Report of U.S. Commission 1, URSI RADIO MEASUREMENT METHODS AND STANDARDS

Review of developments occurring within the United States of America in the fields of Radio Measurement Methods and Standards, 1957–60

The following report briefly summarizes significant developments and lists publications of the last three years. The bibliographies are fairly complete and any omissions that may occur are unintentional. The topics covered are the following.

1. Frequency and Time Interval	E. A. Gerber
2. R.F. and Microwave Power	G. F. Engen
3. Impedance	G. A. Deschamps
4. Attenuation	B. O. Weinschel
5. Noise	B. M. Oliver
6. Field Strength	M. C. Selby
7. Measurement of Physical Quantities by Radio Techniques	M. C. Thompson, Jr.

1. Progress in the United States During the Last Three Years on Frequency and Time Interval Standards and Measurements

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1.1. Quartz Crystal Standards

A new IRE Standard on Piezoelectric Crystals defines methods for the Determination of the Elastic, Piezoelectric, and Dielectric Constants, and for the Electromechanical Coupling Factor. Additionally, it brings order and system into the hitherto confused terminology on piezoelectric crystals [Proc. IRE, 1958].

The biggest problem for precise quartz crystal standards has been the aging of resonators. It is now possible to control the environmental influences on aging to a very large extent. Attention has, therefore recently been directed mostly to the processes within the crystal lattice. The internal friction in natural and synthetic quartz has been studied as a function of temperature and frequency and the anelastic behavior has been explained from the interplay between dislocations and impurities [Granato, Lüeke, 1957; Wasilik, 1957: Mason, 1958; King, 1959]. It has been demonstrated that X-ray irradiation or simultaneous exposure to high electric fields and high temperatures (electrolytic purification) produces changes in the anelastic absorption spectrum [King, 1959].

Great progress has been made in the improvement of the stability of quartz crystals standards. The aging, the Q, and other properties of quartz resonators vibrating in various modes have been studied in the temperature range from 4 to 330 °K. A Q of 50 millions has been observed on one mode at 4.2 °K [White, 1958; Warner, 1958] and the aging rate at this temperature was extremely low, its value of a few parts in 10^{11} per day probably given by the limits of instrumentation [Warner, 1958; Simpson, Morgan, 1959]. The quartz resonators, however, proved to be rather sensitive with respect to shock and vibration, and this observation might explain the fact that the short-time stability at 4 °K, as measured in comparison with an ammonia maser, is less than the stability measured over 2 hr [Morgan, Barnes, 1959]. Quartz resonators kept near room temperature still show a very low aging rate, comparable with that at 4.2 °K; the Q-values, however, are approximately one order of magnitude less [Warner, 1958]. Data on crystal standards are compiled in table 1, together with corresponding data on atomic standards. The term "accuracy" as used in the table is defined as the relative deviation from a previously accepted frequency value; "stability" is defined as the maximum relative frequency change during a specified time interval from the value at the beginning of this interval. It must be pointed out that the data in table 1 are intended to give information on orders of magnitude only. More precise data on accuracy and stability would require a detailed description of the apparatus.

1.2. Atomic Frequency and Time Standards

Great progress in the above field has continued, especially along the lines of first, passive beam devices; secondly, ammonia masers; and thirdly, gas cell devices.

A cesium beam standard has become commercially available under the trade name "Atomichron" [McCoubrey, 1958; Mainberger, Orenberg, 1958; Mainberger, 1958]. To improve its performance the geometry of the microwave structure has been changed and the microwave source has been simplified for greater reliability and reduction of sidebands [McCoubrey, 1958]. The integrated outputs of several Atomichrons have been compared in order to observe the difference in accumulated phase over extended periods. The two best Atomichrons were found to have deviated by no more than 1 μsec after 63 hr or 5 parts in 10^{12} of the measured time interval [Bridgham, Winkler, Reder, 1959]. Cesium beam standards of British and United States design have been compared and the principal sources of error studied [Holloway et al., 1959]. There remains an unresolved discrepancy between the standards of about 2 parts in 10^{10}. Efforts to increase the precision of atomic beam standards have been going into two directions: First, the "broken beam experiment" to increase the microwave interaction time [Kleppner, Ramsey, Fjelstadt, 1958] and secondly, studies of molecular spectra in the millimeter range [Hughes, 1959; Gallagher, 1959] to improve the Q of the quantum mechanical resonator. The described work in passive beam standards has been supported by studies of a more fundamental nature, such as molecular beam resonances for various combinations of nonuniform fixed and oscillatory fields [Ramsey, 1958].

Work on high precision ammonia maser oscillators has been continued at a high rate. The effects on the maser frequency resulting from cavity pulling,

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TABLE 1. *Typical precision frequency standards*

Device	Frequency of resonator	Accuracy†	Stability (with respect to time)	Q of resonator	Operational time of resonator	Space requirement (with freq. translating equipment)	Weight
	Mc/S				*hr*	*ft*^{3}	*lb*
Precision crystal oscillator (commercially available)	1	±1×10^{-6}*	3×10^{-8}/mo	1×10^6	Not specified	⅓	20
Precision crystal oscillator (experimental)	2.5	±1×10^{-6}*	2×10^{-10}/mo 2×10^{-10}/sec	5×10^6	Not specified	½	25
Cs-beam frequency standard (commercially available under the name "Atomichron")	9,193	±2×10^{-10}	2×10^{-11}/day however, no measurable long-term drift	60×10^6	10,000 and better	16	800 (Commercial model 1001)
						12	500 (Military model)
Ammonia maser (experimental, portable, with limited coolant supply)	23,870	±1×10^{-9}	1×10^{-11}/hr 2×10^{-10}/sec	5×10^6	8	1	40
Gas cell (rubidium 87, experimental)	6,835	±1×10^{-9}	1×10^{-10}/mo	300×10^6	Not specified	¾	30 (Estimated)

*Crystal manufacturing tolerances only.

† The accuracy in the table presumes no prior adjustment of the device against a primary frequency standard. If this were done, the accuracy of the device merely approaches the resolution of the measurement equipment at the moment of adjustment.

nonuniform radiation of the beam inside the cavity, hyperfine structure of the spectral line, thermal effects and variations in beam flux and residual pressure have been studied in great detail [Mockler et al., 1958; Vonbun, 1959; White, 1959; Barnes, 1959; Townes, 1957, Vonbun, 1958a]. The following measures, employed either single or in combination, may yield accuracies and stabilities as plotted in table 1: Symmetrical maser structure employing two beams [Mockler et al., 1958], temperature controlled cavity (±0.001° C) [Mockler et al., 1958] or quartz cavity near a temperature for which the expansion coefficient goes through zero [Vonbun, 1959], center line location by using the Zeeman effect [Vonbun, 1958a], precise control of residual pressure [White, 1959]. A small sealed-off maser for missile application maintained its frequency to better than 5 parts in 10^{10} under a static acceleration of 25G [Reder, Bickart, 1959]. Exact data on state separator construction have become available [Vonbun, 1958b]. Two-cavity masers have been studied [Higa, 1957; Wells, 1958] and it has been found that the two cascaded cavities may oscillate at different frequencies. Investigations of the noise in ammonia maser amplifiers resulted in data for the noise figure as a whole [Helmer, 1957] and for the beam temperature [Gordon, White, 1958], and suggest how signal-to-noise ratios can be improved [Beers, 1959]. Studies of the ammonia spectrum itself [Hadley, 1957; Vuylsteke, 1959] and of the interaction between the electromagnetic field and a number of similar atomic systems [Senitzky, 1959], round up the maser work in the reporting period.

A considerable amount of work on gas cells has been done in several places, employing mostly rubidium or cesium as the reference atom. In contrast to beam devices where the Boltzmann distribution of atoms or molecules among the various possible energy states is changed by means of state separators employing electric or magnetic fields, atoms in gas cells are "optically pumped" into a desired ground state hyperfine level. The intensity of the pumping radiation absorbed or scattered by the gas cell changes when the desired microwave transition occurs. This offers a very convenient way of detecting the microwave resonance. Additionally, the introduction of a "buffer gas" into the cell is necessary to reduce the Doppler broadening of the microwave line. However, the buffer gas produces a shift of the center frequency of the hyperfine transition and this shift is a function of temperature and pressure [Beaty et al., 1959; Bender et al., 1958; Arditi, 1960; Andres, 1959; Whitehorn, 1959; Bell, 1958]. Mixtures of buffer gases have been made, however, which make both the temperature and pressure coefficient small and keep the signal-to-noise ratio moderate [Beaty et al., 1959; Arditi, 1960]. The frequency shift in the hyperfine splitting of alkalis caused by added gases has been found to be caused by exchange as well as dispersion forces [Margenau et al., 1959]. In order to obtain a strong signal for the optical detection of the ($M_F=0\rightarrow M_F=0$, $\Delta F=\pm 1$) transition, selective hyperfine filtering of the pumping light [Bender et al., 1958; Bell et al., 1958] or pulses of rf radiation at the Zeeman frequency have been used [Alley, 1959]. With the usage of optical detection, a mixture of 12 percent neon and 88 percent argon as buffer gas, and a temperature stability of 0.1° C, data as indicated in table 1 can be obtained [Beaty et al., 1959].

1.3. Frequency and Time Measurement and Comparison

Two methods have mainly been used for high precision frequency and time measurement: The first employs multiplication of the unknown and the standard frequency to 1000 Mc/s and above, and measurement of the beat frequency; the precision of measurement can be 1.10^{-11} for a 100-sec count [Simpson, Morgan, 1959]. The second method also employs frequency multiplication; however, the period of the beat note is measured [Simpson, Morgan, 1959; Tanzman, 1959]. The sensitivity of the latter method is, for multiplication to 100 Mc/s and for n periods $(6.10^{-10})/n$ [Tanzman, 1959]. Another method uses timing pulses at the instant the two signals to be compared are in opposition. This yields for a comparison of 100 kc/s frequencies and 10-sec beat period a timing accuracy of 1 μsec or an accuracy of frequency comparison of 1.10^{-13} [Thompson, Archer, 1959]. Digital rate synthesis has also been used for frequency measurement [Rey, 1959]. The efficiency of frequency measurements with an atomic clock is given by the ratio: information gained/entropy increase [Peter, Strandberg, 1959]. The term "resolution" of a frequency measurement has been derived, meaning the relative error in the determination of a frequency due to phase modulation, noise, and errors in time interval measurements [Winkler, 1959].

In order to compare two frequencies, their values must be made compatible. For this purpose, and mostly in connection with atomic standards, frequency synthesizers and translators have been developed [McCoubrey, 1958; Mainberger, Orenburg, 1958; Mainberger, 1958; McCoubrey, 1959; Reder, Bickert, 1959; Saunders, 1959]. They consist of harmonic generators, mixers, and phase detectors. Usually, the atomic standard is phase locked either directly or via klystron to a harmonic of a crystal oscillator. Progress has been made in the understanding of hormonic generation with rectifiers and nonlinear reactances. The nth harmonic cannot be generated by ideal rectifiers with an efficiency exceeding $1/n^2$ [Page, 1958]. Usage of nonlinear capacitors will not enable one to greatly exceed the above limitations [Rafuse, 1959; Leeson, Weinreb, 1959]. Frequency multiplication with phase-locked oscillators has been achieved from 100 kc/s to 1000 Mc/s [McAleer, 1958], and above.

A determination of the frequency of the $(4,0\rightarrow 3,0)$ transition in cesium in terms of the second of Ephemeris Time (E.T.) has been made [Markowitz et al., 1958; Markowitz, 1959]. The frequency is 9,192,631,770±20 cps (of E.T.). The second of E.T. is identical with the prototype unit defined by the International Bureau of Weights and Measures in 1956. On January 1, 1959, the U.S. Naval Observatory placed in operation a system of Atomic Time, denoted A. 1, provided by cesium clocks and based on the above frequency. The WWV standard frequency transmissions of the National Bureau of Standards have been based on the U.S. Frequency Standard which is derived from atomic standards. The latter standards in turn have been brought into agreement with A. 1 beginning with January 1, 1960 [National Standards of Time and Frequency, 1960]. Corrections of the WWV transmissions with respect to the U.S. Frequency Standard are published monthly [WWV Standard Frequency Transmissions].

Several studies have been undertaken to make frequency and time comparison possible over long distances. Calculations showed that 10 to 100 kw for frequencies in the vicinity of 20 kc/s are required to provide a worldwide coverage [Watt, Plush, 1959]. Various frequency comparisons between stations in the United States and between United States and British stations controlled by atomic clocks using VLF carriers yielded standard deviations as low as 2 parts in 10^{11} [Pierce, 1958; Reder, Winkler]. Clock synchronization by transportation of atomic clocks has been achieved with an accuracy of much better than 1 μsec for several hours flying time [Reder, Winkler].

In closing, a sort of Michelson-Morley experiment using ammonia masers is worthy of mention [Cedarholm et al., 1958]. Two masers with oppositely directed beams were compared and turned with respect to the earth's motion. It was concluded that the maximum ether drift, if any, is less than 1/1000 of the earth's orbital motion.

1.4. References (as of February 1960)

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Note added in proof.

The book, "Quantum Electronics, A Symposium," Columbia University Press, New York, 1960, edited by Charles H. Townes appeared shortly after the completion of this report and contains additional valuable information which should not go unmentioned. The following comments apply to passive beam devices, masers, and gas cell devices.

A cesium beam standard with an estimated accuracy of $\pm 8.5\times10^{-11}$ is described and the influence of the power spectra of the radiation exciting the Cs transition upon the frequency determination is discussed [Mockler et al., p. 127].

Several papers are devoted to the molecular beam maser They furnish detailed studies and discuss new possibilities. Considerations of the influence of thermal noise on the short term frequency stability yield for the fractional phase error due to thermal noise: $\frac{\langle\Delta\theta\rangle}{\theta}=2\times10^{-13}\ t^{-\frac{1}{2}}$, where t is the time of observation [Gordon, p. 3]. The advantage of new molecules and new transitions, especially in the millimeter and submillimeter range is discussed [Thaddeus et al., p. 47; Barnes, p. 57]. Higher transition frequencies together with a Fabry-Perot interferometer instead of a cavity, will make masers with stabilities of a few parts in 10^{11} feasible [Barnes, p. 57]. The dependence of the molecular beam peak intensity and beam width upon the total flow rate has been calculated [Giordmaine et al., p. 67]. The use of a parabolic focuser with a point source effuser allows reduced molecular flow for the same output in a NH_3—maser [Helmer et al., p. 78]. Operation at very low temperatures of an atomic beam oscillator using hyperfine transitions, may yield a spectral purity of a few orders of magnitude greater than that suggested for the ammonia maser [Heer, p. 17]. Operation at 1.5 °K may even make a solid state maser competitive with beam and vapor clocks if a zero-field transition in a magnetic salt is used [Bloemberger, p. 160].

Additional work on gas cells has been devoted to the explanation of the frequency shifts due to temperature and pressure, and of the line broadening. The frequency shifts can be thought of as being caused by successive small phase changes in the coefficients of the $M_F=0$ parts of the alkali wave junction and the observed line widths as statistical fluctuations in the phase shifts [Bender, p. 110].

2. Radiofrequency and Microwave Power Measurements

G. F. Engen*

In the field of radiofrequency and microwave power measurements, contributions have been made to the bolometric, calorimetric, and other miscellaneous techniques, and the National Primary Standard of power measurement is based upon a combination of refinements in these techniques which have been made at the National Bureau of Standards. These contributions will be described in the given order.

A self-balancing d-c bolometer bridge of high accuracy (0.1% in substituted power) based on a design originated at the National Bureau of Standards [Engen, 1957], and a thermistor bridge type of power meter which provides automatic temperature compensation [Aslan, 1960] have been made commercially available.

A previously unrecognized source of error in bolometric type power meters employing combinations of audio and d-c bias power has been investigated and reported [Raff, Sorger, 1960], and a study has been made of the characteristics of low-temperature bolometer detectors [Birx, Fuschillo, 1958].

A series of broadband (VSWR$<$1.5 over the recommended waveguide frequency band) barretter and thermistor mounts [Kent, 1958a] have been developed by several different manufacturers and are commercially available.

The use of a rhodium-platinum alloy has permitted a reduction in the size of the bolometer (barretter) element and improved broadband performance at microwave frequencies [Kent, 1958b].

An improved method of making the impedance measurements implicit in the "impedance" method of determining bolometer mount efficiency has been developed and excellent agreement achieved with calorimetric determinations [Engen, 1958].

In the area of low-level calorimetry, a microcalorimeter which provides a determination of the effective efficiency of microwave bolometer mounts was placed in operation at the National Bureau of Standards [Engen, 1959]. Through use of this instrument, intercomparisons of microwave power standards were made with Japan and Great Britian in accordance with the Commission I resolution.

Variants of this type of calorimeter [Sucher and Carlin, 1958; James and Sweet, 1958] are available commercially from several sources with advertised accuracies of a few percent, and in one case accessory equipment, which provides a rapid and direct readout, has been developed for use in conjunction with these calorimeters [DiToro, Nadler, and Blanchard, 1959]. A coaxial, self-balancing, direct-reading flow calorimeter for the range 0.01 to 10 w is also commercially available [Hand, 1958].

At lower frequencies (below 300 Mc/s) a dry, static calorimeter using a thin film disk type load has been developed at the National Bureau of Standards which covers the power range 0.1 to 20 w [Hudson and Allred, 1958]. Another version of this instrument is under development which will extend the operating range in both power level and frequency. Other techniques which are currently under additional development at the National Bureau of Standards include a 2,000 w flow calorimeter for frequencies below 1,000 Mc/s, a high-power stirred-water calorimeter for waveguide frequencies, and the electron beam technique of power measurement.

The Microwave Research Institute (Polytechnic Institute of Brooklyn) has investigated the use of a series of probes to monitor the power flow in a transmission line where standing waves are present. The optimum spacing for a series of such probes was determined. The use of ferromagnetic films and evaporated indium antimonide for the monitoring of high power through the Hall effect was also investigated [Sucher, 1959].

Finally, the impedance problems attending the intercomparison of power meters have been investigated and improved procedures developed [Engen, 1958; Hudson, 1960; Engen, 1960].

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*The Conference Proceedings are to be published in an early issue of the IRE Transactions on Instrumentation.

3. Impedance Measurements and Standards

G. A. Deschamps*

Contributions reported in this section were published during the three-year period from January 1, 1957 to January 1, 1960. They consist mainly of refinements and extensions of known methods leading to improvements in the accuracy of measurements and to the development of better impedance standards for high frequencies and microwaves.

A new IRE standard on Waveguide and Waveguide Component Measurements was published [IRE Standards on Antennas & Waveguides, 1959]. The standard contains definition of terms and several sections on impedance measurement methods.

The method of measurement of a two-port device by observing the input impedance (or reflection coefficient) when a variable load (sliding termination or variable resistance) is connected to the output, continues to be applied in several different forms. The junction from a waveguide to a semiconductor device has been calibrated by replacing the device by known resistances and measuring the reflection coefficient in the waveguide [Waltz, 1959]. The insertion parameters of transistors (related to the scattering matrix elements) have been measured by techniques and graphical computations similar to those used for waveguide components [Follingstad, 1957]. The sliding-load method, applied for finding the scattering matrix of a two-port junction over a wide range of frequencies, has been simplified by using fixed positions of the short-circuit in the output waveguide [Deschamps, 1957].

A sliding termination that can be adjusted to produce, in a rectangular waveguide, a reflection coefficient from zero to nearly unity in magnitude and any desired phase has been described [Beatty, 1957].

The guard technique has been extended to measure the capacitance per unit length between two infinite cones of arbitrary cross section having the same apex. Thus the characteristic impedance of the corresponding transmission line is determined [Dyson, 1959].

Capacitance Standards of the order of 1 pf have been constructed and can be used in an electrostatic determination of the ohm [Thompson, 1958; McGregor & others, 1958]. They can be compared by means of a bridge with accuracies of 10^{-6} or better [McGregor and others, 1958]. Coaxial capacitors serve as a starting point in the calibration of impedances at high frequencies up to 300 Mc/s [Powell, Jickling, and Hess, 1958].

At microwave frequencies (X-band), in rectangular waveguides WR–90, nonreflecting terminations have been constructed having a return loss greater than 80 db [Beatty and Kerns, 1958].

Inductive half-round obstacles in a rectangular waveguide can be used as impedance standards. Universal tables of reflection have been computed and a number of standards have been constructed and measured. The agreement with calculated value was to within 0.05 percent in SWR [Beatty and Kerns, 1958].

Quarter wavelength short-circuits have been constructed in WR–90 (X-band) waveguide and accurate calculation made of their reflection based upon the measured conductivity of the metal used in their construction. It is estimated that the accuracy of the result is ±0.002 percent. They have been checked independently by measuring their power loss in the microcalorimeter [Beatty and Kerns, 1958].

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Additional Comments on

IMPEDANCE MEASUREMENTS AND STANDARDS*

G. A. Deschamps

Investigations of magnified and squared SWR responses and the use of auxiliary tuners with directional couplers both led to a modified reflectometer technique permitting accuracies of better than 0.1 percent in SWR measurements [Beatty, 1958].

The use of auxiliary tuners with a directional coupler also permits the construction of a highly accurate phase shifter. Combination of this with the above modified reflectometer yields an impedance meter similar to a bridge and both magnitude and phase of the reflection coefficient may be independently determined to high accuracy [Engen, 1959].

Possible errors in the use of a sliding short-circuit as a phase shift standard have been discussed and a method for avoiding them described. Accuracies of 0.3 degree have been obtained [Magid, 1958].

Techniques for the measurement of the equivalent network parameters of discontinuities coupling two or more modes in multimode waveguides have been described [Felsen et al., 1959; Lewis, 1959].

Measurement of standing waves in a specially constructed line was used to evaluate high dielectric constants at UHF [Williams and Foster, 1957].

Rapid measurement of impedance or transmission properties over a wide range of frequencies continues to be of great interest. A system for measuring phase and attenuation through a component [Linker and Grimm, 1958] from 8.7 to 9.6 kMc/s and an automatic impedance plotter [Watts and Alford, 1957] covering the frequency ranges 180 to 900 Mc/s and 50 to 250 Mc/s were developed.

Automatic continuous measurement of phase at microwave can be done by shifting the frequency to audiofrequency [Mittra, 1957]. A broadband direct reading measuring device has been constructed where the LO tracts the RF in order to produce a fixed intermediary frequency [Dropkin, 1958].

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*This material belongs after the fourth paragraph of the published report (p. 598, J. Research NBS, **64D,** 6,) and must be used with the references on that page.

4. Development in Attenuation Measurements and Standards

Bruno O. Weinschel*

4.1. Definition of Attenuation

When dealing with the propagation of guided waves within uniform transmission lines, the term "attenuation constant" describes the relative decrease of amplitude of voltage or current in the direction of propagation in nepers per unit length [IRE Standards on Antennas and Waveguides, 1953; 1959]. This concept shows the historical origin of the term "attenuation"; however, in relation to measurement of "standard attenuators," it has limited application.

The terms "insertion loss" and "incremental attenuation above minimum insertion loss" are of greater utility. Insertion loss in its general definition [IRE Standards on Antennas and Waveguides, 1953] makes no requirements on the source and load impedance. It is "the ratio, expressed in decibels, of the power received at the load before insertion of the apparatus, to the power received at the load after insertion." However, it is also commonly used to denote the minimum attenuation of variable attenuators.

For lower frequencies, the source and load impedances are specified, but the choice of impedances is somewhat more arbitrary.

It must be realized that a source of constant incident power is in a sense the electrical equivalent of a matched source. This equivalance has practical significance, since the power consuming isolation pad frequently used with an unmatched source may be replaced by a high-directivity directional coupler, which supervises the incident power and maintains it constant by manual or automatic feedback [Engen, 1958].

In contrast to the "insertion loss" of a four terminal network, the definition of the "voltage division ratio" of a four terminal network (e.g., attenuator pad with low-output impedance) utilizes not a matched source but a source of zero impedance which is electrically equivalent to a "source of constant voltage". Voltage division ratio is then defined as "the change in load voltage, due to the insertion of a transmission line component at some point in a transmission system where the voltage in the terminal plane of insertion is held constant before and after insertion of the component, the change in load voltage is expressed as a ratio of the voltage in the terminal plane of the termination before and after the insertion of the component". This definition was used in [Sorger, Weinschel, and Hedrich, 1959].

4.2. Techniques for Insertion Loss or Attenuation Measurements

For limited range measurements (up to 20 or 30 db), high accuracy (better than 0.02 db/10 db) can be achieved by using square law detectors such as a barretter in conjunction with 100 percent square wave amplitude modulation at an audiofrequency. Sorger and Weinschel [1959] shows that the deviation from square law of typical commercial barretters used at power levels below—7 dbm can cause a maximum error in insertion loss measurement of the order of 0.01 db.

For HF and microwave measurements, a more restrictive definition requiring a matched source and a matched load is of greater value [IRE Standards on Antennas and Waveguides, 1959]. The additional restriction is that "the specified input and output waveguides connected to the component are reflectionless, looking in both directions from the component (match terminated)".

For measurements requiring a greater dynamic range, a linear heterodyne detector is more practical. Hedrich and Weinschel [1958] and Weinschel, Sorger, and Hedrich [1959] show that the deviation of a crystal mixer from linearity will not cause insertion loss errors exceeding 0.01 db if the maximum signal power is 20 db below the local oscillator power in the mixer crystal.

Heterodyne systems having greater range are of the parallel IF substitution type. In this arrangement, the piston attenuator which operates at the intermediate frequency is not in the IF channel, but in a separate path coming from a highly stable source. The mixer output is compared to this stable signal by null techniques. By this means, greater freedom from drift is achieved and the minimum loss of the piston attenuator is kept out of the signal path.

Hedrich and Weinschel [1958] and Weinschel, Sorger, and Hedrich [1959] use this method in the frequency range of 100 to 1,000 Mc/s to achieve an accuracy better than 0.02 db/10 db over a 50-db range. Weinschel, Sorger, and Hedrich [1959] also contains a careful analysis of the design of the piston attenuators for this application.

To extend the single step and total ranges of these measuring systems, it is desirable to reduce the low-level limit which is set by noise. This can most easily be done by using a small bandwidth following the first detector. For square law systems, this requires a high degree of frequency stability of the audiofrequency modulation. A bolometer preamplifier with a variable bandwidth has been

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described in Hedrich [1959]. The gain is fairly constant while the bandwidth is changed from 2 to 30 c/s. While this instrument is not recommended for precise standards measurements, the principle is useful.

In order to use a small bandwidth in IF amplifiers, following a first linear detector, it is either necessary that the frequency stability of the RF source and the local oscillator be sufficiently high or that the local oscillator frequency be directly derived from the frequency of the RF source by means of single side band modulation. This latter approach requires a higher level signal, synchronous with the test signal. In this type of frequency stabilization, great care must be taken with isolation. One method for achieving single side band modulation is by phase modulation of a traveling wave tube (serrodyne) [Linkner and Grimm 1958; Mathers, 1957; Cumming, 1957]. These single sideband techniques are not in general use for precision standards measurements, but it is clear that the principle can be so applied. Mathers [1957] reports a dynamic range of 80 db, using an intermediate frequency of 1,000 c/s. Linkner & Grimm [1958] uses a 20,000/ cs intermediate frequency and a simultaneous amplitude modulation at 1,000 c/s, and an attenuation accuracy of ±2 percent up to 24 db is claimed. Mathers [1957] considers not only the attenuation, but also the relative phase. An accuracy of 1° in phase is claimed.

A frequency offset can also be accomplished by mechanical means (rotating phase shifter) or by a ferrite phase modulator [O'Hara and Scharfman, 1959].

Increased frequency stabilization of RF sources or single sideband modulation makes feasible lower intermediate frequencies. The use of intermediate frequencies below 100,000 c/s permits the use of accurate wirewound resistor attenuators as standards instead of the piston attenuator. At lower frequencies mixer noise is generally thought to increase inversely with frequency, however. Greene and Lyons [1959] and Andrews and Bazydlo [1959] deal with the modern mixer crystals and show that the mixer noise above 100 kc/s is rather constant and that below 100 kc/s it increases about 12 db for each factor of 10 of frequency reduction.

The method of measuring attenuation by RF substitution does not require the detector response law to be known. Very wide ranges of measurements are possible by this method. To achieve these greater ranges, two or more previously calibrated attenuators are frequently cascade-connected or the calibrated and test attenuators are cascade-connected. Errors introduced by such cascading are analyzed in [Schafer and Rumfelt, 1959].

Another method of measuring attenuation [Engen and Beatty, 1960] utilizes certain bolometric power measurement and stabilization techniques [Engen, 1957] and [Engen, 1958]. By means of these procedures a system stability and resolution of 0.0001 db is achieved and attenuations in the range 0.01 to 50 db can be measured with accuracies of 0.0001 to 0.06 db.

Due to coaxial cable flexing effects at frequencies above 4,000 Mc/s, it is necessary to use special jigs for alinement, so that measurements can be repeated. Rumfelt and Como [1959] describes a rapid insertion device for coaxial attenuators.

4.3. Self-Calibrating Techniques

NBS Tech. News Bulletin [1957] describes a "self-calibrating" method of measuring insertion ratio. That is, it does not rely on any standard attenuator for comparison, as do the previously mentioned methods.

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5. Noise Measurements and Standards

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Because of the rapid development of low-noise devices such as masers and parametric amplifiers, both the theory of noise, and the technique of its measurement have been extended considerably over the last three years.

Numerous papers have appeared [Pound, 1957; Weber, 1957; Weber, 1959; Senitzky, 1958; Senitzky, 1959; Mueller, 1957; Strandberg, 1957; Shimoda, Takahasi and Townes, 1957; Jones, 1959; Strum, 1958] giving quantum-mechanical analyses of the limiting noise performance to be expected from linear radiation detectors (coherent amplifiers). There is now general agreement on this matter and, while the general quantum mechanical proofs are rather complex, the results are simply stated, as follows. All low-noise coherent amplifiers avoid dissipation at signal frequencies in their input circuits and obtain their amplifying action by induced emission of photons, i.e., by transitions of the system from higher to lower quantum states. Since transitions can also be induced from the lower to the higher state at the expense of signal power (absorption) the lower state must be kept relatively depopulated, and the upper state overpopulated by some sort of pumping action. Making use of the usual Boltzmann factor exp $(-\Delta E/kT)$ for the relative population of states in thermodynamic equilibrium, this overpopulation of the upper state with respect to the lower may be described as an effective *negative* temperature, T_a, of the amplifying medium. As the relative population of the lower state approaches zero (complete pumping), T_a approaches zero (from the negative side). There is then no absorption of signal photons, only emission. Some of the emission will be stimulated (and therefore coherent) and represents signal amplification, but some will be spontaneous and represents added noise. The total noise power spectral density referred to the input is given by

$$W(\nu)=\{h\nu/[\exp(h\nu/kT_s)-1]\}$$
$$+\{h\nu/[1-\exp(h\nu/kT_a)]\}.$$

where ν=frequency,
h=Planck's constant,
k=Boltzmann's constant,
T_s=Absolute temperature of source.

The first term will be recognized as the ordinary expression for the thermal noise of a source at temperature T_s, while the second term represents the spontaneous emission of the amplifier. The second term is reduced as $T_a \to -0$, and approaches the limit $h\nu$. Thus for an ideal coherent detector:

$$W(\nu)=\{h\nu/[\exp(h\nu/kT_s)-1]\}+h\nu$$

$$\approx k\left(T_s+\frac{h\nu}{k}\right) \quad \text{if} \frac{h\nu}{kT_s}\ll 1.$$

The second term is an effective noise temperature of the detector:

$$T_{\text{eff}}=\frac{h\nu}{k}=(4.8\times 10^{-11})\nu.$$

For a receiver at X-band (10,000 Mc/s), $T_{\text{eff}}=0.48°$ K.

Many experiments have been reported [Alsop et al., 1957; Gordon and White, 1957; 1958; Cohen, 1960] confirming these low-noise capabilities of linear receivers.

Using low-noise receivers, studies have been made of the effective temperature of the sky as a function of elevation angle [Ko, 1958; DeGrasse et al., 1959]. The measurements agree well with theory [Hogg, 1959] based upon known absorption coefficients for atmospheric gases and water vapor and known temperature as a function of altitude. Galactic noise is found to be the dominating factor in sky temperature below about 500 Mc/s at zero elevation, and below about 3 kMc/s at the zenith. The minimum sky temperature is near the zenith and galactic poles (normal to the plane of the milky way) and is about 3° K. Thus modern amplifiers of the maser type are reaching the limit of practical performance in communication and detection systems.

Standard noise sources for measurement and calibration purposes have improved over the last 3 years. For low-noise receivers, terminations at known temperature are quite satisfactory reference sources. For receivers with higher inherent noise shot noise diodes and gas discharge sources are currently used. The latter have been developed to have greater stability and more accurately known noise during recent years [Zucher, Baskin, et al., 1958; Olson, 1958].

Commercial instruments have been developed which automatically, and in some cases continuously, monitor the noise figure of receivers.

The theory of noise in linear twoports has been analyzed [Haas et al., 1960] and IRE standards for its measurement have been published [IRE standards on measuring noise in linear twoports, 1959].

The National Bureau of Standards has announced [Tech. News Bull. 1959] that its facilities for calibration of noise standards are nearly complete so that soon convenient cross checking of standards will be possible.

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6. Field Strength Measurements

M. C. Selby*

Progress was made in the development of the art of field-strength measurements by some commercial concerns, as evidenced by products placed on the market. At least 3 m were offered for field-strength and interference measurements at frequencies to about 10 kMc/s, input levels of 20 μv to several volts and internal accuracies (excluding antenna coefficients) of the order of 1 db. These meters were employing superheterodyne receivers, input attenuation up to 80 db, internal or external cw and impulse noise calibration, and they measured average, peak and quasi-peak values [Rosen, 1958; Borck, Rodriguez, 1959].

There were also at least two devices placed on the market to measure near fields for use as RF radiation hazard meters. The frequency and power density ranges in one case were 200 to 10,000 Mc/s at 1 mw/cm^2 to 1 w/cm^2 and in another 2,600 to 10,000 Mc/s at a fixed level of 10 mw/cm^2. The claimed accuracy was of the order of 1 to 3 db. [Electronics, 1958].

Work was initiated at the National Bureau of Standards to develop primary and secondary national standards of cw, field strength and antenna gain at frequencies above 300 Mc/s [NBS Research Highlights, 1958, 1959]. Immediate objectives were the improvement of the stability of an insertion loss measuring system to 0.01 db/hr, evaluation of a microwave absorbing enclosure and of effects of absorbing materials and selection of a waveguide horn as a national standard for frequencies up to 12,400 Mc/s. In line with these objectives a signal source level was stabilized to a ten-thousandths of a decibel and a phase-lock system of frequency control was developed which was capable of locking two free running reflex klystrons—all in noncontrolled evironment.

Intensive work was in progress in numerous laboratories on many special problems involving incidental field measurements. These included problems on interference [Hubbard and Cateora, 1959; Albin and Pearleton, 1958; Morelli, 1958; Epstein and Schulz, 1959; Chapin, 1959; White and Ball, 1960], propagation studies [Knudsen and Larsen, 1960; Agy and Davies, 1959], antenna patterns [Morrow, et al, 1958; Kamen, 1959] and others. Instrumentation and technique in these cases were usually adapted to the particular requirements; however, occasionally one may find under these subjects information applicable to the problem of field measurements in general. Some references to these activities are therefore indicated. Work of interest at 100 to 118 kMc/s was recently conducted as a study in propagation [Tolbert and Straiton, 1959; Tolbert, Straiton and Douglas, 1958]. However, this activity was limited to attenuation measurements and apparently did not attempt measurement of absolute field values.

Considerable information on field theory and measurements at the low end of the frequency spectrum, e.g., from 1 to 300 c/s may be found in papers presented at the 1960 Earth-Current Communications Seminar [J. Research, 1960; Wait, 1960]. An experimental and theoretical study of fields at 18.6 kc/s in a medium of fresh water to depths of 1,000 ft using monopole and loop antennas and encouraging results are described [Saran and Held, 1960].

The continuous efforts of C.C.I.R. Study Group V on measurements of field strength [CCIR Report, 1959] should be followed by those interested in this subject.

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7. Measurements of Physical Quantities by Radio Techniques

M. C. Thompson, Jr.*

During the past few years the use of radio techniques for precise distance measuring in land surveying has met with notable success. Although at this time only two commercial firms are known to be engaged in the manufacture of this type of equipment: [Microdist; Tellurometer] the enthusiasm with which it has been received in the field of geodetics indicates clearly that it is an important scientific achievement.

One of the limitations on the accuracy of electronic distance measuring is the fact that the basic measurements of transit time must be converted to equivalent distance. This requires a knowledge of the propagation velocity along the path being measured and this can practically only be estimated from measurements at discrete points. The errors can, thus, be divided into two general classes: first, the errors in approximating the space average of velocity (or refractive index) along a line several miles long based on a few point measurements; and second, the errors in calculating phase velocity. The latter include: (1) Uncertainty in the value of c, (velocity of electromagnetic waves in vacuum); (2) errors in determining the constants appearing in the psychrometric equation [Smith and Weintraub, 1953] relating refractive index to measurements of pressure, temperature and water vapor content; and (3) the errors inherent in the measurement of these latter physical quantities.

A number of experiments have been examined [Thompson and Janes, 1959; Thompson and Freethey, 1958] to determine the behavior of the error introduced by interpolating velocity corrections along paths of various lengths based on psychrometric observations under various geographical and seasonal conditions. This work shows that the corrected observations using psychrometric methods have standard deviations of several parts per million. Unfortunately, the experimental errors expected from the atmospheric measurements (3 above) are estimated to be of the same order so that the extent of the interpolation error is probably obscured.

In addition to the interpolation and correction measurements errors, the accuracy of electronic distance measuring is limited by the accuracy of c and of the coefficients relating phase velocity to atmospheric composition. Although the value of c recommended by URSI is apparently universally used, no one set of psychrometric coefficients has been adopted. Recommendations have been made, however, to the International Association of Geodesy that values be selected for international use to simplify the problems of comparing research and results of different workers. (The discussion of advances in the determination of c is to be found in other sections of this report.)

The work described above suggests that the present practical limitation on the precision of electronic distance measuring is the error in estimating the proper correction for atmospheric properties. As an aid in resolving this error, the National Bureau of Standards, since 1958, has been working to develop a microwave refractometer having sufficient long-term calibration stability to justify absolute calibration. By the use of such an instrument it should be possible to reduce the errors in electronic distance measuring to less than a part in a million.

The instrument recently developed by M. J. Vetter of the National Bureau of Standards operates on a principle distinctly different from those used by Birnbaum and by Crain. By the use of feedback techniques, the new method effectively removes electronic component (including klystron) characteristics from the performance. Preliminary tests suggest that the electronic stability is of the order of a few parts in 10 million for periods of weeks or longer. The residual errors are essentially a function of sampling cavity design and operating conditions (e.g. temperature compensation, cavity contamination and corrosion, etc.).

References

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