The oscillator developed by Gouriet, which it is stated, has been used in the B. B. C. since 1938,[4] was not described in the technical press until 1947 and then in a book, "Radio Engineering" by E. K. Sandeman. The circuit was independently developed by Clapp in 1946 (described in the PROCEEDINGS OF THE I.R.E., 1948).[2] The circuits developed by Seiler (*QST*, 1941)[6] and Lampkin (PROCEEDINGS OF THE I.R.E., 1939)[7] follow the same criterion, but were not described clearly on the impedance concept.

During the war development of stable oscillators in Czechoslovakia was carried out independently and without exchange of technical information with the West. The circuit of Fig. 3 of this paper was developed by *Radioslavia* in 1945, but publication did not occur until 1949.[1] Meanwhile, the same circuit was developed independently by O. Landini in Italy and was described in *Radio Rivista*, 1948.

Precision Quartz Resonator Frequency Standards*

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Summary—High-precision quartz crystal resonators were recently added as a part of the primary standard of frequency at the National Bureau of Standards. Their reliability over short and long periods of time resulted in establishment of a frequency and time reference system constant to 1 part in 10^{10} per day. Measurement equipment and methods, are described in detail. The equivalent circuit for the crystal unit is discussed and the effects of external influences such as stray capacitance, electric and magnetic fields, connecting cables, ambient temperatures, and amplitude of vibration are considered. An assessment method is discussed. This method is based on the fitting of a natural aging or drift curve for each resonator to an observed curve after sufficient performance data are obtained. The use of resonators with crystal clocks represents one of the simplest and most reliable and economical methods of establishing a precise frequency reference in terms of mean solar time and of noting deviations in the earth's rate of rotation.

INTRODUCTION

HIGH-PRECISION quartz crystal resonators were added in 1951 as a part of the primary standard of frequency at the National Bureau of Standards. Their reliability over short and long periods of time has resulted in improved performance evaluation of the primary oscillators. It is now possible to determine day-to-day changes in standard oscillators, and in the frequencies as transmitted from WWV, with a precision of 1 part in 10^{10}. New developments in research, electronic guidance, control and communication systems indicate a need for a precision and constancy of this order.

As early as 1946 detailed bridge measurements were made on a number of 100-kc GT quartz crystal units to determine their suitability for use in new frequency standards. Bridge measurements on crystal units as resonators enable one to determine such characteristics as temperature coefficient, Q, daily drift, relative stability and susceptibility to vibration. Other important factors readily studied are variation of frequency and series resistance with changes in driving current.

Development of Precision Resonators

Precision crystal units with higher Q values were becoming available, enabling more sensitive comparisons with the primary standard of frequency. Improved GT quartz crystal units were designed and built at the Bell Telephone Laboratories.[1] During development about 40 crystal units were tested at the National Bureau of Standards with the objectives of obtaining reduced initial aging or drifting in frequency, higher operating Q, lower temperature-frequency coefficient and a more linear frequency-amplitude characteristic in the operating range.

Design considerations centered around two principal types, one being generally similar to those used in Loran oscillators but using improved techniques and evaporated gold electrodes. A few of another type were made, similar to the above, but approximately three times as thick. Such an increase in thickness gives a much larger ratio of volume to area and thus was expected to show smaller effects from surface changes with age. Although somewhat higher Q (as high as 4 million at room temperature) was obtained with the thicker plates, aging was not significantly improved over that obtained with the thin crystals and susceptibility to mechanical shock was greater. The values in Table I Column one, opposite, are typical for the better units of each type.

* Decimal classification: R214.2. Original manuscript received by the IRE, January 5, 1954; revised manuscript received, April 21, 1954.

† National Bureau of Standards, Washington, D. C.

[1] J. P. Griffin, "High stability 100-kc crystal units for frequency standards," *Bell Labs. Record*, vol. 30, pp. 433–438; Nov., 1952.

TABLE I

GT Type	Equivalent L, henries	Equivalent Series R	Static C $\mu\mu f$	Q (million)	Frequency drift, parts per 10^9/day Initial	After 1 yr.	After 3 yrs.
Earlier types	17.2	40	58	0.27	20	2.9	1.2
New Thin	23.4	6.4	40	2.3	3.5	0.70	0.15
New Thick	60.7	11	18	3.5	3.4	0.40	0.10

Advantages of Resonators

In an oscillator the resulting frequency stability is influenced by the variations of a number of circuit components, tube aging, power-supply fluctuations, and load variations, in addition to changes in the crystal unit itself. Crystal resonators as measured in a balanced bridge network of low impedance are essentially free of all these difficulties and are not subject to interruptions caused by tube and component failures. They can be measured at very low driving currents where frequency is independent of amplitude. The resonator is an auxiliary standard; its use requires a precision-adjustable oscillator and one or more unadjusted oscillators to serve as a frequency reference and continuous source of standard frequency. However, temporary failures in the auxiliary equipment cause no discrepancies in the resonator-reference frequency.

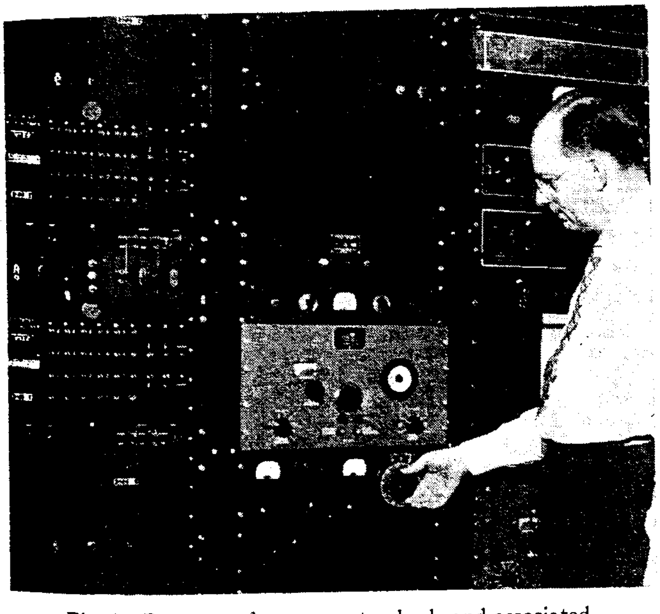

Fig. 1—Resonator frequency standards and associated measurement equipment.

Description of Equipment

The resonator frequency standards as shown in Fig. 1 include the following: (1) temperature control chamber for resonator crystals, near bottom of right rack (with a similar chamber for experimental tests in left rack), (2) special low-impedance bridge, (3) precision adjustable oscillator located above the bridge, (4) high-gain, narrow-band receiver, (5) frequency multipliers and converter, (6) dual electronic frequency counters, in top of left rack.

Temperature Control

The temperature control compartment containing eight resonator crystals is made up of five concentric cubical aluminum boxes with an outer plywood enclosure. Several layers of heavy wool felt are used between alternate walls with mat type heaters and mercury column thermostats on intermediate walls. The thermostats control the operation of the heaters through sensitive relays having mercury-wetted contacts. After more than two years of continuous operation, daily observations of the inner compartment thermometer showed less than 0.01 degree C. variation over the entire period. Maximum daily changes computed from known temperature coefficients of the crystals, were less than 0.001 degree C. A similar outer compartment as used on several new standard oscillators gave an ambient temperature reduction factor of better than 200 to 1. The inner temperature stability obtainable is limited primarily by the functional precision of the inner thermostat rather than by the product of the outer and inner oven reduction factors. The eight crystals in the compartment have temperature-frequency coefficients ranging between ± 20 and 200 parts in 10^9 per degree at the operating point of 41.25 degrees C.

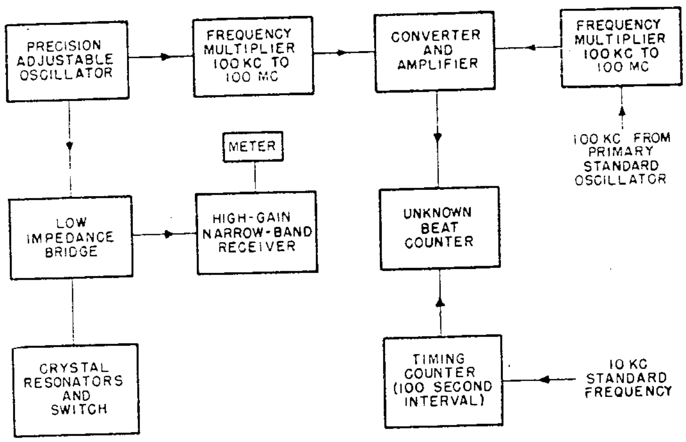

Fig. 2—Block diagram of resonator measuring equipment.

Crystal Measuring Equipment

A block diagram of the resonator measuring equipment is shown in Fig. 2. A 100-kc oscillator, adjustable over a range of approximately ± 1 cycle and with a resetability and 100-second constancy of about 1 part in 10^{10}, is used to drive a special Wheatstone bridge with a resonator crystal connected as one of the bridge arms. In making a measurement the oscillator is adjusted to the series resonant frequency of the crystal and the variable resistive arm is adjusted to equal the equivalent series resistance of the crystal.

A specially constructed narrow-band receiver is ~~used~~ as a balance detector. A balanced input transformer matches the output impedance of the bridge to a three-stage tuned amplifier operating at 100-kc. For large signals, as the bridge is being balanced, the grid of the third stage develops an avc voltage which is applied to the other two grids, thus giving a logarithmic response. A 101-kc output from a crystal oscillator in the receiver is applied with the signal to one pair of diodes of a IN71 germanium quad rectifier to obtain an IF frequency of 1-kc. A two-stage tuned IF amplifier supplies the 1-kc signal to the other pair of rectifiers to operate the dc indicating meter. Half-scale deflection is obtained with an input of less than one-tenth of a microvolt. The half-power bandwidth of the receiver is approximately 30 cycles.

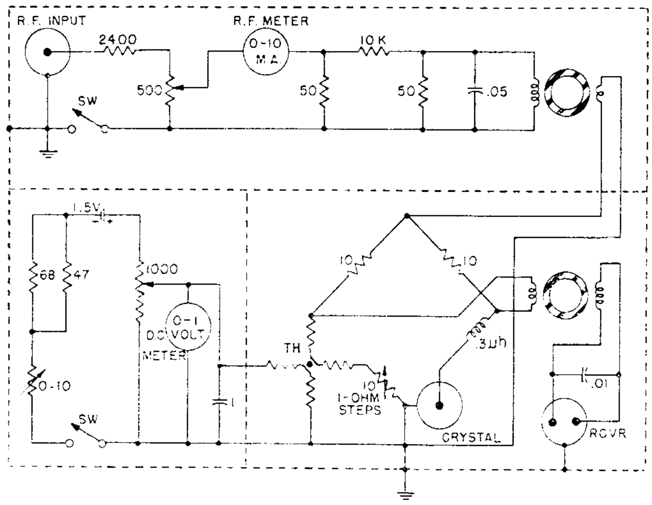

Fig. 3—Circuit of low-impedance crystal bridge.

A circuit schematic of the bridge is shown in Fig. 3. The rf input is connected through an adjustable attenuator and meter to permit setting the bridge input to give a crystal current of approximately 10 microamperes. Impedance matching transformers with low capacitive coupling between windings are used to couple into and out of the bridge network. The fixed bridge arms are 10-ohm matched resistors of low inductance. An inductance compensated 10-ohm resistor with 1-ohm steps is used in the arm adjacent to the crystal in series with a special indirectly-heated, evacuated tungsten thermistor. By means of the decade resistor and the thermistor, resistance values between 4 and 18 ohms can be set within 0.001 ohm. The 0.3 μh rf choke in series with the crystal arm is used to compensate for the small amount of inductance in the decade resistor. Stray reactances in the bridge networks and coupling circuits were kept to a minimum and careful attention was given to shielding and grounding.

Other methods of measuring crystal resonators which require an adjustment of drive frequency only have been considered. These methods are much more readily adapted to automatic measuring systems, but may require considerable development to gain the precision and reliability of the bridge method currently used for manual measurements. The use of a crystal phase discriminator followed by a high gain amplifier and indicator or servo device showed promise. Another scheme, given preliminary tests, slowly swept the drive oscillator through the resonator frequency and automatically disconnected it as resonance was passed. The exponentially decaying resonator output was amplified and limited, multiplied to 1,000 mc and measured by electronic counters. With the high Q crystals a 10-second count was readily obtained. Results were not consistent, nor of desired precision, perhaps because of stray coupling and phase shifts in the amplifier and limiter stages as extremely high gain is required.

Frequency Comparison Equipment

In making crystal measurements it is necessary to compare the adjustable driving oscillator to a high degree of precision with one of the oscillators associated with the primary standard of frequency. This is done by multiplying both the adjustable and standard oscillator frequencies to 100 mc and obtaining the beat or difference frequency from a converter. Frequency multiplication is accomplished by Class C harmonic amplifiers and filters in steps of 2 and 5 in each of three decade stages. The difference frequency is counted for precisely 100 seconds and directly displayed in parts in 10^{10} on the top electronic counter shown in the left rack of Fig. 1. The bottom counter simultaneously counts a standard frequency of 10 kc to determine the counting interval by stopping both units after it has registered a total of 1 million pulses.

MEASUREMENTS

The equipment described has been in daily use for over two years in measuring eight selected crystal units as a part of the primary standard of frequency and in making periodic special tests on experimental units. A similar bridge with plug-in resistance units and an external calibrated attenuator were used in conjunction with the above equipment to make tests of frequency and resistance variation with changes in amplitude of driving current. Commercial bridges and receivers were also used in the earlier 100-kc measurements and at other frequencies, especially 5 mc, with a precision of about 1 part in 10^9.

Equivalent Circuit of a Crystal Unit

The equivalent circuit of a quartz-crystal unit near a major mode of vibration is shown in the inset in Fig. 4. L_1, C_1, and R_1 are the equivalent of the motional impedances in the crystal and C_0 is the static capacitance of the electrodes and the holder. In use an external capacitance also is combined with C_0 resulting from terminals and leads and it is this over-all equivalent network that is effective in a given application. In the bridge measurements, near series resonance, the frequency sensitivity for a given bridge and detector combination is a function of the crystal reactance change with frequency, as shown by the following equation:

$$\frac{df}{f} \approx \frac{dx}{2QR}.$$

For the crystals used, having a Q of about 2 million, successive measurements have shown that a frequency sensitivity of better than 1 part in 10^{10} is readily obtained.

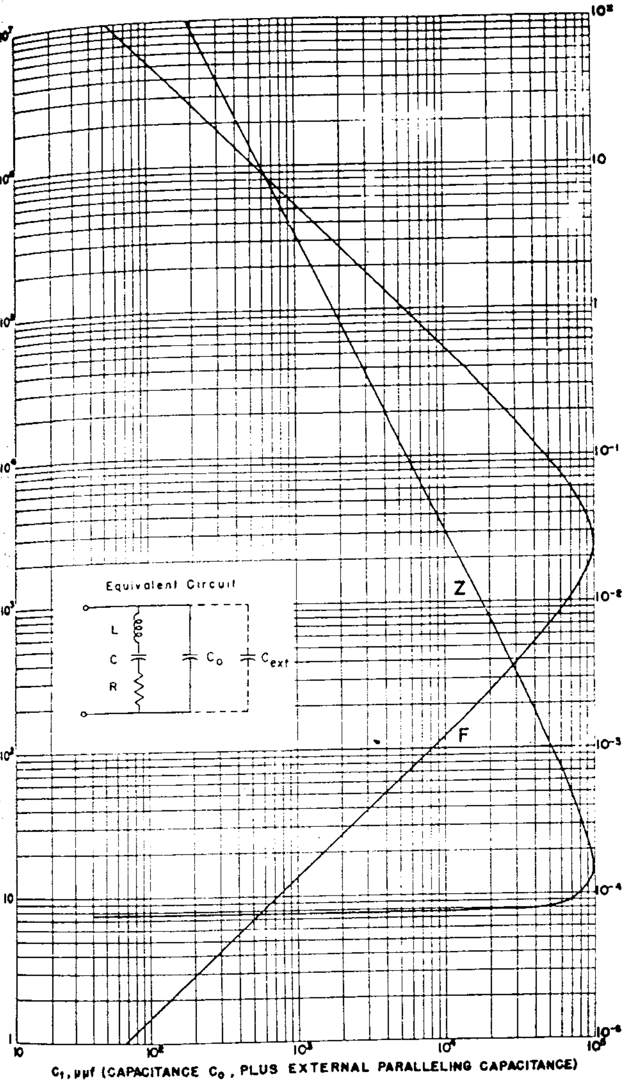

Fig. 4—Crystal frequency and impedance curves.

Experimental Measurements

Frequency and resistance variation versus amplitude of vibration (crystal current) tests were made on each of the crystal units and proved to be one of the most useful methods of determining relative performance. Generally three successive amplitude curves were obtained; on some units reproducibility was excellent while on others deviations, particularly in the first run, were noted. Sudden breaks in the frequency curve were generally associated with corresponding resistance changes. On these units difficulty in balancing the bridge was frequently noted and day-to-day constancy was inferior to those exhibiting stable characteristics. Amplitude curves for three crystal units are shown in Fig. 5. Some crystals had even greater irregularities than shown in Fig. 5 (solid curve) which were attributed to other coupled modes of vibration or mechanical imperfections.

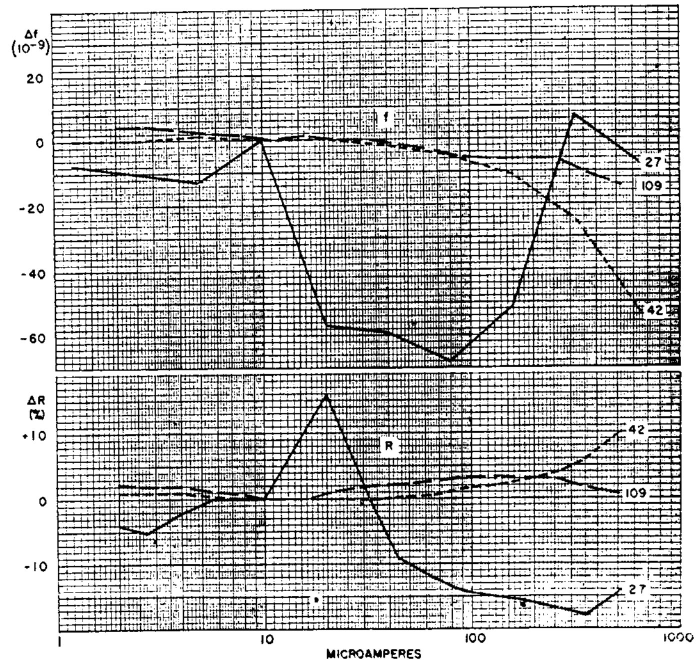

Fig. 5—Frequency and resistance variation versus crystal current for three GT crystal units.

Frequency-temperature coefficients for GT-cut crystals are generally low over a wide temperature range. Precise coefficients near 40 degrees were readily obtained by shutting off the inner resonator oven control; most units ranged between 0 and 200 parts in 10^9 per degree C. Variation of resistance over a wide temperature range for a number of crystals was found to be between 0.5 and and 1.5 per cent per degree C. For instance, units operated at dry ice temperature (−78 degrees C.) had resistances approximately one-half as large (twice the Q) as when operated at room temperature. There is some evidence that the daily frequency drift rate is less at the lower temperatures.

As it is necessary to have external capacitance across the crystal in any useful application, this effect was investigated using bridge measurements. Fig. 4 shows frequency and impedance changes versus paralleling external capacitance observed for one of the resonators. A large amount of useful information is shown on this graph; for example, the portions of the curves below the knees apply to series resonance while the top portions apply to anti-resonance. At the turning point, resonant and anti-resonant frequencies coincide with a single nonreactive impedance. At this point the capacitive reactance of $(C_{ext}+C_0)$ and the nonreactive terminal impedance are both equal to twice the equivalent series resistance of the crystal at series resonance. With additional capacitance a nonreactive impedance cannot be obtained. Considerable capacitance can be added across a high Q crystal unit without appreciably changing the series resonant frequency.

The effect due to a mismatched connecting coaxial cable, however, is more pronounced. For example, with a 7.5-ohm crystal having a Q of 2 million connected to the bridge with a 50-ohm coaxial cable, where the line loss is small compared to the crystal resistance, the frequency is lowered about 2 parts in 10^9 per foot.

A dc polarizing voltage, applied through a 1-megohm resistor and varied over a maximum range of ± 900 volts, showed a frequency variation of very nearly 1 part in 10^8 per volt.

A static magnetic field of 2,000 gausses, applied to an electrostatically shielded crystal unit, changed the frequency less than 5 parts in 10^8.

Other effects noted on the crystal units with unshielded glass envelopes, especially when wrapped with nonmetallic insulating material, were a reduction of as much as 30 per cent in Q and frequency changes as great as $+1$ part in 10^6. Later units were therefore provided with a metal covering to eliminate this difficulty. It was found that changes in the physical orientation of the crystal caused the resonant frequency to vary by as much as 1 part in 10^7. For maximum mechanical strength the horizontal position was considered most desirable and was used where possible.

Procedure for Daily Measurements

A crystal resonator measurement is made by connecting it into the bridge by means of the selector switch and making successive adjustments of increasingly fine order on the drive oscillator frequency, bridge resistance dials and receiver gain to obtain a minimum reading on the indicating meter of the receiver. As fine balance is approached it is necessary to make very small adjustments, observing the effect for several seconds. This is because of the very high crystal Q, which prevents sudden changes in the vibrating frequency of the crystal. When finally balanced, the crystal arm has a nonreactive impedance equal to its series resistance if no uncompensated stray reactance exists in the other bridge arms. Because of the low impedance used no adjustable compensation was provided, any small residual reactance in the bridge is compensated by the crystal arm being very slightly off resonance at balance. The series resistances of the crystal units measured have shown very little change since installation. Resistance data are incidental to the process of frequency determination, although are useful in certain crystal studies.

The frequency of the drive oscillator is measured at balance for each of the crystal resonators by comparing it with a selected reference oscillator as explained previously. Two consecutive measurements made on each crystal daily verify an over-all precision of ± 1 part in 10^{10} in intercomparison of the resonators and the reference oscillator. After sufficient data are available the extrapolated daily frequencies are useful in predicting the relative performance of the reference in a manner similar to that used with a group of oscillators.[2]

When first installed it was planned to use the resonators only to establish a more constant day-to-day reference frequency. However, their consistent reliability over both short and long periods when compared with several new oscillators, led to their consideration for rating existing clocks. Performance data on NBS crystal clocks have been supplied to the Naval Observatory for a number of years. These clocks, when compared by means of the WWV transmitted time signals with other precision clocks, are used to establish a continuous time system to which corrections are made by star observations. By comparing a resonator's frequency at regular intervals with the frequency of the oscillator driving one of these clocks, a mean value of frequency difference during the interval may be obtained. This difference frequency may be used to calculate the equivalent time difference which would have occurred if the resonator crystal had been used to drive a clock. These time differences when summed constitute a "resonator clock" rated in terms of the oscillator clock to which it has been referred. For valid results, the frequencies of both the crystal clock and the resonator clock must have uniform rates (clock accelerations) over periods of time considerably longer than the measurement intervals. For more than two years these computations have been made on four of the best resonators and the equivalent time thus obtained compares favorably with the best crystal clocks. Data on these resonator clocks are also given to the Naval Observatory to supplement the crystal clock data.

Resonator Performance Evaluation

Frequency-drift curves for a two-year period for each of the eight resonator crystals as compared with the weighted 100-day mean frequency determinations for the primary standard are shown in Fig. 6. It may be noted that the crystals drift rather constantly to a higher frequency with a gradually decreasing rate. It has been observed for a number of years that precision crystal oscillators and resonators have drift curves that very closely follow a natural aging or logarithmic law; that is, total drift when measured from $t=1$ to any time t days later is

$$D = \alpha \log_e t.$$

The drift (or aging) rate at any time, t is

$$R = \frac{dD}{dt} = \alpha/t.$$

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

Thus α represents the instantaneous hypothetical drift at $t=1$ day if t is given in days. For crystals older than about 30 days these equations have proved to be highly consistent. It seems obvious that they are not applicable near the region of $t=0$. Even if valid for $t=1$ day, the value for α is not directly measurable, as a crystal starts drifting from the time it is ground and mounted. The magnitude of α and the value for t, may be found by determining two successive drift rates a known number of days (t_2-t_1) apart and solving for α and t_1, in simultaneous equations as follows:

$$R_1 = \alpha/t_1$$

$$R_2 = \alpha/[t_1 + (t_2 - t_1)]$$

Knowing these constants, it is possible to determine the predicted drift rate for any future period. A new daily rate of drift is determined monthly by this method for each of the resonators. These data and similar extrapolations for several oscillators are used in establishing a uniform mean reference standard from which individual frequency standards are calibrated. The eight crystal resonators used as a part of the primary standard of frequency for the past two years have resulted in the ability to determine day-to-day performance of all reliable oscillators and resonators in the group within 1 part in 10^{10} in relative value. The 100-day absolute frequency values are uncertain to about 1 part in 10^8, dependent on the earth's mean rate of rotation.

Assessment Over Long Intervals

Periodic variations, reflected similarly in each of the resonator performance curves as normally plotted on an expanded scale, led to an investigation relating to variations in the earth's rate of rotation. Both random and periodic variations in the earth's rate have been known to exist for a number of years and approximate magnitudes of these variations have recently been reported by numerous observers. Over periods of years the larger changes may be verified by astronomical methods alone. To determine changes as they occur it is necessary to depend on extremely reliable clocks operating over extended periods. The demonstrated reliability of the resonator clocks when rated by means of the improved oscillator clocks at NBS enables these phenomena to be evaluated to a higher order of precision than heretofore possible.

Referring again to Fig. 6, the dashed curve, L_2, represents a computed logarithmic segment which most nearly coincides with the observed drift for resonator No. 2. Each curve is displaced 2 parts in 10^8 at the beginning of the graph for clarity in plotting. In searching for variations in the earth's rate, frequency curves for each resonator based only on the equivalent time changes as shown by 20-day Naval Observatory corrections are used rather than the 100-day mean frequency values as shown in Fig. 6. These curves were compared with the computed logarithmic drift curves for four of the best resonators and the residual deviations from the resulting uniform frequency and time were obtained.

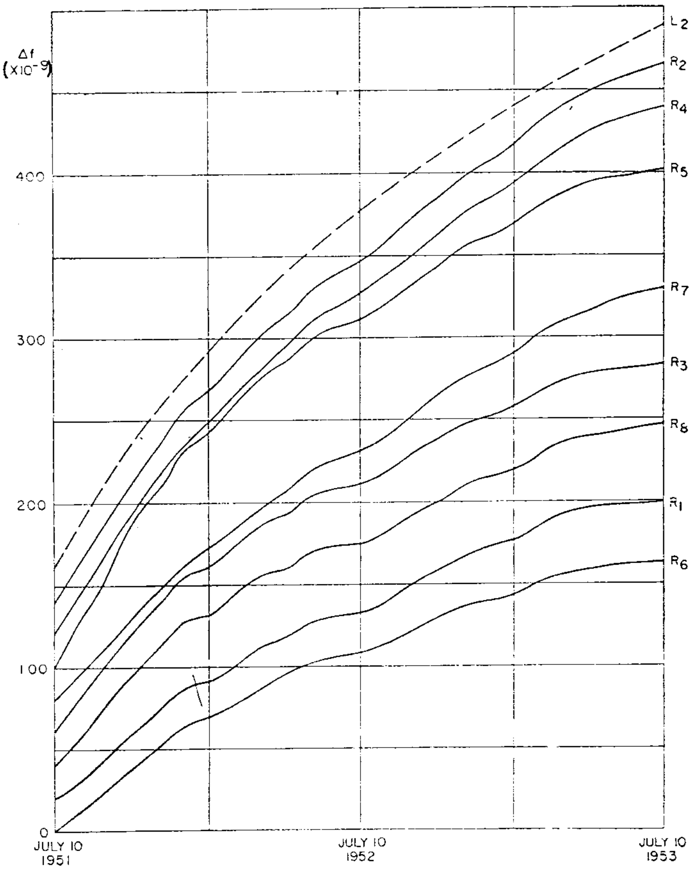

Fig. 6—Frequency drift based on absolute values for eight resonator crystals and computed logarithmic drift for one unit (dashed curve). Δf, expressed in parts in 10^9, indicates change from the fundamental frequency.

Results of these computations are shown in Fig. 7, on the following page. It may be noted that the curves for each of the resonators are very similar. The changes in magnitude and phase of the frequency curves are most significant and may be taken to reflect similar changes, of the opposite sign, in the earth's rate. As the residual frequency curves shown represent differences between slightly dissimilar curves starting from an arbitrary point, it is apparent that the zero reference co-ordinate might be shifted if a different starting point were chosen. Also because of the curve fitting method for zero total integrated time difference, changes in the total interval used or end point chosen would cause somewhat similar effects. The shape of the frequency curve is not appreciably changed by these operations; however, the magnitude and shape of the resulting integrated time curve is considerably altered. Thus, for this curve fitting method, the time-computed frequency values for the beginning and ending of the period should represent mean values at these two end points to obtain the lowest value of maximum time deviation. The values for α and t_1 were computed over a period July 10, 1951 to March 1, 1953 and the curves were continued to complete the two year period. It seems a slightly different starting point might have reduced somewhat the maximum time deviation as shown.

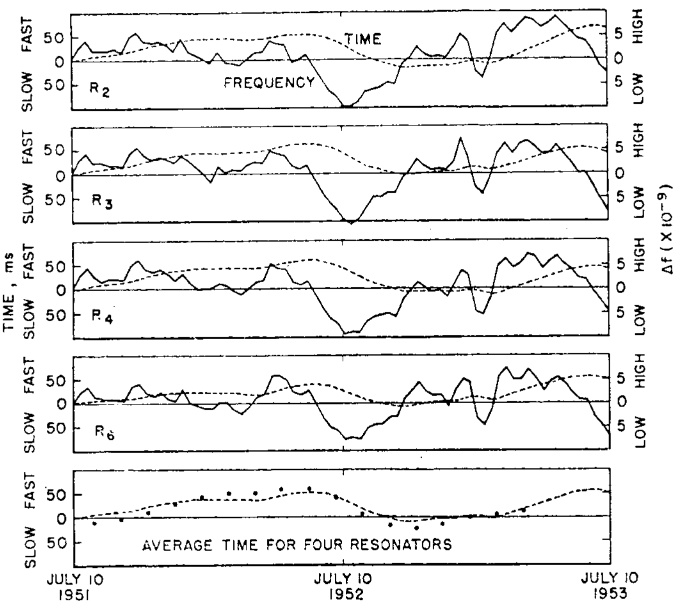

Fig. 7—Residual frequency and time curves for four crystal resonators. With reversed signs these curves reflect variations in the earth's rate of rotation. Dotted points on the average graph show the curve corrected for polar variation.

This was apparent only after considerable computation of the time curves and was believed to be of secondary importance from a frequency standpoint. The first part of the curves may not precisely follow the logarithmic law, as the two-year period taken started only three months after the resonators were installed. Future predictions for these performance curves should be much more precise because of the longer total intervals and the much lower drift rates as the resonators become older. Also, on one unit frequencies and integrated time values were computed for every fifth day to check the validity of the curves using values for only every tenth day. The two curves were practically identical. The average time curve of Fig. 7 with reversed signs may be taken to reflect the approximate variations in the earth's rate of rotation. The resonator frequency and time curves (through March 1953) were computed using Naval Observatory corrections from which the polar variation term had not been removed. Since April 1, 1953 the N2 corrections with polar variation term removed have been used. The dotted points on the average time graph show the curve corrected for combined variation in longitude at the Washington and Florida observatories caused by polar variation.

Fig. 8 illustrates the reliability of the logarithmic method of extrapolation over long intervals. This curve was computed for oscillator No. 24 in a manner similar to that used with the resonators using a single equation for the entire period. Values used were

$$\alpha = 118 \times 10^{-8}/\text{day and } t_1 = 403 \text{ days.}$$

During the entire five-year period the greatest departure from the computed logarithmic curve was 1.8 parts in 10^8; average deviation without regard to sign was less than 1 part in 10^8.

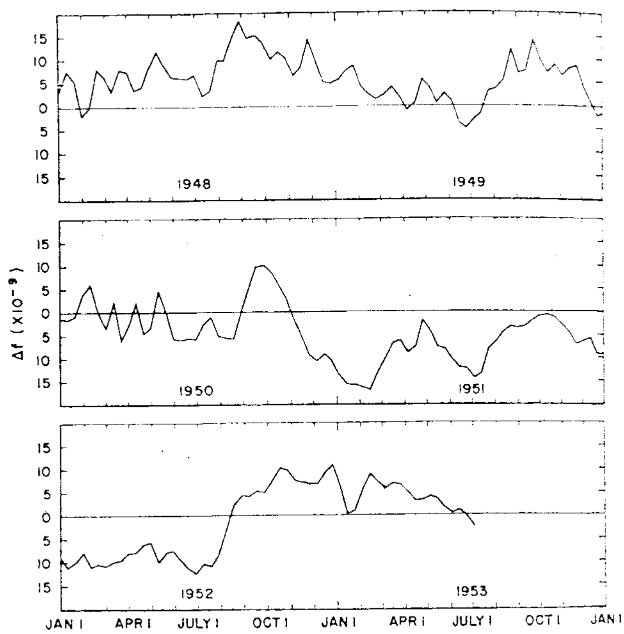

Fig. 8—Residual frequency curve for oscillator no. 24.

Conclusions

Precision quartz crystal resonators and applicable instrumentation have been developed to a degree of constancy and reliability which equals or exceeds the performance of the best crystal oscillators. When used to evaluate the performance of several precision oscillators of similar stability, a relative reference frequency, constant to 1 part in 10^{10} per day, may be established. To determine frequencies and time intervals in terms of the mean solar second, it is necessary to select a period over which the mean values will be considered and to make either periodic step adjustments or to uniformly "steer" the derived values to conform with any significant changes in the earth's rate. Thus occasional monthly or quarterly periodic frequency calibrations, even though difficult, with some invariant standard when available would be highly advantageous, and would establish a uniform frequency and time system.

Meanwhile, the logarithmic method of extrapolation, applied to an undisturbed group of quartz crystal resonators and oscillators, represents perhaps the nearest approach to an invariant frequency and time standard. The use of a group of crystal resonators to rate oscillators of similar constancy represents one of the most reliable and economical methods of establishing a precise frequency reference in terms of mean solar time and of studying deviations in the earth's rate of rotation.