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Progress in radio measurement methods and standards

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TIME AND FREQUENCY

On Friday, October 13, 1967, the General Conference of Weights and Measures adopted the atomic definition of the unit of time, the second. The development of atomic frequency standards is still most heavily weighted toward cesium beam devices, with considerable work also on hydrogen masers [*Vessot et al.,* 1966; *McCoubrey,* 1967]. Probably because of budget problems, there has been little work on thallium beams. There has been significant interest in optical frequency standards with a notable development of a methane-stabilized laser by John Hall [*Barger and Hall,* 1969]. Current emphasis on atomic frequency standards is toward more nearly optimum performance. Atomic frequency standards have an important use in long baseline interferometry [*Gold,* 1967].

One of the most significant publications on the subject of frequency stability is the special issue of the *Proceedings of the IEEE* volume 54, number 2, (February 1966). Since this publication, there seems to be a fairly general tendency among the more sophisticated time and frequency laboratories to use the variance of frequency fluctuations as defined by *Allan* [1966] as a consistent measure of frequency stability in the time domain. The Allan variance (specifically, $N = 2$) has been referenced several times [e.g., *Vessot et al.,* 1966; *Menoud et al.,* 1967; *Mungall et al.,* 1968; *Vessot et al.,* 1968]. Methods of spectrum estimation [*Bingham et al.,* 1967] and the fast Fourier transform [*Brigham and Morrow,* 1967] are important developments for frequency domain specifications of frequency stability. A subcommittee of the IEEE is preparing standard definitions of frequency stability.

Flicker noise is found to affect the frequency, in long term, of all signal generators [see, for example, *Vessot,* 1968]; to affect the phase, in short term, of oscillators, amplifiers, and frequency multipliers [*Halford et al,* 1968]; and to affect the phase of LF and VLF radio signals [*Allan and Barnes,* 1967; *Guetrot,* 1969]. This area needs much study.

In the area of time and frequency dissemination, satellites have received much attention, with VHF transponder satellites showing capabilities of time synchronization to a few microseconds [*Gatterer et al.,* 1968]. The Omega system is to become operational, and it is expected to allow time synchronization. Other active areas of research include Loran C, portable clocks, HF, LF, and VLF [*Morgan,* 1967].

During the past three years, needs for highly precise time synchronizations have steadily increased. One of the most notable needs that developed is for a 3-sigma tolerance of 0.5 μsec worldwide for the Aircraft Collision Avoidance System (ACAS) [*Holt,* 1968]. It is doubtful that the current UTC system strikes an adequate compromise between needs for Universal Time and Atomic Time. The U. S. Study Group VII supplied recommendations for a new compromise UTC system to the Plenary Session of the International Radio Consultative Committee (CCIR) meeting in Boulder, Colorado, in July 1968. International agreement was not reached, but a Working Party was formed to study the matter. The U. S. Naval Observatory and the National Bureau of Standards (NBS) have coordinated their standard frequency and time signals (beginning October 1968) with time coincidence maintained within ±5 μsec of each other.

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CW POWER

Developments in CW power included the investigation of new approaches, extension in range and frequency of existing technology, and the development of new measurement procedures to permit a greater utilization of existing measurement devices.

The development of improved directional couplers [*Hudson,* 1966] and calorimeters [*Crawford and Hudson,* 1967; *Crawford,* 1968] provided improved accuracy and convenience for power measurements in coaxial line.

Microwave power calibrations at NBS were extended in frequency coverage in rectangular waveguide by the continued implementation of prior developments and were extended to coaxial devices through a procedure involving an adaptor evaluation [*Engen,* 1966]. In addition, the utility of the impedance method of evaluating bolometer mount efficiency and of the bolometric technique in general was enhanced by further studies of the barretter substitution error [*Adams and Desch,* 1968; *Jarvis and Adams,* 1968]. A thin-wall directional coupler was analyzed [*Hall and Little,* 1967] for potential application in high power measurements, and the way was paved for further advancement of national standards of the calorimetric type by the development of an improved water bath [*Harvey,* 1968; *Larsen,* 1968].

Developments outside NBS included the following: a new device based on thermally excited mechanical vibrations, described by *Rando* [1966]; and another based on the interaction between the electromagnetic fields and gas molecules, reported by *Senitzky and Liebe* [1966].

The measurement of low power levels by comparison with noise sources was described [*Stelzried and Reid,* 1966], and the implementation of a commercial coaxial power measuring system was reported [*Sorger et al.,* 1966; *Sorger and Weinschel,* 1966]. The characteristics of bolometers were further investigated [*Cohn,* 1968; *Aslan,* 1967], and the subject of multimode power continued to be of interest [*Levinson and Slevan,* 1967; *Levinson and Rubinstein,* 1966].

Finally, this report would not be complete without noting several comprehensive survey papers prepared during this period: *Hudson* [1967], *Rumfelt and Elwell* [1967], *Beatty* [1966], *Beatty* [1968], and *Selby* [1966].

CW VOLTAGE

The art of measuring CW voltage has been extended into the microwave region where profitable and feasible. Increasing interest in this range dates back at least a decade as evidenced by new voltage measuring equipment on the market to 12.4 GHz [*Grove,* 1966; *Best et al.,* 1966]. The most prominent immediate need is for standardization of picosecond-rise-time pulse display oscilloscopes requiring wide bandwidths.

Justifications for measurement of voltage as an independent quantity at frequencies up into the microwave range are very impelling [*Selby,* 1967*a*]. Largely as a result of the above, the NBS has developed a new device, a bolometric voltage and current (BOLOVAC) standard for lumped-constant and transmission-line systems. Originally intended only for voltage, this device is also a source of known voltage (and hence of a known power into a given impedance) and a sink of known current, at frequencies from audio to 12.5 GHz and potentially to 30 GHz [*Selby,* 1967*b*]. For voltage, uncertainties of the order of 0.1% at 0.1 GHz, 1% at 1 GHz, and < 5% at 10 GHz were obtained, as were 1% to 1 GHz for current. Levels of 0.1 to 10 volts and 5 to 100 ma were measured. Agreements of 5% or better were obtained at 1 to 10 milliwatts to 10 GHz in 50-ohm, 7-mm systems.

A precision voltage calibrator for frequencies to 100 MHz, 0.2 to 100 volts, and 2% or less uncertainty was developed [*Calhoun,* 1967]. A decade inductive voltage divider was developed for frequencies to 100 kHz or higher to serve as a standard with uncertainties of less than 5×10^{-7} [*NBS,* 1968*c*].

Increasing application of coaxial lines, urgency of standardization of wide-baseband pulsed-voltage circuitry, critical need of solid-state studies, and other problems involving voltage measurements to 10 GHz and higher [*Selby,* 1967*b*] indicate a trend toward simpler and more reliable measurements of microwave voltage, power, and current, particularly at lower accuracy levels. There is also evidence of higher accuracy needs at lower frequencies, e.g. to 300 MHz [*Calhoun,* 1967].

NOISE

Standard noise sources. High-precision low-temperature noise standards are needed because of recent advances in radio and radar astronomy. Accuracies of ±0.1°K around 4.2°K and ±0.12°K at

78°K were achieved [*Trembath et al.,* 1968; *Stelzried,* 1968]. Problems associated with noise standards and measurements were examined [*Miller et al.,* 1967; *Stelzreid,* 1968], a method of calibration that is independent of the reflection coefficient was devised [*Wait and Nemoto,* 1968], and an accurate method of calibrating a coaxial noise source in terms of a waveguide standard was concocted [*Engen,* 1968].

Band transition noise measurements provide secondary standards in frequency bands where primary standards are not available [*Olson,* 1968].

A method was devised for measuring the probability density function (PDF) of a microwave noise generator by using a sampling technique [*Bates and Ettenberg,* 1968]. Specifying the PDF of a noise generator has advantages over specifying some other properties [*Gottfried and Tancredi,* 1968].

Two-port characterization. An improved way of characterizing the noise performance of a linear two-port as a function of the source admittance has been conceived [*Lange,* 1967].

To reduce the cost of making automatic noise measurements on telephone circuits, the customary 10- to 15-sec noise average time should be reduced. Tests with noise samples from actual telephone circuits have shown that an average time of 375 msec yields measurement errors with a standard deviation of only ¼ decibel [*Ingle et al.,* 1967].

Oscillator noise. The greatest need for sophistication is in the measurement of AM and FM at modulation frequencies less than a few hundred kHz. In measuring AM noise, the threshold of Schottky-barrier diodes is 170 decibels below the carrier in a 1-Hz band 20 kHz away. This is about 9 decibels better than earlier point contact diodes and about 20 decibels better than a superheterodyne threshold. In measuring FM noise, the threshold has been decreased almost a decade by careful alignment of the conventional apparatus augmented by modern ferrite devices. The threshold for a 600-mW signal is 0.0025 Hz in a 1-Hz bandwidth 1000 Hz from the carrier [*Ashley et al.,* 1968]. A flexible oscillator noise measuring system was developed [*Ondria,* 1968], and a method of measuring the near-carrier noise added by an amplifier was devised [*Sann,* 1968].

Miscellaneous. The principles underlying the measurement of radio noise generated by motor vehicles, as adopted in IEEE Standard 263, November 1965, were reviewed and published [*Lang et al.,* 1966].

A method of measuring noise and gain of a linear two-port simultaneously, using only two standard noise sources and an output power meter, was suggested [*Kenney,* 1968].

PULSED VOLTAGE AND POWER

In the U.S.A. during the past 3 years, baseband and RF pulse measurement techniques have undergone rapid development. Central to this development has been the implementation and refinement of sampling techniques in (1) RF pulse power measurements, (2) baseband pulse peak voltage measurements, and (3) baseband pulse time-domain measurements [*Hudson,* 1967; *Ondrejka,* 1967; *Nahman,* 1967].

Commercial pulse measurement products for laboratory use include 25-picosec rise time sampling oscilloscopes, trigger countdown units which provide sampling oscilloscope displays of pulsed or CW RF waveforms up to 18 GHz, and RF peak power meters having an uncertainty of 0.2 decibel. Commercial products also include programmed automated pulse measurement systems that provide digital or stored data readout. Such systems may be programmed to read out numerical values of desired pulse parameters, and they presently are being used in production testing or in measurement situations requiring many measurements within a short period.

At present, research efforts include further improvement of the NBS RF peak power measurement system, which presently provides measurements throughout 0.1 to 2.4 GHz [*NBS,* 1968*a*]. The objectives of this system are reduction of the maximum uncertainty to 1% and an extension to 4 GHz [*Hudson et al.,* 1968]. Also, continuing studies are being made on sampling oscilloscope frequency–time-domain correlation [*Hudson et al.,* 1968], pulse comparison systems [*Hudson et al.,* 1968], slow-wave configurations for cathode ray tube deflection structures [*Hudson et al.,* 1968], and superconductive coaxial cables for vertical channel delay lines [*McCaa and Nahman,* 1968]. Commercial laboratories are continuing to extend the application of sampling techniques, integrated circuitry, and digital computer systems to pulse measurements.

ATTENUATION, PHASE-SHIFT, AND TIME DELAY

The rotary-vane attenuator was further analyzed for systematic errors due to the effects of reflections from the vanes [*Holm, et al.,* 1967] and to the effects of misalignment of the stators [*Larson,* 1967].

These analyses further increased confidence in this device as an attenuation standard. High-voltage pulsed measurements were advanced by the use of transmission-line reflection type attenuators [*Thomas,* 1967]. These attenuators preserve pulse shapes with high fidelity to pulse widths as small as 30 picoseconds. Two new measurement techniques were introduced [*Kaylie,* 1966; *Stelzried, et al.,* 1966]. In one of these, the series IF substitution measurement method was extended to 100 decibels by the use of noise injection and coherent detection. This system was experimentally evaluated at 90 MHz. The other system was based on a precision dc potentiometer and was designed principally for high precision and accuracy at very low insertion losses. The precision attained was better than 0.0001 decibel over the frequency range 10 MHz to 40 GHz. A monograph [*Beatty,* 1967*b*] and a survey paper [*Russell and Larson,* 1967] on measurements and standards appeared in this period.

Three methods of measuring microwave phase shift were improved and applied to sophisticated phase-shift measurements. The null bridge method was adapted to a system in which the phase-shift changes rapidly, namely, through a plasma. The system was capable of measuring a 0.003° phase shift at 9 GHz [*Gardner,* 1966]. A modulated reflection method, similar to one suggested by Schafer in 1960, was developed to measure very long (20 m, equivalent to about 120 guide wavelengths) networks. The measurement system was capable of reproducing measurements within ±0.1° [*Weaver and Alvarez,* 1966]. The double probe slotted-line technique was adapted to the evaluation of microwave phase shifters [*Nolan,* 1966]. The test results were repeatable within 0.3° with an uncertainty of less than 0.1° for the ranges tested. Comparison between laboratories was also made as part of the evaluation. A tutorial review paper [*Dyson,* 1966] contains a theoretical analysis and classification of methods of measuring phase at UHF and microwave frequencies. Another survey paper [*Ellerbruch,* 1967] also appeared.

IMPEDANCE

The topic of lumped-element impedance measurements was reviewed [*Huntley and Jones,* 1967], and the advantages of using precision connectors to increase measurement accuracy were emphasized [*Jones and Huntley,* 1966]. An automatic vector impedance meter for the range 5 Hz to 108 MHz was developed [*Alonzo et al.,* 1967].

Errors in recent slotted coaxial line and waveguide measurement techniques were analyzed [*MacKenzie,* 1966; *Little et al.,* 1967]. Errors in coaxial lines used as impedance standards were analyzed [*Zorzy,* 1966], and electrical parameters of coaxial lines were calculated and graphed [*Nelson and Coryell,* 1966].

A swept-frequency technique for measuring VSWR with slotted coaxial lines was developed [*Sorger,* 1968]. Also developed was a network analyzer that could measure and display complex reflection coefficients [*Anderson and Dennison,* 1967]. The network analyzer was computer-controlled and used for swept- or stepped-frequency operation [*Ely,* 1967*b*].

Methods were devised to retain the high accuracy of tuned reflectometers while avoiding the tuning: (1) the measurement was repeated with a quarter-wavelength section of waveguide inserted [*Little and Ellerbruch,* 1966], and (2) imperfections of the reflectometer were measured and a correction was calculated [*Champlin and Holm,* 1967; *Hackborn,* 1968]. A dual mode reflectometer was devised to measure polarization and ellipticity of reflected waves in circular waveguide [*Hauge and Champlin,* 1967].

With regard to impedance standards for uniconductor waveguide, a formula was derived to account for the effect of finite conductivity on the reflections from half-round inductive obstacle impedance standards [*Kerns and Grandy,* 1966]. Reflection coefficient standards for TE_{01} mode circular waveguide were devised [*Champlin et al.,* 1968], and formulas for reflections from capacitive posts in rectangular waveguide were derived [*Lewin,* 1968]. Standards of small reflection coefficient consisting of below cut-off holes in the walls of rectangular waveguide were described [*Beatty,* 1967*a*].

An IEEE standard [*IEEE,* 1968*a*] for precision coaxial connectors giving specifications and recommended test procedures was published.

ANTENNA CHARACTERISTICS

Significant work pertaining to measurement techniques included a discussion of measurement procedures for standard antennas above 1 GHz [*Bowman,* 1967] and comments on the accuracies of horn gain measurements [*Jull,* 1968; *Bowman,* 1968]. The performance of tapered anechoic chambers [*King et al.,* 1967], a slant antenna range [*Arnold,* 1966], and the effects of ground reflections on range measurements [*Moeller,* 1966] were discussed. Other developments included a method for resolving multipath field components [*Mittra and Stearns,* 1967], improved gain computations by pattern integration [*Ludwig,* 1967], swept-frequency gain measurements [*Fitzgerrell,* 1966], and the determination of antenna polarization by amplitude measurements only [*Knittel,* 1967; *Beckman,* 1967].

A most interesting measurement was the determination of the gain and pattern of a 210-foot parabola at *S* band using the Surveyor 1 spacecraft on the moon as a transmitter [*Levy et al.,* 1967]. *Hatchett and Gariott* [1967] discussed in-space measurement techniques of large aperture antennas. The patterns of large circular loops [*Rao,* 1968] and the gains of vertically polarized antennas and half-wave dipoles over ground [*Fitzgerrell,* 1967*a, b*] were obtained.

Techniques using radio stars were developed for determining the patterns of large antennas [*Smith,* 1966*a, b*] and the pointing accuracy of satellite ground stations [*Arbenz et al.,* 1966]. Also reported were absolute flux measurements of Cassiopeia A and Taurus A at 3.64 and 1.94 cm [*Allen and Barrett,* 1967], surveys of radio sources which resulted in catalogs of flux density and angular coordinates [*Dixon and Kraus,* 1968; *Kellerman et al.,* 1968; *Hoglund,* 1967; *Fomalont et al.,* 1967] and polarization measurements of radio sources at selected frequencies [*Hobbs and Hollinger,* 1968; *Seielstad and Weiler,* 1968; *Sastry et al.,* 1968].

Some near-field developments were the computation of line-source antenna patterns from near-field measurements [*Martin,* 1967], techniques for mapping electromagnetic fields on photographic film [*Iizuka,* 1968*a, b*] and with liquid crystals [*Augustine,* 1968], possible uses of microwave holography [*Kock,* 1968; *Deschamps,* 1967], and methods of simulating complex aperture distribution functions to determine far-field patterns [*Ingalls,* 1966; *Beste,* 1966].

Useful theoretical results included gain-beamwidth relations for log periodic arrays [*Kreutel,* 1967], approximations for the directivity and beamwidth of large scanning arrays [*Drane,* 1968], a method of computing the directive gains of nonuniformly spaced arrays [*Tang and Chang,* 1966], and a technique for predicting radiation patterns over irregular terrain [*Liepa,* 1968]. The geometrical theory of diffraction was used to compute the patterns of rectangular and parallel plate waveguides [*Ryan and Rudduck,* 1968], to analyze the patterns of horns [*Yu et al.,* 1966], and to calculate the impedance and patterns of a monopole on a conducting plane [*Lopez,* 1966]. Blockage effects were included in computing the patterns of Cassegrain systems [*Pace,* 1968], and the radiation characteristics of circular and linear antennas for partially coherent illumination were discussed [*Mitchell,* 1966].

FIELD STRENGTH

Developments in field strength measurements have included the introduction of new techniques and the improvement in operational flexibility of the commercially available electronically tuned equipment.

A novel approach to field strength standardization above 30 MHz was proposed [*Lawton,* 1968]. This method consists of measuring the current on a small sphere placed in the field.

The calibration of loop antennas was facilitated by analysis of the near-zone magnetic field of a small transmitting loop [*Greene,* 1967*a*].

New instruments described in manufacturers' literature include an 'interference analyzer,' which permits measurement of transient signals as well as signals of varying frequency over the frequency range 15 kHz to 1 GHz. Also described is a spectrum analyzer with a YIG preselector, which operates above 1 GHz and is suitable for field strength measurement using appropriate signal source and antennas.

Reviews of field strength standards and measurement techniques were published [*Greene,* 1967*b*; *Bowman,* 1967].

NBS calibration services and problems involved in field strength meter calibration were discussed [*Taggart,* 1968].

An endeavor was made during the last several years to arrange international comparison of field strength meters, but these attempts have, as yet, led only to correspondence.

The IEEE method generally employed in the U.S.A. for the measurement of receiver oscillator radiation has been under review by the EIA subcommittee 4.9. A modification of this method employing a fixed combination of broadband antennas that does not require change or rotation of antennas has been extensively tested and is expected to be proposed as a standard method.

The IEEE issued a report that gives a brief description of the methods generally used for field strength measurement and calibration, together with estimates of accuracies [*IEEE,* 1968*b*].

There is still a great need for standardization regarding the measurements of field strength other than

CW, i.e. measurements in the time or frequency domain, or both.

RF PROPERTIES OF MATERIALS

General sources for information on dielectric and magnetic activities are the Annual Report and Digest [*NAS-NRC,* 1967] of the NRC Committee on dielectrics, the Transactions of the IEEE group on Electrical Insulation, and the Transactions of the IEEE group on Magnetics, which sponsors INTERMAG (International Conference on Magnetics.)

Dielectric measurements. Measurements of ϵ' and tan δ at RF using a capacitive test cell continue along guidelines contained in publication D-150 of *ASTM* [1968]. See *Bussey* [1967] for references to other basic work.

At microwave frequencies there is still the question of whether to use a simple slotted, short-circuited transmission line or to use some other system, usually the TE_{01} circular mode, to reduce conductor losses and to avoid airgap errors. The latter system is used at NBS [*Bussey,* 1967] for solids and liquids in the range $\epsilon' = 2$–100 with tan δ from 10^{-5} to 1. It was used by *Champlin et al.,* [1967] for semiconductor material and by *Cohn and Kelly* [1966] for ϵ' of the order of 100.

Measurements on several cryogenic liquids were reported [*Mathes,* 1967]. The theory of dielectric measurements on liquids by a millimeter wave reflectometer was extended [*Lovell and Thiel,* 1968]; a least-squares fit to the reflected power as a function of sample thickness was used to obtain the complex permittivity. The Fabry-Perot resonator was used for dielectric measurements on solids [*Degenford and Coleman,* 1966].

The stripline gave convenient dielectric measurements at 10 GHz, especially of ϵ' [*Olyphant,* 1968]. The unsymmetric microstrip was also used [*Vendelin,* 1967].

Availability of standard reference specimens for complex dielectric constant was announced [*NBS,* 1968*b*]. These specimens are vitreous materials. The use of polymeric materials as reference standards was investigated thoroughly [*Scott and Kinard,* 1967] and recommended.

Sometimes in order to verify dielectric measuring equipment, a material of recent manufacture is used, but the published permittivity of several or many years ago is used for comparison. It would be better in many cases to utilize the above standard reference materials.

Magnetic measurements. Much research on line width, spin waves, and anisotropy of radio magnetics is reported annually in the Conference on Magnetism and Magnetic Materials and published in the special February or March issue of the *Journal of Applied Physics.* This area of work is well reviewed through 1966 in a previous paper [*Bussey,* 1967]. NBS measurements and research on tensor permeability using a bimodal cavity were reported [*Schmidt et al.,* 1967]. Fundamental magnetization measurements and their absolute calibration were investigated [*Case and Harrington,* 1966*a, b*]. Permeability measurements on radio cores were extended [*Rasmussen,* 1966; *Rasmussen and Allred,* 1967].

BROADBAND MEASUREMENT TECHNIQUES

Swept-frequency measurement techniques were reviewed and a new system for automatically measuring reflection and transmission coefficients of two-ports was briefly described [*Ely,* 1967*a*]. A sampling mixer was developed for the above system [*Anderson and Dennison,* 1967], and the system was computer-controlled [*Adam,* 1968]. Corrections for system errors were made automatically [*Hackborn,* 1968], and the range was extended to 100 decibels by signal treatment [*Deardorff and Trimble,* 1968]. Transistor parameters were measured [*Satoda and Bodway,* 1968], and future possibilities with automated systems were indicated [*Ely,* 1967*b*].

A system for displaying return loss and transmission loss on a swept-frequency basis was described [*MacKenzie et al.,* 1969]. It operates over a frequency range of 20 MHz to 7 GHz. Automated transmission measurements were made over a frequency range of 50 Hz to 250 MHz, of losses up to 150 decibels [*Geldart et al.,* 1969].

Parameters of transistors and other two-ports are automatically measured over a frequency range of 0.25–4.2 GHz [*Leed,* 1966].

A swept-frequency ratio measurement technique operating over 0.1–12.4 GHz was developed [*Sorger et al.,* 1966]. Load VSWR's and equivalent source VSWR's are determined as well as the residual VSWR of the slotted line [*Sorger,* 1968; *Adam,* 1966].

The temperature coefficient, bias coefficient, and stability of inductors are automatically analyzed at frequencies up to 2 MHz [*Chasek and Drechsler,* 1968].

Faults in transmission lines were analyzed by frequency-domain reflectometry [*Thompson and Hart,* 1968].

Techniques and apparatus for use with swept frequency and automated measurement systems were developed as follows:

A TDR susceptance calibrator was described [*Anderson,* 1966]. A dc to 12.4 GHz sampling oscilloscope was developed [*Best et al.,* 1966; *Grove,* 1966]. The impulse response of two-ports was measured [*Nicholson,* 1968]. Real time signal averaging was used to improve noise by 60 decibels [*Deardorff and Trimble,* 1968]. A frequency offset was obtained from a single oscillator by sweeping, with a time delay in one channel [*Rogers,* 1967]. Many new instruments are now programmable and are designed to transmit their information to computers.

It appears that the incorporation of computers into measurement systems will increase because the following benefits can be realized:

1. Stored calibration data can be used to correct for system's deficiencies, thereby reducing error.
2. Measurement data can be transformed into other forms, i.e., polar to Cartesian coordinates, impedances to scattering coefficients, etc.
3. Measurements can be repeated and correlated to reduce influence of random fluctuations (noise).
4. Measurements can be examined statistically.

LASER MEASUREMENTS

Progress is reported in the following fields: the accurate measurement of laser power and energy, the development of absolutely stabilized gas lasers, and the accurate measurement of the frequency of far infrared lasers.

Several improved liquid absorption calorimeters have been constructed and were found to agree within an accuracy of 1% [*Jennings,* 1966; *Jennings et al.,* 1968]. By means of beam splitters calibrated with these calorimeters, devices have been built to measure energy in the range from 1 to 100 joules with an accuracy of $\pm 2\%$ at the wavelengths of 0.694 and 1.06 μ. Measurements of the output of CW lasers in the range from 0.45 to 1.06 μ were made by synthesizing a radiation pulse with a time shutter; an accuracy of $\pm 6\%$ was achieved. A novel laser calorimeter [*Astheimer and Buckley,* 1967] has been developed; it uses a pyroelectric crystal to absorb the laser radiation and produces a change in surface charge proportional to the change in temperature. This calorimeter covering pulse energies to 1.5 joules and CW power from 0.1 to 80 watts and a wavelength range from 0.48 to 10.6 μ was tested. Although an accuracy of $\pm 5\%$ was indicated, additional work will be required before the accuracy of this device is established. There is a clear requirement for accurate laser energy and power meters over the spectral range covered by existing lasers, namely, from approximately 500 to 0.25 μ.

The subject of frequency-stabilized gas lasers has been reviewed recently [*Hall,* 1968; *Polanyi and Tobias,* 1968]. Interferometric comparison of the same 633-nm He-Ne laser stabilized to the Lamb dip with the Kr^{86} standard lamp at NBS (U.S.A.), NPL (England), and PTB (Germany) gave λ_{vac} = 632.991418 nm to 5 parts in 10^9 [*Mielenz et al.,* 1968]. However, several typically produced lasers of the same type were found to have wavelengths somewhere between 632.99147 and 632.99134 nm. Changes in the discharge tube gas pressure and composition appear to be important causes in such variations [*White,* 1967; *Sosnowski and Johnson,* 1968].

A sharp and stable reference for stabilization can be obtained by placing a gas cell with an absorptive transition at the laser wavelength inside the laser cavity [*Lee and Skolnick,* 1967]. This principle was used to stabilize a 3.39-μ He-Ne laser to a 3.39-μ rotation-vibration line of CH_4 with a reproducibility of better than $\pm 1 \times 10^{-11}$ [*Barger and Hall,* 1969]. Another approach to solving the problem of a stable and sharp wavelength reference is to use a beam of atoms illuminated at right angles to eliminate the Doppler broadening [*Ezekiel and Weiss,* 1968]. These developments appear to offer the promise of obtaining a stabilized laser with a wavelength reproducibility superior to that of the Kr^{86} standard lamp.

Absolute frequencies of gas laser transitions in the far infrared have been measured [*Hocker et al.,* 1967*a, b; NBS,* 1968*d*] and an accuracy of several parts in 10^8 has been obtained for the 118.6-μ transition of the water vapor laser [*Frenkel et al.,* 1967].

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