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U. S. A.

Review of progress within the United States during the triennium 1963 through 1965

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1.1. — HIGH PRECISION ATOMIC FREQUENCY STANDARDS

Atomic frequency and time interval standards had advanced to such a high level of performance that in October 1964, the International Committee of Weights and Measures designated the $(F = 4, m_F = 0) \rightleftarrows (F = 3, m_F = 0)$ transition in the ground state of Cs^{133} temporarily for the physical measurement of time. They assigned the value

0,192,631,770 c/s

to this transition. Thus the physical basis for time measurement has changed from an astronomical unit to an atomic unit of time (Bureau International des Poids et Mesures, 1964).

During the period 1963 through 1965 the accuracy capability of the United States Frequency Standard has improved from 1 part in 10^{11} (one standard deviation, (σ) to 1 part in 10^{12} (1 σ). The accuracy of the hydrogen maser is considered to be about 3 parts in 10^{12} due mostly to uncertainties arising from the wallshift. The most recent value for the hyperfine structure separation in hydrogen hydrogen is

$$1,420,405,751.7860 \pm 0.0046 \text{ Hz}$$

[Beehler, Halford, Harrach, Allan, Glaze, Snider, Barnes, Vessot, Peters, Vanier, Cutler, Bodily, 1966].

Recent experiments and theory on the transition process in atomic beam devices have suggested new methods of testing for accuracy. Preliminary results indicate that an accuracy of 1 part in 10^{13} is possible with cesium beams, with guarded optimism, of course (Harrach, 1965; Harrach and Shirley, 1965].

Much improved commercial cesium beam standards are more compact, more reliable and more accurate [Bagley and Cutler, 1964*a*, *b*; Holloway and Lacey, 1964; Orenberg, 1964]. Experiments have demonstrated an accuracy capability of the Hewlett-Packard cesium beam standards within a few parts in 10^{12} [Bodily, 1965; Beehler *et al.*, 1966]. Impressive clock carrying experiments using these commercial devices have compared the separate atomic time scales maintained at NBS, Boulder, the US Naval Observatory, and Neuchâtel, Switzerland, to one microsecond. They have compared the frequencies of 21 different atomic devices in 11 different countries [Bodily, 1965].

Work still proceeds on thallium beams. The present accuracy is about 1 part in 10^{11} [Beehler and Glaze, 1963].

An optically pumped rubidium maser operating on the 6834 MHz transition of Rb^{87} has been developed capable of excellent short term stability. It does not appear suited for a primary standard [Davidovits and Stern, 1965].

Transitions in H_2S at 216 GHz have been observed with Ramsey excitation in a molecular beam electric resonance apparatus. Measured linewidths are about 900 Hz [Strauch, Cupp, Derr, and Gallagher, 1965].

Extensive research is presently going on to better understand the noise properties of atomic frequency standards. Aside from its basic interest it has important bearing on the improvement in electronic design needed for the next generation of frequency standards [IEEE-NASA, 1965].

1.2. — High precision quartz frequency standards

Over the past few years, many thorough investigations have been made to improve the long and short-term stability of precision quartz crystal controlled oscillators. Improvements in holders, temperature control, relief of stress, and lattice perfection have given improved stability.

Tremendous progress has been made in calculating the various modes of motion in crystal plates and determining their amplitude distribution [Mindlin and Lee, 1965]. The results of these studies are closely tied to many of the problems we have today, e.g., the suppression of unwanted responses in crystal units by contouring or by control of electrodes for « energy trapping » [Shockley, Curran and Koneval, 1963]. It has become possible to confine the energy of vibration principally to the electroded portion so that the mounting structure cannot adversely influence the vibration of the plate [Curran and Koneval, 1964, 1965; Spencer, 1965].

Material success has been achieved in the use of X-rays to study strain and displacement in vibrating crystal plates. This technique also shows imperfections in the material which result in lattice distorsions. Any motion resulting in a curvature of the lattice can easily be detected by the topographic X-ray method and figure 1 illustrates the degree of sensitivity that may be obtained. This figure shows the various modes of motion of a 3.2 MHz contoured thickness-shear vibrator with their relative responses.

Practical oscillators appear to have three main sources of noise contributing to frequency fluctuations [Cutler, 1964; Hafner, 1964; Edson, 1965] :

(*a*) Thermal and shot noise within the oscillator itself which actually perturb the oscillation.

(2) Additive noise associated with accessory circuits which does not perturb the oscillation, but merely adds to the signal.

(3) Fluctuations of the oscillator frequency due to either the crystal unit or circuit parameter changes.

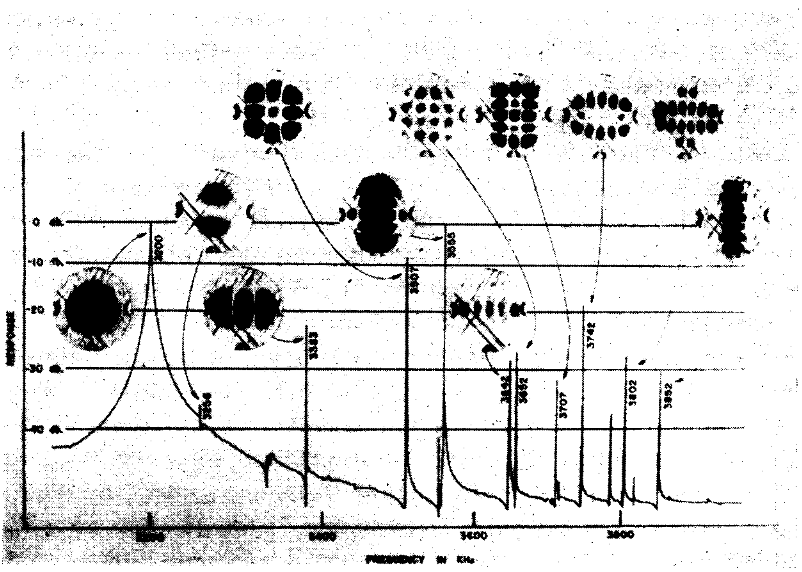

Fig. 1. — Responses and distribution of strain in contoured 3.2 MHz crystal vibrator.

1.3. — Scientific aspects of universal and/or atomic time and frequency transmissions

The relative trend and uncertainties of Universal Time (UT) with respect to Atomic Time (AT) bear directly upon studies of variations in the rate of rotation of the earth, indirectly upon the question of the relative uniformity of the astronomical ephemeris time scale (ET), and upon their technological usage in engineering and scientific laboratories.

The last three years have seen increased and improved surveillance and study of characteristics of various time and frequency signal systems for broadcast purposes. Recently it has been demonstrated experimentally on WWVB broadcasts that a system employing non-offset carrier frequencies and seconds intervals, but utilizing occasional adjustments toward UT of the phase of the emitted seconds ticks (by 200 ms every two or three months), satisfies the day-to-day requirements for ship navigation.

The general long-term parabolic trend of UT with respect to ET noted by Brouwer [1952] adequately rectifies the trends over some short periods, but not so well for an intermediate period over the last 145 years. This trend does not remove certain large or small excursions, some of which may have periodic components, and some certainly exhibit a random fluctuating behavior marked on occasion by erratic changes.

One of the most significant technological advances in time signal dissemination via radio emission has been in the use of phase control techniques. This has resulted in a greater frequency stability as well. All NBS radio transmissions now employ this method. Thus the epochs of time ticks from WWV, WWVH, and WWVB are directly related to the US standard scale of time.

National and international synchronization of transmissions has been improved carrying highly stable clocks between stations (see section 1).

Two experiments have been conducted which may herald the birth of a new era in international time synchronization techniques. These have utilized satellites Telstar and Relay II as relay devices for high frequency time signals. These supplement earlier studies of the international comparison of standards via radio emission. Several studies have been made confirming the stable propagation characteristics of VLF and LF emissions for time and frequency signals. A continuing effort is being made to employ two carriers in the dissemination of time signals at LF and very promising results are being obtained in a combined NBS-NASA study.

1.4. — Standards and measurements at 30 kHz to 1 GHz.

A supersensitive detector was developed for a complex-insertion ratio measurement system having accuracies of about 0.005 dB/10 dB at 30 MHz; signals of 36×10^{-12} volts were detected as against a miniumm theoretical of 30×10^{-12} volts rms at a noise figure of 2 dB [Allred and Lawton, 1964]. A modified twin-T-bridge was developed capable, for the first time, of measuring resistances of 100 to 10,000 ohms at 2 MHz in terms of capacitance increments with accuracies of ± 0.05 % and at reduced accuracies to 15 MHz [Huntley, 1965]. A set of Q-factor standards has been made available for frequencies to 45 MHz based on accumulated data and experience over 5 years; accuracies of ± 2 % were obtained for Q's of 100 to 240 at 15 MHz and ± 7 to 9 % for Q's to 600 at higher frequencies [Jones, 1964]. A unique adjustable characteristic-impedance coaxial line was developed for more efficient use of the time-domain reflectometry techniques for impedance measurements [Cruz and Brooke, 1965]. The decrement method was successfully used to measure Q's greater than 100,000 of cryogenic circuits at frequencies to 300 MHz [Hartwig, 1964].

A novel T-junction has been developed to enable calibrations and inter-comparisons of voltmeters of any practicable input impedances (with VSWR's ranging from 1 to 200) at frequencies to 1 GHz and higher from microvolts to 100 V and higher with superior accuracy; effects of standing waves and higher modes are essentially eliminated; a fraction of the power is required for calibration purposes as compared with determinated systems which is particularly advantageous at relatively high voltages [Selby, 1965]. To overcome *d-c* polarization effects in high-voltage-insulation tests, one-mircosecond pulses were employed with peaks to 30 kV, and one-microampere currents were measured to 5 % by charge-storing techniques [Watson and Sharbaugh, 1964].

A miniaturized dipole-antenna-receiver combination was developed to measure 0.1 to 1000 volts per meter, 150 kHz to 30 MHz, complex-near-zone fields with an accuracy of ± 2 dB; the receiver, a calibrating oscillator, battery supply, and attenuator are located inside the 13-inch long by 1-3/8 inch diameter cylindrical dipole; a semiconducting plastic transmission line feeds the information from the antenna to a remote readout unit [Greene, 1965]. A prototype 3-MHz model of precision thermal noise-power comparators for a range equivalent to 75 to 30,000° K at accuracies of 0.2 to 1 % has been described; it measures the noise-spectral density in a 7.5 kHz band and eliminates high speed switching by employing a coaxial magic T, a CW generator, two separate amplifier and frequency channels feeding an analog multiplier, and a product averaging RC network [Arthur, Allred, and Cannon, 1964].

1.5. — Standards and measurements at 1 to 300 GHz

Developments are reported in the following fields : power, noise, reflection coefficient, phase shift, attenuation, and field strength.

With regard to bolometric power measurements, the following developments were reported : evaluation of substitution error in dual-element mounts [Engen, 1964*b*], replacement of dual-elements by a center-tapped thermistor bead [Aslan, 1965], tuned reflectometer types of power meters [Engen, 1964*a*], swept-frequency measurements of mount efficiencies [Pramann, 1965], efficiency measurements at 2 and 5.4 millimeters Szente, Miller, and Mallory, 1963; Miller, Mallory, and Szente, 1963], accurate calibrations of coaxial mounts with reference to standard mounts in rectangular waveguide [Engen; 1965].

Power in multimode waveguides was measured [Schiffman, Young, and Larrick, 1965].

Pyroelectric effect detectors [Steier and Yamashita, 1963], a ferro-electric bolometer [Cohn and Rodgers, 1964], and microwave radiometers [Williams and Chang, 1963; and Fujimoto, 1964] were developed for use at millimeter and submillimeter wavelengths.

Improvements were reported in waveguide mounts for gas-discharge types of standards noise sources [Miller, Daywitt, and Campbell, 1964], and in their calibration techniques [Wells, Daywitt, and Miller, 1964]. Mismatch errors in noise performance measurements were analyzed [Brady, 1964]. Noise sources cooled by liquid helium were calibrated [Stelzried, 1965].

With respect to coaxial line standards, the use of air-filled lines was discussed [Sanderson, 1964; Weinschel, 1964], and a line of variable characteristic impedance was developed to calibrate time domain reflectometers [Cruz and Brooke, 1965*a*, *b*].

Techniques were developed in which a sliding load is mechanically coupled to a slotted line's probe [Weinschel, Sorger, Raff, and Ebert, 1964; Beatty, 1965*a*; and Sanderson, 1965*a*].

The NBS standard phase shifter and measurement system in WR-90 (IEC-R 100) waveguide was described [Ellerbruch, 1965]. A differential type of standard phase shifter was devised [Beatty, 1964*a*] and analyzed [Ellerbruch, 1964].

With regard to standard attenuators : true in-line coupler fixed standards were devised [Larson, 1964], additional sources of error in rotary vane attenuators were investigated [Larson, 1963, 1965*b*], and a table of attenuation versus vane angle was published [Larson, 1965*a*].

Analysis of insertion loss concepts [Beatty, 1963, 1964*b*] was applied [Beatty, 1964*c*] to attenuation measurements. The modulated subcarrier method was analyzed [Little, 1964]. Methods were devised [Stelzried and Petty, 1964; Beatty, 1965*b*; and Smith and Sokolowski, 1965] to measure small losses.

Attenuations of groove guides [Tischer and Someroski, 1964; Ruddy, 1965], and beam waveguides [Beyer and Scheibe, 1963; Valenzuela, 1963; and Simonich and Ishii, 1965] were measured. Prisms were used as standard attenuators [Taub and Hindin, 1963; Fellers and Taylor, 1964] at millimeter and submillimeter wavelengths.

Accurate measurements were made at 4.08 GHz of the gain of standard horns [Chu and Semplak, 1965]. The Fresnel gain concept was examined [Soejima, 1963]. At 8.6 Gc/s, the effect of lossy earth on antenna gain was determined [Coe and Curtis, 1964; Curtis, 1964]. Anechoic chambers were evaluated [Buckley, 1963]. Antenna gain was determined from measurements of scattering cross-section [Garbacz, 1964]. Modulated scatterers were used to measure field strength [Harrington, 1963; Iizuka, 1963; Vural and Cheng, 1964; and King, 1965]. Scattering cross-sections of metal spheres were measured [Blore, 1963].

1.6. — Precision coaxial connectors

Precision coaxial measurements suffered from mismatch errors and lack of repeatability of connectors. Several designs of precision coaxial connectors are now available. They were standardized by the IEEE Subcommittee on Precision Coaxial Connectors as related by Fossum [1964]. These connectors were tested in several laboratories for the committee including Alford Mfg. Co., Amphenol, General Radio Co., National Bureau of Standards, Rohde and Schwarz, and Weinschel Engineering.

By definition, a GPC or General Precision Connector includes a dielectric support. An LPC or Laboratory Precision Connector uses air dielectric. An LPC is employed for the most accurate measurements with air sections per Sanderson [1964].

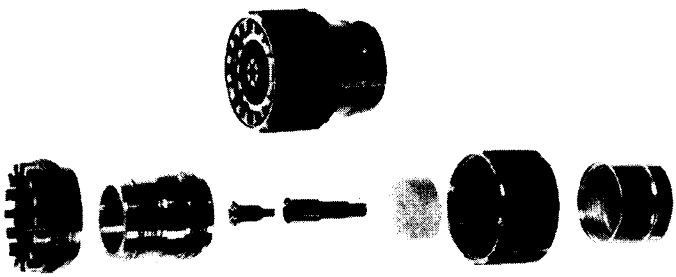

Fig. 2. — Assembly and exploded view of 14 mm General Precision Connector, General Radio # 900-BT.

Because of the low VSWR of precision coaxial connectors, impedance measurement methods had to be improved. Three methods are used : the tuned reflectometer, the slotted line and time domain reflectometry.

All three methods use auxiliary precision airline sections as reference standards. The reflectometer uses both a sliding load and a sliding short within a precision airline section [Beatty, Engen and Anson, 1960; Beatty and Anson, 1962; Little and Wakefield, 1965]. A slotted line substitution technique [Sanderson, 1961; Sanderson, 1962; Zorzy, 1963*a*], uses a half wave length section while Sanderson [1964] prefers a quarter wave length. Weinschel *et al.*,[1964] use a coupled sliding load. The time domain reflectometer [Cruz and Brooke, 1965*b*] is calibrated by airline sections. A useful impedance standard is a coaxial transmission line with perfect dimensions. The lower frequency limit due to skin effect is computed by Weinschel [1964].

Design considerations are received by Sladek [1965]. Zorzy [1963*b*] describes a slotted line with 14 mm GPC covering the frequency range of 300 MHz to 9 GHz. Sanderson [1965*b*] describes a slotted line recorder system.

URSI is interested in the standardization of coaxial precision connectors and a preferred impedance per Recommendation 4 [URSI, 1963] of their International Commission I. US Commission 1 URSI supported [URSI, 1964] the IEEE Standard and suggested [URSI, 1965] the development of a 3.5 mm coaxial precision connectors and supporting instrumentation for use up to 40 GHz.

1.7. — Swept-frequency techniques

Greater quantity, precision, bandwidth, and stringency of parameter control have forced the development of accurate swept-frequency techniques with parameter display on oscilloscope or recorder in order to handle the increased data. This survey concentrates on progress in the field of swept measurements from 30 MHz to the upper limit of microwave applications. The primary quantities measured are amplitude and phase. In terms of these, other parameters may be displayed — for example, loss, gain, power, phase shift, reflection coefficient, VSWR, impedance, etc. Two types of detection are used in swept-frequency instruments : video detection, and mixer detection. Video detectors are capable of providing swept amplitude information, but not phase information. Improved accuracy in video-detection instruments has followed from advances in leveled swept oscillators, connectors, pads, detectors, etc. Higher directivity couplers yield more accurate reflection-coefficient measurements. Progress has been made in extending the dynamic range of video detectors up to 60 dB by compensated output circuitry.

Mixer detection in swept-frequency instruments utilizes a non-linear device into which two rf signals at different frequencies are introduced, the output signal being at the difference frequency. The leading type of swept mixer system is now the homodyne, which uses one rf signal source from which the two rf signals are derived. The mixer output signals are processed to produce *d-c* analog voltages proportional to (1) rf phase independent of amplitude, (2) rf amplitude independent of phase, and (3) quadrature components of the rf test signal. The latter yields either the transmission or reflection coefficient in polar coordinates, or impedance on a Smith Chart. Homodyne instruments now provide accurate single-sweep measurements of phase, amplitude, and impedance in full waveguide bands and in coaxial bands up to 5 : 1. Other recent improvements include linear 360° phase readout, higher accuracy, faster sweep rates, and simplified operation. In addition to specialized instruments for phase and impedance, multifunction instruments permit selection of phase, amplitude, or impedance displays by means of a function switch.

1.8. — Measurements of electromagnetic properties of materials

Sources, other than journals, for dielectric and magnetic activities include the index of magnetism, available from the American Institute of Physics, and the annual Magnetic Materials Digest. The NAS-NRC Committee [1965] issues an annual digest of the literature on dielectrics, and also an Annual Report, Conference on Electrical Insulation. A different Electrical Insulation Conference Proceedings, mostly on insulation, is issued by the IEEE.

Magnetic Measurements. — A knowledge of what quantities are important greatly influences magnetic studies and applications. The Morgenthaler-Schlomann parallel pumping method has become well understood for measuring spin wave line width and for elastic-spin wave coupling [Eshbach, 1963]. Excitation methods and dispersion relations for various spin, elastic, and magnetostatic waves are important for microwave delay lines [Kaufman and Soohoo, 1965]. Spin wave coupling to the uniform precession, which arises mainly from rough surfaces and from polycrystallinity, is important in ferrimagnetic devices. Spin wave coupling knowledge was advanced theoretically by Motizuki, Sparks, and Seiden [1965] and by Sparks' new book. A new method of measuring this coupling was presented [Risley and Bussey, 1964].

Low frequency permeability measurements were reviewed [Harrington and Rasmussen, 1965]. Line width, permittivity and magnetization measurement methods for ferrite polycrystals are specified [ASTM, 1963].

Small ferrimagnetic (and ferroelectric) material resonators have unloaded Q's and external Q's which enter into line width or loss measurements and into filter uses [Matthei, 1963].

Dielectric Measurements. — Insulation and dielectric measurements are covered in a book of specifications — ASTM Standards on Electrical Insulating Materials [ASTM, 1963]. For microwave dielectric measurements, see the chapter by Altschuler [1963].

Measurements performed by three national standards laboratories were intercompared [Bussey *et al.*, 1964]. High temperature measurements were made on many dielectrics [Westphal, 1963].

Ellipsometry techniques, applicable in millimeter waves, were covered by a conference [Passaglia *et al.*, 1964]. Conductivity measurements on semiconductors were often obtained by microwave dielectric measurements, and Houlding [1965] surveyed recent measurements of the Q of varactors.

Low loss tangents were measured by a convenient immersion technique for polyethylene [Hazen, 1965]. Two fluid dielectric immersion in a guarded ring capacitor observed by a ratio transformer gave highly accurate dielectric measurements [Harris and Scott, 1963]. Errors due to conductance of a foreign surface layer on a dielectric were analysed by L. Frenkel [1964].

Optical effects in materials, especially those related to devices, were measured. A new effect was predicted [Brown *et al.*, 1964]. Modulation was reviewed by Anderson [1965].

A variational theory of the impedance of waveguide junctions was given [Kerns, 1963]. The junction may contain anisotropic materials.

1.9. — Laser standards and measurements

The phototube, calibrated against a standard source of radiation, was the first method used for measuring laser power and energy, the latter by a time integration of the photo-current [Maiman *et al.*, 1960]. To limit the radiation incident on the phototube, a variety of calibrated attenuators have been used : neutral density filters [Glick, 1962, 1963]; an integrating sphere [Schiel, 1963]; a coarse diffraction grating [Gerharz, 1964, 1965]; and a diffuse reflector whose distance from laser to reflector or reflector to photocell may be controlled [Leite and Porto, 1963]. A variety of methods for energy measurements have appeared : a carbon cone [Li and Sims, 1962; Calviello, 1963] and a blackened metal cone [Koozekanani *et al.*, 1962] simulating black body absorbers whose temperature changes are measured, respectively, by thermistors and bolometers; a liquid calorimeter [Damon and Flynn, 1963]; and a bolometer consisting of a bundle of 1,000 feet of fine enameled wire [Baker, 1962]. The deflection of a ballistic torsion pendulum due to the linear momentum of radiation has been used to measure the high energy of a pulsed laser beam [Stimler *et al.*, 1964]. No accuracy is cited in the above-mentioned papers except for the estimate of 10 percent by Li and Sims [1962]. However, Jennings [1966] has recently designed a liquid calorimeter whose accuracy and precision are given as approximately one percent.

All work on frequency stabilization has thus far been done with the He-Ne gas laser operating in a single mode. Although good short time frequency stability (8×10^{-14} over a few tens of milliseconds) was achieved in free running oscillators [Jaseja *et al.*, 1963], an automatic feedback control system must be used to obtain long term stability and frequency resettability. Shimoda and Javan [1964] obtained about 1 part in 10^9 by heterodyning two 1.15 μ lasers using a control system based on modulating a resonator mirror position piezoelectrically. Bennett, Jr., *et al* [1964] obtained about 1 part in 10^{10} over a period of 8 hours on the 3.39 μ transition by modulating the dispersion of the medium by varying the plasma discharge and hence the inversion density. A shift in the oscillation frequency due to this modulation can be overcome by modulating instead one of the Ne levels by optical pumping [Boyne *et al*, 1965].

Because gas lasers are finding wide application as light sources for interferometric length measurements [Morokuma, 1963; McNish, 1964; Mielenz, 1964], a knowledge of the laser wavelength in terms of the fundamental standard of length is necessary. Comparing interferometrically the wavelength of the $3s_2$-$2p_4$ Ne line of the He-Ne laser with standard lamps, Mielenz *et al* [1964, 1965] obtained the following results :

$$\lambda_{vac} = 6329.9145 \pm 0.0002 \text{ Å (with 91 \% Ne}^{20} \text{ and 9 \% Ne}^{22})$$

$$\lambda_{vac} = 6329.9147 \pm 0.0003 \text{ Å (with Ne}^{20})$$

Byer *et al* [1965] have studied under high resolution a pulsed Hg^+ laser which oscillates simultaneously in many modes. However, the clear definition of the Doppler profile (about 1/3 that in the He-Ne laser) defines the center wavelength to high accuracy without requiring stabilization of cavity length. It was found that

$$\lambda_{vac} = 6151.1650 \pm 5 \times 10^{-4} \text{ Å (Hg}^{202}).$$

The laser is clearly useful as a secondary standard of length. As work in this area matures, it is possible that the laser itself may be used to establish an independent standard of length.

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USSR

National Committee Report

by M. E. ZHABOTINSKI and L. V. LEOVKIN

Described herein are the results of certain investigations pertaining to frequency standards, quartz oscillators, power measurements, etc., carried out in the USSR in 1963-1965.

1. — ATOMIC AND MOLECULAR FREQUENCY STANDARDS

The USSR's Time Service employs ammonia beam masers with isotopic ammonia, in which the recuperation of ammonia is used. The reproducibility of frequency in the course of two years was within $(1 + 2).10^{-11}$, the frequency value being 22 789 421 701 $\pm$ 1 cycles per second.