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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 (ν_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±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 velocity 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.

References

Anderson, T. C., and F. G. Merrill (1960). Crystal-controlled primary frequency standards: Latest advances for long-term stability, IRE Trans. Instr. **I–9,** 136–140.

Arditi, M. (1961). Frequency control by gas cell standards, Proc. 15th Annual Symp. Frequency Control (U.S. Army Research and Development Lab., Ft. Monmouth, N.J.), pp. 181–202.

Arditi, M., and T. Carver (1961). Pressure, light and temperature shifts in optical detection 0–0 hyperfine resonance of Alkali metals, Phys. Rev. **124,** 800.

Baltzer, O. J. (1961). Frequency control by means of a phase tracking VLF receiver, Proc. 15th Annual Symp. Frequency Control (U.S. Army Research and Development Lab., Ft. Monmouth, N.J.), pp. 251–260.

Barnes, J. A., D. W. Allan, and A. E. Wainwright (1962). The ammonia beam maser as a standard of frequency, IRE Trans. Instr. **I–II,** 26–30.

Barnes, F., D. Burkhard, and M. Mizushima (1961). Choice of a molecular transition for frequency control in the millimeter wave region, Proc. 15th Annual Symp. Frequency Control (U.S. Army Research and Development Lab., Ft. Monmouth, N.J.), pp. 204–209.

Barnes, F. S. (1962). The choice of a molecule for a beam frequency standard, IRE Trans Instr. **I–11,** 191–195.

Barnes, J. A., and L. E. Heim (1961). A high-resolution ammonia beam-maser-spectrum analyzer, IRE Trans. Instr. **I–10,** 4–8.

Barnes, J. A., and R. C. Mockler (1960). The power spectrum and its importance in precise frequency measurements, IRE Trans. Instr. **I–9,** 149–154.

Beehler, R. E., W. R. Atkinson, L. E. Heim, and C. S. Snider (1962). A comparison of direct and servo methods for utilizing cesium beam resonators as frequency standards, IRE Trans. Instr. **I–11,** 231–238.

Beehler, R. E., R. C. Mockler, and C. S. Snider (1960). A comparison of atomic beam frequency standards, Nature **187,** 681–682.

Beers, Y. (1961). Comparison of the sensitivities of the beam maser and cavity absorption spectrometers, Rev. Sci. Instr. **32,** 23–27.

Brans, C., and R. H. Dicke (1961). Mach's principle and a relativistic theory of gravitation, Phys. Rev. **124,** 925.

Carpenter, R. J., E. C. Beaty, P. L. Bender, S. Saito, and R. O. Stone (1960). A prototype rubidium vapor frequency standard, IRE Trans. Instr. **I–9,** 132–135.

Cutler, L. S. (1961). A frequency standard of exceptional spectral purity and long term stability, IRE International Convention Record **9,** 183–190.

Derr, V. E., J. J. Gallagher, and M. Lichtenstein (1961). Deuterated ammonia submillimeter maser—a progress report, Proc. 15th Annual Symp. Frequency Control (U.S. Army Research and Development Lab., Ft. Monmouth, N.J.), pp. 210–224.

Dicke, R. H. (1962). Mach's principle and invariance under transformation of units, Phys. Rev. **125,** 2163

Dicke, R. H. (1962). Timekeeping satellites, Proc. 16th Annual Symp. Frequency Control (U.S. Army Research and Development Lab., Ft. Monmouth, N.J.), p. 249.

Doherty, R., G. Hefley, and R. Linfield (1960). Timing potential of Loran-C, Proc. 14th Annual Symp. Frequency Control (U.S. Army Research and Development Lab., Ft. Monmouth, N.J.), pp. 276–297.

Ganssen, A. (1962). The proton magnetic resonance oscillator, a radio frequency source of high spectral purity, IRE Trans. Instr. **I–11,** 166–170.

George, James (1962). Recent advances in cesium beam technology and characteristics of Rabi and Ramsey cesium beam tubes 17 inches in length, IRE Trans. Instr. **I–11,** 250–256.

Giordmaine, J. A., and T. C. Wang (1960). Molecular beam formation by long parallel tubes, J. Appl. Phys. **31,** 463–471.

Goldenberg, H. M., D. Kleppner, and N. F. Ramsey (1960). Atomic hydrogen maser, Phys. Rev. Letters **5,** 361–362 .

Goldenberg, H., D. Kleppner, and N. F. Ramsey (1961). Atomic beam resonance experiments with stored beams, Phys. Rev. **123,** 530.

Hafner, E. (1960). Stability of crystal oscillators, Proc. 14th Annual Symp. Frequency Control (U.S. Army Research and Development Lab., Ft. Monmouth, N.J.), pp. 192–199.

Hastings, H., and W. Markowitz (1960). Stabilization of VLF transmissions at NBS, Proc. 14th Annual Symp. Frequency Control (U.S. Army Research and Development Lab., Ft. Monmouth, N. J.), p. 275.

Helmer, J. C., F. B. Jacobus, and P. A. Sturrock (1960). Focusing molecular beams of NH_3, J. Appl. Phys. **31,** 458–463.

Hopfer, S. (1960). Design considerations for a self-contained ammonia maser oscillator, Proc. 14th Annual Symp. Frequency Control (U.S. Army Research and Development Lab., Ft. Monmouth, N.J.), pp. 330–353.

IRE (1961). WWV and WWVH Standard frequency and time transmission. Proc. IRE **49,** 1335.

Kleppner, D., H. M. Goldenberg, and N. F. Ramsey (1962a). Properties of the hydrogen maser, Appl. Optics **1,** 55.

Kleppner, D., H. M. Goldenberg, and N. F. Ramsey (1962b). Theory of the hydrogen maser, Phys. Rev. **126,** 603.

McCoubrey, A. (1960). Missileborn atomichron frequency standard, Proc. 14th Annual Symp. Frequency Control (U.S. Army Research and Development Lab., Ft. Monmouth, N.J.), pp. 315–327.

McCoubrey, A. O. (1961). Frequency control by microwave atomic resonance, Microwave J. **4,** 65–73.

Marcuse, D. (1962). Hydrogen cyanide molecular beam-type maser, IRE Trans. Instr. **I–11,** 187–190.

Marcuse, D. (1961). Maser oscillation from HCN maser at 88.6 kMc's, Proc. IRE **49,** 1706–7.

Marcuse, D. (1961). Stimulated emission from HCN gas maser observed at 88.6 kMc, J. Appl. Phys. **32,** 743.

Markowitz, W. (1962). The atomic time scale. IRE Trans. Instr. **I–11,** 239–242.

Markowitz, W. (1962). Time measurement techniques in the microsecond region, The Engineers Digest No. 135, p. 9.

Markowitz, W., and R. G. Hall (1961). Frequency control of NBA on an international system, Proc. 15th Annual Symp. Frequency Control (U.S. Army Research and Development Lab., Ft. Monmouth, N.J.), pp. 168–179.

Merrill, F. G. (1960). Frequency and time standards. A status report, IRE Trans. Instr. **I–9,** 116–120.

Mizushima, M. (1962). Theory of resonance frequency shifts due to the radiation field, Proc. 16th Annual Symp. Frequency Control (U.S. Army Research and Development Lab., Ft. Monmouth, N.J.), pp. 267–286.

Mockler, R. C., and R. Beehler (1960). NBS atomic frequency standards, Proc. 14th Annual Symp. Frequency Control (U.S. Army Research and Development Lab., Ft. Monmouth, N.J.), pp. 298–309.

Mockler, R. C. (1961). Atomic beam frequency standards, in Advances in Electronics and Electron Physics Vol. 15, L. Marton, ed. (Academic Press, Inc., New York, N.Y.), pp. 1–71.

Mockler, R. C., R. E. Beehler, and C. S. Snider (1960). IRE Trans. Instr. **I–9,** 120–132.

NBS (1940). Standard frequencies and time signals from NBS stations WWV and WWVH, NBS Misc. Publ. 326.

Newman, J., L. Fey, and W. R. Atkinson (1963). A comparison of two independent atomic time scales, Proc. IEEE **51,** 498.

Packard, M. E. (1962). The optically pumped rubidium vapor frequency standard, IRE Trans. Instr. **I–11,** 215–223.

Penselin, S., T. Moran, V. W. Cohen, and G. Winkler (1961) Precision measurements of hfs of stable Rb isotopes by atomic beams, Bull. Am. Phys. Soc. **6,** 513.

Peter, M., H. G. R. Venkates, and M. W. P. Strandberg (1960). Molecular trajectories in electric fields and state selection in a beam of sodium, J. Appl. Phys. **31,** 693–696.

Pierce, J. A. (1960). The GBR experiment: A transatlantic frequency comparison between cesium-controlled oscillators, Proc. 14th Annual Symp. Frequency Control (U.S. Army Research and Development Lab., Ft. Monmouth, N.J.), pp. 267–274.

Ramsey, N. F., and K. Kleppner (1962). The atomic hydrogen maser, IRE Trans. Instr. **I–11,** 177–182.

Rarity, J., L. Saporta, and G. Weiss (1961). The Effects of Frequency Multipliers on the Uncertainty of a Frequency Measurement. U.S. Army Research and Development Lab., Ft. Monmouth, N.J., pp. 261–277.

Reder, F., P. Brown, G. Winkler, and C. Bickart (1961). Final results of a world-wide clock synchronization experiment (Project WOSAC), Proc. 15th Annual Symp. Frequency Control (U.S. Army Research and Development Lab., Ft. Monmouth, N.J.), 226.

Reder, F. H., and C. J. Bickart (1960). Advantage of a cascaded-cavity NH_3 maser over the single cavity maser, Rev. Sci. Instr. **31,** 1164–1165.

Reder, F. H., and G. M. R. Winkler (1960). Preliminary flight tests of an atomic clock in preparation of long-range clock synchronization experiments, Nature **186,** 592–593.

Rey, T. J. (1961). APC with pulse reference, Proc. 15th Annual Symp. Frequency Control (U.S. Army Research and Development Lab., Ft. Monmouth, N.J.), 278–281.

Richardson, J. M., R. E. Beehler, R. C. Mockler, and R. L. Fey (1962). Les Étalons Atomiques de Fréquence au N.B.S. Comité Consultatif pour la Définition de la Seconde aupres du Comité International des Poides et Mesures, 2^{e} session—1961 (Gauthier–Villars and C^{ie}, Paris), pp. 57–67.

Sachs, R. H. (1962). Theory of timekeeping in space, Proc. 16th Annual Symp. Frequency Control (U.S. Army Research and Development Lab., Ft. Monmouth, N.J.), pp. 250–255.

Saporta, L., and G. Weiss (1962). The effects of noise on oscillator frequency stability, Proc. 16th Annual Symp. Frequency Control (U.S. Army Research and Development Lab., Ft. Monmouth, N.J., pp. 439–447.

Shirley, Jon H. (1963). Some causes of resonant frequency shifts in atomic beam machines. I. Shifts due to other frequencies of excitation, J. Appl. Phys. **34,** No. 4, 783–788.

Shirley, Jon H. (1963). Some causes of resonant frequency shifts in atomic beam machines. II. The effect of slow frequency modulation on the Ramsey line shape, J. Appl. Phys. **34,** No. 4, 789–791.

Stone, R. R., Jr. (1962). Synchronization of local frequency standards with VLF transmissions, proc. 16th Annual Symp. Frequency Control (U.S. Army Research and Development Lab., Ft. Monmouth, N.J.), pp. 227–240.

Stone, R.R., Jr., W. Markowitz, and R. G. Hall (1960). Time and frequency synchronization of Navy VLF transmissions, IRE Trans. Instr. **I–9,** 155–161.

Sykes, R. A., W. L. Smith, and W. J. Spencer (1962). Performance of precision quartz crystal controlled frequency generators, IRE Trans. Instr. **I–11,** 243–247.

Townes, C. H. (1960). Sensitivity of microwave spectrometers using maser techniques, Phys. Rev. Letters **5,** 428–430.

Venkates, H. G., and M. W. P. Strandberg (1960). Operating characteristics of a molecular beam maser, J. Appl. Phys. **31,** 396–399.

Vessot, R. F. C., and H. E. Peters (1963). Design and performance of an atomic hydrogen maser, IRE Trans. Instr. **I-11,** 183–187.

Vonbun, F. O. (1960). Fused silica cavity for a maser oscillator, Rev. Sci. Instr. **31,** 900–902.

Watt, A. D., R. W. Plush, W. W. Brown, and A. H. Morgan (1961). World wide VLF standard-frequency and time signal broadcasting, J. Res. NBS **65D,** 617–627.

Winkler, G. (1960). A superior atomic clock for continuous long time operation, Proc. 14th Annual Symp. Frequency Control (U.S. Army Research and Development Lab., Ft. Monmouth, N.J.).

Winkler, G., and F. Reder (1960). Preliminary results on Project WOSAC, Proc. 14th Annual Symp. Frequency Control (U.S. Army Research and Development Lab., Ft. Monmouth, N.J.), pp. 254–260.

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.