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THE NATIONAL PRIMARY STANDARD OF RADIO FREQUENCY

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ABSTRACT

The primary frequency standard consists of two independent groups of piezo oscillators. Section I consists of four piezo oscillators with frequencies of 100 kc/s. Section II has two piezo oscillators, one with a frequency of 100 kc/s, the other 200 kc/s, from which a 100-kc/s output is obtained by means of a submultiple generator. The absolute frequency of one of the units of each section is checked daily against Arlington time signals by a synchronous-motor clock driven by the 100th submultiple of the frequency of the controlling unit. Daily measurements provide a check on the frequency variations of the standard over an extended period. Frequency variations over short intervals are shown by an automatic recorder of the frequency difference between one of the units of section I and each of the other five units.

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I. INTRODUCTION

Among the functions of the National Bureau of Standards as given by the act under which it was established are the maintenance and improvement of the various national standards and the testing and calibration of measuring apparatus. The Radio Section of the Bureau has as one of these functions the carrying out of the above activities with respect to the national primary standards of radio frequency. The Bureau has had to improve the apparatus and increase the precision and the accuracy of the primary frequency standards to meet the increasingly rigorous demands of scientific and engineering advances. The primary frequency standards have taken different forms during the last decade, i. e., standard wave-length circuits, vacuum-tube driven tuning forks and associated harmonic amplifiers, simple temperature-controlled piezo oscillators, and, finally, the more complex piezo oscillators maintained under the most constant conditions such as are essential if the great precision desired is to be realized. During the development of the piezo oscillator to the important place it holds today as a radio-frequency standard, the Bureau has enjoyed the cooperation and assistance of several research laboratories and instrument manufacturers conducting similar work.

The present primary standard [1] contains two independent groups of piezo oscillators designated sections I and II. Section I consists of four piezo oscillators with fundamental frequencies of 100 kc/s. Section II has two piezo oscillators, one with a fundamental frequency of 100 kc/s and the other 200 kc/s, with a submultiple generator controlled from the latter which provides the desired 100-kc/s output.

The absolute frequency of one unit of each section is checked daily with the Arlington time signals by means of synchronous-motor clocks. The voltages which control the synchronous motors are an exact 100th submultiple of the frequencies of the controlling standards. The daily measurements provide a check on the frequency variations of the standard over an extended period. The variations over short-time intervals are indicated by an automatic recorder of the frequency difference between one of the piezo oscillators in section I and the other five units of sections I and II.

II. DESCRIPTION OF PRIMARY STANDARD

In 1929 the Bureau acquired section I of the primary standard as developed by the Bell Telephone Laboratories. It is shown in figure 1.

As this apparatus has been described (1)[2] in detail by the designer, only a brief description will be given here. A specially cut toroidal quartz plate is used in order to obtain a small temperature coefficient of frequency. This quartz toroid is mounted on a horizontal rod of fiber passed through the hole. Disks of aluminum at either end of the fiber rod serve as electrodes. The spacing of the electrodes is kept constant by a section of pyrex glass tubing, the ends ground flat and parallel, placed between them. The plate holder is wrapped in felt, ½ cm thick, and placed within a thick-walled cylinder of aluminum. On the outer surface of this cylinder heater coils are wound for maintaining the temperature of the quartz plate constant. Alternate layers of felt and copper are placed over the heater coils to serve as heat attenuation. A thermometer and a mercury thermoregulator for controlling the temperature are placed within the wall of the aluminum cylinder. This temperature-controlled chamber is mounted on a brass plate with a bell jar sealed over it. The air pressure is maintained about 5 cm of mercury below atmospheric pressure. The oscillator and amplifier circuit arrangements are located beneath the brass plate. Each unit is mounted on damped springs in a temperature-controlled cabinet, as shown in figure 1.

There are a number of factors which govern the constancy of the frequency of the piezo oscillator. Among these are temperature, pressure, humidity, and voltages applied to the oscillator tube. The choice of dimensions and orientation of the quartz plate makes the temperature coefficient of frequency of the order of 1 part in a million per °C (1) as compared with 20 to 30 parts in a million for a solid quartz disk of the same frequency. The variation of temperature at the quartz plate due to the periodic operation of the heater control is less than 0.001° C (1), which is small enough to produce a negligible variation in frequency.

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[1] Primary standard will be used hereafter meaning primary frequency standard.

[2] The figures given in parentheses here and elsewhere in the text refer to the numbered references at the end of this paper.

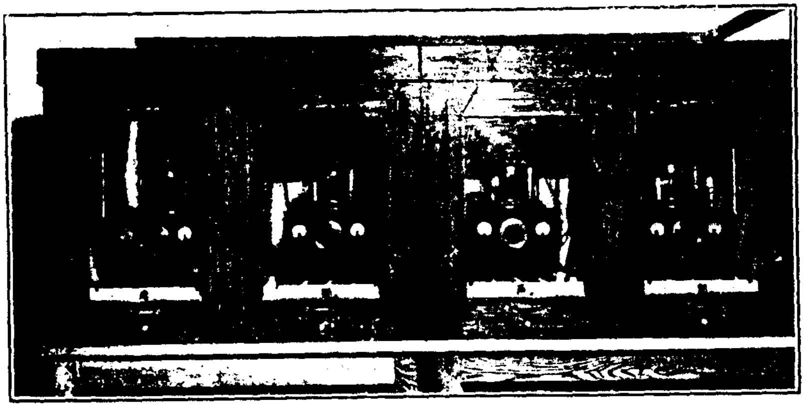

FIGURE 1.—*The four piezo oscillators of section I of the primary frequency standard mounted in temperature-controlled cabinets.*

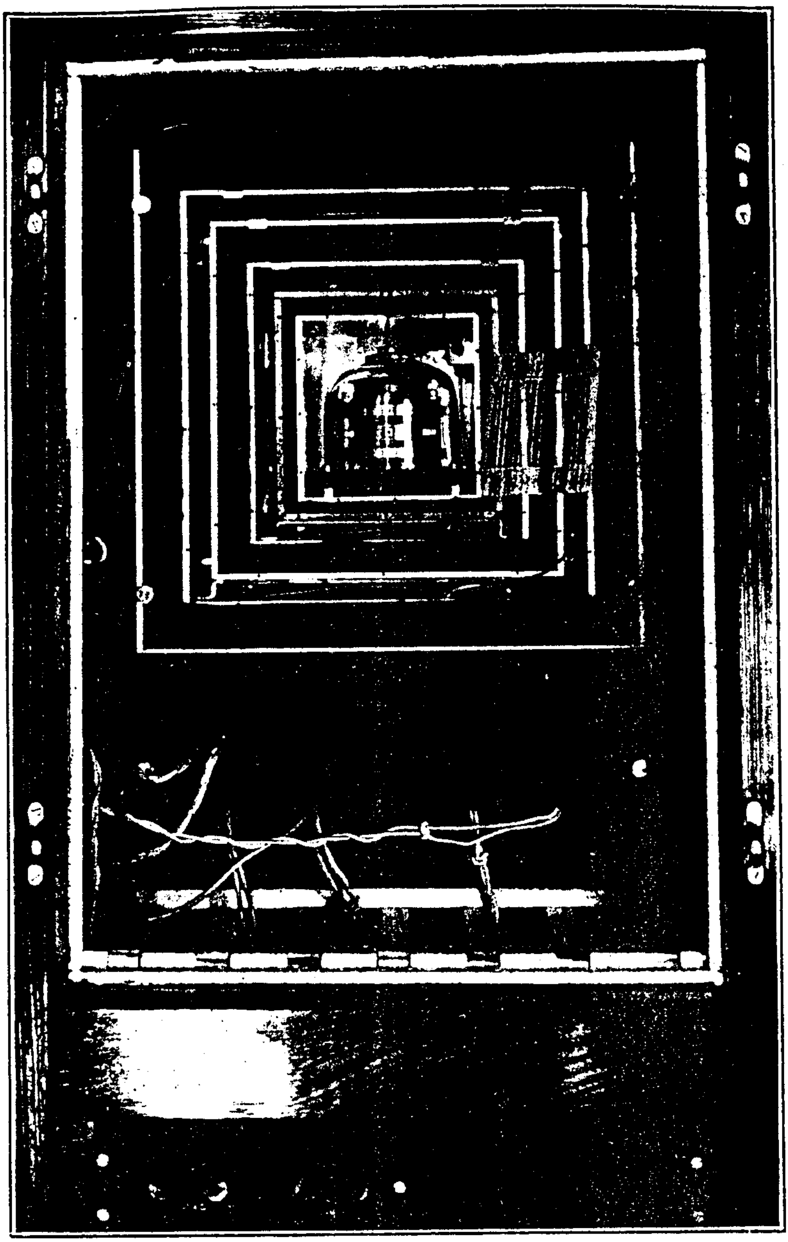

Figure 2.—*Primary no. 25 showing construction of temperature-controlled boxes.*

To protect the quartz plate from humidity and pressure variations it is kept under a bell jar at a pressure slightly below atmospheric. Considerable difficulty was experienced in finding a wax suitable to seal the glass bell jar to the brass plate and maintain the joint airtight over considerable periods of time. The wax used at present is made by combining crude rubber, vaseline, and beeswax at a temperature slightly higher than the melting point of the rubber. The exact proportions of the various constituents depend on the temperature to be maintained on the brass plate. Any seasonal variation in temperature in the outer temperature-controlled cabinet produces a change in pressure under the bell jar due to the change in temperature of the air in the jar. This variation is quite small with the present temperature control. The pressure within the bell jar continually decreases as indicated on the closed-tube manometer during the normal operation of the piezo oscillator.

There are three ways of adjusting the frequency of these piezo oscillators to 100 kc/s. A coarse adjustment may be made by changing the air gap in the plate holder by turning a central threaded portion of one electrode. A somewhat finer frequency adjustment may be made by changing the air pressure under the bell jar. An increase in pressure of 1 cm of mercury produces an increase in frequency of 1 part in 10 million. The finest adjustment may be made by means of a small cylindrical condenser, having a maximum capacity of about 5 $\mu\mu$f, shunting the electrodes of the plate holder. An adjustment of one division on the dial of this condenser corresponds to a change of frequency of about 1 part in 100 million (1). The total adjustment changes the frequency 1 part in 100 thousand.

Each piezo-oscillator circuit arrangement is of the familiar type in which the quartz plate is connected between the grid and filament of the oscillator tube and a tuned circuit is connected to the plate. The constants of this tuned circuit are such as to produce the least variation in frequency with temperature variation or aging of the circuit. Three 100-kc/s amplifiers provide independent output voltages to control the submultiple generator, to compare with the reference oscillator, and for other frequency measurements.

The submultiple generator is a series of multivibrators and amplifiers, which provide voltages at 10,000 and 1,000 cycles per second. These frequencies are exact submultiples of the frequency of the controlling standard. Three output amplifiers are provided on both the 10- and the 1-kc/s stages.

If the piezo oscillator has a frequency of exactly 100 kc/s, the frequency of 1,000 cycles per second will drive a synchronous motor geared to the hands of a clock at such a rate as to keep correct time. On the shaft of the synchronous motor are generators of 100 and 10 cycles per second, which are therefore submultiples of the original piezo-oscillator frequency. The generators are connected to amplifiers so that these frequencies are also available for use in the laboratory.

At the present time section II of the primary standard has but two piezo oscillators built a year apart in the course of experimental development and study of piezo oscillators. These two units differ in design from each other and from the four units described above. In the two years that the one unit has been in use, valuable performance data have been obtained, which have been useful in the design of other piezo oscillators now under construction.

The older of the two piezo oscillators, shown in figure 2, served as a design unit from which an improved standard model was developed. The circuit arrangement used is similar to that described above. The 100-kc/s circular quartz plate is clamped between 3 pointed screws bearing 120 degrees apart in a V-shaped groove on the cylindrical surface of the disk. All metal parts of the holder were made of stainless steel, and a pyrex glass was used for insulating parts. The quartz-plate mounting was placed under a bell jar with its edge ground flat to fit a pyrex glass plate serving as a base. A small copper tube and valve were provided and all openings sealed so that the bell jar could be evacuated. The pressure was reduced to ½ atmosphere. No difficulty was experienced with air leakage. A sectional drawing of the quartz-plate assembly is shown in figure 3. The frequency of the quartz plate decreases 1 part in 10 million per volt increase in plate potential. The variations in the voltage on the plate of the oscillator tube were minimized by using a type-874 voltage-regulator tube.

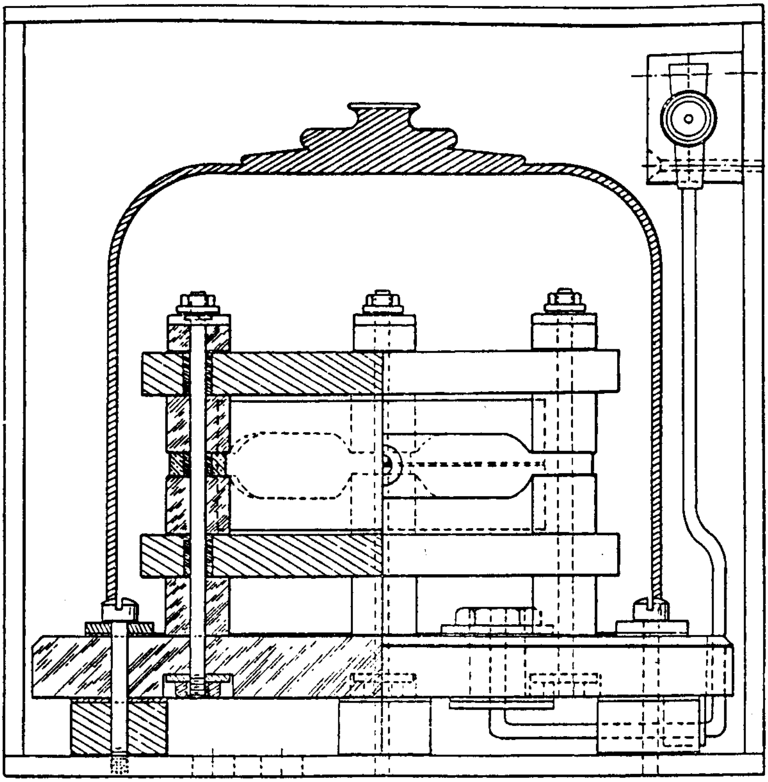

FIGURE 3.—*Assembly of quartz plate and mounting within bell jar, primary no. 25.*

The second unit of section II is still in an experimental state, not conforming to the standard design which has been evolved. However, its frequency characteristics were found to be quite satisfactory. This unit was the result of an uncompleted study of the method of cutting and mounting toroidal quartz plates in a clamped holder as applied to the resistance-capacity type of circuit arrangement, the quartz plate being connected between the plate and grid of the tube. A circuit diagram of the piezo oscillator is given in figure 4. A mathematical study of this type of piezo oscillator by Terry (2) showed that changes in filament or plate voltages or in other circuit elements such as might be experienced in normal operation produced only slight frequency changes. This type of piezo oscillator therefore seemed particularly suitable for use as a standard. A 200-kc/s, 30-degree circular quartz plate was cut and portions removed until it resembled a small wheel with heavy outer rim and a small central hub held in place by two thin spokes. The hub was drilled on both sides, leaving a small web in the center. The approximate dimensions of the plate were, outside diameter 37 mm, inside diameter 26 mm, and thickness 10.5 mm. The wheel was mounted on short metal rods fitting into the holes. Circular electrodes were held in position on either side of the wheel. No pressure control was provided in this unit. The output of this type of piezo oscillator is quite feeble, requiring more amplification than with the more usual type. Other disadvantages are the fragility and difficulty of preparing this type of quartz plate. Its improved frequency stability tends to compensate for these disadvantages. For example, an increase of 100 percent in the plate voltage applied to the oscillator tube in this type of piezo oscillator changed the frequency less than 1 part in a million. Large changes in the load resistance, plate condenser, and grid condenser gave relatively small frequency changes. Hence changes in the circuit elements and voltages applied, such as may be expected in the

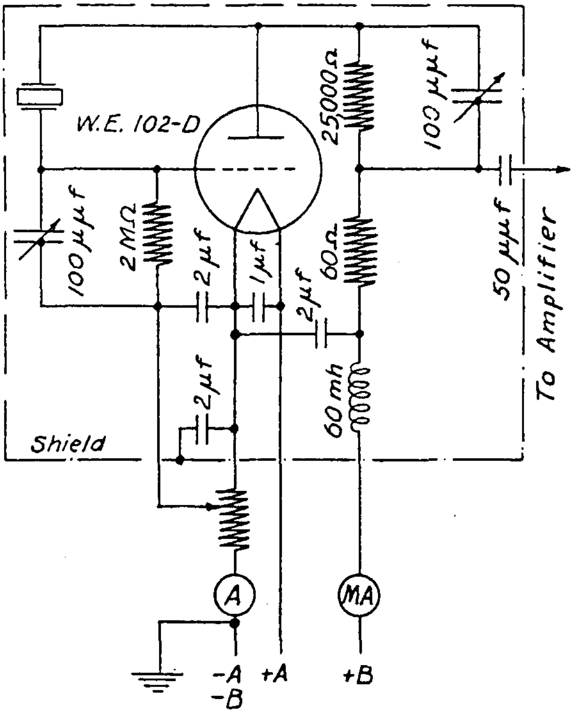

FIGURE 4.—*Electrical circuits of primary no. 26.*

course of usual operation, are almost without effect on the frequency of this piezo oscillator. The mounted quartz plate used has a temperature coefficient of frequency of about 1 part in a million per °C.

The power supply is quite a problem due to the numerous tubes of the various units. Section I requires 700 watts of power and section II 400 watts continuously, and additional power is needed intermittently for supplying heat to the piezo oscillators and for operating the various motors and relays.

Each section of the primary standard has a separate power supply. Working batteries of 18 and 135 volts supply the filament and plate voltages, respectively. Stand-by batteries of 26 and 190 volts are connected through variable resistors to the working batteries for filament and plate voltage supply. All batteries are of the lead-acid type. A marginal relay connected across each working battery operates a motor which adjusts the charging rate to maintain the working battery voltage constant to better than 1 percent.

When section I of the primary standard was first installed, a motor-generator was used to supply power for maintaining the batteries at constant voltage. The motor operated from the 3-phase, 220-volt, 60-cycle power lines. Because of the large variation in the load at the Bureau, the voltage of the power line varied greatly and produced a corresponding change in the voltages supplied by the generators. The two sets of batteries with the automatic adjustment of charging rate smoothed out the fluctuations to a large degree. Frequently the voltage supplied by the generators decreased to such a value that, when the protective relays failed, the battery discharged through the generator, reversing its field and at times burning out a relay winding.

In the fall of 1931 the motor-generator was replaced by full-wave rectifiers operating from 3-phase, 220-volt, 60-cycle lines. Copper-oxide rectifiers supply the plate power and tube rectifiers supply the filament power. No further trouble has been experienced with the power supply. The power-supply units for section II are similar to those for section I. The direct current from each rectifier passes through a filter circuit arrangement which, with the two sets of storage batteries, is effective in reducing the 360-cycle pulsations to a negligible amount before reaching the primary standard units.

A separate 24-volt storage battery is used to supply heater current for the temperature control of the quartz plates and for operating relays such as those used to control the operation of the outer heaters for which the 60-cycle lines supply power. This battery is charged from the 110-volt direct-current lines which are sufficiently constant in voltage for the purpose.

It is quite important to keep both the filament and plate voltages of the primary standard constant, because voltage fluctuations will introduce frequency changes of different amounts for the different units. The two marginal relays used to maintain constant voltage for section I of the primary standard are similar. A solenoid connected in shunt with the battery whose voltage is to be controlled is mounted with its axis vertical. An iron armature is placed in the solenoid so that its weight is balanced by the force exerted by the field within the coil. Whenever the voltage of the battery decreases, the armature moves downward to close a contact and adjust the motor-driven rheostat to increase the charging rate. An increase in voltage moves the armature upward to close a contact and decrease the charging rate.

The system of voltage regulation in section II originally had two voltage relays, one for the filament and the other for the plate voltage. The principle of operation was essentially the same as that of the marginal relays in section I. The relays had an energized coil balanced in the field of a fixed magnet against the pressure exerted by a helical spring. As the coil moved, one of the two connections was made, depending upon whether the voltage was excessively high or low. These contacts, through a single-tube amplifier, operated a series of two relays which controlled the motor-driven rheostat. The arrangement was unsatisfactory on account of sticking of the contacts and sluggishness in the movement of the coil due to friction in the bearings.

A voltage-divider circuit arrangement was then used, in which the controlled plate voltage was the working battery and a UX874 voltage-regulator tube, connected through a current-limiting resistor across the working plate battery, provided a reference-standard voltage of approximately 90 volts. The voltage relays were changed to serve as zero-center galvanometers by shorting the series resistance and readjusting the spring so that the coil rested in the midposition with no current flowing. This galvanometer, connected in the customary position in a potentiometer circuit, kept the circuit balanced by adjusting the working plate battery voltage. The filament voltage was controlled in a similar manner, except that the working plate battery voltage was used as the reference voltage. The difficulty due to bearing friction was overcome by superimposing a small 60-cycle voltage upon the current through the galvanometer. It was still necessary to clean the contacts at frequent intervals.

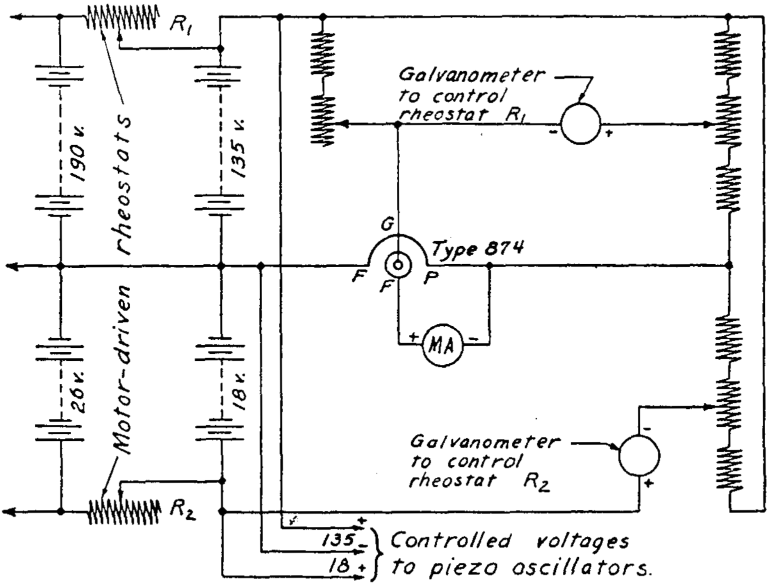

FIGURE 5.—*Voltage control system for section II of primary standard.*

These zero-center galvanometers have been replaced by galvanometers with motor-driven contactors. These units made it possible to eliminate the amplifier and a relay, and provided positive operation of the single relay which controls the motor-driven rheostat This arrangement readjusts the charging rate once in 10 seconds if needed, by operating the rheostat one second in the direction dictated by the instrument balance. The circuit arrangement used is shown in figure 5. This system of automatic voltage control gives somewhat better regulation than the system used in section I because it is not affected by changes in the room temperature, has higher sensitivity, and fewer parts that are liable to failure. It has the disadvantage, however, that it does not respond as quickly to large changes in the power-supply voltage. If a power failure occurs, it requires about two minutes for this system to reach a balance, whereas the system in section I will make the full adjustment in one operation of the rheostat.

All of the various parts of the automatic voltage control units are operated on direct current supplied by the heater batteries.

III. METHODS USED IN DETERMINING FREQUENCY AND DESCRIPTION OF APPARATUS

In order to calculate the absolute frequency of one of the units of the primary standard, the number of vibrations of the quartz plate in a known interval of time must be known. The time interval of 24 hours is determined by radio time signals from the U. S. Naval Observatory. The number of vibrations of the quartz plate is indicated by the synchronous-motor clock controlled by the frequency standard under observation. Each second indicated by the synchronous-motor clock requires 100,000 vibrations of the quartz plate. The frequency f, in cycles per second, then, is given by the following equations,

$$f=\frac{N\times 10^5}{T}=\frac{(N-T)10^5}{T}+10^5=\left(1+\frac{N-T}{T}\right)10^5$$

where N=elapsed time in seconds indicated by the synchronous motor clock and T=time interval in seconds given by the time signals. The quantity $(N-T)$ represents the total gain or loss of time indicated by the synchronous-motor clock with respect to standard time. Letting $(N-T)=\pm D$, where plus is a gain in time and minus is a loss in time,

$$f=\left(1\pm\frac{D}{T}\right)10^5$$

If the time measurements are made for a time interval of 1 day or some integral multiple of a day,

$$f=\left(1\pm\frac{d}{86400}\right)10^5=10^5\pm 1.1574d,$$

where d=gain or loss in seconds per day.

The time interval to be chosen in this method of frequency determination is dependent on the constancy of the frequency standard itself and the accuracy with which it is desired to know the frequency. The length of interval must be short enough so that it is reasonably certain that the frequency was either constant during the interval or can be represented with the required accuracy by a linear variation. On the other hand, the interval must be long enough that the errors caused by the random variations in the determination of the time interval and the counting of the vibrations of the quartz plate are within the accuracy with which it is desired to determine the frequency.

A chronograph shown in figure 6 has a sheet of wax-coated paper mounted on a disk driven at a speed of 0.5 rps by a 100-cycle synchronous motor. Two styluses mounted on a carriage travel along a radius of the disk as it revolves and thus draw almost coincident spiral lines on the waxed paper. Second pulses from a cam-operated contact on the clock driven by the primary standard are impressed on one stylus, and radio time signals from the Naval Observatory on the other one, resulting in two sets of radial lines formed by the displacements in the spiral lines as shown in figure 7. The angle between each set of radial lines is read on a graduated circle and interpreted in seconds difference in time between the two time signals, as 180° on the paper record represents 1 second of time. This time difference may be accurately determined within a few thousandths of a second. The record on the disk of paper is made in a period of 1½ minutes. The value of the time difference as read is an average for that period of time.

In order to check the determination of the frequency of the primary standard, a number of additional measurements of time differences are taken each day. Both of the clocks operated from units of the primary standard are checked with the time signals from Naval Radio Station NAA to give a direct determination of the frequency. Both clocks are also checked against the Shortt clock at the Bureau. One clock is measured in terms of the other. With these various measurements available, simple computations will check the accuracy of the measurements and thereby minimize personal error.

Absolute measurements of frequency are made on only one of the piezo oscillators in each section. The beat indicators and the accompanying recorder make it possible to determine the frequency of the other units, as well as to provide a record of the operation of each standard in terms of the others. This record is the best information available as to the constancy of the standard controlling the synchronous-motor clock during the time interval over which the frequency is averaged. When first installed each beat indicator was connected to a telephone-message counter which added up the number of beats for the three pairs of piezo oscillators. A record of the beat counter readings, together with that of a seconds counter, was made photographically each 1,000 seconds. This method of recording required many moving parts which were quite difficult to keep in operation. Another disadvantage was the large amount of work required to develop, record, and compute the results.

The present beat-frequency recorder is an adaptation of a method of measuring low audio frequencies developed by the Bureau (3). The beat frequency, usually from 0.1 to 0.3 cycle per second, operates a polarized relay, T, figure 8. At each operation of relay T the condenser C_1 is discharged through the highly damped galvanometer G. Condenser C_2 and resistor R_2 act as a filter to smooth out the discharge current through G. Because of its long period of about 60 seconds the galvanometer takes a position depending on the average current through it, the current depending on the value of the beat frequency. The potential for charging condenser C_1 is obtained from the constant plate voltage of the primary standard.

The galvanometer used is a special microammeter made to record 6 successive measurements in different colors in approximately 17 minutes. One of these measurements is a calibration of the galvanometer made by a frequency of 0.2 cycle per second obtained by a cam-operated contactor on the 1,000-cycle synchronous motor. This calibration is made frequently at 0.1 and 0.4 cycle per second. Figure 9 shows part of a recorder chart, with the central calibrating record and 5 beat-frequency records. Each small division of the scale represents a change in beat frequency of 0.004 c/s which represents, at the oscillator frequency of 100 kc/s, a variation of 4 parts in 100 million.

When it is desired to study the variations in frequency of any one of the piezo oscillators the frequency is multiplied to the 100th harmonic by a tuned multiplier circuit arrangement and beat against the 100th harmonic of another unit of the primary standard. This difference frequency is then recorded on a continuous recorder on which each small division represents a beat frequency change at 100 kc/s of 5 parts in 1 billion. With a record speed of 12 in./hr it is not difficult to note and time quite small variations in frequency difference. This recorder is of great assistance in locating and eliminating small frequency variations in the primary standard. It is expected that a description of the recorder and the accessory units will be published in the Journal of Research of the National Bureau of Standards under the title "Monitoring the standard frequency emissions", by Evan G. Lapham.

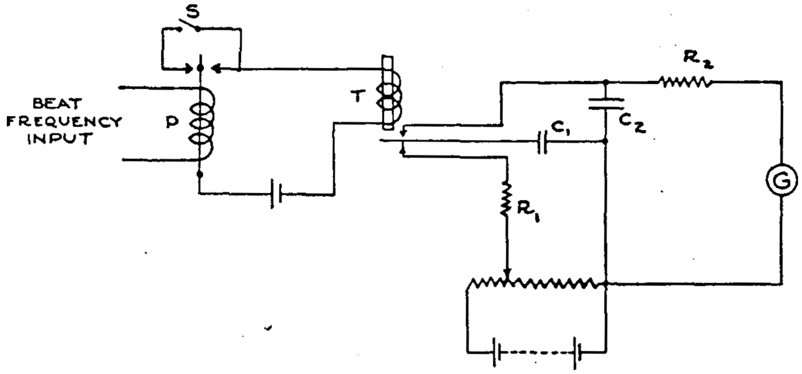

FIGURE 8.—*Graphic beat-frequency recorder.*

The frequency of the primary standard is calculated over a 10-day interval in terms of the uncorrected time signals and over a 6-day interval in terms of corrected time signals. The 10-day interval is required to give the desired accuracy as there is a maximum probable error in the time interval, as indicated by the uncorrected time signals, of 0.06 second which, if averaged over a 10-day period, reduces the maximum probable error in the frequency determination, due to this cause, to 7 parts per 100 million. This factor is considerably larger than the probable error caused by inaccuracies in the determination of the number of vibrations of the quartz plate in the time interval. The error in this measurement is not greater than ± 0.002 second or ±200 cycles, which would cause an error in the frequency determination over a 10-day interval of only 0.5 part per 100 million. The maximum errors in terms of the corrected time signals over a 6-day interval are 4 parts per 100 million due to error in the time interval and 0.8 part per 100 million due to error in the determination of the vibrations of the quartz plate.

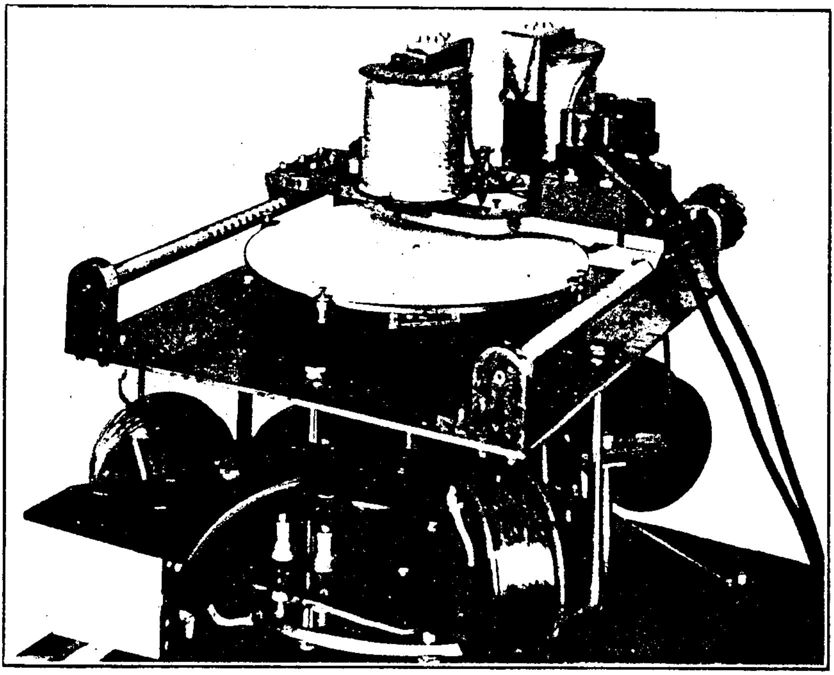

FIGURE 6.—*Electric chronograph driven by 100-cycle synchronous motor used for checking primary standard with NAA time signals.*

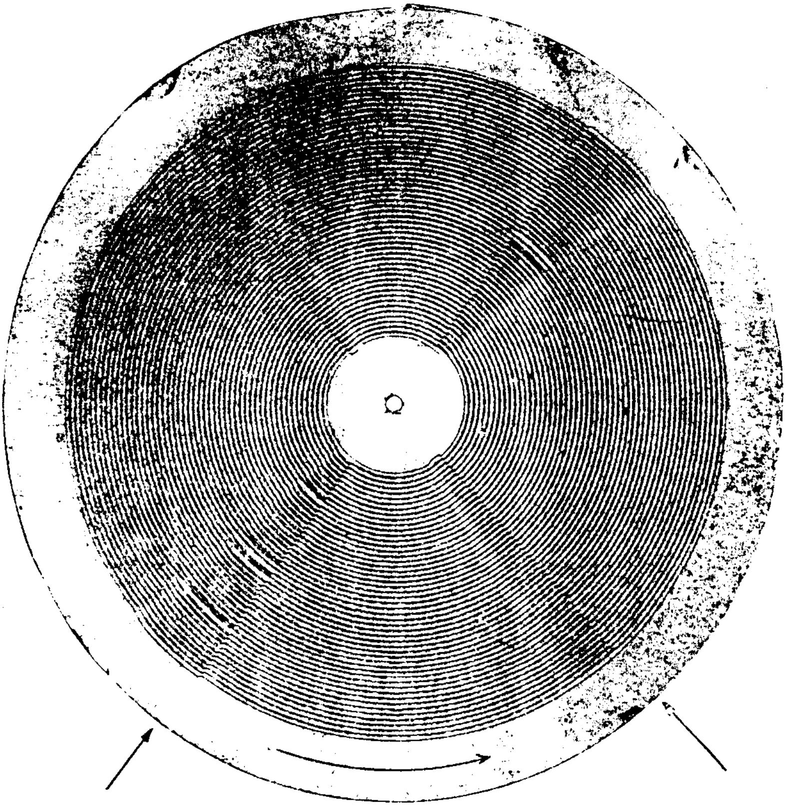

Figure 7.—*Sample record obtained with electric chronograph.*

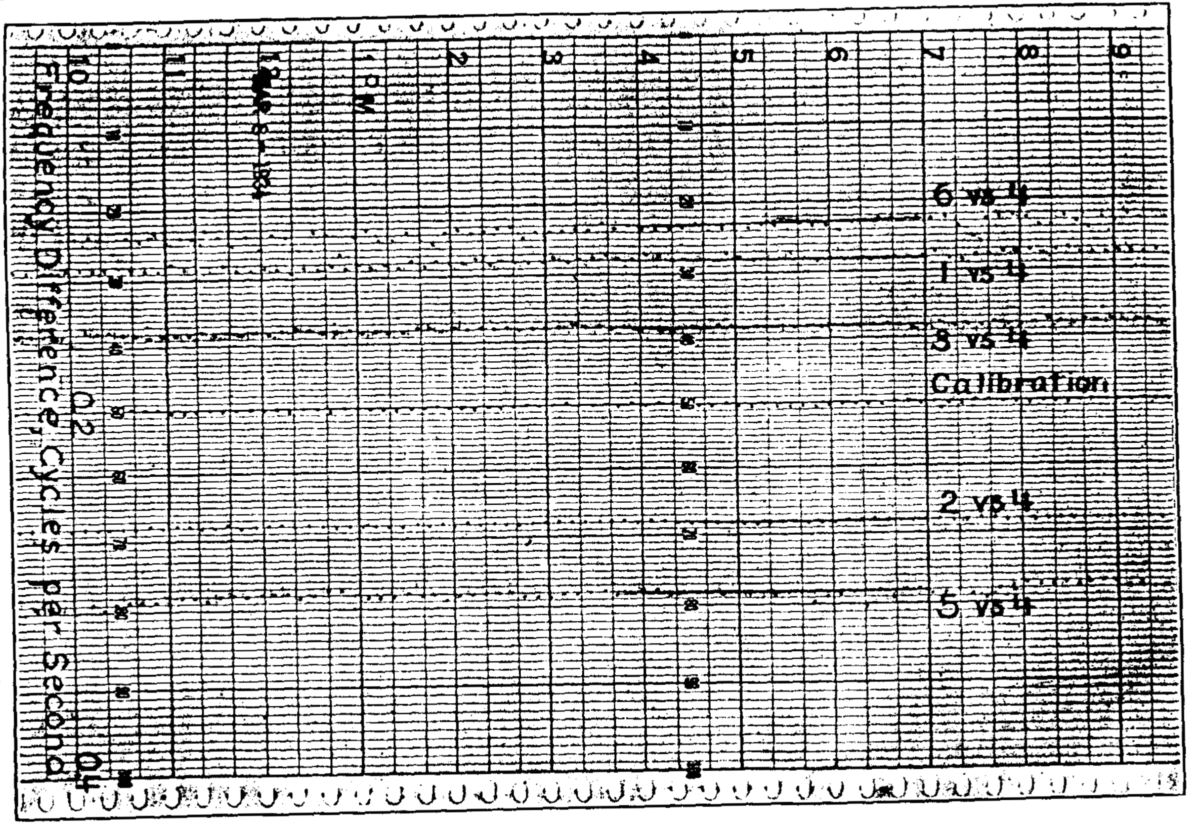

FIGURE 9.—*Sample record obtained with graphic beat-frequency recorder.*

The frequencies of the units of the primary standard are very seldom constant. The fact that a frequency drift exists and that the value of the frequency, derived from a comparison with the standard time interval is the average for the time interval and occurs at the midpoint of the interval, necessitates extrapolating the data obtained from the uncorrected time signals ahead for 5 days. To facilitate this extrapolation the frequency is plotted on cross-section paper so that the average rate of change of frequency can be readily determined. The final corrected values are plotted on the same sheet with the values obtained from the uncorrected time signals. Using this value of the frequency and the beat indicator record, daily values are computed for the frequencies of each of the other units of the primary standard.

IV. USES OF THE PRIMARY FREQUENCY STANDARD

The advantage to any radio laboratory of having available a frequency standard of great accuracy, giving submultiple frequencies as described above, is apparent. The application of such a device to many electrical and scientific investigations will likewise be readily apparent. A number of cases where these frequencies are being advantageously used at the Bureau are given below. However, one of the most important applications of the national primary frequency standard is its dissemination for use by the general public for checking frequency standards maintained by radio and electrical instrument manufacturers and testing laboratories, radio transmitting stations, university laboratories and others desirous of accurate frequency values. Dissemination of the frequency standard is accomplished by two methods, first by radio transmission and second by direct wire connection to one of the primary frequency standards.

The general method of providing standard frequencies by radio transmissions has been in use by the Bureau for eleven years. During the last four years a transmission on 5,000 kc/s (4) was available four hours a week. These transmissions were useful throughout most of the United States. As these transmissions are held accurately upon frequency by comparison with the primary standard, anyone using the transmissions in effect has direct access to the primary standard.

The method of dissemination of frequencies from the primary standard by means of a direct wire connection to one of its units is limited to a small area in the vicinity of Washington because of the expense of a long wire line. Such a connection has been used for over two years by one laboratory near Washington. A frequency of 10 kc/s from one of the primary standards is impressed upon a telephone line leased by the measurement laboratory.

A frequency of 1000 cycles per second from the primary standard is used in the Bureau laboratories in the measurement of absolute value of resistance, and in the calibration of inductors and mica condensers. This frequency is also used in calibration of the tuned reeds for the reed indicators used in directing airplanes on their courses.

A frequency of 100 cycles per second from the primary standard is used in measurements on air condensers and in the calibration of audio-frequency standards. This frequency is amplified to drive the synchronous motor of the time signal chronograph. A frequency of 60 cycles per second provided by section II of the primary standard is used to calibrate the reeds in reed indicators for airplanes and as a timing frequency for velocity meter tests. This frequency is also used to control the frequency of a 60-cycle generator used in the testing of electrical instruments. A frequency of 10 cycles per second is useful in calibrating audio-frequency standards.

The one-second contactor is used for intercomparing time rates of clocks driven by the primary standard and various time standards, and also as a source of constant seconds pulses for counting numbers of α-particles emitted by a radium sample. The frequency of 0.2 cycle per second serves to calibrate the beat recorder and also as a source of constant signal pulses for counting α-particles emitted by a radium sample.

V. PERFORMANCE AND DISCUSSION

Since the installation of section I of the primary standard, many changes have been made in the individual units themselves, in the wiring, and in the instruments and methods of calculating the frequency, all of which have added to the accuracy with which the frequency is known. Certain limitations are recognized as present which may perhaps be removed later. There is considerable evidence that the units of section I are subject to similar variations in frequency. This may be due to the similarity in their construction or to stray coupling between the standards. The fact that the output amplifiers use triodes which have considerable grid-plate capacity, and also that the units have a common power supply make it seem all the more likely that a small amount of coupling might be present. Frequency checks with one or more units operated on a separate power supply would show that one or the other section had changed. The advantage of two independent sections is therefore evident.

The improvements in the equipment since its installation have resulted in a considerable extension of the periods of continuous operation of the synchronous-motor clock. The longest period of continuous operation of the synchronous-motor clock in section I is a little over seven months. The synchronous-motor clock in section II operated without stoppage for about the same length of time. The average period of continuous operation for the two synchronous-motor clocks for the last two years is over four months. Accidental stoppage and failure of the 1000-cycle output due to aging of the amplifier tubes account for most of the discontinuity in operation. Contrary to expectations, only in a very few instances have the stoppages of the synchronous-motor clocks been traceable to the submultiple generators. As far as the determination of the frequencies of the standards is concerned, the continuity of operation of the synchronous-motor clocks is quite satisfactory. Interruptions in the operation of the clocks, however, would interfere greatly with their usefulness as time standards.

Frequency variations in piezo oscillators may be of two main types: (a) long-time variations or those which would not be noted in intervals of a few hours or a day, but may be noticed over a period of several weeks or months; (b) short-time variations or those which may be measured and may occur irregularly, perhaps instantaneously, or in intervals of a few minutes or less. The frequency variations tolerable in a unit of a primary frequency standard are extremely small in comparison with variations which might be of little consequence in other frequency standards.

An oscillator which is either constant in frequency or displays only a long-time variation is most useful as a frequency standard, as its change in frequency can be predicted and corrections made for the slight drift or change in value. This type of oscillator is convenient for driving a timekeeping mechanism and may ultimately compete with the most exact pendulum clocks used in observatories (5). The performance of this type of timekeeper is of great interest because of its entirely different principle of operation, being unaffected by some factors to which all pendulum clocks are subject.

An oscillator subject to short-time variations is not reliable for instantaneous measurements to better than the order of the maximum short-time variations observed. The measurements could conceivably be made at the time when one of the maximum variations had taken place and would accordingly be in error by that amount.

Piezo oscillators of different designs usually display both of the types of frequency variation mentioned above in different amounts. Each piezo oscillator therefore must be considered individually and efforts made to determine its characteristics and reliability in maintaining its frequency. Where instantaneous measurements of the greatest accuracy are desired, an oscillator showing minimum short-time variations should be employed.

Measurements on the several units of the primary standard show maximum short-time frequency variations of different amounts ranging from less than 1 to several parts in 100 million. The oscillators do not show the same characteristics continually but may change with time. One that has maintained a fairly constant frequency for a long period may change and become unreliable for the highest precision. The opposite case may also occur. It is therefore desirable to periodically check up on the short-time frequency changes of each oscillator. Knowing the details of construction of the several oscillators, it is often possible to account for part of the peculiar behavior observed in some of the standards. None of the instruments used with the primary standard have, however, afforded information by which to predict that an oscillator was about to alter its rate of change of frequency.

It is of interest to know what accuracy can be expected from a group of piezo oscillators that operate continuously, under controlled conditions, as described above. For this purpose the curves of figure 10 have been prepared showing the frequency change with time for the two units of the primary standard which drive the synchronous-motor clocks. To obtain these curves, the daily corrected frequencies for the 1st and the 15th day of each month were plotted. The upper curve covering a period of 21 months shows the frequency variations of no. 12 of section I. The breaks in the curve indicate times when frequency adjustments were made.

The upper curve is representative of the standards in section I. It should be noted that the frequency of these units may drift either higher or lower at a rate of ±3 parts in 10 million per month. The average frequency over a period of a year or more, however, increases in value. Although it is not apparent in the curve shown, the average rate of change of frequency would be of the order of 1 part in 1 million per year. The maximum deviation from the average is approximately ±1 part in 1 million.

The lower curve of figure 10 shows the frequency variations of no. 26 of section II, for a period of 15 months. This is the experimental unit previously mentioned, which is not equipped with pressure control. If the pressure had been maintained more uniform, a more regular curve would probably have been obtained. During this period the frequency has been subject to a fairly gradual increase of approximately 1 part in 10 million per month. Although there have been periods when the frequency has drifted at a somewhat greater rate, these periods have been of comparatively short duration, so that the maximum deviation from the average is of the order of ±2 parts in 10 million. Owing to the shortness of the period of operation, however, any statement as to its over-all frequency drift is highly speculative.

It is quite an advantage to have section II of the primary standard operated by separate power supply units and with circuit arrangements differing from those of section I. Whenever variations in frequency take place, it is unlikely that all six units of the primary standard would vary alike. If the voltage-control system of one section fails to operate properly, the other section continues to function properly and serves as a basis for frequency measurements.

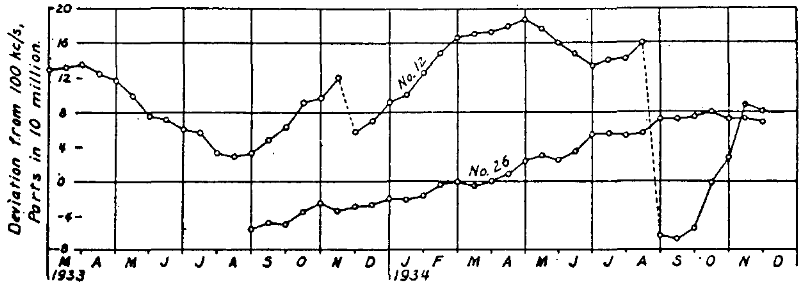

Figure 10.—*Frequency deviation curves for primary nos. 12 and 26.*

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