Vincent E. Heaton

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PRODUCTION OF ACCURATE ONE-SECOND TIME INTERVALS

By William D. George

ABSTRACT

This paper describes the technique wherewith a highly accurate frequency of 1 cycle per second is obtained for broadcasting from the Bureau's radio station WWV. Multivibrators are used in obtaining lower frequencies from a radio-frequency standard. Observations are given concerning the nature of short-time instabilities occurring in controlled multivibrators. The measuring technique is described whereby the accuracy between successive time intervals or cycles is checked to better than one part in a million. It is pointed out that the arrangement can be used for supplying extremely short pulses accurately spaced in time. The frequency of 1 c/s is added as a modulation on standard radio frequencies, which are broadcast each Tuesday and Friday.

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I. INTRODUCTION

Standard radio frequencies have been broadcast for 15 years by the National Bureau of Standards from its radio station WWV. Since April 1935 a standard audio frequency, 1000 c/s, as a modulation on the standard radio frequencies, has been included in certain of the broadcasts. To make the broadcasts still more useful, a highly accurate frequency of 1 c/s, supplied as a modulation on the standard radio frequency, is now included in certain of the broadcasts. This makes available by radio standard time intervals of 1 sec. These are not time signals, in that no attempt is made to set them in phase with standard time, but they are useful for certain work requiring an accurately known time rate. This paper is devoted to a description of the method and equipment for production of the standard time intervals.

II. METHODS OF OBTAINING ACCURATE TIME INTERVALS

The quartz-crystal oscillator, when operated under the most favorable conditions, is recognized as the most precise marker of time intervals. Pendulums and tuning forks could possibly be operated with comparable precision; however, greater difficulty would probably be experienced in doing so.

Ordinarily standard piezo oscillators operate at frequencies near 100 kc/s, and lower frequencies are obtained by means of multivibrators. Frequencies down to about 1,000 c/s are commonly so obtained.

Frequencies below 1,000 c/s are usually obtained by having a 1000-cycle synchronous motor rotate a beam of light, or rotate a generator having the desired number of poles, or operate reduction gears and contractors. With these arrangements, the primary sources of errors in the time interval between successive cycles are the hunting of the synchronous motor and mechanical imperfections. For high accuracy, ordinary mechanical contactors are unsatisfactory. Time intervals obtained from a 1000-cycle synchronous motor may differ by almost 1/2000 sec.

In the present investigation, multivibrators were constructed for stepping down in frequency from 1,000 c/s to 1 c/s in three 10-to-1 stages. The time intervals between successive pulses in the 1-cycle stage were observed to be equal within a few parts in 10^5. The variation was reduced by using separate power supplies for the 10-cycle and 1-cycle stages.

A special circuit arrangement was devised whereby time intervals of 1 sec accurate to better than one part in 10^6 were obtained. These seconds pulses were made to have a special wave shape suitable for reception on ordinary radio equipment; they were made short so as not to interfere with radio-frequency measurements which were being made on the carrier frequency. The pulses consisted of 5 cycles of a 1,000-cycle wave.

III. SHORT-TIME VARIATIONS IN THE OUTPUT OF CONTROLLED MULTIVIBRATORS

The length of successive half cycles in the output frequency of a controlled multivibrator may not be the same because of changes in any of the following parameters: filament emission, circuit constants, plate voltage, or control voltage. However, the statistical average of the output frequency, over a large number of cycles, may be the same as the controlling frequency divided by the frequency division integer. Measurements were made on a balanced multivibrator operating from 1,000 c/s to 100 c/s. The magnitude of phase shift caused by a 10-percent change in different circuit parameters is given in table 1.

TABLE 1.—*Phase shift caused by a 10-percent change in circuit parameters*

10-percent increase made in—	Phase shift	Equivalent phase shift
	Radians	*μ sec*
Filament voltage	−0.0018	−3
Circuit capacity	−.0735	−117
Circuit resistance	−.0646	−103
Plate voltage	−.0130	−21
1,000-cycle control voltage	+.0075	+12

The shifts caused by changes in circuit constants or filament voltage are of little importance because these shifts are likely to occur slowly if good condensers and resistors are used. Rapid variations in plate and control voltages are responsible for practically all random variations (from cycle to cycle) in the output. As they are in opposite directions, the effect can be largely eliminated by operating all the multivibrator equipment from the same power supply and designing the control-voltage input amplifier so that its output voltage will change a relatively large amount with changes in direct plate voltage.

Figures 1 and 2 are curves showing the results of numerous measurements on a balanced multivibrator having a controlled output

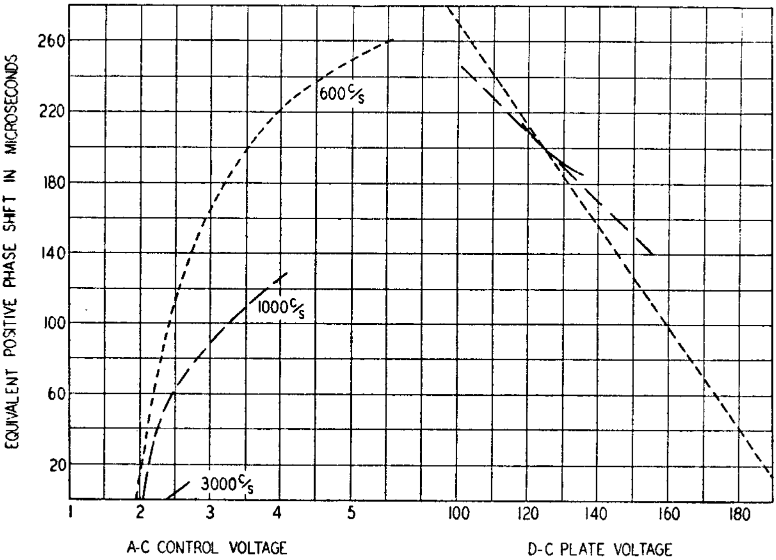

FIGURE 1.—*Experimental observations of phase shift in a balanced multivibrator having a controlled frequency of 100 cycles per second.*

frequency of 100 c/s. The variations caused by changes in plate voltage or control voltage are given for different values of plate voltage, different ratios of frequency division and different values of R/C. It is seen that some advantage was gained in operating the multivibrator at a higher plate voltage, a low R/C ratio, and a small frequency-division. However, these advantages were not very great. Where the uncontrolled frequency was lower than 100 c/s, and E_p was 75 v or greater, the phase shifts were in opposite directions for changes in control voltage and d-c plate voltage.

The phase shift was measured by comparing the output of the multivibrator with the output of a piezo oscillator having a frequency of 200 kc/s or multiples thereof, directly on a cathode-ray oscillograph screen. Advantage was taken of the sharp rise in voltage at the beginning of each half cycle of the frequency obtained from the multivibrator. Figure 3 illustrates the type of oscillograph patterns obtained. Horizontal deflection was obtained, in this case, with a standard-frequency voltage of 1000 kc/s along with the regular sweep frequency of 100 c′/s. Vertical deflection was the output of the 100-

cycle multivibrator. Changing the control voltage and plate voltage on the multivibrator caused the visible 1000-kc wave to move. The phase shift was obtained by counting the number of cycles moving past a mark on the oscillograph screen and noting the direction. A movement of 1 cycle corresponded to a change in phase of 0.0006 radian, equivalent to 1 μs. By observing such patterns over a long period of time the magnitude of random variations was seen to be considerably less than one part in 10^6 in the final circuit arrangement. An attempt

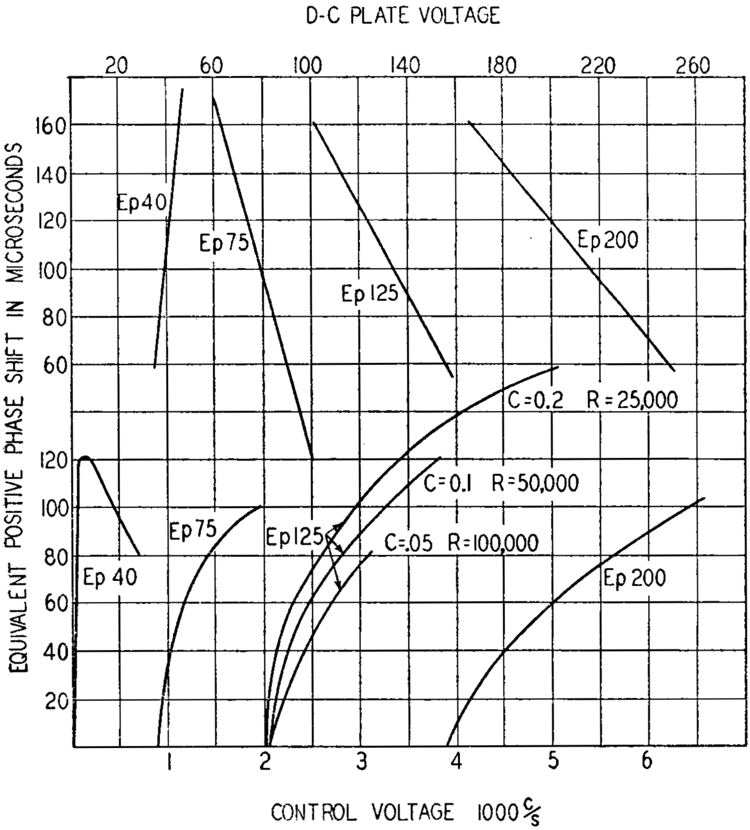

FIGURE 2.—*Experimental observations of phase shift in a balanced multivibrator having a controlled frequency of 100 cycles per second.*

was made to measure the time required for the rapid increase in voltage at the beginning of each half cycle in the multivibrator. With the circuit constants used in the 100-cycle multivibrator (see fig. 4), this rise in voltage took place in much less than 1 μs. The 3-inch cathode-ray oscillograph used was adjusted for maximum brilliancy and no trace of a line was visible at the beginning of a half cycle. In order to obtain figure 3 this rate of change in voltage was decreased by adding a resistor in series with the vertical deflection plates of the oscillograph.

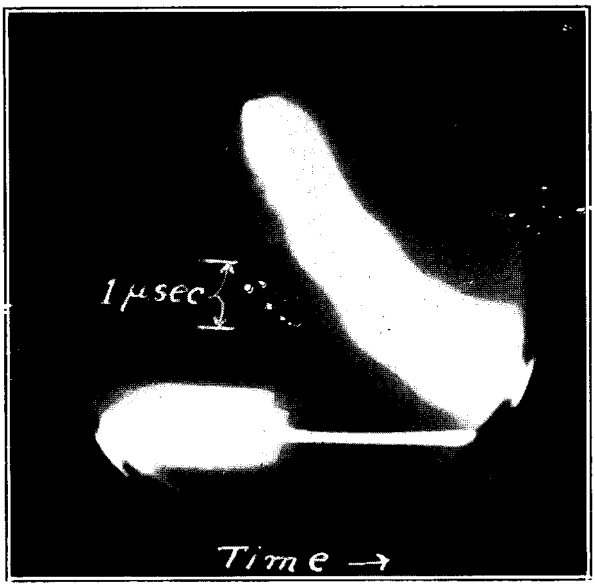

FIGURE 3.—*Oscillograph pattern for measuring phase shift.*

IV. DESCRIPTION OF OPERATION AND RESULTS

A schematic diagram of the apparatus is given in figure 4. Figure 5 shows photographs of oscillograms obtained. The approximtely rectangular wave shape in the multivibrator was amplified with two saturated amplifiers in tandem to obtain a very close approximation to a rectangular wave shape. That is, the output voltage from the fourth tube was present at nearly constant amplitude for 1/200 sec and was off for 1/200 sec. This voltage was used to apply a high bias to and cut off the first push-pull amplifier which amplified the 1,000 c/s; therefore the output of this amplifier consisted of groups of 5 cycles of the 1,000-cycle wave separated by blank spaces of 1/200 sec. A second push-pull amplifier passed this output; however, its plate voltage was applied only once per second. The voltage was applied during a 1/200 sec blank space and removed during the succeeding 1/200 sec blank space. This resulted in an output once per sec of 5 cycles of the 1,000-cycle wave.

To turn on the output amplifier once per sec several arrangements were tried, a relay operated from a multivibrator at 1 c/s, a thyratron operated from a 1-cycle multivibrator, and a synchronous motor operated from an available 300-cycle source and driving a seconds contactor. The synchronous motor arrangement proved most desirable and was used. The motor revolved 5 times per second and on its shaft was a commutator which closed for approximately 1/200 sec for each revolution; a second contactor in series with this (driven by gears), closed once per second. The commutator brush was arranged for adjustment of phase or time of turning on the output amplifier. A variation of $\pm 1/400$ sec in the closing and opening of this contactor was permissible without affecting the accuracy of the seconds pulse, because it closed and opened during the time no input voltage was on the output amplifier.

Figure 5 (a) shows the output wave shape when the groups of waves were occurring 100 times per second; the 1,000 c/s was left on continuously for a short time during this exposure to indicate distortion if present. Figure 5 (c) is the wave form after passing through the speech input equipment of the radio transmitter. Figure 5 (e) shows the pulse frequency greatly amplified and with a standard frequency of 400 kc/s applied to the horizontal deflecting plates of the oscillograph in addition to the sweep frequency. The wave forms shown in the foregoing photograph were similar in all respects, when the groups of 5 cycles were occurring once per second. Oscillograms similar to figure 5 (e) showed the time interval between pulses to be accurate to better than one part in 10^6. Figure 5 (b) is a photograph of the seconds pulses from the equipment, and figure 5 (d) the pulses from a radio receiving set. The latter are 5-minute time exposures with the oscillograph base line covered.

Since these pulses are transmitted it is important that no random phase shifts occur in the transmitting equipment which would destroy their accuracy. High-level modulation is used with transformer coupling in the audio amplifier; a shift occurs for changes in line voltage and for different settings of the attenuator on the speech input amplifier. The attenuator setting is not changed during a broadcast and is ordinarily returned to the previous point for a later broadcast. The variations in line voltage encountered at the transmitter shift the phase less than one part in 10^5.

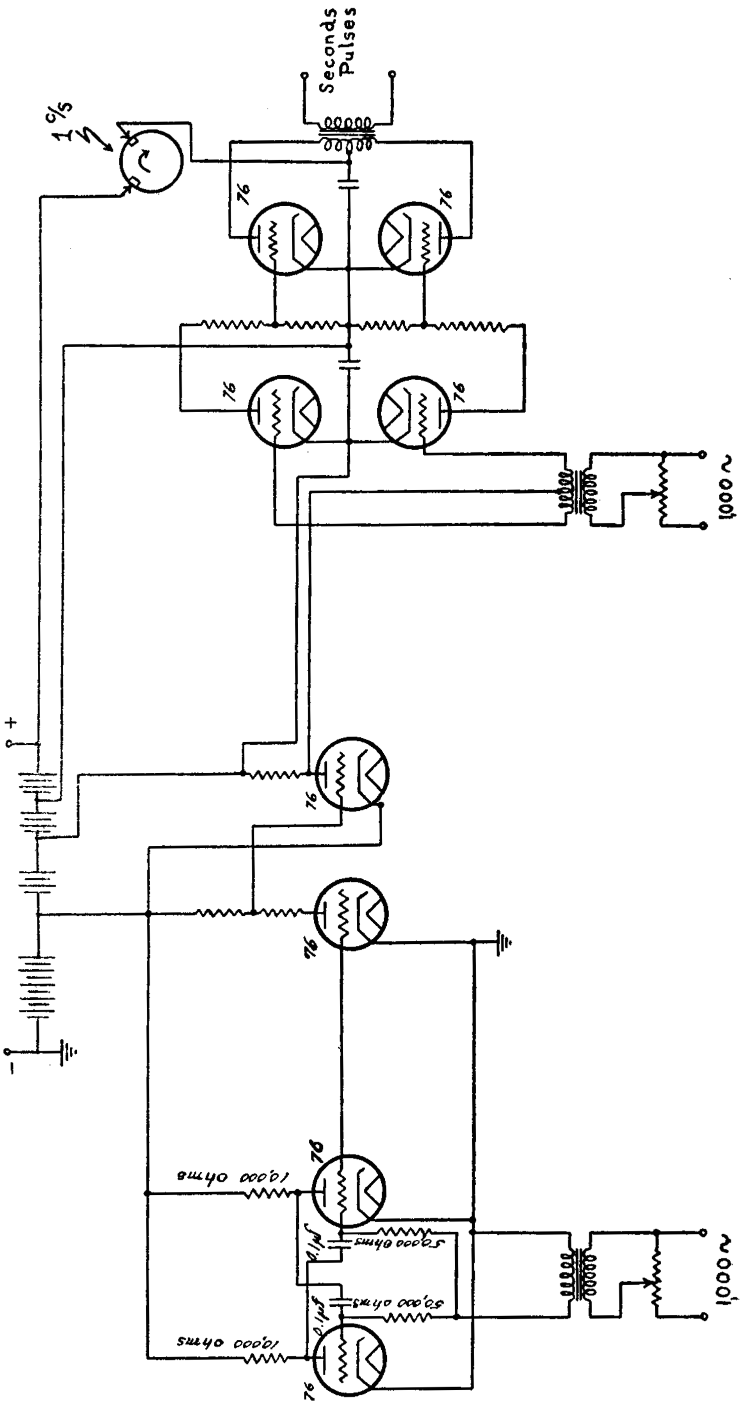

FIGURE 4.—*Schematic diagram of equipment giving seconds pulses.*

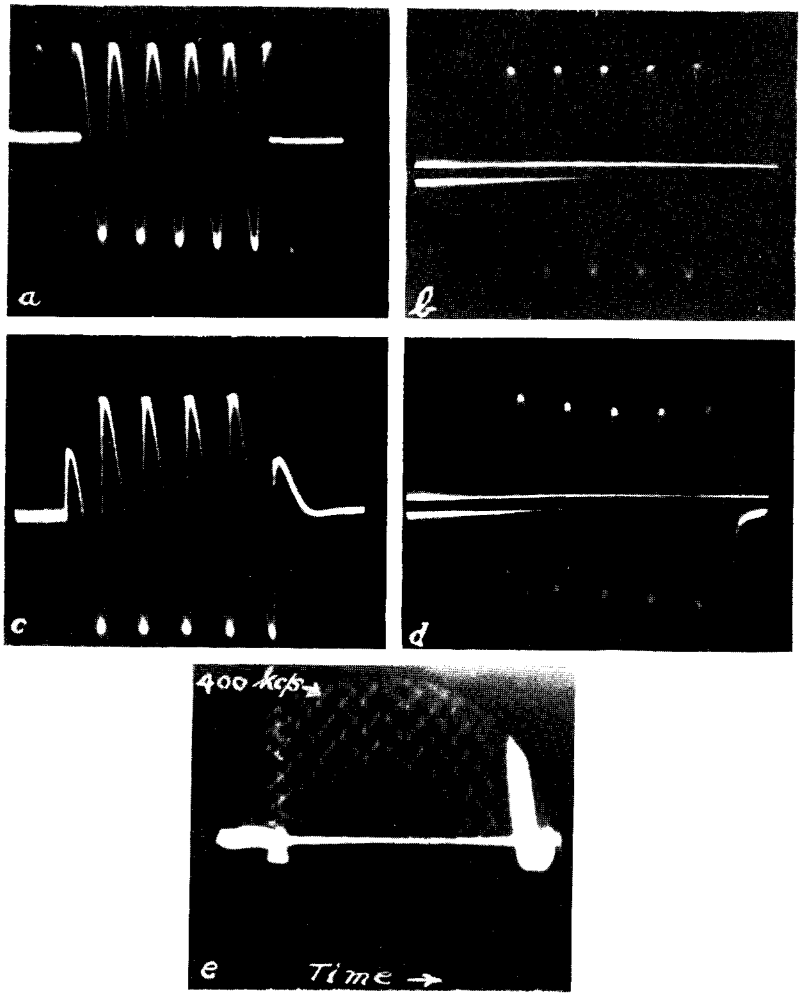

FIGURE 5.—*Wave forms from equipment for seconds pulses.*

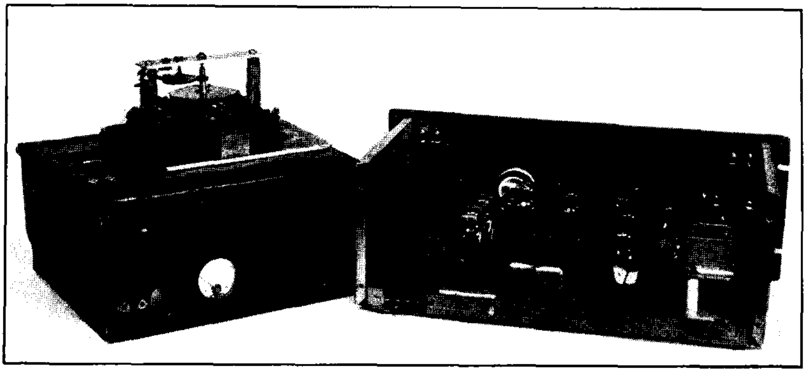

FIGURE 6.—*Equipment for seconds pulses.*

Figure 6 shows the equipment. It is supplied with 1,000 c/s and 300 c/s from other multivibrators.

V. ADDITIONAL USES OF APPARATUS

This system could be used to supply shorter pulses, for example, 5 cycles of a 1,000-kc frequency once per second or even 1 cycle of such a frequency. By using two sets of equipment it would not be difficult to adjust the output pulses to exact synchronism and thereby have a reliable source of seconds pulses over a long period of time. This would be useful in studying the long-time variations of radio-frequency standards with high accuracy. By selecting the proper division numbers for the numerous multivibrators used in such equipment, accurate time intervals of almost any length can be obtained. The method of measuring phase shift could be used with ordinary wave forms in measuring minute changes in phase caused by some changes in a circuit arrangement. A multivibrator could be controlled by the output frequency, and its output compared against a multiple frequency of the input to the device being measured.

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