ADJUSTMENT OF HIGH-PRECISION FREQUENCY AND TIME STANDARDS

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Adjustment of High-Precision Frequency and Time Standards*

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Summary—**High-precision frequency and time standards are becoming more and more widely used in many technical fields. The basic equipment used by the Central Radio Propagation Laboratory of the National Bureau of Standards in providing and broadcasting standard frequency and time signals is discussed. Mention is made of the manner in which it is adjusted and the corrections which may be applied to make use of the ultimate accuracy that may be expected in using these signals for measuring and calibrating similar equipment. Several methods are given for checking the frequency of precision oscillators and precision clock performance. Suggestions are given as to methods of recording and evaluating performance data for such standards. Expected improvements in constancy and accuracy and possible future changes in the types of standards used in physical time measurements are considered.**

INTRODUCTION

HIGH-PRECISION frequency and time standards are becoming more and more widely used in technical and scientific fields. Among their uses are: control sources for standard-frequency and time broadcasting; time standards for astronomical observatories; synchronization of master and slave stations for pulse navigation systems; investigation of long-distance radio transmission phenomena by pulse techniques; as the heart of frequency synthesizers in large communications systems; and in physical research laboratories for precise calibrations and measurements, such as time-rate phenomena and microwave spectroscopy.

While this paper deals primarily with the adjustment and performance of high-precision frequency and time standards, many of the principles involved and techniques discussed should prove helpful to those using the WWV frequencies or time signals in adjusting or calibrating other high or medium precision equipment.

The accuracies presently required by some users of frequency and time services are approximately as shown in Table I.

TABLE I

Service	Accuracy (frequency)	Sec/day (time)
Physical research Astronomers	1×10^{-8}	±0.001
Monitoring stations Surveyors	1×10^{-7}	±0.01
Radio broadcasting Astro-navigators	1×10^{-6}	±0.1
Commercial communication	1×10^{-5}	
Musical instruments	1×10^{-4}	
Commercial power distribution	1×10^{-3}	(±5)

Equipment and Methods in General Use

A high-precision frequency standard may be defined as one whose changes in frequency are less than 1 part in 10^8 per day. This degree of precision now requires continuous operation of the standard oscillator, with the control unit and other critical elements operating in a temperature-stabilized compartment. Very careful shielding, filtering of battery supply leads, and use of buffer amplifier stages are also necessary, especially if more than one oscillator unit is operated at a single location. Such standards now generally employ a GT-cut quartz-crystal[1] operated in a bridge-stabilized oscillator circuit arrangement.[2]

A standard oscillator in wide use operates at 100 kc and has a multiposition switch for coarse frequency adjustments of approximately 4 parts in 10^6 per step. A precision gear-driven capacitor with a drum dial arrangement of 5,000 dial divisions provides for a control of frequency to approximately 1 part in 10^9 per division. A dial with such an expanded scale is of great advantage in making precise frequency adjustments and interpolations.

A minimum of three standard oscillators is recommended for those installations requiring a reasonable maximum of reliability and continuity of service. By intercomparing three standards locally, either once daily or continuously, short-time stability may be determined to a much higher order than possible through radio transmission comparisons. The most reliable standard may thus be determined and used to supply the desired need, with the other units available for standby duty.

For checking frequencies by the time-comparison method, and for supplying the desired audio frequencies and time intervals, each standard oscillator should be operated continuously, and two or more such oscillators should be provided with frequency-dividing and synchronous-clock equipments. The frequency dividers may be pulse counters, fractional frequency generators, locked oscillators, or multivibrators. The choice of type should be influenced by the number of output frequencies and wave form desired, simplicity of adjustment, and reliability of operation required. If seconds intervals are desired for laboratory use, a system similar to that used at WWV, wherein the pulse trains are generated electronically and selected mechanically by a rotating cam, offers certain advantages. An alternate method is to divide the standard frequency down to 1 cps by counter methods, employing an all-electronic system.

A continuously adjustable phase shifter of the polyphase electrostatic or electromagnetic type is desirable in the divider chain, preferably at the 1,000-cycle stage, to permit the clock or seconds signals to be synchronized. This device also provides a convenient means of measuring small daily differences in time kept by different standard-oscillator clocks, including time signals received by radio. Measurements of time differences may be made by adjusting the phase shifter dial until the pulses coincide on an oscilloscope screen when alternately or simultaneously connected.

Other methods for measuring and recording time differences may employ a spark chronograph, or a polyphase modulator and integrating phasemeter.[3]

A harmonic generator and mixer unit may be conveniently used in rapid frequency intercomparison. This device may be provided with two inputs and means to control the inputs which feed into the crystal diode harmonic generators. The common output is connected to a radio receiver for counting the difference beats between two local standards. Two frequency multiplier units having outputs of 500 and 2,500 kc or other convenient frequencies, are recommended to facilitate frequency measurements at higher harmonics.

Standard Frequency and Time Broadcasts from WWV

The radio and audio frequencies as transmitted from WWV, near Washington, D. C.[4] are accurate (with reference to mean solar time) within 1 part in 50 million. The time signals broadcast by WWV are maintained in agreement with U. S. Naval Observatory time within several hundredths of a second. This is done by setting the WWV control oscillator frequency slightly higher or lower than exactly 100 kc by an amount ordinarily not greater than 1 part in 10^8, to advance or retard gradually the broadcast time. For this reason the time broadcast by WWV is uniform, changing by less than 0.001-second average or 0.002-second maximum per day. Fig. 1 shows the frequency and time deviations of the WWV transmissions for the years 1947 and 1948.

The present oscillators at WWV have a gradual and fairly constant drift to a higher frequency of from 0.6 to 1.2 parts in 10^9 per day. The control standard at WWV was adjusted on an average of every twelve days during the past year. Adjustments are usually to a lower frequency but are occasionally made to a higher frequency because of slight discrepancies in the assessment of average drift rate in terms of the Observatory's time determinations. The adjustments

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[1] W. P. Mason, "A new quartz crystal plate, designated the *GT*, which produces a very constant frequency over a wide temperature range," PROC. I.R.E., vol. 28, pp. 220–223; May, 1940.

[2] L. A. Meacham, "The bridge stabilized oscillator," PROC. I.R.E., vol. 26, pp. 1278–1294; October, 1938.

[3] W. A. Marrison, "Evolution of quartz crystal clock," *Bell Sys. Tech. Jour.*, vol. 27, pp. 510–588; July, 1948.

[4] "Technical radio broadcast services, radio station WWV," Letter circular LC886, obtainable from National Bureau of Standards, Washington 25, D. C.

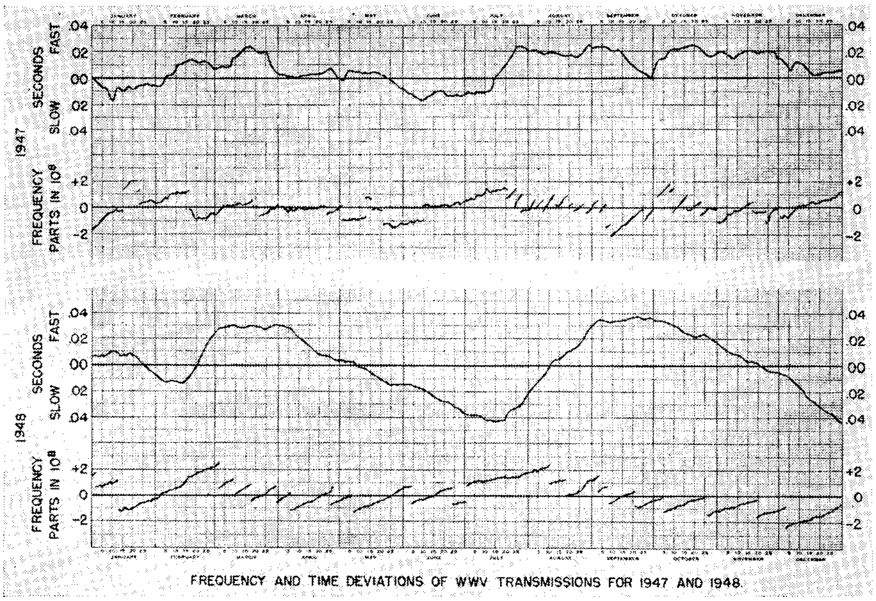

Fig. 1—Frequency and time deviations of WWV transmissions for 1947 and 1948.

are usually made on Fridays between 9 and 10 A.M. EST. but may be made on any day of the week.

A second standard-frequency station WWVH, located in Maui, T. H., has been operating experimentally since November, 1948. The purposes of this station are to learn ways of improving coverage in areas not well served by WWV and to determine the feasibility of operating several standard-frequency stations in different parts of the world on the same frequencies. At present, WWVH provides transmissions on 5, 10, and 15 Mc with carrier powers of 400 watts for each frequency. The carrier frequencies and modulation components are derived from primary frequency standards similar to those at WWV. These oscillators are maintained in agreement with the WWV transmitted frequencies within 2 parts in 10^8 by means of time comparisons over 6-day periods.

The National Primary Standard of Frequency

The present primary standard of frequency consists of three precision frequency standards located at the WWV transmitting site near Greenbelt, Md., and five located at the National Bureau of Standards in the District of Columbia. These eight standards are automatically compared with each other and with Naval Observatory time determinations. The estimated or daily assigned frequencies, accurate to about 1 part in 10^8, are determined by a weighted extrapolation process in terms of the most reliable standards. Corrected frequencies are evaluated, over 100-day intervals, in a manner explained under "Interval-derived frequencies" and "Long-interval performance determinations" in terms of the Naval Observatory time signals for three well-stabilized standard oscillators. The mean of these corrected values applied through the daily beat-frequency comparisons is adopted as the final daily corrected or "absolute" frequency for each standard. This value is obtained some 60 days later and is used as a guide in extrapolating the daily assigned frequencies so as to keep their corrections as small as possible. Agreement of the 100-day corrected frequencies computed separately in terms of each of the three interval-derived curves is generally within 2 parts in 10^9. The principal limitation on the obtainable accuracy is thus evidently caused by the slight wanderings in the determinations of the earth's mean rate of rotation.

Daily and short-time variations in the individual primary frequency standards are of the order of 1 or 2 parts in 10^9 and 1 or 2 parts in 10^{10}, respectively. Fig. 2 is a 24-hour chart recording of the beat frequencies a

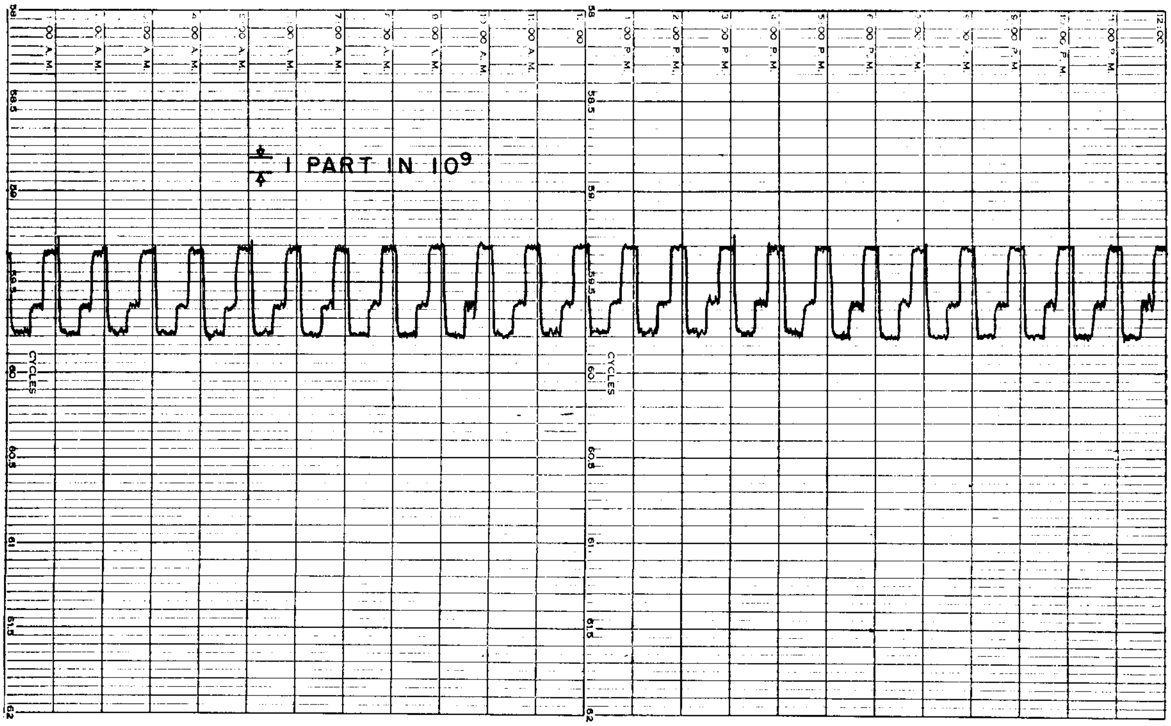

Fig. 2—Chart recording of the beat frequencies at 80 Mc of the three WWV standard oscillators in terms of the monitoring reference oscillator at CRPL.

80 Mc of the three WWV oscillators in terms of the monitoring reference standard, showing the order of these variations. Fig. 3 is a chart recording showing short-time variations in the beat frequency between two standards, on different days, at 80 and 1,280 Mc. The small variations of about 2 parts in 10^{10} are attributable to slight mutual coupling between the units and to heater thermostat operations. Fig. 4 shows chart plottings of the three WWV standards, primary 25, primary W1, primary 65, and the two monitoring reference standards, primary K15 and primary 35, for several months.

Measurement of Precision Standard Oscillators by Frequency Comparisons with WWV

For direct frequency measurements, a harmonic of the local frequency standard is compared with the received WWV signal to determine the difference frequency. Where several standard oscillators are available and regularly intercompared, it is necessary to check only one in terms of WWV. Harmonic power from the local standard to the radio receiver should be adjusted to be about equal to the received signal level so as to obtain a maximum modulation or beat. During severe fading, it may be necessary to count beats that are suppressed but would continue the natural rhythm of those observed. When reception is good, the best results should be obtained by counting beats over a 1- to 2-minute period. When fading is severe, the averaging of a larger number of successful counts of periods of from 10 to 20 seconds may prove most useful.

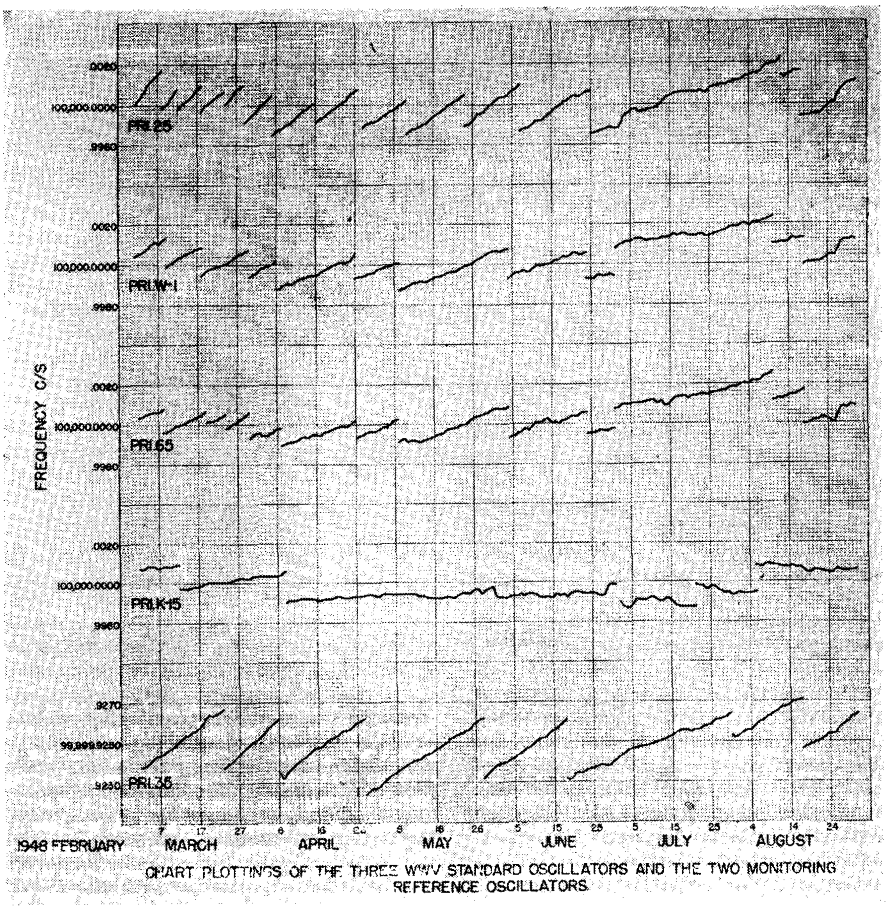

Fig. 4—Chart plottings of the three WWV standard oscillators and the two monitoring reference oscillators.

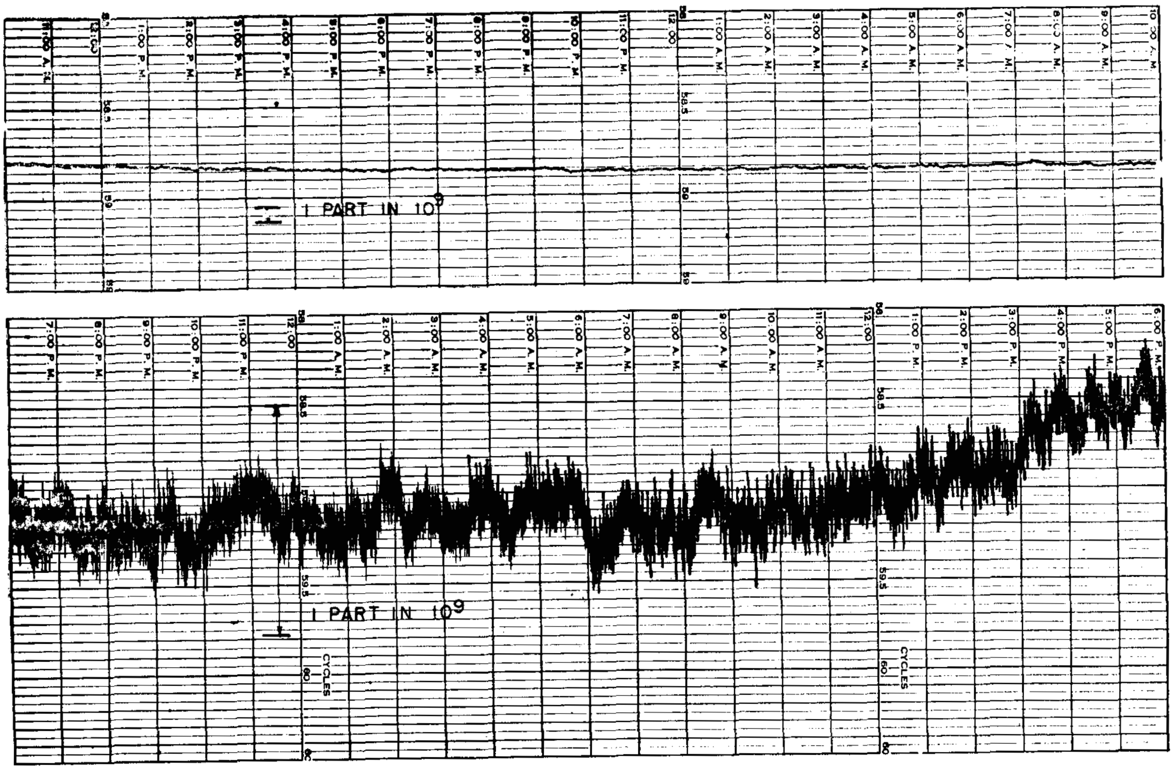

Fig. 3—Chart recording showing short-time variations in the beat frequency between two frequency standards at the National Bureau of Standards, on different days, at 80 Mc (top) and 1,280 Mc (bottom).

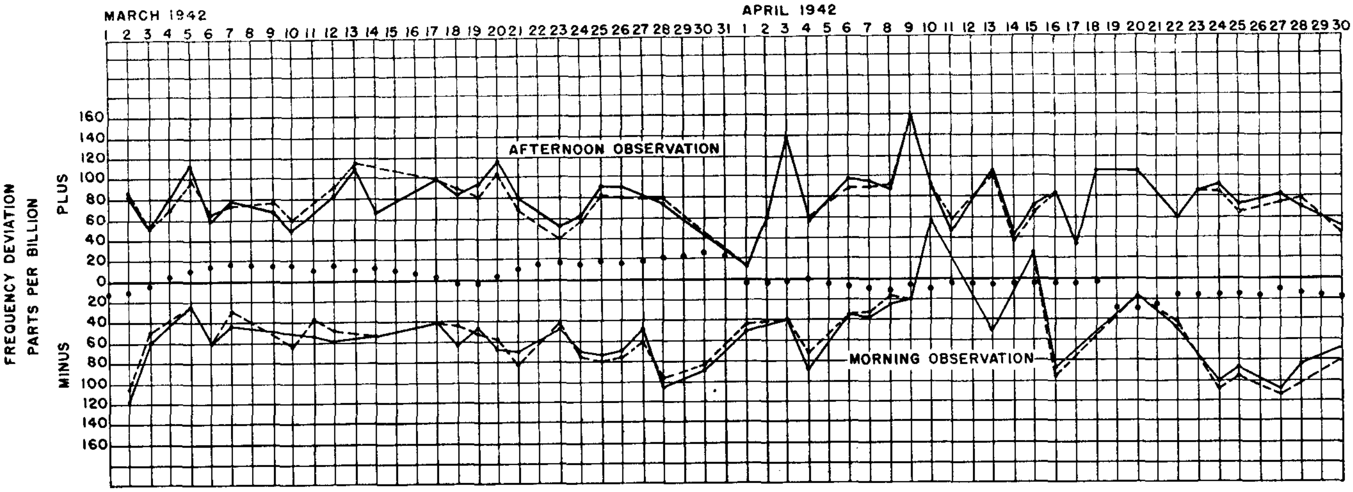

Fig. 5—Illustration of Doppler variation of the WWV received frequencies in terms of two frequency standards at Western Electric's Hawthorne, Chicago, Laboratory. Dotted points are WWV transmitted frequencies.

Experience has shown that it is often quite difficult to adjust a local compared oscillator directly to zero beat frequency with WWV at remote locations by either aural or S-meter means. This is generally caused by numerous rapid variations in signal level, or by propagational flutter in the received frequency. Tests at the National Bureau of Standards where a ground-wave signal from WWV prevails, showed no difficulty in reproducing zero-beat settings of an oscillator dial to ±1 part in 10^9.

Multiple-Setting Interpolation Method

Multiple-setting interpolation is best carried out by setting the fine-frequency dial of the compared oscillator slightly off frequency so as to obtain beats with WWV of from 0.1 to 2 beats per second. Several settings should be made on each side of zero beat, choosing values which are readily distinguished from fading, and a number of beat periods measured by means of a stop watch. Values thus obtained are then converted to beat frequencies in cycles per second and are plotted on rectangular co-ordinate paper as ordinates with dial settings as abscissa. By plotting the beat frequencies obtained below zero beat negative and the ones above zero beat positive, and drawing a straight line through the average of these points, an accurate zero beat dial setting will be indicated where this line crosses the x axis. For this method an adjustment dial having good linearity, very little backlash and one dial division equal to about 1 part in 10^9 is required.

Offset Method

The multiple-setting method is somewhat cumbersome in that it requires a number of separate settings of the dial and computations and involves plotting the data, preferably on rather large graph paper. As the dial setting versus frequency is generally quite linear over a small frequency range, the desired zero-beat setting may be more easily obtained to about the same degree of accuracy by using an offset method. This is done by taking the average of several counts of beats at a single offset point at approximately 1 part in 10^7 from the zero-beat point. The average of these counts in seconds per beat is converted to beats per second which represents the amount the oscillator is then off zero beat at the standard frequency to which the receiver is tuned. This is then converted to parts-in-10^9 deviation from zero beat by dividing the beat in cycles per second by the standard frequency in cycles per second and multiplying by 10^9. To return the oscillator to zero beat it is only necessary to advance or retard the dial the indicated number of parts in 10^9 with allowance for the incremental dial correction factor for the region in which it is operating. The dial correction factor (number of parts in 10^9 per dial division) is most readily obtained by comparing the standard with a similar local standard at several dial settings, and thus avoiding radio transmission difficulties and possible errors.

This method has the advantage of requiring only one offset adjustment. With either method the amount of offset should be made small as any adjustments may temporarily disturb the normal drift rate to some extent, even though the dial is returned to the original setting. If several units are available in the frequency standard arrangement, the oscillator which is off frequency by a small amount and infrequently adjusted may be used to make the comparison with the transmitted frequency. The others may then be evaluated in terms of this standard so that no changes in the others are necessary. The offset standard should be sufficiently off-frequency so as to be certain that it is higher or lower than the received frequency.

Variations in Received Frequency Arising from the Doppler Effect

The accuracy of any method using direct comparison of a local frequency standard with a received standard frequency will be affected by fluctuations in transit time of the received signals. This arises from changes in the radio propagation medium during the measurement period, which make the received frequency slightly lower or higher than that transmitted. This well-established Doppler effect could be readily computed for radio propagation if sufficient information on changes in the medium were available. Its bearing on frequency measurements may be outlined as follows. The ionospheric reflecting layers vary in height considerably with frequency, time of day, season, geographical location, and phase of sunspot cycle. Average conditions are predictable, but conditions on a given day may depart greatly from the mean. Changes in effective layer height will cause the frequency of a received carrier to differ from that transmitted by a fractional amount equal to the rate of change in equivalent path length on kilometers per second divided by the propagation velocity in kilometers per second. For example, if one assumes $F2$-layer propagation and that the virtual height where reflections occur changes from 300 to 400 km in 2 hours, then for a "3-hop" transmission from WWV, Washington, to WWVH, Maui, (7,700-km surface distance) an effective change in frequency of the received signal of -3.2 parts in 10^8 for each hop can be computed. On a similar basis the computation for "4-hop" transmission (at a higher angle of departure) gives -3.7 parts in 10^8 per hop so affected. Of course, it is unlikely that changes of this magnitude will occur simultaneously at all reflection points of the path considered; thus the error caused by the Doppler effect will usually be less than the above figures multiplied by the number of hops.

The WWV frequencies as received at Maui, T. H., in October, 1948, were generally slightly higher in the morning and slightly lower in the afternoon. Measurements based on reception at a time when noon occurred about halfway between transmitter and receiver showed consistent agreement to about 1 part in 10^8, with occasional discrepancies as great as 2 or 3 parts in 10^8.

Observations made in England on WWV's 15-Mc received frequencies in December, 1945, showed errors ranging from 2 to -7 parts in 10^8, with an average variation of -3

parts in 10^8 when compared with very stable primary frequency standards.[5] Similar measurements reported by Booth and Gregory showed slightly greater variations.[6] Fig. 5 shows the variation in WWV's 5-Mc received frequency at Western Electric's Hawthorne, Chicago, Laboratory in terms of two precision frequency standards. It is evident that high-accuracy measurements of frequency in terms of WWV should be made when ionospheric layer heights are likely to be most stable, i.e., with noon or midnight prevailing at about halfway between transmitter and receiver locations. Long-distance north-south transmission may be expected to show greater variations in the morning and afternoon where all of the reflection points are subject to changing conditions at the same time. Long-distance comparisons should, in most cases, prove most reliable when lower angles and fewer modes of propagation prevail. However, one should particularly avoid use of a frequency and time where a dominant mode of transmission is very near the maximum usable frequency at the propagation angle for any of the reflection points, as the effective layer height changes very rapidly under these conditions. It should be mentioned that errors other than those attributed to the Doppler effect were occasionally found possible.

Publications of the National Bureau of Standards are available which are useful in determining the optimum reception frequencies at a given time and location.[7,8]

MEASUREMENT OF PRECISION STANDARD OSCILLATORS BY DAILY TIME COMPARISONS WITH WWV

The average frequency of a standard oscillator may be determined by successively comparing the number of cycles generated (time kept by its synchronously-operated clock) with any sufficiently reliable time signals. If the standard's drift rate or gradual change in frequency is assumed to be constant, its average frequency during the period will be the same as the instantaneous frequency for the center of the period considered. Departures from a constant or uniform frequency drift can be detected by this method only by successive determinations of frequency, and only then if the reference time source is known to be extremely accurate. When using time signals transmitted by radio over long distances (sky-wave propagation), slight errors will result because of variations in the time of transmission of as much as several milliseconds under adverse conditions. For this reason frequency determinations based on time comparisons of less than about two days may be in greater error than direct-frequency comparisons with transmitted standard frequencies.

Interval-Derived Frequency Determinations

The computation of average frequency by time comparisons may be explained by the following equations:

$$f_{av} = f_0 \frac{t_2 - t_1}{T_2 - T_1} \tag{1}$$

where f_0 is the nominal frequency of the oscillator, i.e., that frequency for which the frequency division ratios were chosen; t_1, t_2 and T_1, T_2 represent the time indicated by the clock, and the correct time represented by the time signals respectively at the beginning and end of the period being averaged.

Equation (1) is usually simplified in actual use by referring all measurements to days or multiples thereof and by using measured errors in time indicated by a crystal clock. For example, the average frequency of a 100-kc standard oscillator during interval T is

$$f_{av} = 10^5\left(1 + \frac{\Delta t_2 - \Delta t_1}{T}\right), \tag{2}$$

where Δt_1 and Δt_2 are positive or negative errors in time at beginning and end of the measurement period. The value obtained represents the instantaneous frequency for the center of the period, if uniform drift is assumed, or the value for the entire period if no change in frequency during the entire period is assumed. Instantaneous departures from the average values are generally determined by daily comparisons with other oscillators, involving an averaging based on their predicted daily drifts. This is justified by the probability that the average of the drifts of a number of selected oscillators will be more nearly linear than the drift of any one unit.

Daily measurements of time differences or errors between standard clocks and time signals may be accomplished by adjustment of a calibrated phase shifter dial for pulse coincidence on an oscilloscope screen or by use of calibrated circular or linear sweeps on the oscilloscope. A recording chronograph may also be used to get a continuous record of the time differences of several standard clocks and time signals.

Clock Acceleration

In order to determine the amount of time a crystal clock will gain or lose over a long period it is necessary to consider the effect of the change in frequency (and thus the change in rate of the clock) over the period. For very long intervals it is even necessary to consider the change in the drift rate of the oscillator (change in the change of rate of the clock).

The time a crystal clock will indicate at some future time T_1 at t days distant is:

$$T_1 = T_0 + t + at + bt^2 + ct^3 \tag{3}$$

where at represents the "rate" term, bt_2 the acceleration term, and ct^3 the change in acceleration term.

The terms T_0 and t are always positive. Coefficient 'a' may be positive or negative, and is the principal factor in determining the overall rate of the clock over short periods. Coefficient 'b' is generally positive, and must be considered for periods of more than a few days. Coefficient 'c' is very small and is generally negative. It may be neglected in all but very long-time computations.

The above equation may be more readily understood if times T_0, T_1, T_2, etc., are considered as marking off an absolute, continuous time scale, with the expression $t+at+bt^2+ct^3$ marking off the distance covered by the clock on this time scale in t days. This may be recognized as the well-known equation for linear motion. Usually $t+at$ is combined and considered as the velocity term, but for horological purposes it is more convenient to keep these two terms separate. Horologists express the "rate" of a clock as the seconds gained or lost per day.

Fig. 6 shows the computed daily change in time of a crystal clock for a uniform daily change in frequency of 1 part in 10^9 per day. The clocks are usually set slightly fast in such manner as to lose time, and become slightly slow as the oscillator passes through correct frequency. As the oscillator becomes high in frequency, this time is regained to approximately the original setting when the oscillator frequency is about 1 part in 10^7 high. The oscillator is then adjusted low again and the cycle repeated, this adjust-

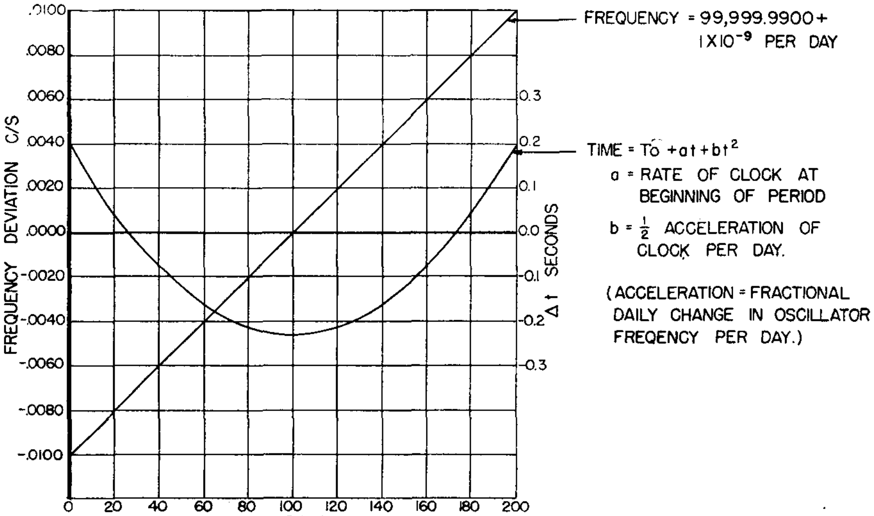

Fig. 6—Frequency-time graphs showing clock acceleration for a daily change of frequency of +1 part in 10^9.

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[5] H. V. Griffiths, "Doppler effect in propagation," *Wireless Eng.*, vol. 24, pp. 162–167; June, 1947.

[6] C. F. Booth and G. Gregory, "The effect of Doppler's principle on the comparison of standard frequencies over a transatlantic radio path," *Post Office Elec. Eng. Jour.*, vol. 40, pp. 153–158; January, 1948.

[7] "Ionospheric radio propagation," Circular 462, issued June 25, 1948, available from Superintendent of Documents, Government Printing Office, Washington 25, D. C. (price $1.00; foreign $1.25).

[8] "Basic radio propagation predictions," CRPL-D series (monthly, three months in advance) available on subscription (price $1.00 yearly, foreign $1.25) from Superintendent of Documents, Government Printing Office, Washington 25, D. C.

ment being required about once or twice per year to maintain frequency limits of ±1 part in 10^7.

Propagation Delay of Time Signals

Changes in the height of the ionosphere layers by which time signals or seconds pulses are received, or propagation by different layers or numbers of hops on successive measurement periods will introduce variable delay in the time of reception. The amount of time delay introduced by transmission time may be computed if the mode of transmission is known or assumed. This delay is nearly 1 millisecond per 186 miles of actual transmission path length. The difference in reception time for signals propagated by various modes and going only one way around the earth is seldom greater than a few milliseconds. By observing the earliest consistently received pulses over a short period, this may be generally reduced to less than 1 millisecond.

As an illustration of the relative delays to be expected from various modes of propagation, the time lags for a curved earth-ionosphere path for several propagation conditions have been computed. These values for transmission from WWV, Washington, to WWVH, Maui, a great-circle ground-path length of about 7,700 km (4,800 mi) are as shown in Table I. Geometrical one-hop transmission over this path is impossible, and two-hop transmission would be expected to occur less frequently than transmission by the higher modes for this path length. If $F1$-layer transmission is assumed the delay should be generally a little less than for the similar $F2$-layer mode. These values assume propagation by a number of geometrical hops and normal reflections at the indicated virtual heights. Scattering, interlayer reflections, ionospheric turbulence, and abnormal conditions are of frequent occurrence.

TABLE I

No. of hops	F layer (210 mi.)	F_2 layer (267 mi.)
	Milliseconds delay	Milliseconds delay
2	26.6	27.2
3	27.0	27.7
4	27.9	29.1
0 ground path equivalent lag (for comparison purposes) is 25.7		

The average variations in delay of the WWV seconds pulses as received at Maui, Hawaii, over a number of one-hour observation periods ranged from 0.1 to 0.2 millisecond for observations on a single frequency, and 0.6 to 1.0 millisecond for observations on the several frequencies receivable at a given time. These variations represent the deviations in a number of loggings of the earliest pulses consistently received over short intervals and not the scatter of multiple pulses received at the same time or consecutively. Variation of transmission delay time of about 2 milliseconds has been reported on high-frequency time signals over the North Atlantic path.[9]

When using the WWV or WWVH seconds pulses at locations where both stations are received, one or the other signal should be selected when making time measurements for frequency determination. This may be done by using a directive receiving antenna or by selecting the proper pulses when making observations. Similarly, at certain locations it is necessary to differentiate between pulses received from both ways around the earth. For example, at Maui pulses are consistently received in the morning from WWV on 15 and 20 Mc by paths going both ways around the earth, with delays of approximately 0.027 and 0.113 second. Quite often, for brief periods, the pulses received over the longer path are stronger than those received over the shorter path because of differences in absorption. When checking a well-stabilized standard clock, the expected time of arrival will be known to a few milliseconds, which helps to discriminate against undesired signals. As with the frequency comparisons, it is desirable to make these measurements when reception conditions are optimum and the ionosphere is stable.

Interval-derived frequency determinations covering periods of 1 or 2 days may not prove much more accurate than those made by direct frequency comparisons under optimum conditions. However, if highly stable oscillators are considered, and the measurement period is increased to about 6 to 10 days, comparison accuracies of a few parts in 10^9 may be obtained.

INTERCOMPARISON OF LOCAL STANDARDS

When more than one frequency standard is available, it is generally desirable to check each local standard at regular intervals or continuously with the local reference oscillator (one checked in terms of WWV). The beat frequencies between the reference and each of the other oscillators are then determined for plotting purposes at the time chosen for evaluating the reference oscillator. This may be done by one of the following methods.

Local Frequency Intercomparison by Use of Harmonic Mixer and Receiver

The harmonic mixer unit has already been mentioned in connection with WWV frequency comparisons. Measurements are made by adjusting the 100-kc input of each source separately by means of the level controls to about S-4 on the radio receiver. Both oscillators are then connected, and the beat counted on the S-meter at any convenient frequency multiple of 100 kc. To get the desired accuracy the beats should be counted using a stop watch for a minimum of 2 beats, or a convenient even number of beats which can be counted in about 2 minutes. The difference frequency in cycles per second at 100 kc is then

$$\text{beat } C/S = \frac{\text{number of beats counted}}{\text{number of seconds} \times \text{receiver frequency in Mc} \times 10^6}.$$

Local Frequency Intercomparison by Use of Oscilloscope

The beat frequency between two 100-kc frequency standards may be readily obtained to a high degree of precision by observing high-order Lissajous patterns on an oscilloscope. This may be conveniently done by connecting the output from a frequency multiplier controlled by one standard to the vertical deflection plates or their wideband amplifier input, and 100 kc from the other standard through the horizontal amplifier to the horizontal deflection plates. The horizontal pattern should be expanded to get sufficient resolution of the multiple pattern. Phase changes, caused by any difference in frequency, will cause the pattern to close and open in continuous sequence. A point near the center of the screen may be chosen where the lines close and the time for an even number of closures measured with a stop watch.

The difference frequency in parts in 10^9 is:

$$\text{Frequency difference} = \frac{500 \times \text{number of closures counted}}{\text{time of count in seconds} \times \text{highest frequency used in Mc}}.$$

A minimum of two closures or a minimum counting time of at least two minutes should be used for the desired accuracy. These observations will not indicate which of the two frequencies is higher. However, by using the frequency from one oscillator to lock in the linear-sweep oscillator in the oscilloscope, observation of the direction of the pattern drift will indicate which of the two frequencies is higher.

Other Precision Frequency Intercomparison Methods

For a complete installation of standard oscillators, some method should be provided for continuously and automatically recording the difference or beat frequencies between the reference oscillator and the others. Several methods will be described, although others may be employed. The direct-reading, or easily computable sensitivity, should be 1 part in 10^9 or better. The maximum deviation capability of the recorder need not be greater than a few parts in 10^8. The instrument should be capable of indicating short-interval stability conforming to a sampling or reading completed in a minute or less time.

One very satisfactory but somewhat elaborate method, which is direct-reading and unambiguous with respect to beat sign, uses a commercial power-frequency 60-cycle recorder to record the beat frequencies at 100 Mc. Two 100-kc to 100-Mc frequency multipliers are used. A continuously adjustable phase shifter of the rotating or electronic type is used to subtract exactly 60 cps (obtained from the standard) from the output of the reference multiplier at 100 Mc. The resultant frequency and the output from the other multiplier are supplied to a converter and the difference frequency of approximately 60 cps obtained. The difference fre-

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

quency is amplified and supplied to the 58 to 62 cps frequency recorder so that the 60-cycle point represents zero difference frequency. This gives a continuous record of the difference frequency to a sensitivity of a few parts in 10^{10} with a range of ± 2 parts in 10^8. The other oscillators can be switched on successively in rotation to record the deviation of each one in terms of the reference oscillator.

A variation of this method which is currently used at National Bureau of Standards is to set the reference oscillator approximately 60 parts low in 100 million, which gives a recordable difference frequency without the use of the phase-shifting mechanism. This method has the disadvantage of putting the reference off frequency by an amount making it unusable for many purposes.

The difference frequency between two standard oscillators may be determined by accurately measuring the time required to complete one beat at the fundamental or a multiplied harmonic of each standard. A method for doing this has been described by H. B. Law, and is used by the British Post Office and the National Physical Laboratory for the comparison of precision frequency standards.[10] A balanced phase discriminator is supplied with two 100-kc frequencies and arranged to trigger a counter chronometer at the beginning and ending of one beat. The chronometer counts a convenient standard frequency (100 or 10 kc) and thus indicates the elapsed time of one beat. The instrument accuracy under ideal conditions is estimated to be 1 part in 10^{11}.

Two electronic counter chronometers may be used in a number of ways to obtain accurate comparison data between standard oscillators. A general method uses one instrument to count the difference or beat frequency between high harmonics of the two compared frequencies, while a second instrument counts cycles of appropriate standard frequency. One unit may be adjusted to serve as a predetermined counter to stop the other unit after a definite count and thus increase the accuracy somewhat. This method of frequency measurement is very flexible and can be used to measure frequencies which fall outside the limits of other very sensitive measurement devices.

A very simple but accurate method of recording low beat frequencies such as obtained from the harmonic mixer and receiver comparison method is to use a recording milliammeter or recording oscillograph. The beats are then evaluated in terms of uniform chart speed or time markers recorded simultaneously. This method offers comparative simplicity for temporary or experimental use, but is quite laborious where a number of readings are required over a long period of time.

Recording and Evaluation of Data

The amount of statistical data taken on each standard should be kept to the minimum necessary to determine the probable performance of each individual unit over a continuous period. The chief reason for taking such data on a number of standards is to determine the most suitable one for use, and to determine its short-time stability in terms of the other available standards. When such a standard is used to control standard-frequency transmissions or to make high-precision calibrations, it should be monitored continuously against one or more similar standards.

As a result of experience gained in the operation of frequency-standard oscillators at the National Bureau of Standards and in particular at the WWVH, Maui, T. H., transmitting station, it may be helpful to outline maintenance, procedures and techniques that have been developed and found useful in this work.

Logging and Plotting of Data

At the NBS it has been found necessary to keep a daily record which includes all frequency and time readings and measurements, as well as the final results of all computations of frequency and time. Changes in control standard, methods, or equipment are always noted. These data are conveniently kept in a record book having a number of ruled columns, or on specially prepared mineographed sheets carrying the desired notations for a particular installation.

The daily computed frequencies for each oscillator are plotted on continuous cross-section paper in a manner as shown in Fig. 4. These data are of considerable aid in studying the relative performance of the individual standards, and in graphically extrapolating predicted values during periods when reception conditions do not permit making the daily frequency or time checks.

It has been found desirable to keep periodic (weekly) instrument readings which include the readings of all battery chargers and power supplies, voltmeter readings on each switch position for the frequency standards and frequency dividers, temperature readings of each standard's oven where applicable, and room temperature at time of readings. These readings are useful in anticipating tube or equipment failure in that adjustment or repair can often be made before complete breakdown occurs.

Adjustments in Frequency and Time

Periodic adjustments in frequency and time of each standard oscillator and time equipment are required to keep within the desired accuracy tolerance and to simplify the measuring and plotting requirements. The frequency and range of these adjustments are influenced considerably by the type of service and standard. For greatest constancy of drift rate and greatest ease in computation, frequency adjustments should be held to a minimum. For many uses the calculation of and allowance for the slight error in frequency or time presents no great difficulty. In other cases, where numerous measurements are being made and services given, it is helpful to establish high initial accuracy so as to eliminate corrections.

Where the working standard (one used or distributed) is held to very close accuracy tolerance, the continuity of service required will determine if the second or standby standard need be held to a similar close tolerance. If continuity of service is only of moderate importance, two equipments may be infrequently adjusted and only the working unit held within very precise limits. The oscillator and time equipment least adjusted should be generally used as the reference or one by which frequency and time determinations are made with respect to WWV. For most purposes an adjustment of the working standard so as to hold its frequency within 1 or 2 parts in 10^8 of WWV's average frequency should prove satisfactory, with the standby and spare oscillators being held to a frequency tolerance of 1 part in 10^7.

Daily phase shifter (time) adjustments may be made if time synchronization is desired, and these daily changes used in computing interval-derived frequencies. Allowance should be made for transmission time lag in setting or using the local time pulses, if extremely precise time synchronization is important.

Short-Interval Performance

High-precision standard-frequency oscillators now in use have short-period stabilities (intervals of one minute or so) ranging from 1 part in 10^9 to 1 part in 10^{10}. In addition to the gradual ageing or drift, various causes will contribute to these short-time frequency fluctuations. Mechanical shock may cause an instantaneous effect through easing of stresses or displacements in the crystal unit or associated components. A slow recovery in frequency may or may not take place. A change in supply voltage produces an immediate effect followed by additional changes as thermal equilibrium is restored. Changes in load impedance will cause frequency variations unless proper decoupling is employed. Unless proper thermal lagging is provided for the crystal compartment cyclic operations of its heaters will also cause variations in the output frequency. The oscillator circuits must be protected from direct or electromagnetic mutual coupling to better than 100 db to reduce frequency "pulling" or tendency to synchronize. Other changes in frequency, often of unpredictable source, may be caused by imperfect connections, faulty components or erratic vacuum tubes. These causes of poor frequency stability can generally be eliminated only by a slow process of substitution and observation.

Where average frequencies are computed for periods of more than a few days, the daily values may be determined by calculating the departure of the reference standard from its average curve in terms of the other reliable standards available. The daily values for the other standards may then be determined by adding the daily beat frequencies for each standard to the computed value for the reference. The mean values of relative frequencies thus obtained represent a weighted extrapolation in terms of the selected group of reliable standards. Considerations involving three independent reliable standards should give a relative daily accuracy within 2 parts in 10^9. The inclusion of six or more standards, as is done in the CRPL primary standard of frequency, results in a relative daily determination of performance of each standard oscillator to within 1 part in 10^9. Very-short period or

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[10] H. B. Law, "An instrument for short-period frequency comparisons of great accuracy," *Jour. IEE* vol. 94, part III, pp. 38–41; January, 1947.

"instantaneous" stability may be determined by intercomparing pairs of standard oscillators by high-precision automatic recording equipment.

Long-Interval Performance Determinations

The determination of deviations over periods of months and years is complicated and obscured by the fact that the earth's mean rate of rotation (even after application of a number of established corrections) is not uniform. Changes in the length of the apparent day as large as 4 or 5 milliseconds, equivalent to a frequency change of about 1 part in 20 million, are believed to have occurred on several occasions within the last half-century. These changes occur at rather irregular intervals and in varying amounts and are, as yet, unpredictable. They are evidenced by an accumulation of error in the earth's observed angular position compared with theoretically predictable astronomical events.

Smaller variations, with periods of several weeks to slightly more than a year, are noted when comparing the earth's observed time with high-precision crystal clocks. Until very recently these variations were attributed almost entirely to clock discrepancies. Agreement of a number of precision clocks and technical improvements in methods of observing and recording star transits indicate that the earth's rate of rotation is subject to a number of more or less random small variations which add up to as much as several milliseconds per day at times. The probable error of a single time determination in terms of a number of star sights is believed to be not greater than several milliseconds and such errors are not cumulative. Some of the time variations are caused by rather irregular wanderings of the earth's poles by as much as 30 feet with a principal component having a period of slightly more than a year. Observational errors, caused by this variation in longitude (which would be zero at the equator) amount to as much as ±20 and 30 milliseconds at the Washington and Greenwich observatories, respectively. These variations may be corrected by applying results of observations of latitude variation at a number of locations and computing the equivalent changes in longitude. The intricacies of time determination in terms of the earth's rate and the conversion from observed sidereal to mean solar time have been discussed by H. Spencer Jones, British Astronomer Royal.[11]

Another factor, although of no immediate concern in determining frequency, is the gradual slowing down of the earth's rate of rotation, chiefly because of tidal friction. This deceleration over the past 2,000 years averages about 0.0016 second per day per century, which amounts to an accumulated time difference of $29T^2$ seconds for a mean solar clock considered as having zero rate at 1900 A.D., where T is the number of centuries from 1900.[12] At present the deceleration is estimated at approximately 0.001 second/day/century, which amounts to an average apparent increase in frequency of about 1 part in 10^8 per century for an absolutely constant oscillator if measured in terms of the earth's rate of rotation.

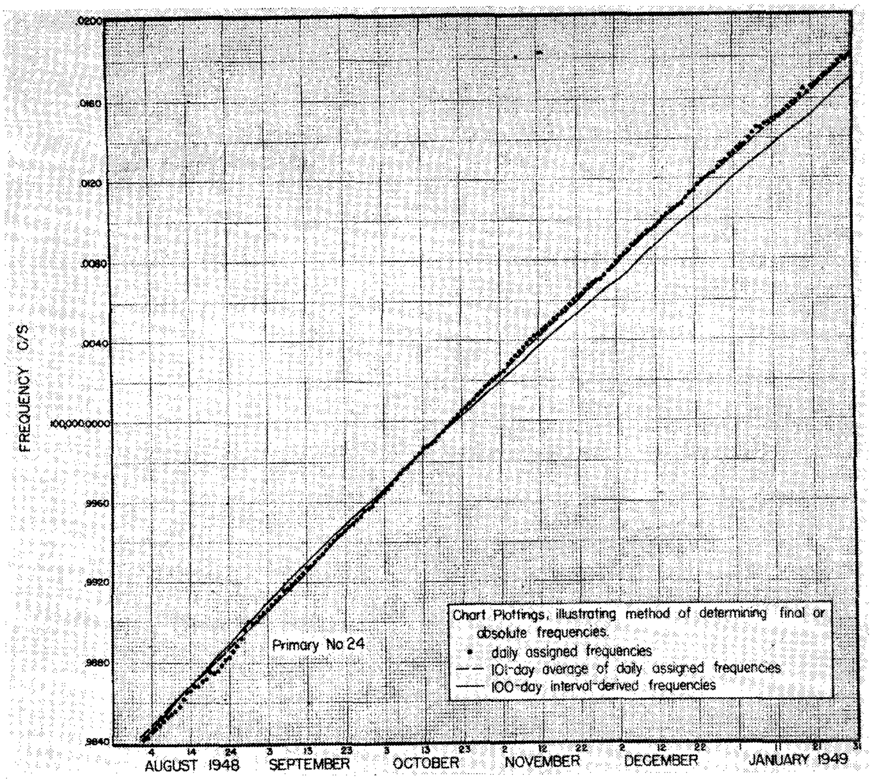

Fig. 7—Chart plottings illustrating graphical method of determining final or absolute frequencies.

The GT wire-supported crystals of the type widely used at present have initial drift rates of 2 to 4 parts in 10^8 per day for unaged units, and 1 to 2 parts in 10^9 per day for units a year old. The drift varies approximately inversely with time for several years, and may thus be predicted and allowances made accordingly.

In the primary standard of frequency of the National Bureau of Standards, three well-stabilized oscillators are evaluated over 100-day periods in terms of Naval Observatory time corrections. This is done as shown in Fig. 7. The dotted points for each day represent the departures from the average curve in terms of the entire group of selected standards as explained previously. The dashed curve represents the average of 101 daily values including 50 before and 50 after the day plotted. These are computed each 10 days and connected by a smooth curve. The solid curve represents the 100-day interval-derived average frequency computed for each day. The final corrected frequency, for this standard only, is then the daily plotted value of the interval derived (solid) curve plus the algebraic departure of the daily assigned (dotted point) value from the daily average (dashed) curve. A displacement of more than 1 part in 10^8 between these two curves indicates that the daily drift rates should be reassessed and the dotted points replotted to bring the two curves more nearly into agreement.

For a 100-day averaging period the daily assigned curves must thus be extrapolated or guided on the basis of past performance for about 60 days in advance of the established average curves. For this reason, a temporary 20-day interval-derived curve is computed as an aid in systematically determining the daily assigned values. Users of the WWV time signal transmissions in the field for average frequency determinations thus have the advantage of the long averaging period applied to the WWV frequency determinations. They may, therefore, approach the full limit of accuracy (1 part in 50 million) by using these signals over intervals of 6 to 10 days to compute average frequencies without knowledge of the time or extent of WWV frequency adjustments. If these adjustment data are known, accuracies several times this order are generally possible.

The corrected daily frequency for the reference oscillator is computed in terms of each of these three oscillators so evaluated by adding algebraically the respective daily beat differences to their corrected values. The mean of these computed frequencies is then taken as the final or "absolute" value of the reference for each day. Should one of the three values disagree excessively with the other two for explainable reasons, only two values are averaged. The values so computed generally agree within 1 or 2 parts in 10^9, which represents the residual error in the graphical method and the unpredictable random deviation of the daily assigned sampled values from the daily mean frequencies. The daily "absolute" frequencies for each of the other standards are obtained by algebraically adding their daily beat differences

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[11] H. Spencer Jones, "The measurement of time," *Endeavour*, vol. 4, pp. 123–130; October, 1945.

[12] G. M. Clemence, "On the system of astronomical constants," *Astronomical Jour.*, vol. 53, pp. 169–179; May, 1948.

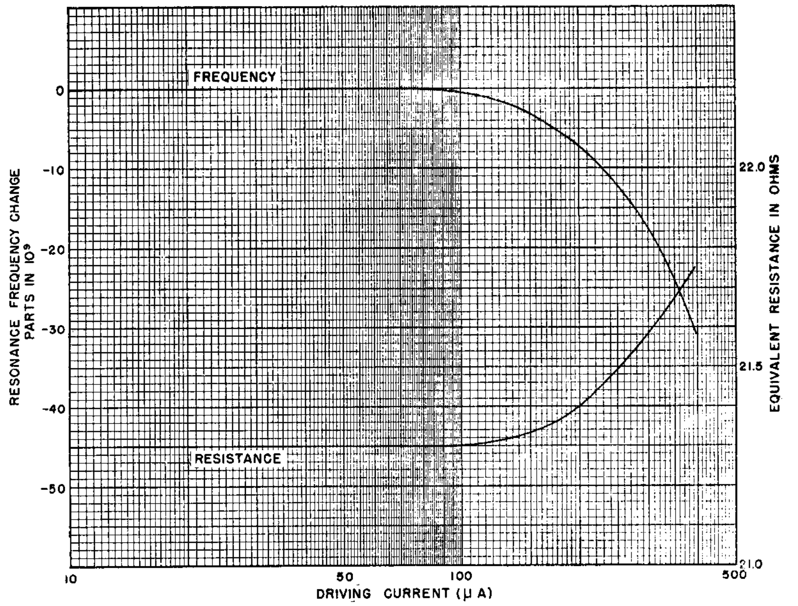

Fig. 8—Graphs showing variations of resonance frequency and series resistance at resonance with changes in driving current for a 100-kc GT-cut quartz-crystal unit.

to the daily "absolute" frequency of the reference standard.

No great difficulty has been experienced in predicting the "absolute" value of frequency for the primary standard in terms of the earth's mean rate of rotation over 100-day intervals to 1 part in 10^8. The mean solar second, which is by definition the physical standard of time, may be expected to change occasionally by as much as ±4 parts in 10^8 in addition to a gradual average change of about 1 part in 10^8 per century. Frequency which is defined in terms of the mean solar second will, of course, deviate from a constant value by a corresponding amount.

Prospective Improvements in Quartz-Crystal Frequency Standards

Quartz-crystal units, measured as resonators in a balanced bridge network, have been compared with the primary standard of frequency with a precision of 1 part in 10^9. In this manner, crystal units most suitable for use in future standard oscillators are currently selected and studied. The use of crystal-unit resonators as primary frequency reference standards has been tried in this manner to some extent and is being further investigated. This method of use eliminates the variations arising from aging or detuning of tubes and circuit components. It has been found that the crystals generally drifted about as rapidly in a nonoscillating condition as they do in continuously oscillating frequency standards. Fig. 8 shows the results of bridge measurements on a typical GT-cut, wire-mounted crystal-unit for variation in excitation current. It may be noted that the frequency decreases and the resistance increases slightly with increases in excitation beyond about 100 microamperes through the crystal-unit at resonance. All crystal oscillator standards operating at present at The National Bureau of Standards are working at amplitudes of 500 microamperes or more, which is slightly beyond the maximum shown on the graph. Attempts to operate with appreciably lower amplitudes, by adjusting the bridge arms to closer limits, have resulted in increased short-time instability although the curves indicate greater stability should result. Extreme care in shielding, decoupling, and attention to the reduction of tube and circuit noise may be necessary to gain improvement in this manner.

Ability to operate the amplifier-bridge loop at a higher stable amplification ratio may be made possible by supplying the thermistor element for amplitude stabilization with direct current obtained from rectified and filtered oscillator output. This may also allow operation of the crystal unit at nearer its natural Q value. The present standards have crystal units with Q values of about 200,000 and operating Q values of about one-half this amount. This gives a bandwidth between half-power points of about 1 cps at 100 kc. The short-period stability of about 1 part in 10^{10} obtained with several of the standard oscillators means that they hold the frequency constant to about 1/100,000 of the half-power bandwidth. Current development work on improving crystal-units shows promise of greatly reducing the initial aging or drifting in frequency and of obtaining an operating Q factor of one million or greater.

The use of direct polarizing voltage across the crystal electrodes as a means of fine frequency adjustment may be advantageous in certain cases. A change in frequency of about 1 part in 10^8 per volt occurs for the present type 100-kc units. This change in frequency is very linear over ranges of several hundred volts of either polarity without apparent loss of Q. It offers an extremely sensitive control method for interpolation or servo applications without the problems that arise from backlash and wear.

Improved temperature control of the crystal inclosure over long periods is needed. A temperature-control method using dual resistance-bridge thermostats is planned for use in several new standard oscillators. The possibility of using magnetic amplifiers in this application to eliminate tube failures is being investigated.

ABSOLUTE FREQUENCY AND TIME STANDARDS

It is now generally accepted that the earth's mean rotation period is neither absolutely constant nor is it predictable with desirable accuracy over short or long periods. Its long-time period is increasing by an amount sufficient to be slightly disturbing to both physicists and astronomers in this era of high precision measurements.

Astronomers are using what is termed Newtonian time.[13] This time is consistent with Newton's laws of motion (with slight modifications for relativity) when applied to the movement of astronomical bodies. So far as has been determined, intervals in Newtonian time are invariable.

The Newtonian second for astronomical purposes has been defined as equal to a mean solar second at 1900 A.D. Astronomical events in the distant past are computable in Newtonian time by applying the proper corrections, based on the earth's known variable rate through the period considered. Future corrections, while not accurately predictable, can be observed and adopted as time progresses. The sidereal year (average period of the earth's revolution around the sun) is believed by astronomers to be a better unit of time. With present techniques it is difficult to determine the period of a single sidereal year to the desired accuracy. It has been estimated that in an interval of 100 years a mean value good to 1 part in 10^9 could be established. To subdivide this long interval into useful physical time units imposes extremely stringent requirements on a standard clock.

Clocks have continued to be improved since the discovery of the escapement mechanism about 1360 A.D., reaching their high degree of dependability in the present-day precision quartz clocks which permit a predictable daily constancy of considerably better than 0.001 second per day. They have an attainable precision of about 10 times that of the best mechanical clocks and are the most precise timekeepers now available, exceeding the constancy of the determination of the earth's rate for periods up to several months. The quartz clock, however, must be set in terms of the earth's mean rate, as it in no way constitutes an absolute standard in itself.

In recent years, aided by the rapid development of microwave techniques, considerable attention has been directed toward use of atomic resonance effects at microwave frequencies.[13]

The first atomic clock was built at the National Bureau of Standards in 1948.[14] This clock makes use of the sharp absorption line of ammonia gas at 23,870.1 Mc to maintain a 100-kc crystal oscillator at constant frequency. This is done by means of an electronic servosystem consisting of frequency

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

[14] "The atomic clock," *NBS Tech. News Bull.*, vol. 33, pp. 17–24; February, 1949.

multipliers, auxiliary frequency-modulated search oscillator, and pulse discriminator circuits. The 100 kc is then divided down to audio frequencies in conventional manner and used to operate a synchronous-motor clock as a time standard. A constancy in frequency of 5 parts in 10^8 has been obtained for periods of several days with this experimental clock when compared with WWV frequency standards. Improvement of this type of standard and the development of more constant types of atomic resonance controlled oscillators are to be expected.

It is shown in the references cited that the sharpness of resonance within individual oscillating molecules is extremely great. Because of collisions of molecules with each other and with the gas cell walls, and the Doppler broadening attributable to natural thermal agitation, the practical working Q of an ammonia gas absorption line ranges between 50,000 and 500,000. This compares favorably with the Q of quartz crystals used in frequency standards which ranges from 100,000 to 1,000,000. It is thus reasonable to hope that a constancy of 1 part in 10^8 to 1 part in 10^9 may be obtained by proper refinements in circuitry and technique. Whether or not this degree of constancy of absolute value can be maintained without or even with precise temperature and pressure regulation remains to be investigated.

Civil time will, no doubt, continue to be defined in terms of the mean solar second, as would ordinary frequency designations. After about 2,000 years, if the earth continues to slow down at its present rate, the mean solar second would be about 1 part in 3 million longer than at present and the accumulated time difference between mean solar time and Newtonian time would amount to about three hours.

CONCLUSIONS

Frequency and time standards, using high-precision quartz crystals, are now available which are capable of supplying frequencies and time intervals constant to considerably better than 1 part in 10^8 per day. In order to achieve an accuracy approaching this order, these standards must be frequently checked in terms of standard frequency or time broadcasts. An accuracy of 1 part in 10^8 represents about the limit obtainable in terms of the earth's mean rate of rotation over a 100-day period. Longer periods of averaging can not be expected to give greatly improved accuracy, because of the possibility of slight oscillator frequency deviations and uncertainties in the uniformity of the determinations of the earth's mean rate.

By using ordinary zero beating methods, a remote frequency standard may be adjusted within 1 part in 10^7 to WWV's received frequency. Special offset techniques permit this setting error to be reduced to less than 1 part in 10^8. Changes in the radio propagation medium may cause the received frequency to differ from that transmitted by as much as several parts in 10^7. By averaging a number of determinations made when noon or midnight prevails about halfway between transmitter and receiver, long-distance frequency comparisons can generally be made with a precision of better than 1 part in 10^8.

The intercomparison of two remote oscillators, constant to 1 or 2 parts in 10^9 per day, by means of transmitted time pulses from one or both of the standards, is possible to a precision of a few parts in 10^9 through comparisons of average frequencies over periods of 6 or more days.

The development of atomic or molecular-resonance standards of high constancy and absolute accuracy may greatly simplify the maintenance of precise frequency and time standards. The practical realization of such standards, which seems reasonably probable in the near future, will eliminate the necessity of making highly precise physical measurements in terms of the earth's variable rate of rotation. Such a standard would supply a means of studying more precisely the motions of the earth and other astronomical bodies.

Considerable work is being done to improve the constancy of quartz-crystal frequency standards, especially with regard to aging or frequency drift and improved temperature control methods.

It is probable that frequency and time standards, which have improved by a factor of ten or more per decade in the last thirty years, will continue to reach new orders of accuracy and constancy. However, these improvements in accuracy will probably be referred to a new kind of standard, rather than to the mean solar second.

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