Nº 91. — Microwave spectroscopic frequency and time standards

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I. — The present frequency and time standard

The present primary standard of time is the mean solar day. The work of de Sitter, Jeffreys, H. Spencer Jones (1) and others has shown that the day is slowly growing longer by a few milliseconds per century due to tidal friction and, in addition, undergoes fluctuations of about one part in 25 million for unknown reasons. Recent work also indicates yearly periodic variations of about a part in 50 million which Munk and Miller (2) ascribe to seasonal fluctuations in the earth's atmospheric circulation.

The accessibility and dissemination of these astronomical time and frequency standards on a world-wide basis has depended on the use of standard frequency broadcasts such as those of WWV. Doppler and other effects, occurring during transmission via the ionosphere, have imposed another limitation on the use of these standards (3). Received frequencies may differ by one part in 4 million from those transmitted or even one in a million during an ionospheric storm.

II. — Microwave spectrum lines

The above limitations on astronomical standards as well as others, make it desirable to look for new, invariant and reproducible standards of time and frequency. Spectrum lines of atoms or molecules in field-free regions and having very high natural Q would serve as ideal standards giving a more basic unit than the arbitrary one provided by the rotation of the earth. The Q of absorption lines is governed by natural line width, induced emission and absorption caused by thermal radiation, Doppler broadening, collisions between molecules and with the walls of the absorption cell and saturation caused by disturbance of thermal equilibrium when too much power is incident on the cell. These factors, except for Doppler effect, can all be considered in terms of the quantum-mechanical uncertainty principle. Any factor determining the mean life-time of a state Δt will cause a line width given by $\Delta f = 1/2\pi . \Delta t$, where Δf is half the line width at half intensity. In practice for microwave lines, natural line width is insignificant, while Doppler, collision and saturation broadening play dominent roles. In the case of NH_3, for the line at 23 870 Mc/s, Doppler broadening at room temperatures will give a Q of about 300 000 while collisions and saturation usually set a limit of 50 000 to 100 000. In atomic beam techniques, collision, Doppler and saturation broadening are all avoided giving a Q for cesium at about 9200 Mc/s of 10 to 30 million, depending on the method of excitation (4). Thallium would have Q's up to 90 million. Probably the highest Q which could be reached using absorption techniques with a gas would be about 800 000 for oxygen, O_2, cooled to 90° K. This would be the Doppler Q for O_2, which could probably be reached for oxygen since it does not saturate easily as compared to ammonia.

Another possibility for a standard would be nuclear electric quadrupole lines directly excited in samples of solids (5). These recently discovered lines would bridge the frequency gap between quartz oscillators and microwave lines using gases.

III. — MAXIMUM ACCURACY OF ATOMIC CLOCKS

Many practical factors limit the accuracy of atomic clocks and spectrographs. However, a basic limit, difficult to reach in practice, is set by the thermal and shot noise present in the equipment (6). A noise-limited resolving power, R. P., can be defined which gives the minimum frequency difference which can be resolved by a clock or spectrograph when limited only by noise. For absorption techniques this is :

$$(\mathrm{R.P.})_0 = 2\,Q \left[\frac{\alpha_0 \cdot \alpha_c}{\alpha_{g\,\min}\,(\alpha_0 + \alpha_c)} \right]^{\frac{1}{2}}$$

and :

$$(\mathrm{R.P.})_{\max} = \sqrt{3}\,Q \left[\frac{\alpha_f \cdot \alpha_c}{\alpha_{g\,\min}\,(\alpha_f + \alpha_c)} \right]$$

where $\alpha_f = \frac{3}{4}\,\alpha_0$. Here $(\mathrm{R.P.})_0$ and $(\mathrm{R.P.})_{\max}$ are the resolving powers at resonance and maximum slope of the absorption line, respectively. The above formulas hold for both linear and square-law detectors. The absorption coefficients of the gas and empty waveguide are α_0 and α_c, respectively, and $\alpha_{g\,\mathrm{min}}$ is the minimum detectable absorption coefficient for the system. For gases like ammonia, with the assumption of other nominal parameters, the above formulas give figures shown in the table below :

Resolving Powers	Linear Detector	Square-Law Detector
At resonance..........	1.2×10^9	4.5×10^7
At max. slope.........	5.0×10^{12}	7.4×10^9

These formulas can be combined with those for power saturation (7) and collision broadening (8) to show that, in the cases shown at the top right and lower left of the above table, the R.P. is independent of Q since the effect of a broad line, caused by high pressure, can be offset by using higher input powers without saturating. This applies particularly to oxygen which has magnetic dipole spectrum lines at about 60 000 Mc/s. The dipole moment is so small that saturation and collision broadening are both greatly reduced as compared to ammonia, while the intensity of the spectrum is only about ten times weaker than ammonia. This can be largely offset by cooling oxygen to 90° K, another property making it rather unique as a standard. The Zeeman effect due to the earth's magnetic field would have to be avoided when using oxygen.

IV. — THE N.B.S. DEVELOPMENT PROGRAM

The National Bureau of Standards has three atomic clocks under development with a fourth type planned. The first one to be operated is the ammonia-regulated quartz-crystal clock shown in figure 1 (9). The method of operation is shown in figure 2 which also illustrates the principles of the cesium, atomic beam clock now under construction (9). The clock shown in figure 1 has run with a constancy of one part in 20 million for a period of four days and nights. The large potential accuracy and simplicity of this clock derives from its use of a quartz clock which is regulated and the fact that only one regulator or servo circuit is used. A greatly improved version is now under development using a much better quartz-oscillator and new multiplier tubes to supply higher

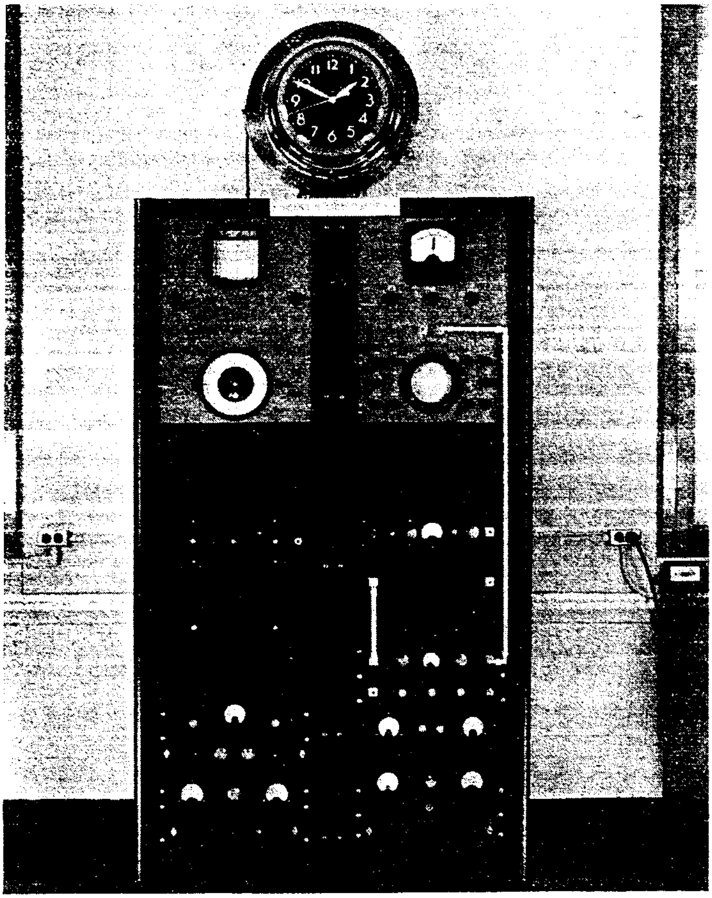


FIG. 1. — The first NBS atomic clock using a quartz-crystal clock regulated by ammonia, NH_3. The ammonia is in the wave-guide absorption cell wound in a spiral around the synchronous motor clock on top. The oscilloscope monitors the 3.3 line of NH_3.

rf power to the absorption cell. Figure 3 shows the third type of clock using an atomic oscillator designed as the exact analogue of the present Wheatstone-bridge quartz-clocks (10). There is a

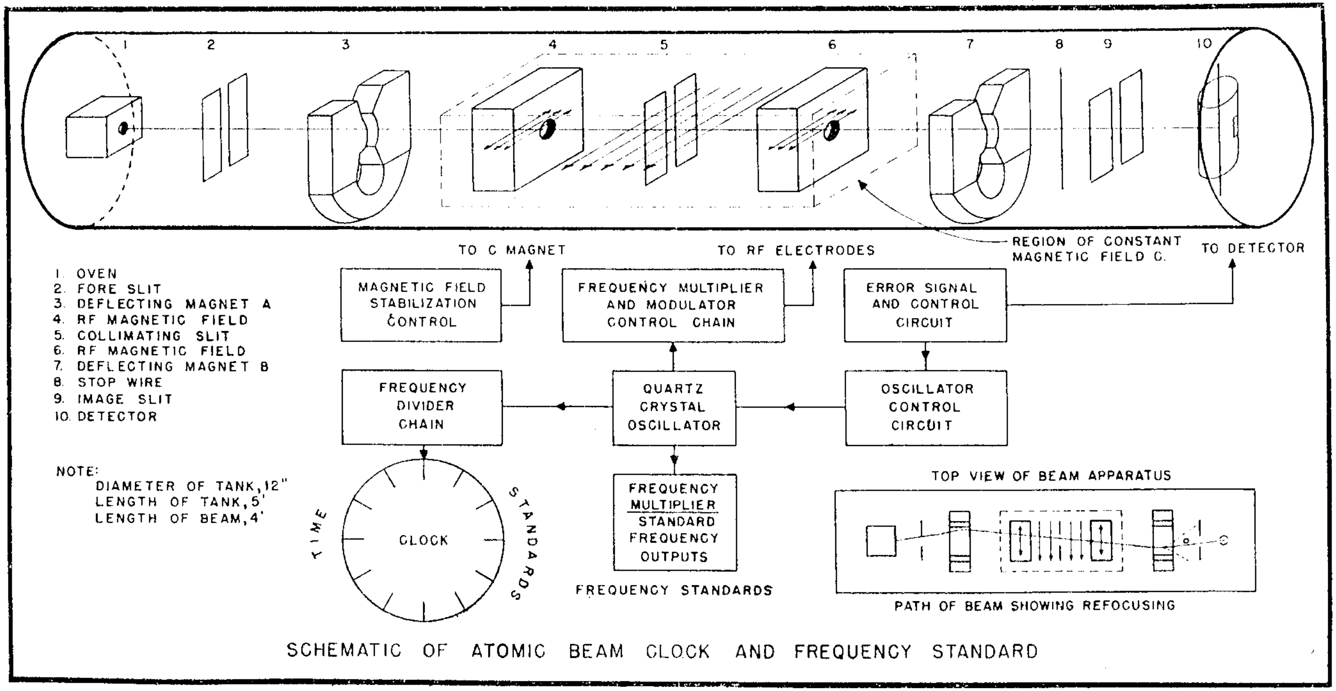


FIG. 2. — This schematic diagram shows the principle of the spectrum-line regulated quartz-crystal clock. The diagram is applicable to the ammonia clock shown in Figure 1 as well as to the cesium atomic beam clock.

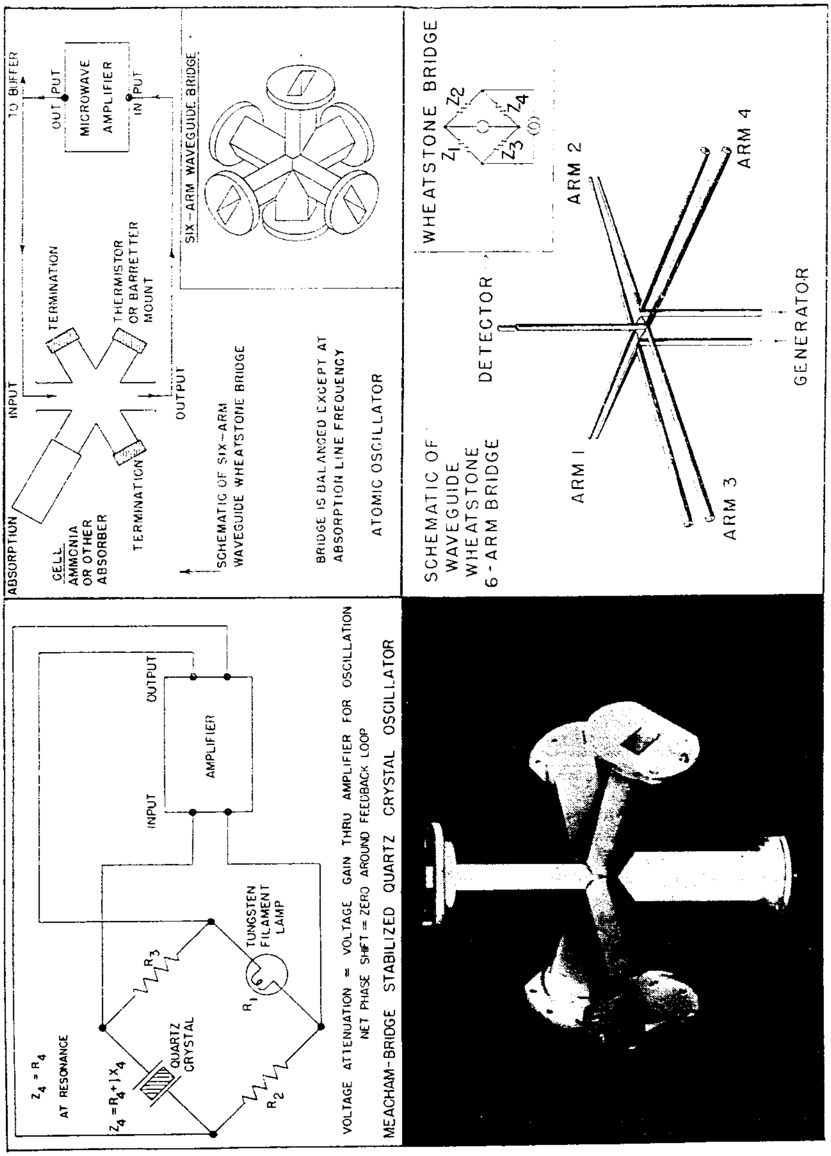


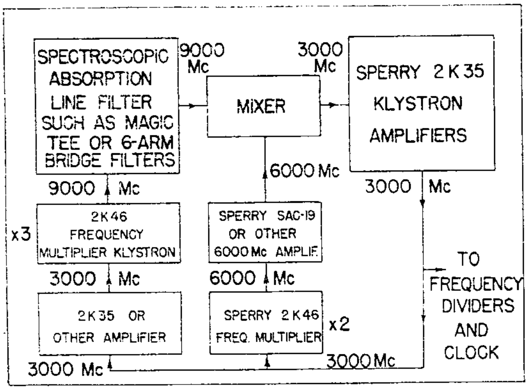
FIG. 3. — Upper left; Diagram of Wheatstone bridge-stabilized quartz oscillator used in quartz clocks. Upper right : Diagram of analogous waveguide Wheatstone bridge atomic oscillator using an absorption cell as frequency control. Lower left : Photo of six-arm waveguide junction having equivalent circuit of a Wheatstone bridge. Lower right : Schematic of analogous transmission line bridge illustrating the principle of the waveguide bridge.

good possibility that this type of oscillator and clock can be built at lower frequencies with solid samples by using the nuclear, electric quadrupole lines discussed above. Such a unit is being planned. A microwave frequency divider for use with the atomic oscillator is shown in figure 4 (10). This divider operated with an accuracy of at least one part in 10 (10) in an equipment which divided from 9000 to 3000 Mc/s. The schematic also indicates how a combined divider and atomic oscillator could be built which avoids the need for high frequency amplifier tubes. Such tubes as well as new multipliers for these applications are shown in figure 5. Figure 6 illustrates a precision microwave spectrograph, essentially completed, for precise measurement of lines as secondary standards. This is being carried out along with a program for compilation and publication of all known lines (11). In addition, further refinement of the spectrograph is being attempted in order to provide a method for measuring the rotation of the earth against a spectrum line, without waiting for completion of the necessary clocks to carry out such a program.

VI. — APPLICATIONS AND CONCLUSION

The ultimate goal of the N.B.S. program is to provide a spectroscopic standard capable of being used as a new, atomic standard of time and frequency to replace the mean solar day and thus to help change over all of the present arbitrary units to atomic ones (12). By multipiying the frequency of an atomic clock up into the millimetre bands there is a possibility that the length and time standards can both be based on one spectrum line by making an « atomic ruler », that is, an interferometer driven by the multiplied frequency from the clock. This would automatically give a new, precise value for the velocity of light. Measurements of the rotation of the earth would provide a new tool for geophysicists while a measurement of the mean sidereal year seems capable of testing whether Newtonian and atomic time are the same to an accuracy of at least one part in 10 (9). This would yield important results for relativity theory and cosmology.

It is a pleasure to thank Mr. B. F. Husten for work on the ammonia clock, to Professors C. H. Townes and P. Kusch for numerous discussions and help on absorption spectroscopy and



PROPOSED COMBINATION ATOMIC OSCILLATOR AND FREQUENCY DIVIDER, USING AMPLIFIERS AT DIVIDED FREQUENCIES, APPLIED TO AN ATOMIC CLOCK

FIG. 4. — Schematic illustrating the principle of the regenerative-modulator microwave frequency divider. The diagram shows, in addition, a combined frequency divider and atomic oscillator of the type shown in Figure 3, which requires amplifiers only at the divided frequency.

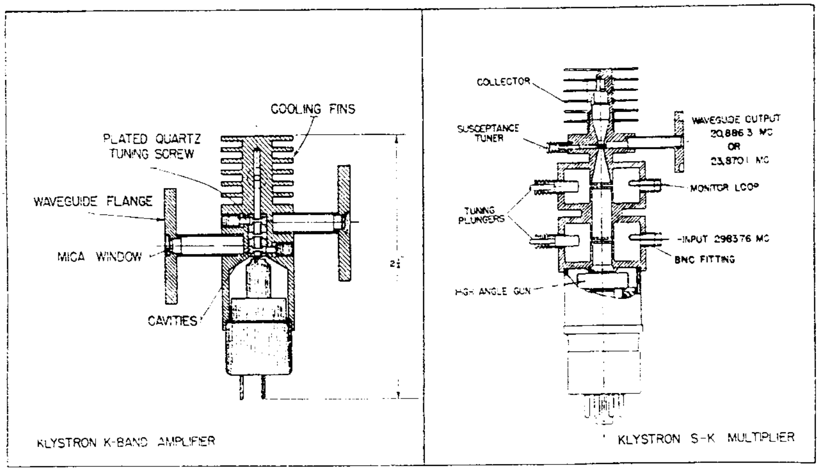
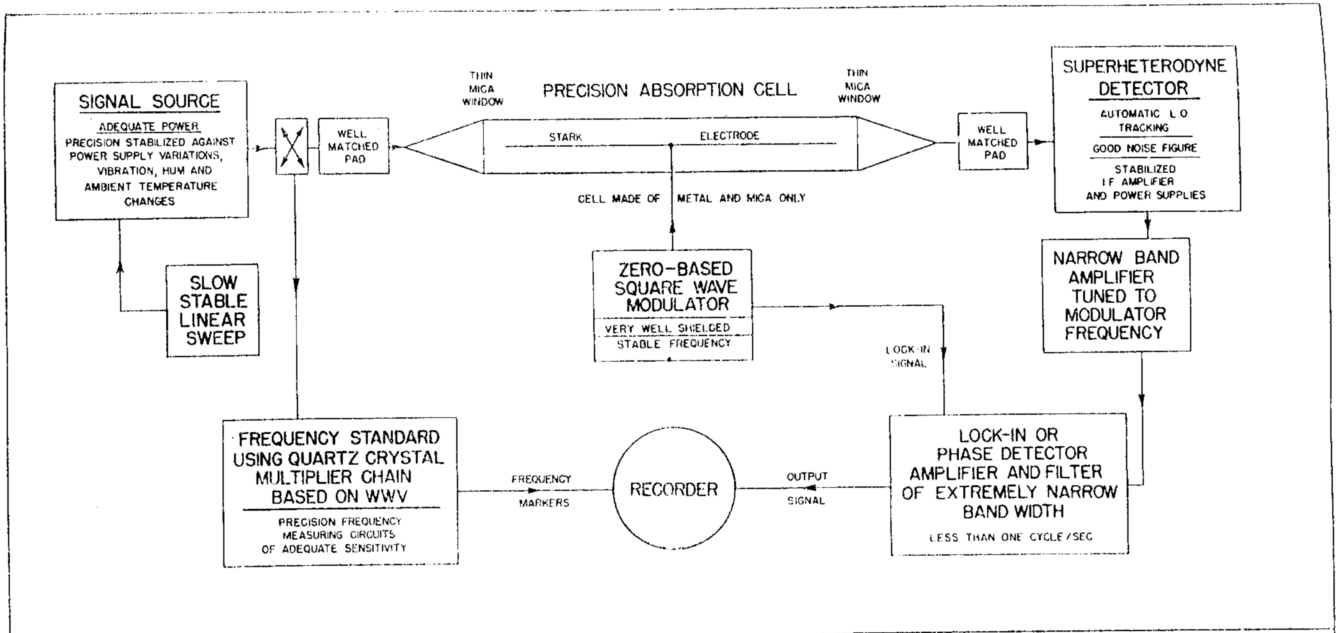


FIG. 5 — Left : Three-cavity klystron amplifier under development at 23 870 Mc/s for application to the atomic oscillator using NH_3. Right : Klystron frequency multiplier tubes for application to regenerative-modulator frequency dividers and also for providing higher power for the ammonia clock shown in Figure 1. These tubes could also be used to make a combined atomic oscillator and frequency divider of the type shown in Figure 4.



THE ABSORPTION CELL SHOULD HAVE PRECISION TAPERS, BE OF LARGE CROSS-SECTION TO HANDLE LARGE POWERS WITHOUT SATURATING AND BE OF AS NEARLY OPTIMUM LENGTH AS PRACTICABLE THE ENDS OF THE STARK ELECTRODE MAY ALSO BE TAPERED OR USE A TAPERED ELECTRODE SECTION OUTSIDE THE WINDOWS CAREFUL SHIELDING IS NECESSARY THROUGHOUT THE SIGNAL SOURCE MUST MAINTAIN CONSTANT OUTPUT AS IT IS SWEPT

FIG. 6. — Schematic of precision microwave spectrograph for measurements of the frequencies of spectrum lines to provide accurate secondary standards. This spectrograph is also under development for measuring the rotation of the earth by comparing the quartz-clock, multiplied frequency to a spectrum line. The quartz-clock is calibrated, in turn, against moon solar time.

atomic beam techniques, respectively, and to Dr. G. M. Clemence for discussion of astronomical time measurements.

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Etalons spectroscopiques hyperfréquences de fréquence et de temps

par H. Lyons

Résumé

On discute dans cette étude la précision des horloges atomiques et l'utilisation de l'absorption des gaz par l'ammoniac et l'oxygène, ainsi que l'emploi de faisceaux atomiques utilisant le cesium ou le thallium, et l'absorption des quadripoles nucléaires dans des solides.

On y expose des applications aux mesures de la rotation de la terre, des unités atomiques et des étalons de longueur et de temps, basées sur une raie du spectre.

N° 92. — A radio-frequency standard capacitor to provide minute capacitance increments

by John A. Connor

Summary

In conducting a laboratory study of the capacitor elements of *h-f* selective circuits, and of their frequency-drift compensation properties, a definite limitation has been found in the available techniques for measuring minute capacitance *increments*. The desirability of having a standard capacitor, capable of producing precise magnitudes of minute capacitance increments, was apparent. This paper is intended to present the basic analytical conclusions