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Frequency and Time Standards

BY

F. D. LEWIS

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Frequency and Time Standards*

F. D. LEWIS†, SENIOR MEMBER, IRE

The following is one of a planned series of papers written at the invitation of the IRE, in which men of recognized standing review recent developments in, and the present status of, various fields in which noteworthy progress has been made.—*The Editor*.

Summary—Improvements in astronomical time measurement techniques and in the definition of time have kept pace with developments in frequency standards. Quartz crystal frequency standards are described, including Essen rings, bars, GT-cut plates, and contoured AT-cut plates. Stable oscillator circuits for quartz-crystal frequency standards are described, including the Meacham bridge-stabilized circuit, the Gouriet-Clapp circuit, and the Lea quartz-resonator-servo circuit. A discussion of the present status of atomic and molecular frequency standards includes the ammonia absorption cell, ammonia oscillator (MASER), and cesium atomic-beam apparatus. Instrumentation for precision frequency measurement is outlined, and a current listing of standard-frequency broadcast stations is included.

Introduction

Measurements of frequency and time have advanced in accuracy as the instrumentation for these measurements has improved. With each improvement in accuracy of measurement, new problems of stability, precision, calibration, and interpretation have become apparent. A review of the recent advances in frequency and time measurement technique is of interest to the radio engineer as an indication of the progress which has been made and of the improvements to be expected in the near future.

Time Measurement

The basis of frequency measurement is, axiomatically, time measurement, and conversely, time measurement can be based on frequency measurement. Before the discovery of atomic or molecular frequency standards, there were not available any alternatives to the calibration of frequency standards by means of astronomical observations. In view of the present early stage in the development of the atomic and molecular frequency standards, it is not yet possible to state that these atomic standards have been used to measure the constancy of astronomical time. However, the groundwork has been laid and soon it will be possible to calibrate astronomical time measurements against spectral-line frequencies. Further discussions of the spectral-line frequency standards are given in another section of this paper.

Accurate time is determined by astronomical observations at a designated observatory in each country where suitable observatories exist. The U. S. Naval Observatory is the only observatory in the United States regularly carrying out such measurements, and is thus the source of all accurate time determinations in this country. Time signals giving time as determined by the Naval Observatory are broadcast by naval radio stations,[1] and in cooperation with the Bureau of Standards, by stations WWV and WWVH which are operated by the Bureau of Standards.

A number of observatories in other countries are cooperating with agencies of their respective governments to furnish time measurements for radio transmission, and many of these observatories provide time measurements of very high accuracy. International comparison of time is carried on principally by means of radio transmission. (See section below on Standard Frequency Broadcasts.)

The problems of time measurement, and even of the definition of "time," have been familiar to the astronomer since long before the days of Sir Isaac Newton.[2] It is nevertheless true that our modern scientific notions of time are derived from the fact that time is the independent variable of Newtonian mechanics. Minor corrections, to take account of relativity, have enabled the original Newtonian concept of time to survive, and to provide a firm basis for astronomical time reckoning. As the stability of time-keeping devices has improved, it has become apparent that astronomers need to agree on a standard unit of time to use for astronomical calculations, and also to provide a basis for checking any variations in such time standards as the rotation of the earth. Consequently, in 1950 an international conference on astronomy recommended that the term Ephemeris Time be used to denote uniform or Newtonian time, and this term (Ephemeris Time) was adopted by the International Astronomical Union in September, 1952, as defining uniform time related to the revolution of the earth about the sun.[1,3] At the present writing,[4] it is impending that the International Committee on Weights and Measures will adopt a definition of the second, as a unit of time, as "the fraction 1/31,556,925.975

* Original manuscript received by the IRE, June 24, 1955.
† General Radio Co., Cambridge 39, Mass.

[1] Circular No. 49, U. S. Naval Observatory, Washington, D. C.; March 8, 1954.
[2] Dirk Brouwer, "The accurate measurement of time," *Physics Today*, vol. 4, pp. 6–15; August, 1951.
[3] Time Service Notice No. 1, U. S. Naval Observatory, Washington, D. C.; May 28, 1953.
[4] E. C. Crittenden, "International weights and measures, 1954." *Science*, vol. 120, p. 1008; December 17, 1954.

of the tropical year 1900." The adoption of this standard unit will serve to provide a time which may be used for data of great precision, such as may be required in frequency standardization.

In the preceding paragraph, the term Ephemeris Time was defined as denoting time based on the orbit of the earth around the sun. It is of interest to discuss the kinds of time and their significance in terms of astronomical phenomena. Ephemeris Time is determined by measurement of the tropical year. The tropical year is the time taken by the earth to make an orbit around the sun from vernal equinox to vernal equinox. By means of clocks, one can divide this tropical year into smaller intervals for application to various problems.

The time which is commonly used as "standard" time on the earth is determined by measuring the rotation of the earth about its own axis, especially with respect to the sun. Because of the ellipticity of the earth's orbit around the sun and the inclination of the earth's equator to the orbital plane, the length of an apparent solar day varies with the position of the earth on the ecliptic. In order to make the keeping of time independent of the seasons, the apparent solar day has been replaced by the "mean solar day," the duration of which is the average value of the apparent solar day over a period of a year. Very precise time measurements require corrections for the variation in longitude (apparent zenith) of the observing station and other small corrections known to astronomers.[5] Time determined by measuring the rotation of the earth was designated by the International Astronomical Union, September, 1952, as Universal Time. By international agreement, Universal Time is also defined as Greenwich Mean Time.

In order to provide a time measurement obtaining in one operation simultaneous data on the rotation of the earth and the rotation of a pair of bodies in space with a substantially constant rotational speed, observations of the moon and stars simultaneously have been undertaken.[6] The data obtained from such observations provides information on both Ephemeris Time and Universal Time, and it is thus possible to obtain an accurate difference term which enables precise conversion of one to the other.

It is expected that the above-mentioned improvements in observation techniques and method of computation of time will enable absolute frequency based on time measurements to be determined to approximately $\pm 1 \times 10^{-9}$.

The frequency of WWV, and of all standard frequency broadcast stations, is presently computed with respect to Universal Time (G.M.T.) which is mean solar time, thus automatically limiting the absolute accuracy to approximately $\pm 2 \times 10^{-8}$. This accuracy could be improved somewhat if corrections for short term variations in the earth's rotation were included in the computations.

Astronomical Time Measuring Instruments

Time determination requires specialized apparatus for the required astronomical observations. When visual observation is employed, the instrument most frequently used is the meridian transit telescope, which is constructed and mounted in such a way that it can be directed only at points along the meridian. The observer then operates the mechanism for recording the times of transit of the selected stars. Early designs of recording mechanisms depended on the reaction time of the observer to some extent. Improved designs have reduced the variation in observation from this cause, but the ultimate accuracy of measurement can only be reached when the observation can be made independent of the observer. Such independence from observer error can be achieved by photographic means, as in the apparatus described below.

Photographic Zenith Tube

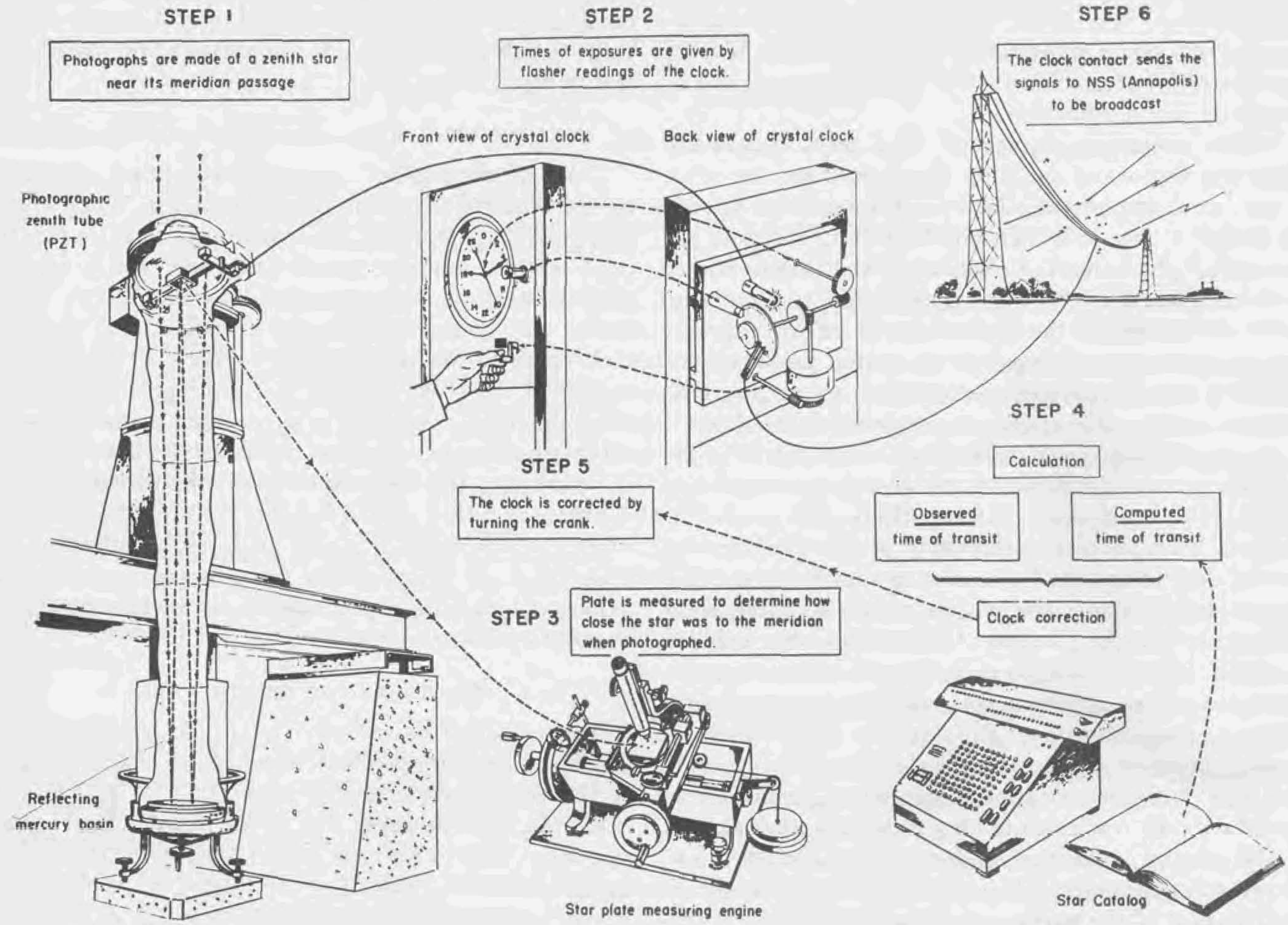
The principal device used by the U. S. Naval Observatory for the routine determination of star transits is the photographic zenith tube (PZT).[7] This device consists of a telescope of a special design for photographing stars near the zenith. A vertical tube is mounted above a mercury basin which, when used as a mirror, supplies automatically the vertical reference as a normal to its surface. The vertical or zenith view of this type of telescope minimizes the effects of atmospheric refraction and thus reduces observational errors. The upper end of the telescope tube supports the lens and the holder for the photographic plate used to record the positions of the stars. The plate holder is driven horizontally by an electric motor at a rate which synchronizes with the motion of the star images during two periods of exposure of the plate. Between the exposures, the carriage is rotated 180 degrees (images on opposite sides of the center of the photographic plate) thus providing simple and accurate geometrical determination of the meridian transit. The times at which the plate is at particular positions during the exposures are recorded on a chronograph driven by the crystal-controlled clocks of the Observatory. The positions of the stars are known, and it is thus possible to compute the correct time. An outline of the steps involved in the determination of time and transmission of time signals by the U. S. Naval Observatory is shown in Fig. 1 (next page). A photograph of a photographic zenith tube, PZT No. 3, at the U. S. Naval Observatory, is shown in Fig. 2 (page following).

Recent improvements in design of the plate carriage, motor drive, and chronographic pick-up of PZT have resulted in improved accuracy of time measurement.

[5] H. M. Smith, "The estimation of absolute frequency in 1950–51," *Proc. IEE*, vol. 99, pt. IV (Monographs), Monograph 39, pp. 273–278; December, 1952.

[6] W. Markowitz, "Photographic determination of the moon's position, and applications to the measurement of time, rotation of the earth, and geodesy," *Astron. Jour.*, vol. 59, pp. 69–73; March, 1954.

[7] W. Markowitz, paper on Photographic Zenith Tube now in preparation (U. S. Naval Observatory).



Official U. S. Navy photograph.

Fig. 1—Steps involved in the determination of time and transmission of time signals.

Dual-rate Moon Position Camera

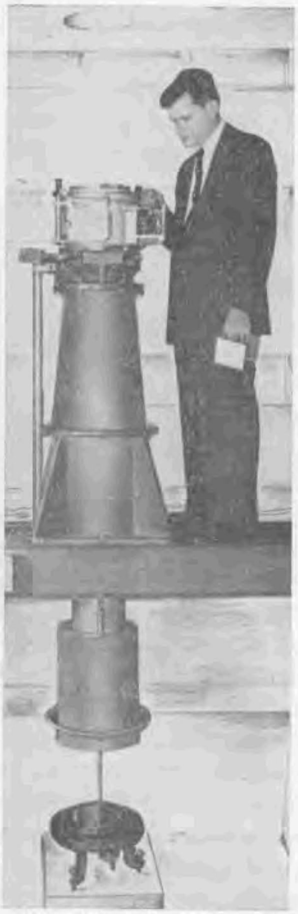
Recently developed apparatus for observation and measurement of the position of the moon is now being applied to the problem of the precise measurement of time. The equipment and technique for obtaining a photograph of the moon simultaneously with that of the necessary stars for the calculation of the moon's position have been developed by W. Markowitz at the U. S. Naval Observatory.[6] The apparatus, or camera, for use on a refracting telescope comprises a special plate holder with a synchronous motor driving a micrometer screw to move the photographic plate at the sidereal rate corresponding to the moon's declination. The clock drive normally used to move the telescope tube is not used during this observation, the moving plate-holder being used instead. The image of the moon falls on a dark filter (attenuator) with a transmission factor of 0.001. This filter is a glass disk, with plane-parallel sides, 1.8 mm thick. Tilting of this disk about an axis parallel to its plane surfaces causes a translation of the image of the moon. A second synchronous-motor-and-micrometer drive controls the speed of tilt of this disk to hold the moon image fixed relative to the stars. A further adjustment enables selection of the axis about which the disk tilts. A chronograph contact registers the instant at which the photographic plate and the filter disk are parallel, i.e., the instant at which there is no relative shift in position between moon image and star images on the photographic plate. This instant thus defines the epoch of observation for time-measurement purposes.

A photograph of the dual-rate moon position camera installed on the 12-inch refractor of the U. S. Naval Observatory is shown in Fig. 3 (opposite page).

With the development of a satisfactory moon-star camera, it has now become feasible to institute a program of observation to chart the long-period variations in the rotation of the earth, and to compare them directly with Ephemeris Time determined from the same observations. (A group of photographic observations of moon and star positions was obtained at Harvard College Observatory, in 1911–17, and reduced at Princeton, but using another method.[6]) An extended series of such observations by several separated observatories is expected to be able to provide a basis for the determination of absolute frequency to 1 part in 10^9.

Frequency Standards

As may be inferred from the preceding discussion, the measurement of time by astronomical observation eventually requires extremely stable clocks in order to



Official U. S. Navy photograph.

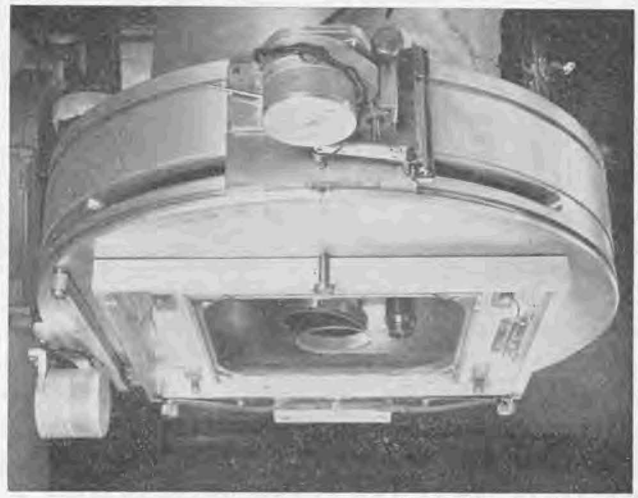
Fig. 2—Photographic zenith tube, PZT No. 3, Naval Observatory, Washington, D. C.

provide means for subdividing a tropical year into 31,556,925.975 parts, each alike in duration. This extreme requirement for clock stability will be partially alleviated by the moon observation program which will provide monthly time checks. Clocks of the highest stability are necessary for scientific purposes such as the measurement of the short-period variations in the earth's rotation and the standardization of frequency.

The first crystal-controlled clock was constructed by W. A. Marrison and J. W. Horton in 1927.[8] Since that date, many engineers and scientists have made important improvements in the various components of the crystal-controlled clock, resulting in the stability mentioned above, and in impressive reliability as a laboratory tool for daily use, a reliability infrequently surpassed by any other electronic devices. Since the crystal clock is essentially a frequency standard with a cycle-counting device attached,[9] we shall here consider the various component parts of the crystal-controlled clock as being frequency standards and associated items, for it is as frequency standards that the radio engineer most often meets these elements of the crystal clock.

[8] J. W. Horton and W. A. Marrison, "Precision determination of frequency," Proc. IRE, vol. 16, p. 137; February, 1928.

[9] W. A. Marrison, "The evolution of the quartz crystal clock," *Bell Sys. Tech. Jour.*, vol. 27, pp. 510–588; July, 1948. Also published as "Bell Telephone System Monograph B-1593," Bell Tel. Lab., New York City, and in *Horological Journal*, vol. 90, pp. 274 ff; May–October, 1948.



Courtesy *Sky and Telescope*

Fig. 3—Moon position camera, attached to the 12-inch refractor of the Naval Observatory.

Crystal-Controlled Frequency Standard Oscillators

In order to set forth the recent progress in frequency standard apparatus, it seems expedient to consider individually the elements making up such equipment. Most crystal-controlled frequency standards comprise (1) a control element, i.e., the quartz crystal unit, (2) a negative resistance element, i.e., the oscillator circuit using vacuum tubes or transistors to supply the power, (3) a thermostat or temperature-control device to keep the control element and other circuit elements at constant temperature, (4) suitable frequency dividers or other means for producing lower output frequencies, which may be used to operate (5) integrating devices, such as clock indicators, to keep a record of the number of cycles in a given period for comparison with astronomical time measurements. A suitable power supply (6) is, of course, required. Item (5) is sometimes eliminated in a secondary frequency standard if adequate reception is available from one or more of the standard frequency broadcasts now being transmitted by various agencies. Various other items of auxiliary equipment are frequently associated with crystal-controlled frequency standards for the purpose of calibration and standardization of the standards themselves, or for the use of the standards in frequency and time measurement.

Quartz Crystal Control Elements[10–12]

Two outstanding properties of crystalline quartz make it especially attractive as a control element for a piezo-electric oscillator, namely, the possibility of obtaining resonators of high Q value, and the exceedingly good stability of the quartz itself insofar as aging effects are concerned. Much of the frequency-standard work

[10] R. A. Heising, "Quartz Crystals for Electrical Circuits," D. Van Nostrand Co., New York, N.Y., 1945.

[11] P. Vigoureux and C. F. Booth, "Quartz Vibrators," His Majesty's Stationery Office, London, England, 1950.

[12] J. P. Buchanan, "Handbook of Piezoelectric Crystals for Radio Equipment Designers," Wright Air Dev. Center (USAF) Tech. Rep. 54-248, Wright-Patterson AF Base, Ohio; December, 1954.

of recent years has been directed to the improvement of Q and aging characteristics of crystals.[13–15] The variation of frequency with temperature, an important matter for a stable oscillator, is a function of the shape of the crystal element, its dimensions and its angle of cut from the mother crystal. The pertinent properties of various types of crystal resonators currently considered suitable for use as frequency standards are considered herewith.

Rings and Bars

Crystal resonators operating in extensional modes offer some attractive properties for use at low frequencies. The choice of a suitable shape generally will provide one or more nodes suitable for use as mounting points, and the proper dimensioning, combined with a proper angle of cut, will produce a low coefficient of frequency vs temperature usually over a relatively narrow, specified temperature range. Such resonators at frequencies of the order of 100 kc have been made in the form of bars or rings.

Essen Ring[15]

A ring-type resonator, developed by Essen of the British National Physical Laboratory, has shown great stability in frequency-standard use. This resonator operates in the extensional mode with six half-wave-length sectors alternately extending and contracting in a direction along its circumference. The exciting voltage is applied to electrodes concentric with the inner and outer surfaces of the ring. Since the motion of the quartz is mainly along the circumference, there is only a little contraction and expansion of the surface of the ring and hence only a small power loss caused by ultrasonic radiation. An evacuated, sealed container has been used to keep the aging rate low, and incidentally also eliminate any residual losses caused by radiation from the ring or its mounting. The British-Post-Office Essen rings are reported to have a Q of two million,[16] while the earlier pin-type mount produced a Q of one million.

The Essen ring requires a fairly sophisticated mounting in order to take full advantage of its inherent high Q value. The mounting problem is simplified to some extent by the existence of the six nodal planes, which are zones of minimum vibration at 60 degrees angular separation around the ring. The earliest mountings made by Essen at N.P.L. employed pointed pins set into grooves cut into three of these nodal planes. Although the pins provided rugged support points, the rings seemed to exhibit some small frequency instability which was thought to be ascribable to the pin mountings. Consequently, a string or thread-type mounting was devised at the British Post Office for the Essen-ring crystal elements used in frequency standards designed there. Fig. 4 is a photograph of the Post Office Essen Ring, and

Courtesy H. M. Postmaster General.

Fig. 4—Photograph of 100 kc Z-cut quartz ring mounted on thread suspension in crystal holder W6, with cover removed.

Fig. 5 shows a sketch of the string mounting. The string-type mounting appears to have overcome the random frequency shifting observed with the pin-type support, but still leaves unsolved a few of the problems with respect to shipment or transportation of the finished quartz ring. The large mass of the Essen-ring crystal element imposes a requirement for relatively great care in shipment, requiring the type of shipment and handling normally reserved for delicate scientific instruments.

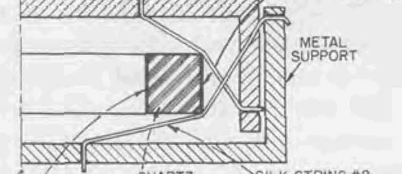


Fig. 5—Sketch of one of three string support points of Essen-ring crystal element.

Long term drift of the Essen-ring crystal is very small.[17,18] Values of drift rates of approximately 1×10^{-8} per month, or approximately 3×10^{-10} per day, have been observed for the Essen-ring oscillators at the U. S. Naval Observatory,[19] with the expectation that lower drift rates will be reached in the future. The lowest

[13] J. P. Griffin, "High-stability 100-kc crystal units for frequency standards," *Bell Lab. Rec.*, vol. 30, pp. 433–437; November, 1952.

[14] A. W. Warner, "High-frequency crystal units for primary frequency standards," Proc. IRE, vol. 40, pp. 1030–1033; September, 1952.

[15] L. Essen, "A new form of frequency and time standard," *Proc. Phys. Soc.* (London), vol. 50, p. 413; 1938.

[16] H. T. Mitchell and A. L. Dobbie, "100 Kc/s Oscillator of High Precision Incorporating an Essen Type Quartz Ring," paper presented at Congrès International de Chronometrie, Paris, France; October, 1954.

[17] H. M. Smith, "The determination of time and frequency," *Proc. IEE*, vol. 98, part II, pp. 143–153 (plus discussion); April, 1951.

[18] L. Essen, "Frequency standardization," *Proc. IEE*, vol. 98, part II, pp. 154–163 (plus discussion); April, 1951.

[19] Private communication.

drift rates of two such oscillators reported by the British Post Office are 0.25 and 0.4×10^{-10} per day over periods of several hundred days.[16] The British Post Office radio laboratory group considers that an Essen-ring oscillator unit is satisfactory for delivery to a user only if its drift rate is less than 5.0×10^{-10} per day averaged over 10 days. The excellent performance of the Essen ring with respect to long-term stability is ascribable, in part, to the fact that the frequency of oscillation of the ring is a function of the mean diameter of the ring, and that the loss, or acquisition, of a uniform layer of material over the entire surface would thus produce only a second-order change in the frequency. Careful processing of the ring and use of the evacuated mounting have further reduced the probability of changes in the crystal frequency.

An Essen ring ground for a frequency of 100 kc has an outside diameter of almost $2\frac{1}{2}$ inches (actually 61.26 mm in one case). This dimension is an indication of the difficulty of fabrication of such a crystal element, since it is necessary to obtain a quartz crystal free from defects with maximum dimensions large enough to allow cutting the ring from it. Because of this drastic requirement for large pieces of high-grade raw quartz-crystal, commercial Essen-ring frequency-standard units intended for moderate-quantity production have not been introduced.

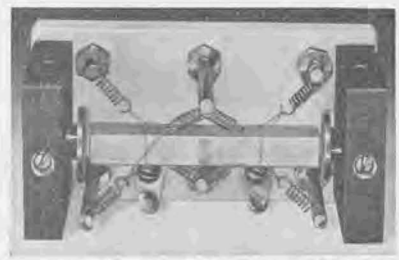
Bars

Quartz bars vibrating in the extensional or longitudinal mode are widely used in frequency-standard oscillators. The attractive features of such bars include the availability of one or more nodal planes for the attachment of mountings, a large ratio of mass to surface for the finished crystal, and only a moderate size requirement for the raw quartz blank. In addition, the processing required is similar to that required for the more commonly used plates, i.e., plane lapping.

Frequency-standard crystals operating in the extensional mode have been used for many years. The German Physikalishe Technische Reichsanstalt group (Giebe, *et al.*) designed, constructed and operated for many years a quartz-controlled frequency standard using a 60-kc Y-cut bar.

A commercial frequency standard using a 50-kc X-cut bar was produced by the General Radio Company, Cambridge, Massachusetts, in 1928.[20]

A new design of overtone-operated X-cut bar was developed by Clapp[21] for use at 100 kc in the present model of the General Radio Company frequency standard (since 1947). This quartz bar (Type 1190-A Quartz Bar), shown in Fig. 6, operates at the second overtone, having two half-wavelength extensional mode sections operating in push-pull, i.e., the portion of the bar from the center to one end extends as the portion from the center to the other end contracts. A nylon-monofilament string suspension is used to support the bar at the two nodal planes, the filaments being maintained in tension by coil springs. Adjustable baffles at the ends of the bar are used to reflect ultrasonic radiation and thus reduce damping and change in frequency caused by changes in air pressure, as the mounting is not evacuated or hermetically sealed. Plated electrodes are applied directly to the surface of the bar on its sides, and are interconnected for second-overtone excitation in the extensional mode. The Q of this bar is approximately 170,000 in the mounting described.



Courtesy General Radio Company.

Fig. 6—Quartz bar for operation at 100 kc in second overtone mode. Note the end baffles to reduce ultrasonic radiation losses, and the string suspension at the two nodes.

Frequency stability of the commercial model bridge-stabilized oscillator, with which this bar is supplied in its temperature-controlled oven, reaches a value of approximately 0.5×10^{-8} per day or better, after an aging period of approximately one year. Many of these oscillators demonstrate considerably better stability than this figure. The long-term drift rate of the frequency standard in use at the General Radio Company has been approximately 5×10^{-7} per year since 1945, an aging rate of 1.2×10^{-9} per day averaged over 10 years.

Extensional-mode bars suitable for stable oscillator use have been made by other crystal manufacturers. Bars of the +5-degree X-cut, fundamental-mode longitudinal-vibration type, which were wire mounted with plated electrodes, have been used in a quartz-crystal-controlled clock in Switzerland.[22] These bars, mounted in evacuated glass envelopes, were supplied by Salford Electrical Instruments (British General Electric Company). They gave stabilities of the order of 0.5×10^{-8} per day, or better, when used in a Gouriet-Clapp oscillator circuit with automatic level control.

GT-Cut Plates

The GT-cut plate, originated by Mason,[23] has been developed to a highly advanced state for use in frequency standardization work.[13] This type of quartz

[20] L. M. Hull and J. K. Clapp, "A convenient method for referring secondary frequency standards to a standard time interval," Proc. IRE, vol. 17, pp. 252–271; February, 1929.

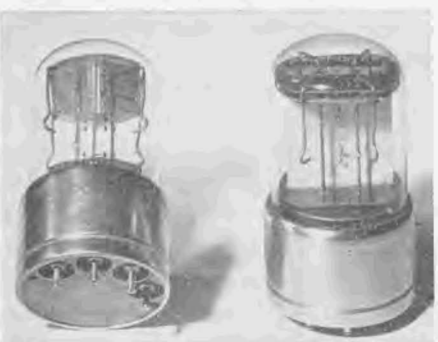
[21] J. K. Clapp, "On the equivalent circuit and performance of plated quartz bars," *Gen. Rad. Experimenter*, vol. XXII; March–April, 1948.

[22] P. Chalande, "The realization of a group of piezo-electric time-keepers," *La Suisse Horlogere* (International Edition in English), La Chaux-de-Fonds, Switzerland, pp. 41–44; October, 1952.

[23] W. P. Mason, "A new quartz crystal plate, designated the GT, which produces a very constant frequency over a wide temperature range," Proc. IRE, vol. 28, pp. 220–223; May, 1940.

plate can be made to have a temperature coefficient of frequency which is less than 2×10^{-7} per degree C., over a relatively wide temperature range. For the plates used as frequency standards, the temperature vs frequency curve is reasonably flat between 0 degrees and 100 degrees C., with optimum flatness in the range from approximately 20 degrees to 90 degrees C. Thus, the GT-cut plate can be made to serve as a stable element at temperatures approximating room temperature, and also at thermostatically controlled oven temperatures.

Early GT-cut plates were mounted on pressure-point contacts.[9,13,24] It is necessary to leave the edges of the GT-cut plate unsupported because they are vibrating with the greatest amplitude of any point on the crystal. Consequently, centrally located mounting points are desirable, the theoretical nodal point being at the center of the rectangular plate. Actually, because of couplings to other modes, the plates are not completely at rest at the central point. In addition, the desirability of keeping the attachment points small and flexible requires the use of several support points, which are now generally made in the form of thin wires attached to the surface of the crystal plate near the center, along the center line of the length of the plate.



Courtesy Bell Telephone Laboratories.

Fig. 7—100 kc GT-cut plates (D168670) in evacuated mountings as used in LORAN timer oscillators.

The use of GT-cut plates in frequency-standard oscillators was given impetus by the LORAN development during World War II which required stable oscillators for timing the pulses used in this radio-navigation system. Wire-mounted-silver-plated-electrode GT-cut plates were manufactured in evacuated glass envelopes for use in the LORAN timer oscillators. These crystals were a development of the Bell Telephone Laboratories, and represent an achievement of considerable magnitude in making a crystal unit largely independent of temperature, atmospheric changes, aging effects caused by exposure to the air, and a fair amount of rough handling in shipment. This crystal unit was designated by the number D-168670 (shown in Fig. 7, above).

Further refinement of this type of GT-cut plate has produced excellent results.[13] The improvements consist of reduction in the diameter of the support wires and their attachment points, improved methods of processing the soldered connections, and careful annealing to relieve strains. Final adjustment to frequency is accomplished by etching the edges. The electrodes are of gold to take advantage of the inherently stable character of this metal in this application. Twenty crystals were constructed for the National Bureau of Standards incorporating these improved design features, and are now in use by the Bureau of Standards at Boulder, Colorado, and at WWV.

The Q value of the D-168670 GT-cut crystals was approximately 140,000 and the frequency drift with time was approximately 1×10^{-8} per day in the LORAN oscillator. The Q value of the improved design is of the order of magnitude of a million, with some values as high as 4,000,000. The daily drift rate of the special GT-cut crystals in use at the National Bureau of Standards is reported as low as 1 to 5×10^{-10} per day, whereas the drift rate of the earlier design was reported as 1 to 3 parts in 10^9 per day after one year of aging.[13,25,26]

The principal advantage of the GT-cut appears to lie in its low temperature coefficient of frequency, and the consequent ability to provide a stable frequency even in the absence of precise temperature control. The National Bureau of Standards has demonstrated that it is possible to use a crystal resonator buried in the earth as a reasonably accurate frequency reference without further temperature control.[27] Such a system has the advantage that continuity of power supply is not necessary in order to preserve continuity in measurement of the aging curve of the crystal resonator, and that it is thus possible to use such a crystal as an emergency standard during a power failure.

It has been determined that GT-cut plates are sensitive to the amplitude of the driving current within the range of current experienced in the bridge-stabilized oscillator circuits normally used with these plates.[25] Although some improvement has resulted from redesign of the oscillator bridge networks to balance at lower values of crystal current, the National Bureau of Standards has incorporated into the group of crystals used as frequency standards several crystals which are used only as reference resonators; i.e., which are not running continuously in oscillator circuits but are measured in bridge circuits at low excitation current levels.[26]

[24] C. F. Booth and F. J. M. Laver, "A standard of frequency and its applications," *Jour. IEE*, vol. 93, part III, pp. 223–241 (with discussion); July, 1946.

[25] J. M. Shaull, "Adjustment of high-precision frequency and time standards," Proc. IRE, vol. 38, pp. 6–15; January, 1950.

[26] J. M. Shaull and J. H. Shoaf, "Precision quartz resonator frequency standards," Proc. IRE, vol. 42, pp. 1300–1306; August, 1954.

[27] T. A. Pendleton, "Underearth quartz crystal resonators," Proc. IRE, vol. 41, pp. 1612–1614; November, 1953.

AT-Cut Plates

The AT-cut quartz crystal plate was developed by Lack, Willard, and Fair in 1934.[28] Other investigators, notably I. Koga, also published data on similar low-temperature-coefficient cuts. This type of plate vibrates in the thickness-shear mode and may be made to have a low temperature coefficient of frequency. It is possible to orient the cut angle to produce an inflection point on the frequency-vs-temperature curve, that is, a zero temperature coefficient of frequency, in the range of temperatures normally used in temperature-controlled ovens. Such a crystal cut has obvious applications as a frequency standard.

Early efforts to use the AT-cut plates as standards[24] were hampered by the difficulty of mounting the plate in such a way as to achieve a mount which would not influence the frequency of the crystal. Low aging drift is almost impossible to attain unless a mount is used which affects the frequency of the crystal to a minimum degree. Booth of the British Post Office used nodal-plane pin-mounted AT-cut plates, operating at 1000 kc, with air-gap electrodes, in partially evacuated holders (air-pressure 3 cm Hg).[29] These crystals were operated at 50 degrees C. They gave drift rates averaging 2 to 5×10^{-9} per day over the years 1941–1944. In view of the fact that the nodal plane is in the center of the thin edges of the AT-cut plate (1.65 mm thick), the difficulty in constructing a stable mounting by this method was considerable.

The most promising recent development in the design of AT-cut plates for frequency-standard use has been carried out by Warner.[30] Warner has shown that a circular AT-cut plate with one side plane and the other side ground to spherical contour, operating at 5 mc in the 5th-overtone mode, can be made with a Q of approximately 2,500,000. A photograph of this crystal unit in an evacuated glass envelope is shown in Fig. 8. Warner further reports a 1 mc crystal of similar design[31] with a Q of 12×10^6. These remarkably high Q values are ascribable to the use of the overtone mode and to the spherical contouring, which "mismatches" the zones of the crystal away from the exact center of the convex side of the plate. The zones near the edge of the crystal are thus rendered incapable of resonant vibration at the excitation frequency and are consequently quiescent. The edge of the contoured plate is thus made suitable for the attachment of rugged mounting supports and connecting leads to the electrodes. The use of a glass-envelope evacuated mounting for this type of crystal plate has resulted in the high Q value quoted above, and in a low aging rate which is currently being verified at a number of laboratories. Indications are that the aging drift of this type of contoured AT-cut plate in an evacuated mount will be as low as that of any previously designed crystal units.

Courtesy Bell Telephone Laboratories.

Fig. 8—5 mc AT-cut contoured plate in evacuated glass envelope, operating in 5th overtone mode.

The advantages of the overtone-mode contoured 5 mc-plate for commercially produced equipment are centered in the relatively small size of the quartz blank required, and the ease of getting a satisfactory mounting. Careful processing is still necessary in order to attain low rates of frequency drift with time, but the ruggedness of the crystal unit and its small size have already suggested numerous applications.

Fundamental-mode AT-cut plates are capable of low rates of frequency change with time if properly processed and mounted, and if used in applications, such as high-stability circuits, where the constancy of the crystal can be exploited. Lea has used a fundamental-mode 5 mc plate in experimental oscillators of high stability,[32] and Sulzer has developed a 1 mc oscillator using a fundamental-mode contoured AT-cut plate.[33]

Oscillator Circuits for Frequency Standards

Resonant devices can be made to oscillate with good frequency stability only if appropriate means are selected for maintaining them in oscillation. Pendulum clocks furnish elegant illustration of this requirement.

[28] F. R. Lack, G. W. Willard, and I. E. Fair, "Some improvements in quartz crystal circuit elements," *Bell Sys. Tech. Jour.*, vol. 13, pp. 453–463; July, 1934.

[29] C. F. Booth, "The application and use of quartz crystals in telecommunications," *Jour. IEE*, vol. 88, part III, pp. 97–144 (with discussion); June, 1941.

[30] A. W. Warner, "High-frequency crystal units for primary frequency standards," Proc. IRE, vol. 40, pp. 1030–1033; September, 1952.

[31] A. W. Warner, "High-frequency crystal units for primary frequency standards," Proc. IRE, vol. 42, p. 1452; September, 1954.

[32] N. Lea, "Quartz resonator servo—a new frequency standard," *Marconi Rev.*, vol. 17, pp. 65–73; 3rd Quarter, 1954.

[33] "High-stability one-megacycle frequency standard," *NBS Tech. News Bull.*, vol. 38, pp. 162–163; November, 1954.

The Shortt clock, representing a highly developed form of the gravity pendulum clock using electrically supplied impulses to maintain oscillation, gives stability approaching that of crystal-controlled clocks. This stability is achieved by a combination of a stable resonator (free-pendulum), and an "oscillator circuit" which supplies a constant amount of power at the same point in every cycle. Similar requirements hold for quartz-crystal-controlled oscillators, each increase in stability of crystal elements calling for improvements in oscillator circuits.

The principal property susceptible to improvement is the stability of the phase shift in the "negative resistance" or amplifier element of the oscillator. There are currently at least three distinct approaches to the oscillator circuit problem, and possibly a great many more as yet not known to the author of this review. The first approach consists of the use of an amplifier with a positive feedback connection to provide regeneration and also frequency control through incorporation of the crystal element in this feedback path, with a negative feedback connection to stabilize amplifier gain and phase characteristics. The second approach comprises the use of the most stable elements in the "optimum" simple oscillator circuit with stabilization of the oscillator active element by appropriate means. The third approach adds to the second approach a servo-operated device for adjusting the circuit elements to maintain the oscillation frequency at a value which gives a constant value of impedance or phase shift in the crystal element.

Bridge-Stabilized Oscillators

The oscillator circuit which has been most widely used for frequency standard oscillators is the bridge-stabilized circuit originated by Meacham.[34] In this circuit [Fig. 9(a)], the feedback voltage which drives the amplifier is the unbalance voltage at the output terminals of a bridge network which includes the crystal with associated adjusting reactances, a resistor with a positive temperature coefficient of resistance, two linear-resistive arms and the necessary coupling circuits. The values of the resistors are so chosen, with respect to the crystal series resistance and the tungsten lamp resistance, that the bridge is unbalanced at low levels of applied signal in such a direction that positive feedback results from the bridge-unbalance output signal. As the amplitude of oscillation builds up, more current flows through the bridge arms, causing the tungsten lamp to increase its resistance and the bridge to approach the balance condition. The ultimate amplitude of oscillation is reached when the bridge unbalance signal becomes small enough so that the transmission loss through the bridge network equals the gain through the amplifier.

The excellence of the bridge-stabilized oscillator circuit stems from two important properties which are the result of the use of the bridge network in the feedback path. The first property is a function of the phase relationship of the input voltage of a bridge with respect to its unbalanced output, or detector output, voltage. Near the balance point of the Meacham bridge, incorporating the crystal resonator as one element, the slope of the phase shift of output voltage vs input voltage is greater than the slope of the phase shift of input voltage vs current through the crystal element alone. This improvement in slope enables design of oscillators in which improvement in stability is accomplished by provision of additional gain to make up for the loss involved in the operation of the bridge network close to the balance point. Improvement in frequency stability generally will result from increase in amplifier gain since the voltage gain goes up as the power of the number of stages, whereas the amplifier phase shift instability generally increases only directly with the number of stages.

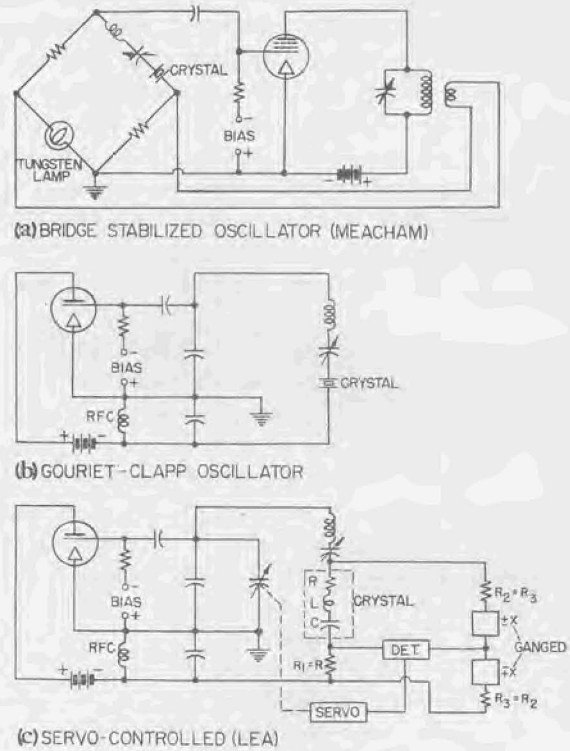


Fig. 9—Oscillator circuits for frequency standards.

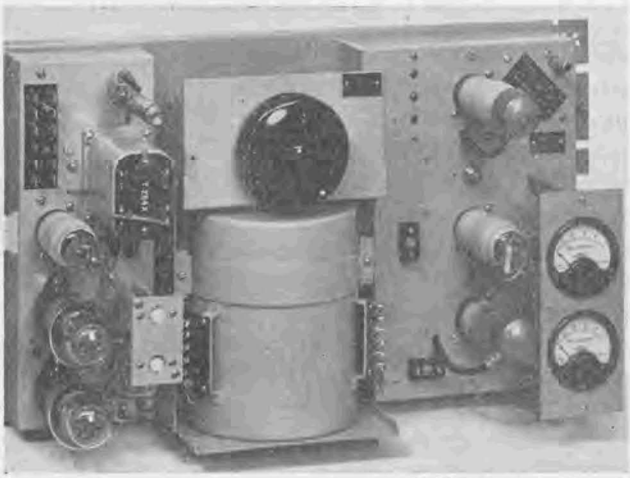
The second property of the bridge-stabilized oscillator, one which is at once an asset and a liability, is the amplitude stabilization property of the bridge network. The tungsten lamp has been almost universally used as the amplitude stabilizing device in the bridge because of its simplicity, ruggedness, and low drift with time. Some efforts have been made to use elements with negative temperature coefficients of resistance, such as thermistors, but the tungsten lamp is, in general, the accepted element. The amplitude stabilization resulting from the self-balancing bridge feedback network is effective, holding its amplitude setting well for long periods. However, the range of levels over which the bridge

[34] L. A. Meacham, "The bridge stabilized oscillator," Proc. IRE, vol. 26, pp. 1278–1294; October, 1938.

network can be made self-balancing, depends on the characteristics of the lamp, and generally higher levels are required than would be desirable for use with some crystal elements.[25]

The above-described properties of the bridge-stabilized oscillator are related to the general properties of amplifiers with feedback connections. It has been shown[35] that the performance of the bridge-stabilized crystal oscillator can be analyzed by separating the feedback circuit into a negative feedback path which stabilizes the gain and phase shift of the amplifier and a positive feedback path including the crystal unit, which determines the frequency of oscillation of the system. From this analysis, it appears that it may be profitable to explore further means for the stabilization of the amplifier circuits of oscillators.

Examples of the Meacham bridge-stabilized oscillator are provided by the LORAN timer oscillator (U. S. Navy, R. F. Oscillator Type 0-76/U),[36] the General Radio Company commercial frequency standard Type 1100-A, and the British Post Office Essen-ring oscillator, a photograph of which is shown in Fig. 10.



Courtesy H. M. Postmaster General.

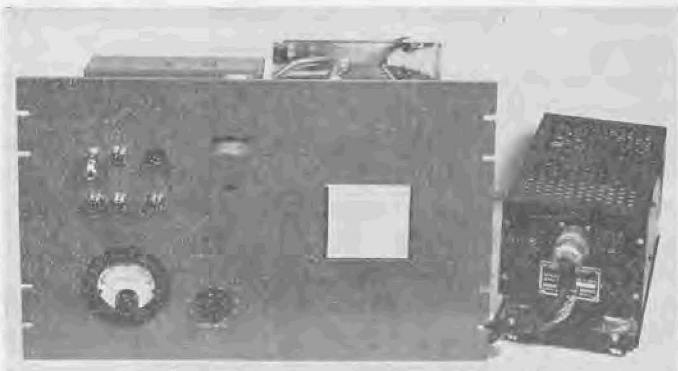
Fig. 10—British Post Office precision frequency standard oscillator, showing oven (center) containing 100 kc Essen ring. This oscillator uses the bridge-stabilized circuit.

Because of unavoidable stray inductance and capacitance, it has been generally found that the bridge-stabilized oscillator circuit is most useful at frequencies of 1 mc or below. Frequency-standard oscillators designed for operation at higher frequencies have, therefore, used the circuits described below.

Gouriet-Clapp Oscillator

The Gouriet-Clapp crystal oscillator circuit, shown in Fig. 9(b), has been used for many years in frequency monitors for broadcasting and in other applications where stable, simple oscillators are required. (This oscillator circuit is sometimes called a "modified Pierce" or "modified Colpitts" circuit. U. S. Patent No. 2,012,-497 was granted to J. K. Clapp for this crystal oscillator circuit in 1935, the series capacitance and inductance being adjusted to series resonance at the crystal series-resonant frequency. A similar circuit was developed independently by G. G. Gouriet of the B. B. C.) Recent availability of stable high-frequency crystals (See section on AT-Cut Plates, above) has prompted application of the Gouriet-Clapp circuit to frequency-standard oscillators in the megacycles/second range. An analysis (See Appendix) of the Gouriet-Clapp circuit with regard to the variations in frequency caused by changes in various circuit elements shows that an oscillator stability of the order of 1 or 2 parts in 10^9 should be realizable with this circuit using a crystal[30] with $Q=2.6\times10^6$ Application of automatic-gain-control to this oscillator circuit by controlling the grid bias of the vacuum tube with an amplified delayed-AGC circuit stabilizes the input impedance of the oscillator tube as well as the gain and crystal current.

Application of this circuit to frequency-standard oscillators has been carried out by Felch and Israel,[37] and in considerably modified form, by Lea (See Servo-Controlled Oscillators, below). The stability achieved has been 3×10^{-9} per day or better, using the 5 mc overtone-mode AT-cut plate,[30] by the former group. A photograph of this 5 mc oscillator unit is shown in Fig. 11.



Courtesy Bell Telephone Laboratories.

Fig. 11—Photograph of USAF Type 0-269 (XW-1)/UR Oscillator, using 5 mc overtone-mode contoured AT-cut plate (see Fig. 8).

Servo-Controlled Crystal Oscillators

All of the oscillator circuits described above have relied on the steep slope of phase-change with frequency in the crystal element to provide corrections for the drifts of phase in the oscillator circuit in order to maintain a constant frequency of oscillation. The bridge-stabilized oscillator alone has provided an enhanced phase-change system to assist the phase-vs-frequency

[35] E. J. Post and H. F. Pit, "Alternate ways in the analysis of a feedback oscillator and its application," Proc. IRE, vol. 39, pp. 169–174; February, 1951.

[36] J. A. Pierce, A. A. McKenzie, and R. H. Woodward, "Loran," McGraw-Hill Book Co., New York, N. Y. ("Model UE-1 Oscillator," pp. 237–240, describes the Type 0-76/U Oscillator); 1948.

[37] E. P. Felch and J. O. Israel, "A simple circuit for frequency standards employing overtone crystals," Proc. IRE, vol. 43, pp. 596–603; May, 1955.

slope of the crystal element. An oscillator circuit which provides a somewhat different method of frequency control has been developed by Lea.[32] A simplified circuit diagram of his servo-controlled oscillator is shown in Fig. 9(c). It should be noted that the servomechanism has been added to an oscillator circuit which, for purposes of illustration, is similar to the Gouriet-Clapp oscillator of Fig. 9(b). The short-term or cycle-to-cycle phase stability of the oscillator is thus dependent on the Q of the crystal, which Q has been degraded to $\frac{1}{2}$ of its original value by the addition of $R_1=R$ (crystal series resistance). The phase "noise" or phase instability of this circuit may thus be twice that of the Gouriet-Clapp circuit using the same crystal unit. However, the long-term stability (for any period longer than the correction time of the servo control) is determined by the ability of the servo system to maintain the oscillator frequency at that value which appears to result in a constant value of impedance in the crystal unit. A bridge circuit comprising the crystal (R, L, C) R_1, R_2, R_3 and ganged modulating reactances $\pm X$ and $\mp X$ is provided by adding $R_1=R$ in series with the crystal, and adding R_2, $\pm X$, $\mp X$ and R_3 in parallel with the crystal branch. R_2 should be equal to R_3, but be large compared with R (crystal) and R_1. A detector, comprising a sensitive AM receiver, is provided with a phase-detector output circuit synchronized with the modulation rate of $\pm X$ and $\mp X$. If the frequency applied to the crystal deviates from the frequency of the crystal series resonance, the voltage drop across the crystal arm of the bridge will change both in magnitude and in phase. The modulating reactances, $\pm X$ and $\mp X$, being modulated continuously at a fairly constant rate, will enable sensing of the direction of phase change of the bridge unbalance voltage (detector output) by scanning back and forth through a small range of reactance unbalance in the modulating arms, and using a phase-sensitive circuit tuned to the modulation frequency at the output of the detector. The output signal from this detector will then be proportional to the magnitude of the deviation from bridge balance, and will have a phase or sign which indicates the direction of deviation of the applied frequency from the crystal resonant frequency. The detector output signal is then applied to a servo system to readjust the oscillator circuit to reduce the frequency deviation to a minimum. By increasing the gain of the detector circuit, it is possible to reduce the magnitude of the deviation required to operate the servo device until the limiting signal-to-noise ratio is reached.

The servo system is thus used to correct for such instability as may arise in the "negative resistance," that is, in the vacuum tube (or transistor) and associated reactive elements. Instability is thought to arise from such factors as cathode-interface impedance, space-charge capacitance, changes in tube geometry with age, transit time variation, and perhaps Miller-effect capacitance changes in addition. A delayed-automatic-gain-control is used by Lea to stabilize level and grid input impedance. The correction time of the servo control used is fairly short, a variable capacitor being driven by a motor to effect the adjustment of the circuit reactance. In its present state of development,[38] the servo-controlled oscillator is stable to better than $\pm 3\times 10^{-11}$, and the average frequency to approximately $\pm 1\times 10^{-11}$, for periods in excess of 10 seconds, the ultimate drift rate for long periods thus being dependent only on the constancy of the crystal element except for the $\pm 3\times 10^{-11}$ error of the circuit. This figure includes changes of tubes, drift of the feedback circuit elements, and supply voltage changes.

Further application of this servo-control principle has produced comparable results using slightly different circuit details. Lea makes use of a motor-driven variable inductance as a single modulated reactance, dispensing with the second modulated element, and delayed AGC. Sulzer[39] has used a chopper to commutate small capacitors in the modulated reactance positions, and a limiter to control level. Both systems operate at a modulation rate different from the power frequency in order to avoid "hum" troubles.

Tuning Forks as Frequency Standards

Tuning forks have been used as frequency standards.[24] The advantages of the tuning fork as a clock-driving source derive mainly from the low frequency of oscillation of the fork and the simplified auxiliary apparatus needed to drive the clock. Interest in small, lightweight, frequency standards for airborne applications has kept the tuning fork from being completely eclipsed. Several manufacturers are producing hermetically-sealed temperature-compensated tuning forks operating in the frequency range of 400 to 1,000 cps, and also at 50–60 cps, and at some frequencies above 1 kc. Performance of the best of these tuning-fork units is comparable with that of commercial-grade crystals as far as stability is concerned. For example, one of these forks (at the Riverbank Laboratories, Geneva, Illinois), operating without temperature control at room temperature in an amplitude-stabilized oscillator circuit, has given stability of the order of $\pm 1\times 10^{-6}$ for several weeks. The Q realizable in a tuning fork is limited, and consequently, the instantaneous phase stability of an oscillator circuit using fork control has to be made as high as possible in order to keep the frequency from fluctuating rapidly. With a modern tuning-fork-controlled oscillator, it is possible to realize a portable time and frequency standard with stability adequate for many purposes.

Microwave Spectral Lines of Atoms and Molecules as Frequency Standards

Much has been written of the many proposals for the use of the constant properties of atoms and molecules as standards of frequency. It will not be possible here to

[38] Private communication, February 1, 1955.

[39] P. G. Sulzer (National Bureau of Standards), "High stability bridge-balancing oscillator," paper in preparation.

give a complete description of the status of the various projects in this field of endeavor, but the projects which appear most promising will be covered briefly. Of the many possible spectrum lines in the microwave region, the 3,3 inversion-line of the ammonia molecule (NH_3) and the transition (4,0 3,0) of the cesium atom seem to be nearest to practical application. Both of these spectrum lines have already been used as the bases of frequency calibrating apparatus,[40] and it is probable that their use will result in the first frequency standards of high precision with complete freedom from long-term aging drift. If present theories of atomic structure are rigorously correct, and there appears to be no reason for suspecting otherwise, then the frequencies representing the spectral lines should never change. We should, therefore, be able to use these invariant frequencies as frequency standards without reference to astronomical phenomena except for initial calibration. It is probable that the first frequency and time standardization using these spectral lines as standards will be done by using them as calibration standards to measure the constancy of the frequency of a conventional frequency standard or of the oscillator of a quartz-crystal-controlled clock, and thus enable accurate establishment of the time-keeping rate of the clock for comparison with astronomical time. As the perfection of atomic frequency standards progresses, it may prove feasible to use them as standard-frequency oscillators for routine laboratory measurements.

The problem then resolves itself into the design of equipment and the application of the information obtained from the equipment. Since the techniques for the two spectrum lines mentioned above are so widely different, they will be treated individually.

Ammonia Spectrum Line Developments

It is probable that the earliest published reference to the possibility of using microwave spectrum lines as frequency-stabilizing elements is in a paper by Pound[41] published in 1946, although other investigators had perceived the possibility of using the microwave spectral lines as frequency calibration points. Shortly after publication of Pound's paper, a paper by Smith, de Quevedo, Carter and Bennett[42] confirmed the application of Pound's method of stabilization using the 3,3 line of ammonia (NH_3) as the frequency reference. The stabilized oscillator system comprised a reflex klystron, a wave-guide hybrid system, a wave-guide resonator filled with ammonia, and a "dc" feedback connection to the klystron repeller electrode to close the loop. In effect, the ammonia was used as a resonant element to provide a rapid change of phase of a reflected wave in a Pound-type discriminator, the rate of change of phase with frequency being rapid enough to give an effective Q estimated at 12,500.

The use of the 3,3 inversion line of ammonia at approximately 23,870 mc for this stabilization experiment was the extension of many years of investigation of this particular spectrum line. Cleeton and Williams measured this ammonia absorption in 1934,[43] and a number of papers appeared immediately after World War II[44–46] giving further information which indicated that the 3,3 line of ammonia was a strong line (high absorption of energy), and that it was not affected in frequency by such variable factors as pressure, temperature, and magnetic field, although the apparent resolution or breadth of the line depends on pressure and temperature.

The most accurate determination of the frequency of the 3,3 inversion line of ammonia appears to be that by Shimoda,[47] who gives a value of $23{,}870{,}130.97 \pm 0.10 \pm 1$ kc for this line. This figure includes terms of ± 0.10 kc instrumental error, and ± 1 kc uncertainty concerning the absolute value of the reference frequency standard.

Servo-Controlled Ammonia Oscillators

A method of oscillator stabilization using a control loop and an ammonia absorption cell as a frequency-stable element has been applied to frequency-standard oscillators. Hershberger and Norton[48] stabilized a klystron oscillator at the ammonia-line frequency, and also offset from this frequency by a known intermediate frequency increment. Lyons[40,49] applied a similar approach to the stabilization of a crystal-controlled frequency-standard oscillator, and thus to the control of a clock by reference to the ammonia absorption-line frequency. Fletcher and Cooke stabilized a klystron at the ammonia-line frequency.[50]

The basic principles of such a servo-controlled oscillator are shown in Fig. 12(a) (next page). An oscillator, with a controllable frequency adjustment, supplies a signal to a modulation system which adds modulation to the signal, which is then referred to the ammonia-filled absorption cell. The signal is modified by passage through the cell, the modification then being detected and evaluated by the circuits of the servo control with

[40] H. Lyons, "Spectral lines as frequency standards," *Ann. N. Y. Acad. Sci.*, vol. 55, pp. 831–871; November, 1952.

[41] R. V. Pound, "Electronic stabilization of microwave oscillators," *Rev. Sci. Instr.*, vol. 17, p. 490; November, 1946.

[42] W. V. Smith, J. L. G. de Quevedo, R. L. Carter, and W. S. Bennett, "Frequency stabilization of microwave oscillators by spectrum lines," *Jour. Appl. Phys.*, vol. 18, p. 1112; December, 1947.

[43] C. E. Cleeton and N. H. Williams, "Electromagnetic waves of 1.1 cm wavelength and the absorption spectrum of ammonia," *Phys. Rev.*, vol. 45, pp. 234–237; February 15, 1934.

[44] C. H. Townes, "The ammonia spectrum and line shapes near 1.25 cm wavelength," *Phys. Rev.*, vol. 70, p. 665; November, 1946.

[45] W. E. Good, "The inversion spectrum of ammonia," *Phys. Rev.*, vol. 69, p. 539; May, 1946.

[46] B. Bleaney and R. P. Penrose, "Ammonia spectrum in the 1 cm wavelength region," *Nature*, vol. 157, p. 339; May, 1946.

[47] K. Shimoda "Atomic clocks and frequency standards on an ammonia line," *Jour. Phys. Soc. Japan*; Part III, 1954.

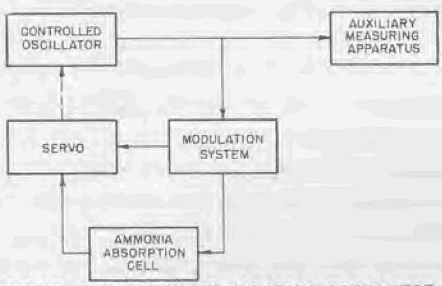
[48] W. D. Hershberger and L. E. Norton, "Frequency stabilization with microwave spectral lines," *RCA Rev.*, vol. 9, pp. 38–49; March, 1948.

[49] H. Lyons, "The atomic clock, an atomic standard of frequency and time," *NBS Tech. News Bull.*, vol. 33, pp. 17–24; February, 1949.

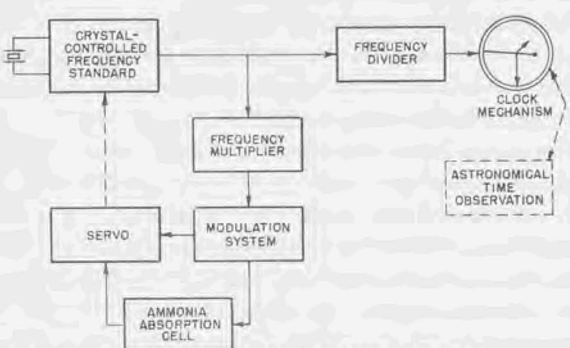
[50] E. W. Fletcher and S. P. Cooke, "The stabilization of a microwave oscillator with an ammonia absorption line reference," Cruft Laboratory, Harvard University, Tech. Report No. 5; 1948, Tech. Report No. 64; 1950.

reference to the modulation system. The servo control then supplies a correction to adjust the frequency of the controlled oscillator to the desired value.

Hershberger and Norton[48] swept the frequency of a separate klystron local oscillator back and forth across the frequency of the ammonia cell, and detected the pulse resulting from the absorption peak. Simultaneously, they applied this FM signal to a mixer with a signal from the controlled oscillator (a reflex klystron) and amplified the beat-notes near zero-beat (pulses) resulting from this interaction. The phase of the two sets of pulses was compared, and a correction signal obtained which was contrived to move the controlled oscillator pulse to coincidence with that from the ammonia cell. A further arrangement was constructed which used an offset, or intermediate-frequency, beat-note from the controlled-oscillator part of the circuit to provide the control pulses. By using a stabilized intermediate frequency, a stable controlled frequency resulted.



(a) BASIC SERVO-CONTROLLED AMMONIA OSCILLATOR SYSTEM



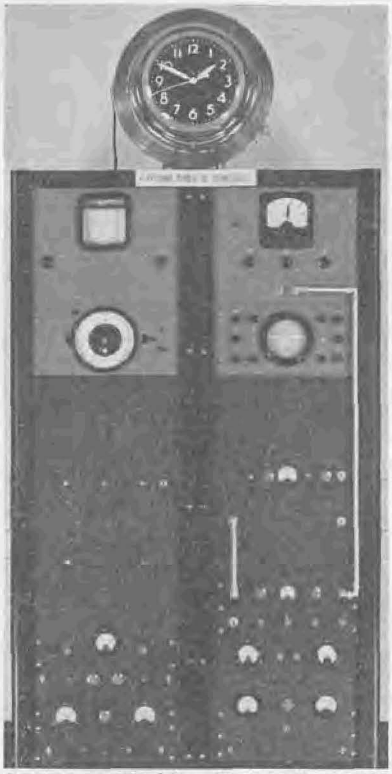
(b) SERVO-CONTROLLED AMMONIA ("ATOMIC") CLOCK

Fig. 12—Servo-controlled ammonia-absorption-cell oscillator systems.

The atomic clock development program under Lyons at the Bureau of Standards has explored the possibility of stabilizing a crystal-controlled frequency standard against the ammonia absorption cell.[40,49] The ammonia-stabilized clock uses a system of stabilization similar to the one discussed above [see Fig. 12(b)], but resulting in a lower output frequency which can be used to operate a clock mechanism for comparison with astronomical time measurements. The controlled oscillator feeds a frequency multiplier chain which eventually provides output near the frequency of the ammonia line. At one stage in the multiplier system, a frequency-modulated signal is added to that from the multiplier stage, and the proper sideband signal selected to provide a harmonic falling on the 23,870 mc frequency of the ammonia cell. Thus it is possible to provide a frequency-modulated signal derived from the frequency standard, sweeping back and forth in the vicinity of the ammonia frequency, with good short-term stability of the center (or carrier) frequency. The intermediate-frequency frequency-modulated signal (that which was added to the multiplied frequency of the controlled oscillator) is compared with the appropriate harmonic of the controlled frequency-standard oscillator, a signal pulse being produced each time the swept intermediate-frequency signal passes a given reference frequency. The FM signal, at 23,870 mc $\pm$modulation, undergoes absorption each time it sweeps past the ammonia absorption frequency in the cell, this absorption being observed as a negative reference pulse out of the detector at the receiving end of the ammonia absorption cell. The servo circuits are operated by the phase or time difference between these two pulses and are arranged to produce a correction of the crystal oscillator frequency to keep the crystal-controlled frequency standard locked to the ammonia line. The result which is sought is to produce a clock with no net long-term drift in its time-keeping rate, and with good short term stability, or low acceleration. A clock constructed on these principles gave a performance estimated at $\pm 2\times 10^{-8}$ for a period of the order of one week. The average frequency or integrated time error was not determined. A photograph of the first ammonia clock built at the National Bureau of Standards (1948–1949) is shown in Fig. 13 (opposite). The ammonia absorption cell is mounted in a coil around the large clock indicator above the racks.

A different approach to the servo-control system problem was used by Fletcher and Cooke.[50] Their modulation system used frequency modulation of the controlled oscillator at a relatively high modulation frequency but with a low modulation index. This modulation produced two sidebands which were on either side of the frequency range affected by the ammonia absorption line. An amplitude-modulation detector was used at the output of the absorption cell. If the phase of the carrier (23,870 mc) of the FM oscillator became shifted from its original phase by the action of the ammonia absorption, amplitude modulation resulted upon recombination with the unshifted sidebands.[51] This amplitude modulation occurred at the modulation frequency of the FM ("intermediate frequency"), the AM signal being recovered by the AM detector at the receiving end of the absorption cell. This intermediate frequency signal was then amplified and compared in phase with the modulating signal, the output of the phase comparison circuit being applied to the repeller electrode of the controlled klystron oscillator as a dc adjustment of the average frequency of oscillation.

[51] M. G. Crosby, "Communication by phase modulation," PROC. IRE, vol. 27, pp. 126–136; February, 1939.



Courtesy *Annals of New York Academy of Sciences*

Fig. 13—Photograph of first ammonia clock built at National Bureau of Standards.

A stabilized oscillator using an ammonia absorption cell modulated by a Stark-effect modulator was constructed by Townes[52] in 1951.

Difficulties in the Use of Ammonia Absorption to Stabilize Oscillators

Certain basic difficulties beset the use of the ammonia absorption technique for the stabilization of oscillators.[40,52] The principal difficulties of an inherent nature (properties of molecules) are (1) the natural breadth of the spectral line, (2) Doppler-effect broadening, (3) pressure broadening caused by collisions between molecules, (4) broadening caused by collisions with the walls of the absorption cell, and (5) saturation effects. The natural line breadth is related to the radiation from the molecule and the amount of thermal radiation falling on it. It is inherent and cannot be changed except by choice of the molecule or atom to be used. The other effects are usually much greater, in any case. Doppler-effect broadening is proportional to the velocity of the gas molecules parallel to the propagation direction of the radio-frequency energy in the cell. It can be reduced by cooling, but the ammonia freezes[46] out if cooled far enough to provide much reduction. Pressure broadening results because the energy absorption process is interrupted if a molecule collides with another during the absorption, and has to start again with a new phase possible. This effect can amount to 15 mc bandwidth at a pressure of 1 mm of Hg, but it diminishes with pressure reduction. Wall collisions cause broadening, but amount to a relatively minor item, of approximately 15 kc bandwidth maximum. Saturation effects result from the possibility of all available molecules having already been excited to the higher energy state, and those which are emitting energy supplying enough quanta to re-excite those which require excitation. The only energy then absorbed at the inversion line frequency is that lost to thermal radiation by collision and radiation damping of the moledules. The power input level to the absorption cell at which saturation effects set in is proportional to the square of the pressure in the cell, and hence is conflicting with pressure broadening effects as far as the selection of a pressure level for the cell is concerned.

In addition to the theoretical limitations set forth in the preceding paragraph, the design and construction of the microwave rf system for an ammonia-absorption-cell stabilized oscillator is complicated by the difficulties of working in the frequency range close to 23,870 mc. The signal-to-noise ratio of the system is affected by the noise in the detector, in particular, and could be improved if the saturation effects did not limit the allowable power input. The design of a cell to hold the ammonia gas is complicated by the necessity for maintaining a low standing-wave ratio over the band of frequencies used by the modulation system chosen. A schematic showing the principal features of one design of ammonia absorption cell is shown in Fig. 14 (next page), and a photograph of an ammonia absorption cell is shown in Fig. 15 (next page).

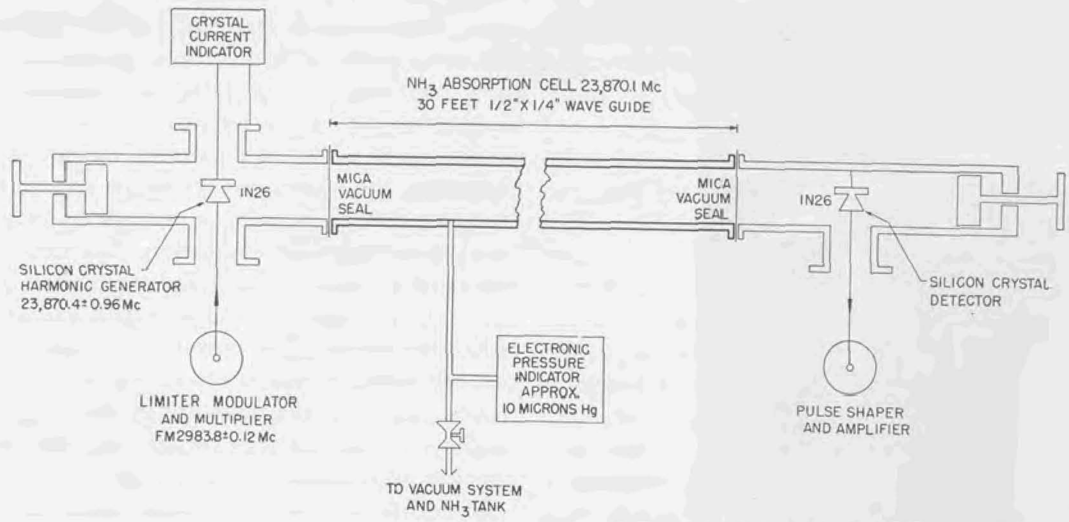
Further work on the solution of these problems appears unlikely in the future as a result of the success of other approaches to the atomic-frequency-standard problem, although experimental work on absorption cells will undoubtedly continue.

Ammonia Oscillator

A completely different arrangement for the use of the 3,3 inversion-line of NH_3 as a frequency standard has been devised by Townes,[53] of the Department of Physics, Columbia University, New York City. Ammonia gas at room temperature contains molecules in various energy states. Slightly less than half of the molecules are in the upper-energy states, while the remaining molecules are in the lower states. The lower-energy-state molecules have an electric dipole moment which makes it possible to accelerate them in a given direction by putting them in an electric-field gradient. The molecules in the upper states are accelerated in the opposite direction along this same electric-field gradient. Thus a sorting or selecting device may be constructed by setting up an appropriately shaped transverse-electric-field gradient in a region traversed by a stream of ammonia molecules, the lower-energy-state molecules being diverged away

[52] C. H. Townes, "Atomic clocks and frequency stabilization on microwave spectral lines," *Jour. Appl. Phys.*, vol. 22, pp. 1365–1372; November, 1951.

[53] J. P. Gordon, H. J. Zeiger, and C. H. Townes, "Molecular microwave oscillator and new hyperfine structure in the microwave spectrum of NH_3," *Phys. Rev.*, vol. 95, pp. 282–284; July 1, 1954.



Courtesy *Annals of New York Academy of Sciences*

Fig. 14—Diagram of ammonia absorption cell for atomic clock.

Courtesy *Annals of New York Academy of Sciences*

Fig. 15—Photograph of ammonia absorption cell for atomic clock.

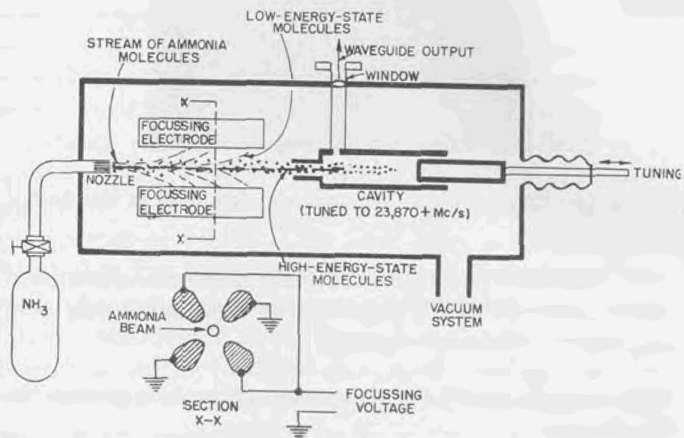


Fig. 16—Ammonia oscillator (Townes).

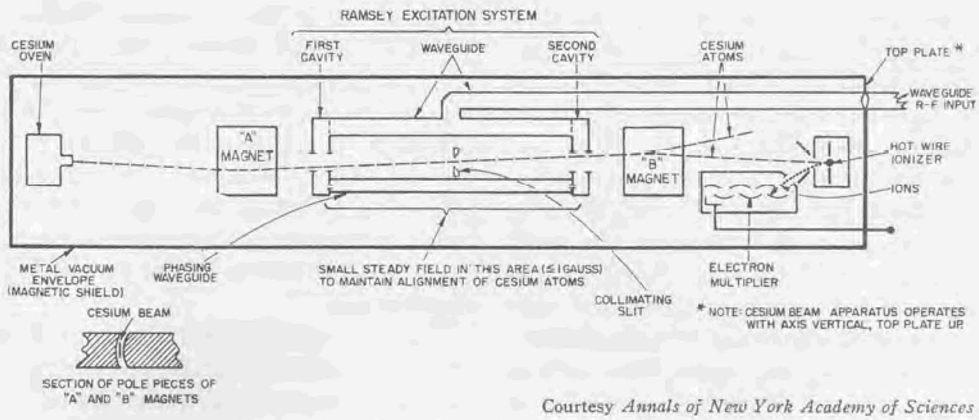
from the axis, and the higher-energy-state molecules converged by the focusing system. By this means, a useful portion of the high-energy molecules in a given stream may be selected and focused at the end of the electrode system.

Such a system is shown schematically in Fig. 16, with a resonant cavity to receive the focused high-energy molecules through a waveguide-below-cutoff entrance port. This device operates to produce oscillations at the inversion-line frequency of the ammonia by the following mechanism: the high-energy-state molecules which enter the resonant cavity are acted upon by any radio-frequency fields present in the cavity, and also these molecules can contribute to these field components by emission of energy. Some of the molecules in the cavity undergo transition to the lower state by emission of a quantum of energy at 23,870 mc. When the rf field at this frequency builds up to a sufficient value, the transitions are stimulated and the molecules then give up their quanta in an ordered, coherent manner, thus providing a source of power at 23,870 mc. The magnitude of the power available is adequate to supply the losses in the radio-frequency circuit, and to provide an additional small amount of power for measurement purposes (estimated 10^{-8} to 10^{-9} watt).

The general class of devices of this sort has been designated MASER, from the initials of the description "*m*icrowave *a*mplifier by *s*timulation of *e*mitted *r*adiation." In the case discussed above, the gain of the amplifier is greater than the losses in the system, and hence an oscillator is the result.

The exact frequency at which the oscillations are produced depends on several factors, the two most significant ones being the Q of the cavity and the tuning of the cavity relative to the inversion-line frequency. In the first experimental models of this device, detuning

17



Courtesy *Annals of New York Academy of Sciences*

Fig. 17—Cesium atomic-beam frequency-standard apparatus.

the cavity produced a "pulling" effect of approximately ±2,000 cycles. At the present time, the best method of estimating the correct center frequency of the 3,3 inversion line of ammonia appears to be setting to the midpoint of the pulling range. Other methods may be devised with better reproducibility of setting, such as the use of the frequency at which oscillations are just observable when the Q of the system (cavity plus load) is reduced to the point where self-oscillations are barely possible.

Two of these oscillators are reported to have been operated simultaneously, beating one against the other in a receiver tuned to their frequency. The oscillators were detuned to produce a 50-cps beat note, and the instability was observed to be less than ±0.1 cps. Over a period of an hour, the average variation in the beat-note was less than ±2.5 cps and the peak deviation was less than 5 cps.

It is estimated that a fully engineered version of this type of oscillator may reach a long-term stability of $\pm 1\times 10^{-12}$. The absolute accuracy of the oscillation frequency cannot now be specified, but it is apparent that the oscillator may be set by simple methods to within approximately ±20 cps of the correct frequency, or $\pm 1\times 10^{-9}$, and that improvements in setting techniques will improve this figure.

Cesium Atomic-Beam Frequency Standard[40,54,55]

Another atomic spectrum line which may be used for frequency standardization is the line at 9,192.63197+ mc which is observed in cesium of atomic weight 133 by atomic-beam techniques. The atomic or molecular beam apparatus for measuring nuclear magnetic moments by resonant absorption was developed by Rabi and coworkers at Columbia University.[56] The original laboratory equipment gave a minimum indication upon the absorption of a quantum of any frequency, whereas the present models give a maximum indication upon the absorption of a quantum at the desired frequency only. The energy level difference corresponding to this frequency in the cesium atom is associated with the spin vector of the valence electron and its relation to the nuclear magnetic moment of the atom, the two energy levels corresponding to the case of the electron spin vector being aligned with and in the same direction as the nuclear magnetic moment, and the case in which the spin vector is directly opposed to that of the nucleus. When an atom of cesium is acted upon by a magnetic field of exactly the correct frequency, the internal structure of the atom can absorb a quantum of energy corresponding to the transition described above. The external evidence of this change in energy level is provided by a change in the magnetic moment of the atom. The atomic-beam apparatus shown in Fig. 17 is designed to enable detection of the changed magnetic moment of the atoms, and hence to determine the correctness of the frequency of the exciting field in the cavities. The width of the resonance curve of the absorption line is inversely proportional to the time the atom spends in the exciting field, the time in this case, using the two-cavity excitation method, being the time taken to traverse the path from the entrance of the first cavity to the exit from the second cavity.

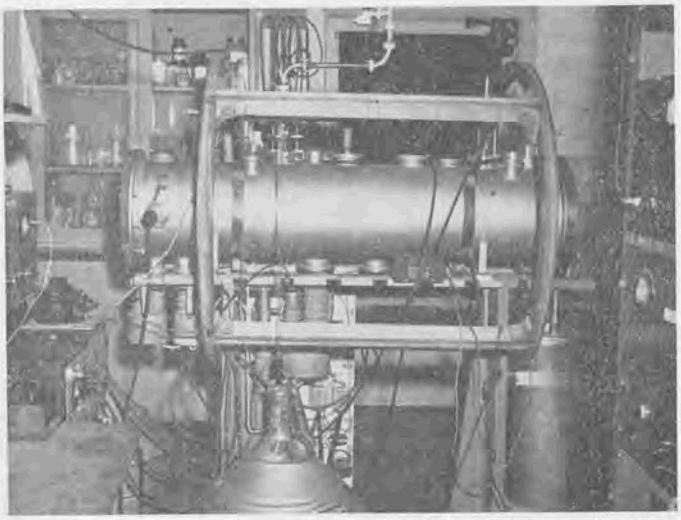
The cesium-beam apparatus shown in the diagram (Fig. 17) is typical of current designs. A stream or beam of cesium atoms is emitted by the oven through a nozzle which provides a ribbon-shaped beam of approximately 0.02-inch thickness, the emission of cesium being approximately 10^{-6} grams per day. The atoms pass through the inhomogeneous magnetic field between the pole-pieces of the A magnet. Those atoms with the appropriate dipole moment are deflected by the magnetic field gradient of the A magnet as indicated in the diagram, and are turned back toward the axis of the apparatus. The cesium atoms then traverse the first rf cavity in which they are exposed to a magnetic field at 9,192+ mc which can produce the energy level change desired in the atoms. The atoms then drift through the

[54] J. R. Zacharias and J. G. Yates, "VIII, Atomic Beam Research; A Cesium Clock," Quarterly Progress Report, Research Laboratory of Electronics, Mass. Inst. Tech., Cambridge, Mass., pp. 30–34; October 15, 1954.

[55] N. F. Ramsey, "Nuclear Moments," John Wiley and Sons, Inc., New York, N. Y., ch. 3, sec. D, "Molecular Beam Resonance Methods," pp. 37–52 (An extensive bibliography is given on this general type of molecular beam apparatus); 1953.

[56] I. I. Rabi, S. Millman, P. Kusch, and J. R. Zacharias, "The molecular beam resonance method for measuring nuclear magnetic moments," *Phys. Rev.*, vol. 55, pp. 526–535; March 15, 1939.

distance between tne cavities (50 to 100 cm) and then through the second rf cavity. The radio-frequency magnetic field in the cavities is set to the same phase by careful adjustment and is checked by means of a probe inserted in the phasing waveguide connecting the two cavities. The net effect of the use of two separate in-phase cavities is similar to the effect obtained by using a long cavity with zero phase-shift between the ends, with the exception that, at frequencies slightly separated from the center of the resonance curve, an interference pattern occurs which shows up as a large amplitude ripple in the main absorption curve. This method of excitation, originated by Ramsey,[57] provides a sharper peak at the center of the resonance curve than is provided by the use of a single excitation field, reducing as it does the Doppler effect to a very small value. The atoms which have absorbed (or emitted) a quantum in the space between the magnets have then changed their magnetic dipole moment and are deflected in the opposite direction by the magnetic field gradient in the *B* magnet, while those atoms which have not "flopped" are deflected a second time, as before, and are not refocused on the detection device. The detection device comprises a surface ionizer, of the hot wire type, which is hit by the neutral atoms, and ionizes them. The cesium ions thus formed are then accelerated and focused by the appropriate electrodes and injected into the secondary-emission electron multiplier. The output current of the electron multiplier collector electrode is thus a measure of the number of atoms making the transition, and hence of the resonance curve of the transition.



Courtesy National Bureau of Standards.

Fig. 18—The National Bureau of Standards cesium atomic-beam equipment.

Fig. 18 shows a photograph of the atomic-beam portion of the cesium-beam frequency-standard apparatus constructed at the National Bureau of Standards.[40] The path length between the rf cavities is 50 cm. The effective Q obtained was 30 million. The atomic beam was horizontal in this apparatus. The excitation for the rf system is supplied through the waveguide entering the top of the container. Control of the ambient magnetic field affecting the equipment is provided by the large coils surrounding the vacuum envelope. The crystal-controlled excitation system is not shown in this photograph.

Current practice makes use of a small amount of frequency modulation of the exciting oscillator and appropriate phase-sensitive circuits to control the average frequency of the exciting oscillator. Hence the cesium-beam apparatus is a form of servo-controlled oscillator with a highly specialized form of absorption cell in which the Doppler effect is very small, collision broadening is absent, and which uses a very sensitive, low-noise, detection circuit not heavily limited by saturation or detector thermal noise level.

The excitation oscillator used in such a system must be adequately stable in order to avoid spurious effects, and the auxiliary equipment associated with the atomic-beam apparatus requires careful design in order to provide the best stability and accuracy for the over-all frequency-standard apparatus. The excitation system used at the Bureau of Standards is crystal-controlled at a relatively low frequency and uses a multiplier chain to reach the operating frequency of the cesium beam. Another suitable oscillator system has been constructed at M.I.T., using a Western Electric Type 416-B microwave triode working at approximately 3,064 mc and tripling with crystal diodes.

The cesium-beam apparatus which has been run at M.I.T. is reported to have a stability of $\pm 1 \times 10^{-9}$ for short periods, with the mean frequency showing less drift than this value. Refinements in this apparatus are expected to improve the over-all stability. A newer projected design is also being undertaken in an effort to improve the over-all performance by several orders of magnitude.

A commercial model of the cesium-beam atomic frequency standard is now being designed (by the National Company, Malden, Massachusetts) and should be available shortly.

Further Atomic Frequency Standards

Although the spectrum lines of atoms and molecules in the microwave frequency range are almost limitless in number, only a few of these spectrum lines offer attractions comparable with those of the lines described above. Dicke is carrying out work at Princeton which may result in the use of a line of the sodium spectrum as a reference. Some frequency calibration measurements on oxygen absorption lines are being carried out at the National Bureau of Standards. However, at the

[57] N. F. Ramsey, "A molecular beam resonance method with separate oscillating fields," *Phys. Rev.*, vol. 78, pp. 695–699; June 15, 1950

TABLE I

PRINCIPAL CHARACTERISTICS OF STANDARD-FREQUENCY AND TIME-SIGNAL STATIONS

Stations	Hawaii	Johannesburg[5]	Rugby	Tokyo	Torino	Uccle[22]	Washington
Call-sign	WWVH	ZUO	MSF	JJY	IBF	—	WWV
Service	Experim'l	Experim'l	Experim'l	Experim'l	Experim'l	Experim'l	Regular
Carrier Power (kW)	2[1]	0.1	0.5	1	0.3	0.02	10[1]
Type of antenna	Vertical dipole	Inverted L	Vertical dipole	Vertical dipole	Horizontal dipole[18]		Vertical dipole
Number of simultaneous transmissions	3	1	3	1	1	1	6
Number of frequencies used	3	1	3	3	1	1	6
Transmission							
Days per week	7	7	7	7–2[13]	1[19]	7	7
Hours per day	22	24[6]	24[9]	24	6[20]	22	24
Standard frequencies used							
Carriers (mc)	5, 10, 15	5	2.5, 5, 10[10]	2.5,[13] 5,[14] 10[15,16]	5	2.5	all
Modulations (cs)	1,[2] 440, 600	1[7]	1,[2] 1,000	1,[17] 1,000	1,[2] 440, 1,000	None	1,[2] 440, 600
Duration of tone modulation (minutes)	4 in every 5[3]	—	5 in every 15	9 in every 20	5 in every 10[21]	—	4 in every 5[3]
Accuracy of frequencies (10^{-8})	±2	±2[8]	±2	±2	±2	±1	±2
Max. oscillator drift (10^{-8}) per month	+2	+4	+0.5	+1	+4	—	+1
Max. value of steps of frequency adjustment (10^{-8})	1	2	2	2	2	—	1
Duration of time signals in minutes	continuous	continuous	5 in every 15	continuous	5 in every 10	None	continuous
Accuracy of time intervals	$\pm 2\times10^{-8}$ $\pm 1\ \mu s$	$\pm 2\times10^{-8}$ $\pm 10\mu s$	$\pm 2\times10^{-8}$ $\pm 1\ \mu s$	$\pm 2\times10^{-8}$ $\pm 1\ \mu s$	$\pm 2\times10^{-8}$ $\pm 1\ \mu s$	—	$\pm 2\times10^{-8}$ $\pm 1\ \mu s$
Method of adjusting time signals	Steering[4]	Steering[4]	By steps of 50 ms[2]	Adjusted to mean of time signals	Steering[4]	—	Steering[4]

[1] Maximum values, reduced power is used on certain frequencies and on certain days, [2] 5 cycles of 1,000 cps modulation pulses, [3] 440 and 600 cps alternately, [4] No phase adjustment to the signals themselves, [5] Transmission by the Union Observatory (Union of South Africa), [6] Interruptions for short periods, [7] 100 cycles of 1,000 cps modulation pulses, [8] In relation to WWV, [9] Interruption from the 15th to the 20th minutes of each hour, [10] Transmission on 60 ks also, [11] The 1st of the month, if necessary, [12] See carrier frequencies, [13] From 0700 to 2300 U.T., [14] Mondays, [15] Wednesdays, [16] Transmissions on 4 and 8 mc too, [17] Interruptions during 20 ms, [18] Maximum radiation: North-East and South-West, [19] Tuesdays, [20] From 0800 to 1100 and from 1300 to 1600 U T., [21] 440 and 100 cps alternately, [22] Transmission by the Belgian Royal Observatory.

present time it seems safe to assume that the spectrum lines discussed above will be the first for which practical application will be found as frequency standards.

STANDARD FREQUENCY BROADCASTS

Standardized radio frequencies are now broadcast by a number of agencies in various nations,[57,58] and usually include time signals. Table I, above, provided by the International Radio Consultative Committee, through the courtesy of B. Decaux, International Radio Consultative Committee Study Group VII, gives the principal characteristics of standard-frequency and time-signal stations. This table is correct as of August, 1954.

CHANGES IN WWV TRANSMISSIONS[59]

The presently used method of adjustment of the frequency of WWV is a slight modification of the method described in a previous reference,[25] namely, that the frequency of the standard-frequency oscillator is steered to keep Universal Time as determined by the U. S. Naval Observatory. which advises WWV on regulation of the oscillator. The slight modification is that the frequency is readjusted by no more than 1×10^{-9} parts per day. The frequency of WWV is measured by the National Bureau of Standards at Boulder, Colorado, and the correction data are supplied for the adjustment of the transmitter. Tables of corrections to the broadcast time signals are furnished, as previously, by the Time Service, U. S. Naval Observatory.

The transmitters at WWV are using single-sideband transmission of tone modulation on some of the carrier frequencies. The carrier is radiated continuously by one transmitter unit, the sideband giving the tone modulation being generated from the same frequency-standard oscillator by appropriate frequency dividers, modulators, and filters, and then radiated through a separate antenna.

PRECISION FREQUENCY MEASURING EQUIPMENT

Extension of the frequency range and accuracy of precision frequency measuring equipment has, of necessity, been carried out to keep pace with the microwave measurement field and the improved stable oscillators described above.

[58] H. B. Law, "Standard frequency transmission equipment at Rugby radio station," *Proc. IEE*, vol. 102, part 3, pp. 166–173; March, 1955.

[59] U. S. Bureau of Standards Letter Circular LC 1009, and Supplement; December 1, 1954.

PRECISION STANDARD-FREQUENCY CALIBRATORS

As was stated in the section of this paper devoted to time standards, the exact calibration of a quartz-crystal-controlled clock in terms of time is the only method now available for establishing an accurate frequency calibration of the oscillator driving the clock. The accuracy of a frequency measurement carried out by comparison with astronomical time measurements has been limited in the past by the errors in the measurements of time, by the fluctuations in the rate of rotation of the earth itself, and by the fluctuations in the rate of the clock driven by the crystal-controlled oscillator.[5,7,17,25] Clock stability having now been improved by a significant amount, it is expected that the new methods of astronomical observation (see Dual-Rate Moon Position Camera, above) and improvements on the standard methods of observation (improved photographic zenith tube) will result in better data on the relative variations of the variable factors.

In order to provide the high-stability clocks described above, it has been found essential to maintain several quartz-crystal clocks in a frequency-standard installation, and to intercompare these clocks to establish their performance as to relative rate and acceleration, i.e., their rates relative to each other. Current practice for such intercomparison in the United States appears to favor the use of one frequency-standard oscillator slightly off-set from the correct standard frequency to produce beat-notes with the other correctly adjusted, standard-frequency oscillators. Such a system then permits measuring and recording of the relative frequencies of the various oscillators by measuring and recording the beat-note frequency. The precision of measurement of such a system may then be increased by multiplying the frequencies of the oscillators to be compared, and using the beat-note measuring equipment as before.[9,25,60] Beat frequency measuring equipment has been constructed using digital electronic counters to measure the duration of a beat cycle between two standard oscillators, and to record this duration as a voltage produced by a suitable resistance-bridge circuit.[61,62]

Other methods of measurement involving comparison of frequencies have been devised. One system makes use of a frequency-multiplier stage multiplying the frequency, f_1, of the oscillator to be measured, by 10, and of a similar multiplier stage for multiplying the frequency of the reference standard, f_2, by 9. The two signals, $10f_1$ and $9f_2$, are then beat together, the beat-note being at approximately the frequency of f_1 or f_2 but containing 10 times the error of f_1 and 9 times the error of f_2. This process is then repeated except that the original $9f_2$ signal is used to heterodyne the 10th harmonic of the first beat note. By continuing this process on to the desired point, and subtracting out the original f_2 frequency in the final beating process, the error frequency can be multiplied sufficiently to increase the sensitivity of indication of the frequency change to the required degree. Recording may then be accomplished by utilizing commercially-available recording-type frequency meters.[26]

An interesting variation on these methods makes use of an off-set reference frequency produced by means of a rotary phase-shifter capable of continuous rotation. This phase-shifter is driven at a constant rate by a synchronous-motor-drive operated by the frequency standard, the input frequency from the reference standard thus being shifted by 1 cycle per second for each revolution-per-second of the 360 degree phase shifter. The unknown frequency is then heterodyned by this shifted standard frequency, which has been multiplied to the appropriate value, and the resulting beat note recorded as above.[62]

Although the methods of frequency measurement described above are those most recently described, spark chronographs and other electric time recorders are still widely used, and integrating phase meters, similar to the polyphase modulator device described by Marrison,[9] are sometimes used for comparing the relative frequencies of frequency standard oscillators.

MICROWAVE FREQUENCY MEASURING EQUIPMENT

Accurate measurements of frequencies in the microwave range require apparatus for the generation of standard frequencies and for comparison of these frequencies with the unknown frequencies to be measured, with appropriate interpolating equipment to provide accurate measurement over a continuous range of frequencies. Apparatus for precision frequency measurement in the microwave region generally includes (1) frequency multipliers or harmonic generators to produce harmonics of known standard frequencies, and (2) a receiver or detector for mixing the unknown signal with the standard frequency in order to produce a beat frequency, which is then measured by (3) an interpolation system.[18,63–65] Application of frequency-scanning or spectrum-analyzer techniques to the detector unit has been used to improve ease of operation. Digital electronic counters have been applied to the problem of measuring the beat-note for interpolation purposes.

The most effective way presently available for generating microwave harmonics of standard frequencies appears to be by means of the use of crystal diodes as harmonic generators.[61–66] The driving power for a crystal-diode harmonic generator is usually furnished by a conventional negative-grid vacuum-tube frequency-multiplier chain,[61] although klystrons are used at the extreme end of the range.[65] Application of crystal-diode

[60] J. M. Shaull, "High precision automatic frequency comparator and recorder," *Tele-Tech*, vol. 14, pp. 58 ff.; January, 1955.

[61] J. M. Shaull, "Frequency multipliers and converters for measurement and control," *Tele-Tech*, vol. 14, pp. 86 ff.; April, 1955.

[62] J. McA. Steele, "The standard frequency monitor at the national physical laboratory," *Proc. IEE*, vol. 102, part 3, pp. 155–165 (with discussion); March, 1955.

[63] R. G. Talpey and Harold Goldberg, "A microwave frequency standard," PROC. IRE, vol. 35, pp. 965–969; September, 1947.

[64] C. G. Montgomery, Ed., "Technique of Microwave Measurements," McGraw-Hill Book Co., New York, N. Y., pp. 343–375; 1947.

[65] L. J. Rueger and A. E. Wilson, "The microwave frequency standard," *Radio-Electronic Engrg*, pp. 5-ff.; March, 1953.

[66] F. D. Lewis, "Harmonic generation in the U-H-F region by means of germanium crystal diodes," *Gen. Rad. Experimenter*, vol. 26, pp. 6–8; July, 1951.

harmonic generators has produced some relatively simple calibrating equipment covering frequencies up to 10,000 mc. (Model 100, Presto Recording Corp., Paramus, New Jersey).

The use of locked-oscillators in frequency-multiplier systems has been extended to the microwave range, one piece of apparatus of this type designed specifically for microwave measurement purposes now commercially available (Model FM-4, Gertsch Products Inc., Los Angeles, California).

Frequency Dividers

Although many frequency measurement systems require frequency multipliers to reach the microwave region, it is also possible to use a microwave oscillator as a source and to divide its frequency for the operation of auxiliary measuring equipment, such as interpolation systems, and clock mechanisms. The regenerative-modulator divider circuit[67] appears to be well suited to use with presently available microwave components.[68] Frequency divider systems operating at lower frequencies can have a wider choice of circuits, regenerative-modulator dividers,[9] multivibrators,[20] and counter-type dividers[69–71] being widely used.

Decade Frequency Generators

Standard-frequency oscillators of extremely high stability are usually constructed in such a manner that their frequency of operation can be adjusted by relatively small amounts only.[36] Hence for measurement purposes, it is desirable to be able to generate frequencies controlled by the reference standard oscillator in order to provide known standard frequencies in the region in which it is desired to make measurements.

The easiest solution to this problem requires only a harmonic generator, or distorter, which can be tuned to the harmonic desired. This solution is usually inadequate for general measurement purposes since only a narrow range is covered at any one harmonic, and the exact calibration of this range must be established during the measurement. Furthermore, even though the range covered is narrow, the harmonics of lower-frequency stages of the system frequently interfere to cause ambiguity and difficulty in identification of the harmonic actually desired.

If the entire range of harmonics of a standard frequency is available simultaneously, it is usually possible to count the intervals from a known reference point. This system is widely used in commercial frequency-standard apparatus.

As the maximum frequency range of measurements has increased, techniques for improving the facility of identification of a given harmonic frequency have been developed. These techniques have taken the form of tuned selective circuits of narrow bandwidth for selecting an individual harmonic,[72] and of relatively complex systems of harmonic generation, harmonic selection, mixing, and filtering to generate a given frequency relatively free from spurious components. Commercial models of this type of standardized-decade-frequency generator[73] have been produced having good rejection of spurious beat notes and unwanted modulation components.

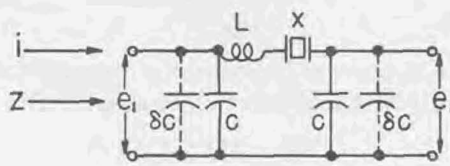


Fig. 19—Case I.

Appendix

Case I (Fig. 19)

C, C = Shunt capacitive elements (assumed equal).

L = Series inductance to bring crystal to series resonance when e_2 is 180 degrees out of phase with i.

X = Crystal.

δC, δC = Output and input capacitances of driving and driven tubes (assumed equal).

i = Input current.

e_1 = Input voltage developed.

e_2 = Output voltage.

Crystal Parameters.[74]

$Q_x = 2.6 \times 10^6$,

$R_x = 100\ \Omega$,

$L_x = 8.27\ h$,

$C_x = 0.000122\ \mu\mu f$,

$f = 5$ mc.

Circuit Analysis (Assuming crystal operating at series resonance). Let:

$$X_L = \omega L = 2X_c$$

where X_L is reactance of L, X_2 is reactance of one capacitance, C. The resistance of L is assumed small enough to be neglected.

$$B = \omega(C + \delta C).$$

Then

$$e_1 = \frac{i}{jB} \frac{(1 - BX_L) + jBR_x}{(2 - BX_L) + jBR_x}$$

$$e_2 = \frac{i}{B} \frac{1}{-BR_x + j(2 - BX_L)}.$$

[67] R. L. Miller, "Fractional frequency generation utilizing regenerative modulation," Proc. IRE, vol. 27, pp. 446–457; July, 1939.

[68] H. Lyons, "Microwave frequency dividers," *Jour. Appl. Phys.*, vol. 21, pp. 59–60; January, 1950.

[69] R. W. Frank, "A computer-type decade frequency synthesizer," 1954 IRE Convention Record, Part 10, "Instrumentation and Industrial Electronics," p. 46; 1954.

[70] R. W. Stuart, "A high speed digital frequency divider of arbitrary scale," 1954 IRE Convention Record, Part 10, "Instrumentation and Industrial Electronics," p. 52; 1954.

[71] G. K. Jensen and J. E. McGeogh, "Four-decade frequency divider," *Electronics*, vol. 28, pp. 154–155; April, 1955.

[72] J. M. Shaull, "Wide range decade frequency generator," *Tele-Tech*, vol. 9, p. 36; November, 1950.

[73] The Plessey Co., Ltd., Ilford (Essex), Eng.; A. Schomandl, Munich, Germany; Rohde and Schwarz, Munich, Germany; Telefunken, A. G., Berlin, Germany.

[74] A. W. Warner, "High-frequency crystal units for primary frequency standards," Proc. IRE, vol. 40, pp. 1030–1033; Sept. 1952.

For e_2 180 degrees out of phase with i

$$B = \frac{2}{X_L}$$

$$\frac{e_1}{i} = Z = \frac{X_L^2}{4R_x} - i\frac{X_L}{2}$$

$$\frac{e_2}{i} = -\frac{X_L^2}{4R_x}.$$

Numerical Values.
Let

$$\frac{e_2}{i} = -\frac{X_L^2}{4R_x} = -\frac{100}{3}.$$

(This value of transfer impedance is also satisfactory for Case II, thus enabling direct comparison.) Then:

$$X_L = 115.5\ \Omega$$

$$L = 3.68\ \mu\text{h}$$

If the Q of L is 230, which is reasonable for a coil of this inductance at this frequency, then

$$X_L/R_L = 230 = 115.5/R_L$$

$$R_L = \frac{115.5}{230} \approx 0.5\ \Omega,$$

which is negligible, as assumed above.

$$C + \delta C = 552\ \mu\mu\text{f}.$$

Assume 0.1 per cent change in L:

$$X_L = 115.5 \times 10^{-3} = 0.1155\ \Omega.$$

This change in reactance must be balanced by a change in crystal reactance to correct phase back to original value. This requires a small change of frequency, Δf. For small changes of frequency close to the series resonance frequency, the crystal reactance

$$X_q = X_0\left(\frac{\omega}{\omega_0} - \frac{\omega_0}{\omega}\right)$$

where X_0 is reactance of crystal inductance, X_L, at series-resonance frequency; $X_0 = 2(5\times10^6)\times8.27 = 2.6 \times10^6\Omega$:

$$X_q = X_0\left(\frac{f+\Delta f}{f} - \frac{f}{f+\Delta f}\right)$$

$$X_0\frac{(f+\Delta f)^2 - f^2}{f(f+\Delta f)} \cong X_0\frac{2f\Delta f + \Delta f^2}{f(f+\Delta f)}.$$

Neglecting higher order terms,

$$X_q = X_0\frac{2\Delta f}{f}$$

$$\frac{X_q}{2X_0} = \frac{\Delta f}{f}$$

X_q then must equal ΔX_L;

$$\frac{\Delta f}{f} = \frac{\Delta X_L}{2X_0} = \frac{0.1155}{2.6\times10^6} = 2\times10^{-10}.$$

Assume 0.1 per cent change in each shunt capacitance, C:

$$\frac{\Delta f}{f} = 2\times10^{-10}.$$

(This is equivalent to 0.5 $\mu\mu$f in each tube capacitance.) Assume 1 $\mu\mu f$ change in one tube capacitance:

$$\frac{\Delta f}{f} = 2\times10^{-10}.$$

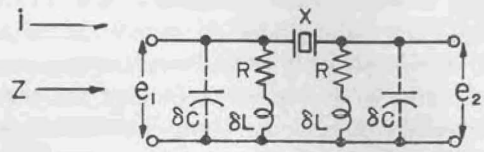


Fig. 20—Case II.

Case II (Fig. 20)

R. R = Shunt resistive elements, X = crystal, δC, δC = output and input capacitances of driving and driven tubes, assumed equal; δL, δL = compensating inductances, i = input current, e_1 = input voltage developed, and e_2 = output voltage.

Crystal Parameters. Same as Case I.

Circuit Analysis. e_2 will be in phase with i when crystal is at series resonance if the shunt impedances are both resistive. This occurs when

$$L = R^2\delta C$$

$$\frac{e_1}{i} = \frac{R(R+R_x)}{2R+R_x}$$

$$\frac{e_2}{i} = \frac{R^2}{2R+R_x}.$$

Numerical Values. Let:

$$\frac{e_2}{i} = \frac{R^2}{2R+R_x} = \frac{100}{3}.$$

Then:

$$R = 100\ \Omega.$$

Assume:

$$C = 10\ \mu\mu\text{f},$$

then

$$L = 0.1\ \mu\text{h} = R^2C.$$

Assume 0.1 per cent change in each shunt resistance, R:

$$\frac{\Delta(2R^2\delta C)}{L_x} = 4.8\times10^{-11},$$

$$\frac{\Delta f}{f} = 2\times10^{-11}.$$

Assume 0.1 per cent change in each compensating inductance, δL:

$$\frac{\Delta f}{f} = 1 \times 10^{-11}.$$

Assume 1 $\mu\mu$f change in one tube capacitance, δC:

$$\frac{\Delta f}{f} = 6 \times 10^{-10}.$$

Recapitulation

On the assumption that these circuits operate so that the crystal is at series resonance, and that the transfer impedance e_2/i is the same for both (100/3), there is little to choose between them. Case II is less sensitive to changes in circuit constants than Case I by an order of magnitude (2×10^{-11} vs 2×10^{-10}), but Case I is less sensitive to changes in tube capacitance by half an order of magnitude (2×10^{-10} vs 6×10^{-10}).

If over-all stability of 10^{-9} is assumed to be about all that can be reasonably expected, the frequency variations ascribed to the crystal coupling network and associated tube capacitances therefore do not seem to present a problem in either circuit. The next part of the analysis is devoted to the remaining part of the closed loop.

Loop Closure

Assume: Transconductance of tubes $= g_m = 1{,}000$ μmho $= 10^{-3}$. Then:

Gain of crystal-coupling-circuit portion

$$= \frac{100}{3} \times 10^{-3} = \frac{1}{30}$$

from grid of driving tube to grid of driven tube. Gain of remainder of closed loop must therefore $= 30$.

Assume: Two tubes, coupled through simple parallel-resonant circuit, transconductance of tubes $= g_m = 1{,}000$ μmho $= 10^{-3}$.

$$\text{Gain} = 30 = R_\beta g_m = 10^{-3} R_\beta$$

$$R_\beta = 30\ k\Omega = 3 \times 10^4$$

where $R_\beta =$ impedance of coupling network at resonance.

Assume: Interstage capacitance $= 20$ $\mu\mu$f, coil resonant with this capacitance.

$$C_\beta = 20\ \mu\mu\text{f}$$

$$X_\beta = 1{,}592\ \Omega \text{ at 5 mc}$$

$$L_\beta = 50.7\ \mu\text{h}$$

$$Q_\beta = 18.9 \text{ at 5 mc}$$

$$\tan \theta_\beta = Q_\beta\left(\frac{\omega_\beta}{\omega} - \frac{\omega}{\omega_\beta}\right),$$

where R_β, C_β and L_β are tuned-circuit parameters, Q_β is the storage factor at the resonant frequency $f_\beta = \omega_\beta/2\pi$, and θ_β is the phase angle of the coupling system.

Assume: 1 $\mu\mu$f change in one tube capacitance

$$\frac{\Delta\omega_\beta}{\omega_\beta} = 2.5 \times 10^{-2}$$

$\tan \theta_\beta = 0.943$ (actual frequency $f = \omega/2\pi$ assumed constant). For crystal coupling network,

$$\tan \theta_\mu = Q_\mu\left(\frac{\omega_\mu}{\omega} - \frac{\omega}{\omega_\mu}\right),$$

where Q_μ is the storage factor at the resonant frequency $f_\mu = \omega_\mu/2\pi$, and θ_μ is the effective phase angle of the crystal coupling network.

Case I

$$Q_\mu = Q_x = 2.6 \times 10^6$$

$$\frac{\Delta f}{f} = 2 \times 10^{-7}$$

Case II

$$Q_\mu = \frac{2.6 \times 10^6}{3}$$

$$\frac{\Delta f}{f} = 6 \times 10^{-7}.$$

Recapitulation. Frequency shift from change in phase-shift of the loop is more important than changes in the crystal coupling network by three orders of magnitude (6×10^{-7} vs 6×10^{-10}). Case I is less sensitive than Case II to changes in capacitance in the closing loop by a half order of magnitude because a factor of three in effective Q_μ is sacrificed in Case II to work the crystal in and out of shunt resistive elements. Both circuits, however, are seriously limited by phase-shift in the closing loop.

It was noted that the coupling circuit was tuned entirely by the interstage capacitance, but this assumption need not be made. If additional capacitance is added at this point, the effect of a change in tube capacitance on the resonant frequency will be reduced, but the storage factor, Q_β, and consequently the rate of change of phase with frequency will be increased to the same extent. The phase shift introduced by a given change in tube capacitance will therefore remain the same, whether or not additional shunt capacitance is employed. If no extra capacitance is added the effect of any change in inductance is a minimum, however, and can be ignored.

It should be noted that in Case II there is zero phase shift in the crystal coupling network, whereas in Case I there is 180 degrees phase shift. Case II is therefore more readily adaptable to two-tube operation. A reasonably simple solution for Case I might be the use of a cathode-coupled twin triode for one of the two tubes.

Coupling systems designed for lower rate of change of phase shift might be worked out, but it would seem a more promising avenue of approach to eliminate the network entirely by going to a single-tube circuit in which the driven and driving tube for the crystal coupling network were one and the same.

Single-Tube Version

To make a single-tube version, the reverse problem exists regarding phase-shift in the Case II and Case I circuits. Case I is more readily adaptable than Case II because of its 180 degree phase shift in the crystal coupling network. To make the Case II circuit work it would be necessary to go to some such expedient as use of a cathode-coupled twin triode.

Since there is no additional gain provided elsewhere, the gain from the grid of the "driving" tube to the grid of the "driven" tube must be unity (actually the same grid), and this specification therefore determines the transfer impedance of the crystal coupling network in terms of the tube transconductance. Assume:

$$\text{Transconductance} = g_m = 1{,}000\ \mu\text{mho} = 10^{-3}$$
$$i = i_p = -g_m e_g = -10^{-3} e_g = -10^{-3} e_2.$$

Case III

$$\frac{e_2}{i} = -10^3 = \frac{-X_L^2}{4R_x},$$
$$X_L = 632\ \Omega$$
$$L = 20.1\ \mu\text{h}$$
$$C, C = 101\ \mu\mu\text{f}$$

Assume 0.1 per cent change in L:

$$\frac{\Delta f}{f} = 1 \times 10^{-9}.$$

Assume 0.1 per cent change in each shunt capacitance, C:

$$\frac{\Delta f}{f} = 1 \times 10^{-9}.$$

Assume 1 $\mu\mu$f change in one tube capacitance:

$$\frac{\Delta f}{f} = 6 \times 10^{-9}.$$

Case IV (Two-Tube Circuit)

$$\frac{e_2}{i} = 10^3 = \frac{R^2}{2R + R_x}$$
$$R = 2{,}050\ \Omega$$
$$\delta L = 42\ \mu\text{h} = R^2 \delta C.$$

Assume 0.1 per cent change in each shunt resistance, R:

$$\frac{\Delta(2R^2\delta C)}{L_x} = 2 \times 10^{-8}$$
$$\frac{\Delta f}{f} = 1 \times 10^{-8}.$$

Assume 0.1 per cent change in each compensating inductance, δL:

$$\frac{\Delta f}{f} = 5 \times 10^{-9}.$$

Assume 1 $\mu\mu$f change in one tube capacitance, δC:

$$\frac{\Delta f}{f} = 3 \times 10^{-7}.$$

Recapitulation. In the single-tube version, Case I is markedly superior to the Case II circuit. To obtain the necessary gain, the impedance level of the crystal coupling network of Case II becomes too high, and dependence of frequency upon circuit parameters is substantial. The worst variation comes from changes arising from variations in tube capacitance, which are worse than those in Case I by almost two orders of magnitude.

In the single-tube, Case I, oscillator (Case III), however, the changes in frequency from this source are still only 6×10^{-9}, and it seems probable that sensible circuit design could reduce tube capacitance variations to about 0.1 $\mu\mu$f, rather than 1 $\mu\mu$f. Requirements of 0.1 per cent stability in circuit parameters are not unreasonable, and it therefore seems feasible to construct an oscillator of this type to yield circuit stability of 10^{-9}.

The advantage of using dc control of effective g_m for amplitude control, rather than a thermal bridge, is indicated by the sensitivity of the frequency to phase shift in circuits other than the crystal coupling network. Anything that reduces gain around the loop requires increased gain elsewhere, and this gain can only be obtained at the expense of great care in maintaining low rate of change of phase shift. It seems probable that the simple Case III circuit, using one oscillator tube and a stable, amplified, delayed AVC system with semi-starved operation of the oscillator tube will give not only an inexpensive solution but, perhaps, the best one.

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ADDENDA

for

Frequency and Time Standards

BY

F. D. LEWIS

1. Since the original publication, the International Second has been defined as 9,192,631,770 oscillations of the cesium atom as observed in the atomic-beam apparatus at zero C-field (the magnetic field existing in the drift space between the cavities in Fig. 17). This is now the primary definition of the second, coinciding with the Ephemeris second (pp 1046–7), but being more readily determined for calibration purposes.

2. Under "Further Atomic Frequency Standards" (p 1062), it is interesting to note that the "optical pumping" scheme, which was a basic part of Dicke's experimental work at the time of the original paper, has been applied in the rubidium-87 gas-cell frequency standards which are now commercially available.

An additional application of the **MASER** principle was successfully carried out by Ramsey and Kleppner at Harvard, using atomic hydrogen and a magnetic state selector. In both the hydrogen maser and the rubidium gas-cell, the walls of the cell are lined with polytetraflouroethylene to improve the operation of the device by reducing the effects of wall collisions on the active atoms.

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