0 to 30 db can be obtained at 300 Gc/s, but the insertion loss is 2 to 3 db. Variable attenuators have been constructed with attenuation of 1 to 30 db. A variable phase-shifter has been produced by the use of variable short circuits in two of the ports of the directional coupler [Taub, Hindin, Kinckelmann, and Wright, 1963; Hindin and Taub, 1962].

Broad-band directional couplers in multimode waveguide have been developed for use in the 35–580 Gc/s band with low insertion loss and good directivity [Marcatili and Ring, 1962].

Standing-wave indicators using cylindrical sleeve sections have been constructed in TE_{01} circular guide. In the same waveguide a high-power attenuator is being developed by permitting the energy to leak out from the guide into a lossy medium [Simmons, 1963].

A channel dropping filter operating at 56 Gc/s converts TE_{01} mode energy in circular guide to TE_{10} mode energy in rectangular guide. Bandwidth is 185 Mc/s and insertion loss is 1.4 db [Marcatili, 1961].

6.3. Miscellaneous Devices and Techniques

A continuously tunable radiometer which does not require a coherent source is useful for making transmission measurements in the 50 to 90 Gc/s band. The instrument utilizes a continuously tunable electromechanical band-pass filter and has demonstrated high sensitivity [Long and Butterworth, 1963].

A perturbation method of measuring millimeter-wave fields has been devised. It utilizes a small metallic reflector which is rotated in the field and which can be scanned through the field. Signal reflected from the rotating reflector is mixed with a reference signal for measurement [Wolfert and Schiller, 1963].

A technique for measurement of dielectric and magnetic properties in the 3 to 100 Gc/s range has an accuracy of ± 0.1 percent. The measuring structure is made up of a dielectric rod between two parallel conducting plates. Dielectric and magnetic properties are computed from resonant frequencies, dimensions, and unloaded Q [Hakki and Coleman, 1960].

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7. Precise Measurements of Distance and of the Velocity of Light Using Lasers

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One of the major accomplishments of the past 3 years in the area of radio science has been the development of coherent sources of light called optical masers or lasers. These devices have greatly extended the range of frequencies over which the techniques developed in the normal radio and microwave ranges can be applied. The most immediate applications appear to be in the areas of basic science, communications, and precise distance measurements.

A number of types of lasers is now available. These include pulsed and continuous optically pumped solid-state lasers, *Q*-switched solid-state lasers, continuous rf discharge and optically pumped gas lasers, and electron injection semiconductor lasers. The type which appear to be most applicable to precise distance measurement are the *Q*-switched solid-state laser and the gas laser.

In the *Q*-switched laser [Hellwarth, 1961; McClung and Hellwarth, 1962] a large inverted population difference between two energy levels of a crystal is produced by optical pumping while the *Q* of the optical cavity is low. The *Q* is then rapidly switched to a high value, usually by opening a Kerr cell shutter in the optical path or rotating a 90-degree prism so that its plane of retroreflection becomes perpendiclar to a plane reflector forming the other end of the optical cavity. This gives a rapid buildup of power in the cavity and a quick dumping of the inverted population in the crystal. Output pulses as short as 10 nsec with a peak power output of over 50 Mw and a narrow output beam width have been obtained [Marshall, Roberts, and Wuerker, 1962]. This type of device appears superior to microwave methods for radar-type measurements of long distances under some circumstances.

Gas lasers [Javen, 1959; Faust, McFarlane, Patel, and Garrett, 1962], on the other hand, have much lower output power but run continuously. Their demonstrated spectral purity of a few parts in 10^{13} [Jaseja, Javan, Murray, and Townes, 1962], and independent resettability of about 1 part in 10^{9} [Javen] make possible extremely accurate measurements over quite long vacuum paths. With such devices the limitation on path lengths over which interference measurements can be made appears to lie mainly in the problem of finding the whole fringe number or in path stability rather than in the coherence length, as was previously the case. Gas laser output wavelengths of 0.63 μ [White and Ridgen, 1962] to 12.9 μ [Faust, McFarlane, Patel, and Garrett, 1962] have already been obtained. These wavelengths can be supplemented by using beat wavelengths between two laser modes corresponding to different optical transitions as the basic unit of measurement. For example, if the 1.1143-μ [McFarlane, Patel, Bennett, and Faust, 1962] and 1.1177-μ [Javan, Bennett, and Herriott, 1961] transitions in neon are employed, the best wavelength will be 0.32 mm. Still longer beat wavelengths can be obtained by using two different axial modes for the same optical transition or by using a microwave modulator [Bloembergen, Pershan, and Wilcox, 1960; Pershan and Bloembergen, 1961] to modulate the light output from either a laser or a conventional light source. Quite short beat wavelengths may be obtainable on a pulsed basis with a microwave modulator operated with a high modulation index, but for continuous operation the index which can be used appears to be limited by heat dissipation in the modulator crystal.

Paths of up to 864 m have previously been measured in terms of shorter paths by means of white light fringes with multiple reflections [Fabry and Buisson, 1919; Honkasalo, 1960]. With lasers, measurements over quite long paths can also be done by using automatic fringe counters or by using several different wavelengths and beat wavelengths calibrated with respect to each other over shorter paths in order to obtain the whole fringe number. Probably the simplest method is to use white light fringes to set the long path to an integral multiple of a shorter path for which the whole number of laser fringes is known, and then to measure the long path to the desired fraction of a fringe with a laser source. With such procedures the accuracy of measuring long and stable vacuum paths will probably be limited mainly by the uncertainty in the length standards.

For a precise measurement of the velocity of the light c at optical wavelengths, a common method is to use two optical frequencies ν_1 and ν_2 with a difference $\Delta\nu$ known in frequency units. The number of beat wavelengths over a distance L known in length units is measured. If n_1 and n_2 are the number of fringes for the two wavelengths, then $\nu_2 = n_2 \cdot \frac{c}{2L}$, $\nu_1 = n_1 \cdot \frac{c}{2L}$, $\Delta\nu = (n_2 - n_1) \cdot \frac{c}{2L}$, and $c = 2L \cdot \frac{\Delta\nu}{(n_2 - n_1)}$. For a given path length L, it is normally advantageous to use as high a difference frequency $\Delta\nu$ as can be determined accurately so that $n_2 - n_1$ will be large. Making L large is also desirable in order to make $n_2 - n_1$ large, as long as the additional path length does not increase the uncertainty in terms of fractions of a fringe to which $(n_2 - n_1)$ can be measured.

At the National Bureau of Standards an attempt is planned to measure the beat frequency of about 831 Gc/s between the two neon laser lines at 1.1143 and 1.1177 μ which were mentioned earlier. The method, which was suggested by Z. L. Bay, is to intensity modulate the beam of a special cathode ray tube at the 831 Gc/s beat frequency by illuminating the photo-cathode spot with both laser lines. If the frequency applied to the horizontal deflection plates is near a subharmonic of the beat frequency, a slowly running intensity modulated pattern will be produced on the face of the tube. For a roughly 10 Gc/s deflection frequency and fairly rapid initial acceleration of the beam, the percentage modulation of the pattern should be adequate for measurement of the running frequency and thereby of the beat frequency [Statz, Paananen, and Koster, 1962]. If this attempt is successful, the method is intended for use in a velocity of light measurement over a suitable path length.

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Appendix: Measurements Standards and Calibration Laboratories in the United States

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Part 1

A measurements capability survey, conducted for a group of 181 laboratories in the United States, provided the basic background for the compilation of this report. From this survey, a number of measurements laboratories were determined to have accuracy capabilities better than average in one or more fields of microwave measurements. These laboratories have been listed below, with coded notations to indicate the specialized capabilities. The coded notations appear as a separate listing.

Laboratory	Location	Capabilities
AVCO-Electronics	Cincinnati, Ohio	F1, F2, P1, P2, V1, Z1, Z2, Z3
AVCO R.A.D	Wilmington, Mass	F1, A1, A2, A3, (A4 to Gc/s), P1, Z3 (Z4–18Gc/s)
Ballantine Lab. Inc	Boonton, N.J	V1, V2
Ball Bros. Research Corp	Boulder, Colo	F1, F2, A1, P1, V1, Z1
Bell Telephone Lab	Allentown, Pa	F1, F2
Bell Telephone Lab	Murray Hill, N.J	F1, P1, P2, P3, (P4), Z1, Z2, Z3, (Z4) (60 Gc/s)
Bendix-Kansas City Div	Kansas City, Mo	F1, P2, Z2
Bendix-Pacific Div	N. Hollywood, Calif	F1, F2, F3, (F4), Z1, Z2, Z3, (Z4) (to 18 Gc/s)
Bendix-Radio Div	Baltimore, Md	F1, V1, Z1, Z2, Z3, (Z4) (to 40 Gc/s)
Boeing Co. (Aerospace Div)	Seattle, Wash	F1, A1, A2, A3, P1, P2, P3, Z1, Z2
Boonton Radio Co	Rockaway, N.J	Q1, Q2
Borg-Warner Research	Des Plaines, Ill	P1, V1
Collins Radio Co	Cedar Rapids, Iowa	F1, P1, P2, V1, Z1, Z2, Z3
Cook Electric Co	Morton Grove, Ill	(V1 to 4 Mc/s), Z1, Z2, Z3 (Z4 to 18 Gc/s)
Douglas Aircraft Co	Santa Monica, Calif	F1, F2, F3, (F4), A2, A3, (A4), Z3, N3 (to 18 Gc/s)
Empire Devices, Inc	Amsterdam, N.Y	N1, N2, N3 (N4 to 40 Gc/s)
Ewen Knight Corp	East Natick, Mass	N2, N3, (N4) (to 75 Gc/s)
Frequency Engrg. Lab	Asbury Park, N.J	F3 (F4 to 40 Gc/s)
Gen. Dynamics-Astronautics	San Diego, Calif	F1, F2
Gen. Dynamics-Convair	San Diego, Calif	P1, P2, P3, (P4), V1, V2, Z1, Z2, Z3, (Z4) (to 40 Gc/s)
General Electric Co	Philadelphia, Pa	F1, F2, F3, V1, V2
General Radio Co	West Concord, Mass	F1, F2, F3, Z1, Z2, Z3
Hewlett-Packard Co	Palo Alto, Calif	F1, A1, P1, P2, P3, V1, Z2, Z3
Hughes Aircraft (Aerospace)	Culver City, Calif	F1, F2, A3, (A4), P3, V1, Z3, (Z4), N2, (to 40 Gc/s)
IT&T Standards Lab	Clifton, N.J	F3, V1
Lincoln Lab. (M.I.T.)	Lexington, Mass	(F4, P4) (Note 1)
Martin Co	Baltimore, Md	F1, F2, F3 (F4 to 18 Gc/s), P1, V1, Z1, Z2, Z3 (Z4 to 40 Gc/s)
McDonnell Aircraft Corp	St. Louis, Mo	Z2, Z3
Motorola AC Spark Plug Div	Chicago, Ill	F1, F2, P1, P2, P3, V1, Z1, Z2, Z3
Motorola Comm. & Elect	Chicago, Ill	F1
National Bureau of Standards	Boulder, Colo	F1, F2, F3, (F4), A1, A2, A3, P1, P2, P3, (P4), V1, V2, E1, Z1, Z2, Z3, Q1, Q2, N3 (to 18 Gc/s)
NAA-Columbus Div	Columbus, Ohio	F1, F2, F3, P1, P2, V1, Z1, Z2, Z3
Northeastern Engrg. Inc	Manchester, N.H	F1, F2, F3
Ohio State Univ-Antenna Lab	Columbus, Ohio	F1 (A4, P4) (Note 1)
Philco WDL	Palo Alto, Calif	F1, A1, A2, A3, P1, P2, V1, Z2, N1, N2
Pickard & Burns, Inc	Waltham, Mass	F1, F2, F3
Polytechnic Inst. of Bklyn	Brooklyn, N.Y	A2, A3, P2, P3, Z2, Z3
Premier Microwave	Portchester, N.Y	Z3
RCA Laboratory	Moorestown, N.J	(P4 to 25 Gc/s) (A4—Note 1)
RCA Standards Lab	Cambridge, Ohio	F1, V1, V2, Z1
Sandia ALO Standards Lab	Albuquerque, N.Mex	F1, F2, F3, A1, A2, P1, V1, Z3
Space Tech. Lab	Redondo Beach, Calif	F1, F2, F3, P1, P2, P3, Z1, Z2, Z3
Specific Products	Woodland Hills, Calif	F1
Stoddart Aircraft Radio Co	Hollywood, Calif	A1, A2, P1, P2, Z1, Z2
Sperry Gyroscope Co	Great Neck, N.Y	F1, F2, F3, (F4), P1, P2, P3, (P4), Z2, Z3, (Z4), N2, N3, (N4) (to 40 Gc/s)
Strand Laboratory	Newton, Mass	F3, (F4) (to 36 Gc/s)
Texas Instruments Inc	Dallas, Texas	F3, V2
U.S. Air Force	Newark, Ohio	F1, F2, A1, A2, A3, P1, P2, P3, (P4), V1, V2 (to 40 Gc/s)
U.S. Army ERD Laboratory	Fort Monmouth, N.J	F1, F2, F3, (F4) (to 30 Gc/s)
U.S. Bureau Naval Weapons	Pomona, Calif	F1, F2, A1, A2, P1, P2 P3, V1, V2, Z1, Z2
USA Frankford Arsenal	Philadelphia, Pa	F1, P1, P2, P3, V1
Univ. of California	Los Angeles, Calif	F3, (F4) (to 36 Gc/s)
Univ. of Ill. (Antenna Lab)	Urbana, Ill	Z3, (Z4) (to 60 Gc/s)
Univ. of So. Carolina	Columbia, S.C	(F4), (Z4) (30 to 70 Gc/s)
Varian Associates	Palo Alto, Calif	F1, F2, F3, N2, N3
Varian Assoc-Bomac Div	Beverly, Mass	F1
Weinschel Engineering	Gaithersburg, Md	F1, F2, F3, A1, A2, A3, P1, P2, P3, Z1, Z2, Z3
Western Electric Co	Winston-Salem, N.C	F1, F2, F3, A1, A3, P3, Z3
Weston Instrument	Newark, N.J	P1, P2, P3
Westrex Communication	New York, N.Y	F1

Note 1—Work, in 150 to 300 Gc/s range, is at lower accuracies than specified in code.

Capability codes

Measurement field	10Kc/s–300Mc/s	300Mc/s–3Gc/s	3Gc/s–12.4Gc/s	12.4Gc/s–300Gc/s
Frequency (to better than 1×10^{-8})	F1	F2	F3	F4
Attenuation (to better than 0.01 db/db-40db range).	A1	A2	A3	A4
Power, CW unbalanced (to 1% or better).	P1	P2	P3	P4
Voltage, CW unbalanced (to 1% or better).	V1	V2	V3	V4
Field strength, CW (to 5% or better)	E1	E2	E3	E4
Voltage standing wave ratio (to 1% or better).	Z1	Z2	Z3	Z4
Q (to 1% or better)	Q1	Q2	Q3	Q4
Noise, noise figure (at state-of-the-art).	N1	N2	N3	N4

The results of the survey, although indicative of the capabilities of the laboratories surveyed, is not to be regarded as complete or exclusive. It is expected that a continuing effort by Commission will provide supplementary data for later reports, and become more nearly a compendium of the total measurements standards capabilities within the United States.

Part 2

In the field of radiofrequency standards and measurement the United States, in common with several other countries of the world, looks to a central, legal entity for affirmation or confirmation of accuracy in measurements. The National Bureau of Standards, operating through the medium of its laboratories in Washington, D.C., and Boulder, Colo., occupies a preeminent position, and its measurement research activities are followed intently.

Metrologists in general and the Bureau in particular recognize the wealth of talent subsisting in the many measurements laboratories which support government services or are part of research and industrial operations. These activities, complete with their own facilities and personnel, contribute much knowledge to metrology and serve to cross-pollinate fertile minds at the Bureau. As a consequence, the state-of-the-art of measurements accuracy advances as a natural outgrowth of Bureau research, or as a result of independent research elsewhere which in time is confirmed by the Bureau as a legalized standard or recognized technique.

A survey has been made of the measurement activities of a number of organizations which are performing measurement calibrations and research. These activities may be either loosely or closely associated, in a technical sense, with the Bureau and have gained recognition on a national scale for their individual capabilities. In addition, the Bureau itself supplies calibration services for the benefit of its own research activities, as well as for the country's activities at large, by operating the Radio Standards Laboratory at Boulder.

During the past three years, NBS has made available [Mockler, Beehler, and Snider, 1960; Atkinson, Beehler, Heim, and Snider, 1962], through the medium of its standard frequency broadcasts, an accuracy of 1.1×10^{-11} as established by its cesium atomic standard—NBS–II. Derivation of this accuracy was aided to a considerable extent by employment of crystal oscillators controlled by highly stabilized, accurately cut quartz crystals [Sykes, Smith, and Spencer, 1962] supplied by the Bell Telephone Laboratories, formerly operating in North Andover, Mass., but transferred in 1962 to Allentown, Pa. [Sykes, Spencer, Smith, and Bell, 1962].

The Western Electric Co. at Winston-Salem, N.C., has developed ultrastable rf oscillators in the 2.5 and 5.0 Mcs range with frequency drifts less than 4×10^{-11} after one year operation. These units are presently employed in VLF broadcasts for the US Navy and for use in the US Coast Guard Loran-C stations [Hunter and Starr, 1961].

Independent, corroborative work carried on by the U.S. Army Electronic R & D Laboratory at Fort Monmouth during this period established the accuracy of cesium atomic standards when used as synchronized clocks [Redar, Winkler, and Bickart, 1961]. In addition, an evaluation program carried out by this Laboratory [Searles and Brown, 1962] measured the performance of rubidium vapor frequency standards developed by the Varian Associates Laboratory [Packard, 1962]. Varian's rubidium standard accuracy and stability, as determined by the USAER&D Laboratory and by the NBS Boulder Laboratories, was demonstrated to differ less than 4.7×10^{-11} parts from the U.S. Frequency Standard [Varian Assoc., 1962]. This standard, utilizing hyperfine transitions in optically pumped rubidium vapor, has now been made available commercially. Meanwhile, development of an atomic hydrogen frequency standard is in process [Vessot, 1962].

Development of a third cesium atomic frequency standard utilizing a 3-m oscillating field separation is well on its way to completion at NBS. It is anticipated that use of a servosystem to control the frequency of the quartz oscillator will reduce the quartz spectral line width by 50 percent and increase the stability of the system. Initial experiments indicated a thallium beam standard was operable but had low efficiency.

The laboratory established by Pickard and Burns, Inc., at Waltham, Mass., at the present time is developing its own conception of the cesium frequency standard, under Air Force contract. During the survey period the company made available, through commercial channels, a phase-locked receiver to be employed in very-low-frequency phase comparison techniques employed in the precise control of frequency and timing.

Work on frequency standards utilizing maser principles has continued at several locations. At NBS, refinements to the ammonia beam maser consisting of the addition of a servo system to control the cavity tuning, resulted in determining the ability to reset the frequency to be about 3 parts in 10^{11}. Meanwhile, at Fort Monmouth the USAERD Laboratory has continued its work on ammonia and hydrogen masers, supported in part by analyses conducted by the University of Colorado [Barnes, 1962] and specialists of the Martin-Marietta Corp. [1962–1963] in Baltimore, Md. In addition, laboratories at the following locations reported that they have conducted independent work on masers—International Telephone and Telegraph Co. in Clifton, N.J., Bell Telephone Laboratory at Murray Hill, N.J. Columbia University at New York, N.Y., Harvard University at Cambridge, Mass. [Ramsey and Kleppner, 1962], Massachusetts Institute of Technology at Cambridge, Mass., PRD Electronics, Inc., in Brooklyn, N.Y., and Varian-Bomac at Beverly, Mass.

During the past three years, the NBS Radio Standards Laboratory at Boulder has increased its measurement capabilities of rf voltage (coaxial-CW) to the values shown in table 1.

TABLE 1. *Voltage (CW, coaxial)*

Voltage range	Frequency range	Measurement accuracy
		Percent
1 μv to 10 μv	30 kc/s to 500 Mc/s	5
10 μv to 100,000 μv	30 kc/s to 10 Mc/s	2
10 μv to 100,000 μv	10 Mc/s to 400 Mc/s	3
10 μv to 100,000 μv	400 Mc/s to 900 Mc/s	5
0.1 v to 400 v	30 kc/s to 10 Mc/s	0.1
0.1 v to 400 v	30 Mc/s	0.2
0.1 v to 400 v	100 Mc/s	1.0
0.1 v to 20 v	300 Mc/s & 400 Mc/s	3.0

A number of laboratories throughout the country have given evidence of their capability to measure voltages within the same regions, to an accuracy approaching that of NBS. Among those reporting are the radio frequency standards laboratories at Hughes Aircraft in Culver City, Calif.; Western Electric Co., in Winston-Salem, N.C.; Microwave Research Institute in Brooklyn, N.Y.; Bendix Corp. in Kansas City, Mo.; Hewlett-Packard Co. in Palo Alto, Calif.; Sperry Gyroscope Co. in Great Neck, N.Y.; Sandia Corp. in Alburquerque, N. Mex.; Stoddart Aircraft Radio Inc. in Hollywood, Calif.; Ballantine Laboratories in Boonton, N.J. [Uiga and White, 1960]; Douglas Aircraft Co. in Santa Monica, Calif.; Metrology Dept. BuWepsRep at Pomona, Calif.; Weinschel Engineering Co. at Gaithersburg, Md.; Boeing Co. Aero-Space Division at Seattle, Wash.; AVCO–R.A.D. at Wilmington, Mass.

Present capabilities for measuring rf power in unbalanced circuits at the NBS Radio Standards Laboratory [Hudson, 1960; Ecklund, Hudson, and Ondrejka, 1962] are listed in table 2. These capabilities include also the recent advances in the microwave region [Engel, 1961].

Other laboratories reporting a closely related ability include the following: Hewlett-Packard Co. of Palo Alto, Calif.; Bendix, Kansas City, Mo.; Sperry Gyroscope, Great Neck, N.Y.; Sandia, Albuquerque, N. Mex. [Mavis, Denney, and Still, 1962]; Stoddart Aircraft, Hollywood, Calif.; Metrology Dept. BuWepsRep, Pomona, Calif.; Weston Instruments, Newark, N.J. [Weston]; Hughes Aircraft, Culver City, Calif.; Microwave Research Institute, Brooklyn, N.Y.; Bell Telephone, Murray Hill, N.J.; Weinschel, Gaithersburg, Md. [Raff and Sorger, 1960; Weinschel and Hedrich, 1961]; Boeing, Seattle, Wash.; AVCO–R. A. D. at Wilmington, Mass; PRD Electronics, Brooklyn, N.Y. [Hopfer, 1962]; and FXR Inc., Woodside, N.Y. [Aslan, 1960].

A great deal of measurement research and development during these past 3 years has been centered in the determination of insertion loss or attenuation. Outstanding work has been productive of results advancing measurement accuracy by more than one order of magnitude. The results at NBS, tabulated in table 3, were derived from the research work of several specialists at the Boulder Laboratories [Cook and Allred, 1960; Engel and Beatty, 1960; Shafer and Bowman, 1962] supplemented by the collaborative work of Weinschel [1961] and Sorger.

TABLE 2. *Power*

Power range	Frequency range	Accuracy
1. CW, coaxial		
		Percent
0.1 mw to 5 w	30 kc/s to 30 Mc/s	0.15
0.1 mw to 5 w	30 Mc/s to 300 Mc/s	0.25
0.1 mw to 5 w	300 Mc/s to 1000 Mc/s	0.5
5.0 w to 1 kw	30 kc/s to 1000 Mc/s	1.0
2. Pulsed, coaxial		
2 mw to 2 kw	900 to 1200 Mc/s	3.0
3. CW, microwave		
1 mw to 1 w	8.2 to 18 Gc/s	0.5

TABLE 3. *Attenuation (CW, coaxial)*

Attenuation range	Frequency range	Accuracy
db		*db*
0 to 60	30 Mc/s	$\pm\left(0.002+0.001\frac{A}{10}\right)$
60 to 100	30 Mc/s	$\pm\left(0.003+0.001\frac{A}{10}\right)$
0 to 60	100 Mc/s	$\pm\left(0.005+0.001\frac{A}{10}\right)$
60 to 100	100 Mc/s	$\pm\left(0.01+0.001\frac{A}{10}\right)$
0 to 70	1, 10, 60, 300 Mc/s	$\pm\left(0.02+0.001\frac{A}{10}\right)$
0 to 60 (fixed pads)	300 Mc/s to 8 Gc/s	±0.1 db/10
0 to 60 (variable atten)	300 Mc/s to 8 Gc/s	±0.05 db/10

Within the United States, several laboratories report capabilities for measuring attenuation which are favorably comparable with NBS. In addition to Weinschel, Gaithersburg, Md., they are: Boeing, Seattle, Wash.; Bell Telephone, Murray Hill, N.J.; Microwave Institute, Brooklyn, N.Y.; Douglas Aircraft, Santa Monica, Calif.; Sandia, Albuquerque, N.M.; Bendix, Kansas City, Mo.; Stoddart Aircraft, Hollywood, Calif.; Metrology Dept. BuWepsRep, Pomona, Calif.; USAF Health Annex, Newark, Ohio; National Aviation Facilities Experimental Center, Atlantic City, N.J.; US Army Lexington Signal Depot, Lexington, Ky.; Martin Co., Denver, Colo.; Frankford Arsenal, Philadelphia, Pa.; and Sperry, Great Neck, N.Y. [James, 1962].

In the area of field-strength measurements, a great deal of work remains. With the advent of more stringent requirements upon government contractors to mitigate radiofrequency interference has come renewed demands upon NBS, and initiation of individual laboratory research. Measurements laboratories are forced to develop techniques both to establish signal and noise field strengths, and to determine optimum signal to noise relationships for reception of intelligence. Typical is the work of the Jet Propulsion Laboratory, Pasadena, Calif., in measuring system noise temperatures [Schuster, Stelzried, and Levy, 1961].

Conversely, laboratories also are engaged in the study of controlled propagation of noise as a research tool or as an environment to be applied in testing. Such laboratories as Hughes Aircraft in Culver City, Calif. [Mukaihata, Walsh, Bottjer, and Roberts, 1962; Rickey and Forward, 1962]; Empire Devices at Amsterdam, N.Y. [Knapp, 1960]; Polarad Electronics, Long Island City, N.Y.; Bomac Laboratories, Beverly, Mass.; Weinschel Engineering, Gaithersburg, Md. [Raff and Sorger, 1960]; Stanford University, Palo Alto, Calif. [Siegman, 1961]; Ohio State University, Columbus, Ohio [Ko, 1961]; Sylvania Electric Products, Mountain View, Calif. [Tralle, 1962]; Varian Associates, Palo Alto, Calif. [Varian]; NBS, Boulder Laboratories [Estin, Trembath, Wells, and Daywitt, 1960; Wells, Daywitt, and Miller, 1962]; Airborne Instruments Laboratory, Mineola, N.Y.; Massachusetts Institute of Technology, Cambridge, Mass., and Bell Telephone, Murray Hill, N.J., have reported direct application of their talents to specialized problems in these fields.

In an attempt to resolve some of the more pressing measurement problems which have arisen during the past 3 years, some consideration has been given to known but neglected principles. As a technique for the measurement of rf voltages, particularly magnitudes greater than 1000 v, study has been directed to employment of the Stark Effect as a relative measurement of voltage. Preliminary work is in progress at NBS, Boulder [Beers and Strine, 1962] and shows promise in its comparative simplicity by eliminating the necessity for voltage dividers. Direct comparison of rf to d-c voltages is conceivable. Possible resolutions in measurement of one part per million using field strengths of 10^4 v/cm are forecast.

The accuracy of coaxial line measurements has always been handicapped by the errors introduced by the fittings. Several advances have been made toward the establishment of a universal compatible connector. Research work by Weinschel Engineering and General Radio Co. [Sanderson, 1961; Sanderson, 1962] on very accurate VSWR measurements has been coordinated with the connector development work of organizations such as General Radio Co., West Concord, Mass. [Zorzy, and Muehlberger, 1961] and NBS, Boulder [NBS, 1962]. In August 1962, a meeting of the AIEE Subcommittee on Standardization of Precision Coaxial Connectors was held at NBS Boulder. They attempted to resolve conflicts in mechanical dimensions and electrical impedances of the several commonly employed connectors. As a result of the meeting, the committee submitted to the parent AIEE Electronic and High Frequency Instrumentation Committee a Recommended Practice for Precision Coaxial Connectors.

The occurrence of radio telemetering transmission blackouts during the test reentry of missile elements into the atmosphere triggered measurement research into relationships between plasma generation and radio signal attenuation approximately 5 years ago. Since that time much original work has resulted in measurement techniques to establish cause and effect. Typical is the research at Ohio State University [Tischer, 1960] to accomplish the measurement of electromagnetic properties of a physically bounded plasma. This work has been enlarged at NBS [Northover, 1962; Johler, 1962; Marini, 1960; Branscomb, 1960] to measure reactions in a less restricted environment.

Application of optic principles to millimeter waves in the unbounded or nonwave guide state at the University of South Carolina [Litman, Fellers, and Mosely, 1961] established the use of prismatic devices as directional couplers or attenuators which are susceptible to theoretical calibration. These principles have been utilized in the development of a wave meter and a reflectometer through application of interferometric principles. Similarly, the conception of a plasma piston, magnetically accelerated toward an electromagnetic wave to generate millimeter waves by the mirrorlike reaction from the plasma, illustrates an imaginative application of the Doppler effect. Utilization of two-port networks by the University of Illinois Laboratory [Mittra and King, 1962] and the Microwave Research Institute of Polytechnic Institute of Brooklyn [Altschuler, 1962] has assisted in determining some propagation characteristics of plasmas.

The surge of activity encompassing normally propagated millimeter waves has resulted in development at Bell Telephone Laboratories, Murray Hill, N.J., of measurement devices to measure transmission gain or loss in waveguide and delay distortion [IRE, 1962].

An excellent example of mutual support of effort to disseminate knowledge of measurement techniques has been the work of the Metrology Depart of BuWepsRep in Pomona, Calif. during the past 3 years, in circulating specialized design notes to standards and calibration laboratories. These cover the fabrication and application of precision measurement instruments developed, for the most part, at the National Bureau of Standards. A number of laboratories not conversant with the work of the Bureau have, in this manner, been made aware of the value and application of micropotentiometers, thermal voltmeters, standard frequency comparators (high frequency), and phase tracking receivers.

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