U.S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS
WASHINGTON

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Letter
Circular
LC-751

METHODS OF USING STANDARD FREQUENCIES BROADCAST BY RADIO

May 16, 1944

U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS
WASHINGTON

May 22, 1944

STANDARD FREQUENCY BROADCAST SERVICE

OF NATIONAL BUREAU OF STANDARDS.

This service comprises the broadcasting of standard frequencies and standard time intervals from the Bureau's radio station WWV near Washington, D.C. It is continuous at all times day and night, from 10-kilowatt radio transmitters except on 2500 kilocycles per second where 1 kilowatt is used. The services include: (1) standard radio frequencies, (2) standard time intervals accurately synchronized with basic time signals, (3) standard audio frequencies, (4) standard musical pitch, 440 cycles per second, corresponding to A above middle C.

The standard frequency broadcast service makes widely available the national standard of frequency, which is of value in scientific and other measurements requiring an accurate frequency. Any desired frequency may be measured in terms of any one of the standard frequencies, either audio or radio. This may be done by the aid of harmonics and beats, with one or more auxiliary oscillators.

At least three radio carrier frequencies are on the air at all times, to insure reliable coverage of the United States and other parts of the world. The radio frequencies are:

2.5 megacycles (= 2500 kilocycles = 2,500,000 cycles) per second, broadcast from 7:00 P.M. to 9:00 A.M., EWT (2300 to 1300 GMT).
5 megacycles (= 5000 kilocycles = 5,000,000 cycles) per second, broadcast continuously day and night.
10 megacycles (= 10,000 kilocycles = 10,000,000 cycles) per second, broadcast continuously day and night.
15 megacycles (= 15,000 kilocycles = 15,000,000 cycles) per second, broadcast from 7:00 A.M. to 7:00 P.M., EWT (1100 to 2300 GMT).

Two standard audio frequencies, 440 cycles per second and 4000 cycles per second, are broadcast on the radio carrier frequencies. Both are broadcast continuously on 10 and 15 megacycles. Both are on the 5 megacycles in the daytime, but only the 440 is on the 5 megacycles from 7:00 P.M. to 7:00 A.M., EWT. Only the 440 is on the 2.5 megacycles.

The 440 cycles per second is the standard musical pitch, A above middle C; the 4000 cycles per second is a useful standard audio frequency for laboratory measurements.

In addition there is on all carrier frequencies a pulse of 0.005-second duration which occurs at intervals of precisely one second. The pulse consists of five cycles, each of 0.001-second duration, and is heard as a faint tick when listening to the broadcast; it provides a

(over)

useful standard of time interval, for purposes of physical measurements, and may be used as an accurate time signal. On the 59th second of every minute the pulse is omitted.

The audio frequencies are interrupted precisely on the hour and each five minutes thereafter; after an interval of precisely one minute they are resumed. This one-minute interval is provided in order to give the station announcement and to afford an interval for the checking of radio-frequency measurements free from the presence of the audio frequencies. The announcement is the station call letters (WWV) in telegraphic code (dots and dashes), except at the hour and half hour when a detailed announcement is given by voice.

The accuracy of all the frequencies, radio and audio, as transmitted, is better than a part in 10,000,000. Transmission effects in the medium (Doppler effect, etc.) may result at times in slight fluctuations in the audio frequencies as received; the average frequency received is however as accurate as that transmitted. The time interval marked by the pulse every second is accurate to 0.000 01 second. The 1-minute, 4-minute, and 5-minute intervals, synchronized with the seconds pulses and marked by the beginning or ending of the periods when the audio frequencies are off, are accurate to a part in 10,000,000.

The beginnings of the periods when the audio frequencies are off are so synchronized with the basic time service of the U.S. Naval Observatory that they mark accurately the hour and the successive 5-minute periods.

Of the radio frequencies on the air at a given time, the lowest provides service to short distances, and the highest to great distances. Reliable reception is in general possible at all times throughout the United States and the North Atlantic Ocean, and fair reception throughout the world.

Information on how to receive and utilize the service is given in the Bureau's Letter Circular, "Methods of using standard frequencies broadcast by radio", obtainable on request. The Bureau welcomes reports of difficulties, methods of use, or special applications of the service. Correspondence should be addressed National Bureau of Standards, Washington, D.C.

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U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS
WASHINGTON

Letter
Circular
LC-751
(Supersedes LC-731)

May 16, 1944

METHODS OF USING STANDARD FREQUENCIES BROADCAST BY RADIO.

The National Bureau of Standards broadcasts standard frequencies and related services from its radio station WWV at Beltsville, Md., near Washington, D.C. An improved and extended broadcast was announced August 1, 1943, which makes widely available at all times the following services: (1) standard radio frequencies, (2) standard time intervals accurately synchronized with basic time signals, (3) standard audio frequencies, (4) standard musical pitch, 440 cycles per second, corresponding to A above middle C. The broadcast is continuous day and night on two or more of the carrier frequencies, 2.5, 5, 10, and 15 megacycles per second; the frequencies currently in use are stated in the announcement "Standard frequency broadcast service of National Bureau of Standards," obtainable on request. Address request to National Bureau of Standards, Washington 25, D.C.

As stated in the announcement, the accuracy of all the frequencies, radio and audio, as transmitted, is better than a part in 10,000,000. Transmission effects in the medium (Doppler effect, etc.) may result in slight fluctuations in the audio frequencies as received at a particular place; the average frequency received is, however, as accurate as that transmitted. The time interval marked by the pulse every second is accurate to 0.000 01 second. The modulation frequencies 440 and 4000 cycles per second are not broadcast during the first minute of each five minutes starting on the hour and each five minutes thereafter. This marks time intervals of 1 minute, 4 minutes, 5 minutes, and longer which are accurate to a part in 10,000,000 and whose beginnings and ends are synchronized with the seconds pulses. The beginning of the periods when the audio frequencies are off are so synchronized with the basic time service of the U.S. Naval Observatory that they mark accurately the hour and the successive 5-minute periods.

The broadcast on 5, 10, and 15 megacycles per second is from 10-kilowatt transmitters having power outputs, when modulated, of 9.4 kw for 5 Mc/s, 9.1 kw for 10 Mc/s, and 8.9 kw for 15 Mc/s. The power output on 2.5 Mc/s is 1.0 kw. Peak amplitude modulation is 100 percent. Two or more carrier frequencies are on the air at all times, and reasonably good 24-hour service is provided over much of the world.

In making use of the broadcast, one should select the carrier frequency that gives best reception at a particular time in a given locality. This can be done by tuning to the different frequencies and selecting the most suitable, or by making a study of conditions which affect the propagation of radio-frequency waves. The latter is a fairly involved procedure because of the large number of variables. Also, a separate calculation must be made for each transmission path, this being applicable only for a particular time of day, season, and year, and certain phenomena, as yet unpredictable, are involved. Fortunately, these variations are not rapid and it is possible to give an approximate guide to choosing the carrier frequency for best reception. The following tabular data are for radio receivers located in the northern hemisphere between latitudes of approximately 20 and 50 degrees and local times of noon and midnight at Washington. Reception conditions at other times of day may be estimated by assuming a gradual change from one condition to the other. The ground wave from the transmitter may be received on each of the frequencies out to distances of about 50 miles. Beyond this distance is usually a skipped area, and beyond this the area in which good reception is normally possible. There are times of poor reception due to ionospheric storminess or transient effects which disturb the upper-air regions through which high-frequency radio waves travel.

Table 1

Approximate Distance Ranges, Summer 1943 and 1944

Local Time	Frequency, kc/s	Tone Reception, miles	Carrier Frequency Reception, miles
Midnight	2,500	0 to 700	0 to 1900
Midnight	5,000	300 to 1800	300 to 3000
Midnight	10,000	1200 to 10,000	1200 to 12,000
Noon	5,000	0 to 350	0 to 525
Noon	10,000	500 to 1100	500 to 1800
Noon	15,000	1800 to 3000	1800 to 5500

Table 2

Approximate Distance Ranges, Winter 1943-44

Midnight	2,500	0 to 2000	0 to 5000
Midnight	5,000	900 to 8000	900 to 8500
Midnight	10,000	1700 to 9500	1700 to 11,000
Noon	5,000	0 to 900	0 to 1400
Noon	10,000	600 to 2600	600 to 3700
Noon	15,000	1100 to 4300	1100 to 8000

Reception of the different frequencies can be improved by using selective and directive receiving antennas located some distance from local noise sources, and connected to the radio receiver with a low-impedance low-loss transmission line. There is a possibility of improving reception by using more than one radio receiver operating on different frequencies or the same frequency and different antennas and having combined outputs.

Part 1A (page 4 hereof) gives methods of using the standard radio frequencies for the adjustment or measurement of standard oscillators in simple cases where the frequencies have such numerical values as to be readily checked directly. Caution is necessary when making radio-frequency measurements to avoid confusion between the carrier frequency and the side frequencies, due to modulation.

Part 1B (page 5 hereof) gives details for the checking of very low frequency and low-frequency oscillators (10 to 300 kc/s) of any value, and medium-frequency oscillators (300 to 3,000 kc/s) which are multiples of 10 kc. Two examples of measurement are given.

Part 1C (page 7 hereof) gives details for the checking of medium-frequency, high-frequency, and very high-frequency oscillators of any value (300 kc/s to 300 Mc/s). An example of measurement is given.

Part 1D (page 8 hereof) gives details for the checking of very high, and ultra-high-frequency oscillators of any value (30 Mc/s to 3,000 Mc/s). An example of measurement is given.

Part 2 (page 11) describes the use of the standard time intervals or seconds pulses. The seconds pulses are of value in physical measurements, in geodetic, seismological, and similar work, and in rapid checking of pendulums and chronometer rates, and wherever short time intervals of great accuracy are needed. They are accurately synchronized with basic time signals of the U.S. Naval Observatory and they mark accurately the hour and the successive 5-minute periods.

Part 3 (page 13) describes methods of using the 4000 cycles and the 440 cycles as standard audio frequencies. This part gives methods of checking a local frequency, controlling a source of audio or other frequency, and producing a standard of time rate.

Part 4 (page 18) gives information on the continuous broadcast of the standard musical pitch, 440 cycles per second, for musicians, musical instrument manufacturers, and others interested in standard pitch.

Part 5 (page 19) includes two schematic diagrams which show in block form the equipment used at WWV.

Part 6 (page 19) is a bibliography, in which references are given to articles describing other methods of frequency measurement, and devices for use in frequency measurements. The references describe methods which range from those using very simple apparatus and giving results only moderately accurate, to those using complicated apparatus and giving results accurate to better than a part in ten million.

Part 1A - Checking Standard Oscillators - Submultiple Frequencies.

Standard oscillators are usually made to operate at frequencies which are integral multiples or submultiples of 100 kc/s, for example, 10, 50, 200, 500 kc/s, etc. Such frequencies are submultiples of the radio frequencies broadcast by WWV. The frequency of oscillators of this type is generally fixed by the dimensions of some stable material such as quartz, a metal alloy, or rigidly constructed coils and condensers that can only be adjusted over a very narrow range of frequency. This considerably simplifies the measurement or adjustment of standard oscillators in terms of the standard frequency broadcast. This is because a harmonic of the oscillator practically always produces in the radio receiver output a beat frequency which is lower than the high limit of audibility. (Exceptional cases are more complicated and are treated below). The equipment involved in a frequency comparison, in addition to the standard oscillator, consists of one, two or three separate devices depending on the magnitude of the harmonic output of the oscillator and whether its frequency is to be measured or only adjusted to the correct value.

An amplitude-modulation radio receiver is one necessary requirement. Almost any receiver capable of picking up one of the standard frequencies broadcast is suitable; however, one of the many good communication-type receivers is better. Receiver features that provide convenience are direct-reading frequency dial, positive-vernier tuning drive, bandspread tuning at any point in the frequency range, and carrier-strength or signal-strength meter.

If harmonic output of the standard oscillator is low, equipment should be supplied for intensifying the harmonics. (One type of harmonic generator is shown as the circuit arrangement associated with one tube in Fig. 1).

Coupling between the r-f input of the receiver and the output of the local oscillator or its associated harmonic generator should be adjusted in addition to the receiving set controls until suitable audibility of the difference frequency is obtained. The standard oscillator is then high or low by the difference frequency.

To measure this beat frequency or difference frequency, a stopwatch, a beat counter, an audio-frequency meter, frequency bridge, calibrated oscillator or other device may be used. The difference frequency in cycles per second divided by the WWV carrier frequency in megacycles per second gives the deviation expressed as parts in a million.

To determine whether the standard oscillator is high or low one may change its frequency in a known direction and observe whether the difference frequency increases or decreases. If an adjustment of the standard oscillator frequency is undesirable, additional equipment is required and may consist of one of the following:

(1) A radio receiver with sufficient selectivity to separate the standard and unknown frequency. This usually requires a crystal filter.

(2) A manually operated phase shifter connected in the output of the standard oscillator. Advancing or retarding the phase is equivalent to increasing or decreasing the frequency. The change occurs only during the phase-shifting operation.

(3) A cathode-ray oscilloscope for observing a lower frequency, derived from the oscillator (for example, 1000 or 4000 cycles per second) with respect to the WWV modulation frequency. (See Section 3 hereof on audio-frequency measurements).

(4) An auxiliary oscillator which can be adjusted first to zero beat with WWV and then to the oscillator frequency. The direction of the latter adjustment then determines whether the standard oscillator is high or low.

(5) A beat frequency oscillator (supplied as standard equipment on communication-type radio receivers) can be adjusted to zero beat with WWV and then the direction of frequency adjustment noted which gives zero beat and the oscillator under measurement is received alone. This method requires care and a knowledge of whether the local heterodyne oscillator of the radio receiver is high or low.

Part 1B - Incommensurate Submultiple Frequencies. - Low-frequency oscillators of any value - Medium-frequency oscillators which are multiples of 10 kc/s.

A few standard oscillators are designed for frequencies that bear no integral submultiple ratio to all the standard frequencies broadcast from WWV, for example, 60 kc/s, 108 kc/s, and 150 kc/s. To measure or adjust these oscillators the main components of apparatus already described are required. An auxiliary oscillator is a necessary component. It should be designed to have good frequency stability over a short period of time. A fundamental frequency of 100 kc/s is preferred for the auxiliary oscillator and its output should be followed with a harmonic generator. This method is also applicable to a stable oscillator of any radio frequency below about 300 kc/s and any frequency up to about 3000 kc/s which is a multiple of 10 kc/s.

Measurements are made by first setting the auxiliary oscillator to exactly 100 kc/s in terms of the standard-frequency broadcast. The radio receiver or an additional radio receiver is then tuned to a frequency which is a harmonic of the auxiliary oscillator and at the same time a harmonic of the oscillator to be measured, then

$$100a = bf$$

where f is the frequency to be measured and a and b are integers, 2, 3, 4, etc., which designate the harmonic of the auxiliary oscillator and the unknown respectively. Values as high as 1000 have been used. The expression can not be satisfied exactly for all frequencies below a practical value of about 300 kc/s. However, this is not required. When audio-frequency measuring equipment is available it is only necessary to select a harmonic of the 100-kc auxiliary oscillator that is within audio range of a harmonic of the oscillator frequency to be measured. The difference frequency is then determined and taken into account in a measurement or adjustment (see example on this page).

Example of measurement.- Consider a piezo oscillator of 108 kc/s which it is desired to measure to a high degree of accuracy. The minimum amount of measuring equipment consists of a stable auxiliary oscillator, a frequency-calibrated radio receiver, and beat-frequency measuring apparatus. The auxiliary oscillator is adjusted to 100 kc/s in terms of WWV. Then from the foregoing expression,

$$100a = 108b$$

which for minimum beat frequency in this case is satisfied for the 27th harmonic of the 100-kc auxiliary oscillator and the 25th harmonic of the 108-kc piezo oscillator. These harmonics have the same nominal frequency, 2700 kc/s. The radio receiver or a second radio receiver is then tuned to 2700 kc/s and the difference frequency or beat frequency measured. A high or low determination is made as outlined under part 1A of this pamphlet. Beat-frequency measuring equipment is not necessary when the only requirement is to adjust the piezo oscillator to correct frequency. Higher harmonics can be used which will increase the beat frequency, and in some cases the accuracy of measurement. In the foregoing example the tuning of the second radio receiver could be 5400 kc/s, 10,800 kc/s, 16,200 kc/s, or even higher frequencies. The difference frequency in cycles divided by the frequency in megacycles to which the radio receiver is tuned gives the deviation expressed as parts in a million.

Example of Measurement when the expression 100a = bf can not be exactly satisfied at harmonic frequencies which are low enough for practical use. Consider a piezo oscillator of 301.5 kc/s; the harmonic of this frequency which is also a harmonic of 100 kc/s is too high for reception on ordinary radio receivers. However, one may select a lower harmonic which is almost a multiple of 100 kc/s as shown in the following table:

Harmonics of 301.5 kc/s		Radio receiver tuned to	Beat note
No.	Frequency	kc/s	cycles
65	19,597.5	19,600	2500
66	19,899	19,900	1000
67	20,200.5	20,200	500
68	20,502	20,500	2000
69	20,803.5	20,800	3500

The frequency of the piezo oscillator is then determined by measuring the beat note which exists between it and a harmonic of the 100 kc/s, adding or subtracting this as the case may be, to the latter harmonic frequency, and dividing the results by the harmonic number. The C and D scales of a slide rule are useful in determining which harmonics of a given frequency are multiples of 100 kc/s.

Part 10 - Medium-Frequency, High-Frequency, and Very High-Frequency Oscillators of Any Value.

The method of measurement is the same as that already described, i.e., the beat note between the unknown frequency and a known frequency derived from a previously standardized local auxiliary oscillator is measured. A high or low determination is made and the beat frequency added to or subtracted from the known derived frequency. Measurements are made at the fundamental of the unknown oscillator frequency. A requirement is that the beat frequency never exceed 5000 cycles per second because higher beat frequencies are not as audible and do not pass through the intermediate- and audio-frequency amplifiers of the ordinary radio receiver. Additional equipment is necessary to supply known frequencies, multiples of 10 kc/s separated by 10 kc/s, of sufficient amplitude to be received throughout the desired frequency range, up to 300,000 kc/s and higher. This same equipment, controlled from a single auxiliary oscillator, must supply other frequencies, as required, multiples of 20 kc/s, separated by 20 kc/s, multiples of 100 kc/s separated by 100 kc/s, and multiples of 1000 kc/s separated by 1000 kc/s. The 20-kc and 10-kc multiples are not required at the same time; the others are. Furthermore, all derived frequencies should have approximately the same amplitude. A circuit arrangement suitable for supplying various derived frequencies (harmonics) is shown in Fig. 1. An arrangement of equipment for a frequency measurement is shown in Fig. 2; this also shows the auxiliary oscillator requirements which may be a 1000-kc oscillator and frequency dividers for supplying the lower frequencies 100 kc/s, 20 kc/s, and 10 kc/s, or a frequency multiplier may be used for supplying 1000 kc/s from a 100 kc/s oscillator. Since 10 kc/s and 20 kc/s are not needed at the same time this could be one frequency divider with an appropriate switch for changing its dividing ratio. Available frequencies from the harmonic-generator modulator may be represented as,

$$1000\ K_1 \pm 100\ K_2 \pm K_3$$

where K_1 and K_2 are harmonic numbers or integers, K_1 extending up to 300 or more and K_2 up to 5. K_3 is either 10 kc/s and its harmonics or 20 kc/s and its harmonics.

With equipment as shown in Fig. 2 a measurement is made by first adjusting the auxiliary oscillator to exact frequency in terms of WWV. Then the radio receiver on which WWV was received, or preferably a second radio receiver is adjusted to receive the unknown and known frequencies at the same time. The harmonic-generator modulator equipment is supplied with the frequencies 1000 kc/s, 100 kc/s, and 20 or 10 kc/s in the order given until a beat note is obtained and measured. The radio receiver is then calibrated to determine which of the known frequencies was being received to give the beat frequency. A high or low determination is made as previously described, part 1A, and the measurement completed. Calibration points on the radio receiver can be located by observing its signal strength meter or by operating its beat-frequency oscillator, the latter giving aural indications at each of the known frequency points, as the receiver is tuned.

On certain radio receivers of poor stability and crowded frequency scale, the determination of its calibration to the nearest 1000 kc/s may be difficult; in such cases the auxiliary equipment could be further improved by addition of known output frequencies of 5000 kc/s or even 10,000 kc/s.

Example of measurement.- Consider a stable unknown frequency of approximately 33,275.2 kc/s which it is desired to measure in terms of the standard frequency broadcast. Fig. 2 is a schematic arrangement of equipment considered. Five operations may be listed as necessary and distinct:

(1) Adjustment of auxiliary oscillator to 1000 kc/s in terms of WWV using radio receiver No.1.

(2) Adjustment of radio receiver No. 2 for reception with approximately the same amplitude of the harmonic-generator modulator output and the unknown frequency.

(3) Calibration of the radio receiver No. 2 for frequencies of 33,000 kc/s, 33,100 kc/s, 33,200 kc/s, 33,300 kc/s, and 33,280 kc/s.

(4) Measurement of the difference frequency or beat frequency when the No. 2 receiver is tuned to 33,280 kc/s.

(5) Determination of whether the beat frequency is to be added to or subtracted from 33,280 kc/s.

Careful manipulation of the equipment is necessary in carrying out operations 3 and 5 and it is usually best to recheck the results. In this case the frequency of the auxiliary oscillator could be decreased a small amount and the beat frequency noted to decrease, thus indicating that the beat frequency 4800 cycles is to be subtracted from 33,280 kc/s to give the result 33,275.2 kc/s. However, high or low determinations could be made by other methods outlined in part 1A of this pamphlet.

Part 1D - Very High-Frequency and Ultra-High-Frequency Oscillators, Alternate Method.

Oscillators in this region, up to 3000 megacycles, can be measured by the method previously described; however, it is required that they

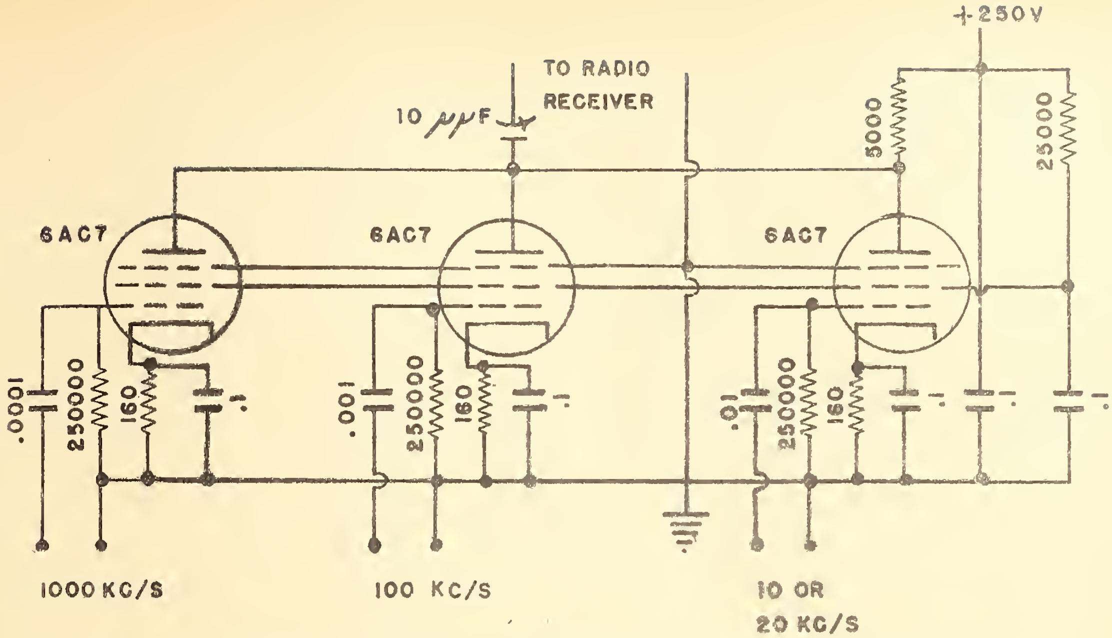


FIG. I. Harmonic Generator Modulator, simplified schematic.

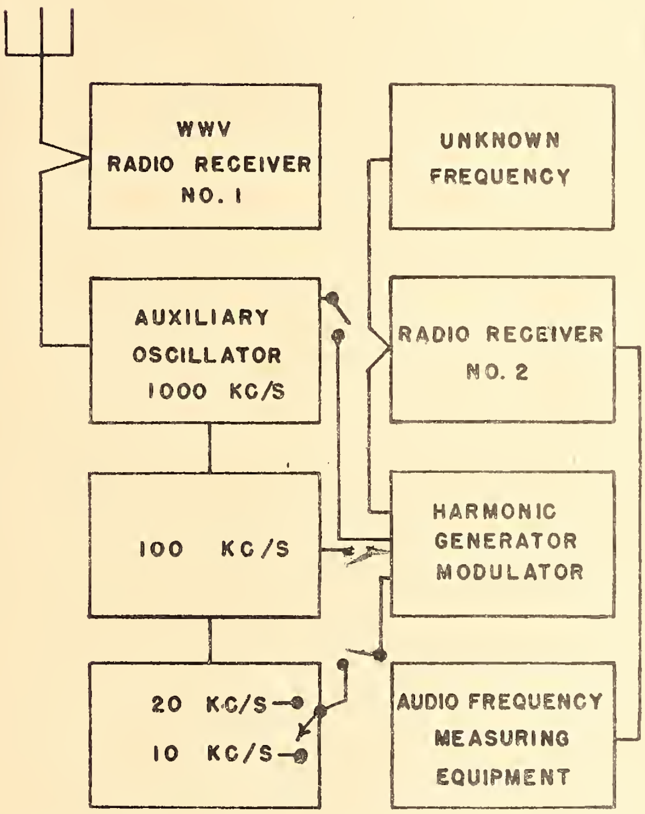


FIG. 2. Diagram showing necessary equipment and its arrangement for very high frequency measurements.

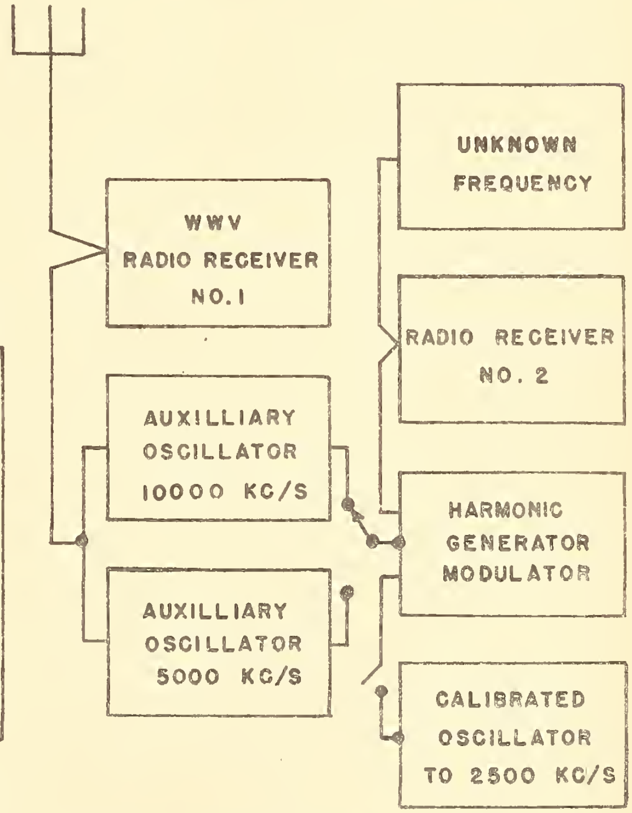


FIG. 3. Diagram showing necessary equipment and its arrangement for ultra high frequency measurements.

have unusual frequency stability and that a very selective radio receiver having ample band spread be used. The method here described is a modification of that shown in Fig. 2 and with it (see Fig. 3) frequency measurements can be made more quickly and conveniently.

Equipment required is:

(1) Two local auxiliary oscillators; a desirable arrangement is to have the frequency of one equal to twice that of the other. These may be separate oscillators since they are not used at the same time or a single oscillator may be used and the second frequency obtained by frequency division or multiplication.

(2) A calibrated oscillator adjustable over a range of frequency equal to half that of the lowest auxiliary oscillator frequency and starting at the low audio frequencies.

(3) A harmonic-generator modulator similar to that shown in Fig. 1 except having one less tube.

(4) A calibrated radio receiver capable of receiving the frequency to be measured.

Output from the local auxiliary oscillator and from the calibrated adjustable oscillator is supplied to the harmonic-generator modulator making available at its output frequencies which may be represented as

$$F_1K \pm F_2$$

where F_1 is the auxiliary oscillator frequency and F_2 is the adjustable oscillator frequency, K represents harmonic numbers of integers. The value of K is determined from the calibration of radio receiver No. 2, Fig. 3, and adjustment of F_2 can be made so that radio receiver No. 2 will respond to any frequency to which it is tuned. There is one disadvantage of the method, viz, when F_2 is adjusted so that its frequency is very near the value $1/2F_1$ two closely spaced frequencies appear in the harmonic-generator modulator; to eliminate this it is necessary to use a second auxiliary oscillator frequency; one having a value equal to $2F_1$ is suitable. An arrangement of this kind may be considered as first supplying all harmonics of a given auxiliary oscillator frequency, and second supplying only the even harmonics of the same frequency.

In making a frequency measurement five operations are necessary:

(1) Adjustment of auxiliary oscillator to exact frequency in terms of WWV using radio receiver No. 1.

(2) Adjustment of radio receiver No. 2 for reception with approximately the same amplitude the harmonic-generator modulator and the unknown frequency.

(3) Calibration of radio receiver No. 2, i.e., determination of K for the foregoing expression.

(4) Adjustment of the calibrated oscillator until zero beat is had in radio receiver No. 2.

(5) Determination of whether the frequency arrived at for F_2 under operation (4) is to be added to or subtracted from F_1K to give the correct result.

At the very high frequencies and above, the usual radio receiver is not sufficiently selective to tell whether F_2 is added or subtracted. This may be determined by one of the following methods after operation (4) has been completed.

(a) Increase the unknown frequency until an audible beat note is obtained; if an increase in F_2 is required to restore zero-beat, then add F_2. If a decrease in F_2 is required then subtract F_2.

(b) Decrease F_2 until an audible beat-note is obtained; if increasing the auxiliary oscillator frequency (F_1) restores zero-beat F_2 should be added, while if a decrease in the auxiliary oscillator frequency is required F_2 should be subtracted.

(c) The reverse of method (b).

(d) Decrease F_2 until radio receiver No. 2 just ceases to respond to the harmonic-generator modulator output; retuning this receiver will restore the response. If retuning is to a lower frequency then add F_2; if retuning is to a higher frequency then subtract F_2.

(e) The reverse of method (d).

As previously pointed out, when F_2 is very nearly equal to $1/2F_1$ the value of F_1 should be increased by 2, i.e., the second auxiliary oscillator frequency should be used.

In all the foregoing description, when an audible beat frequency is heard in radio receiver No. 2 without use of the calibrated oscillator, supplying frequency F_2, the unknown frequency is very nearly a multiple of auxiliary oscillator frequency F_1. Its measurement is then done by methods already described under part 3.

Example of Measurement. Consider an unknown frequency of 502,450 kc/s and frequency measuring equipment consisting of: (a) two auxiliary oscillators 5000 kc/s and 10,000 kc/s, (b) an adjustable calibrated oscillator extending from the low audio frequencies to 2500 kc/s, (c) a harmonic-generator modulator, (d) a radio receiver (No. 1) for WWV, (e) a calibrated radio receiver (No.2) for the unknown frequency.

The five operations are:

(1) Adjustment of the local oscillators to 5000 and 10000 c/s in terms of WWV, using radio receiver No. 1.

(2) Adjustment of radio receiver No. 2 for reception of the harmonic-generator modulator output and the unknown frequency with approximately the same amplitude.

(3) Calibration of radio receiver No. 2 at frequencies of 500,000 kc/s and 505,000 kc/s.

(4) Adjust the calibrated oscillator until zero beat is had in receiver No. 2; that is, adjust the calibrated oscillator until the harmonic-generator modulator has an output frequency equal to the unknown frequency. A value of 2450 kc/s would be obtained.

(5) Determination of whether the calibrated oscillator frequency arrived at (2450 kc/s) to give the foregoing condition is to be added to or subtracted from 500,000 kc/s. This may be done by lowering the calibrated oscillator frequency until receiver No. 2 does not respond to the harmonic-generator modulator output; however, retuning this receiver to a lower frequency will restore the response, indicating that the value 2450 is added to give the result 502,450 kc/s. Other methods previously described may be used if frequency stability of the unknown is good.

The foregoing description of frequency measurement was primarily intended for measuring the frequency of a local oscillator. The same principles and methods may be used to measure the frequency of a distant radio station. In doing so a superheterodyne type of radio receiver is nearly always used for reception and one must be careful, when the field intensity of the station is high and the radio receiver is of poor quality, to be sure that it is not tuned to an image point, i.e., a frequency which is different by twice the intermediate frequency of the radio receiver. This can be determined by tuning the radio receiver. If the beat note does not change the receiver is correctly tuned. One must also be sure that the difference frequency obtained is that between the local oscillator and the radio frequency received; interfering radio stations may give beat frequencies that are misleading.

Part 2 - Standard Time Intervals.

As stated in the announcement, the time interval marked by a pulse every second as transmitted is accurate to 0.000 01 second. The 1-minute, 4-minute, and 5-minute intervals, synchronized with the seconds pulses and marked by the beginning and ending of the periods when the audio frequencies are off, are accurate to a part in 10,000,000. The beginnings of the periods when the audio frequencies are off are so synchronized with the basic time service of the U.S. Naval Observatory that they mark accurately the hour and the successive 5-minute periods, thus making the broadcast useful as a source of time signals.

Under ideal receiving and measuring conditions one could, with specialized equipment, measure a single one-minute time interval to one part in 10,000,000. However, this requires a time determination to better than 0.000 01 second, which is ordinarily difficult to obtain. Longer time intervals can more easily be measured to one part in 10,000,000; for example an interval of 24 hours, measured to this accuracy requires a time determination to 0.01 second. For high accuracy the radio receiver should have a constant supply voltage and be correctly tuned. A carrier intensity meter or tuning indicator is desirable for detecting fading. Automatic volume control is helpful. An oscilloscope with a suitable viewing screen is useful in determining whether consecutive pulses have the same wave form and whether high accuracy is possible. Carrier outputs of the radio transmitter are completely modulated by the seconds-pulses which consist of 5 cycles of a 1000 cycle per second frequency. A band-pass filter may be used in the radio receiver output to reduce noise and separate the pulses from 440 and 4000 cycles. Use of the filter is permissible for most practical purposes; however, it may cause a slow rise in the pulse voltage and reduce the accuracy of measurements in certain applications.

With appropriate chronographs or oscillographic recording equipment the seconds pulses can be used to measure short or long time intervals. With such equipment, or by visual or aural means, the seconds pulses can be used to calibrate most time-measuring devices.

The seconds pulses are also useful as a basis of measuring frequencies. One method of using them to measure a constant low frequency, that is known to be in error by less than 1/2 cycle per second, is to observe on a cathode-ray oscilloscope the received seconds pulses when using the unknown frequency for the sweep frequency. The frequency of drift of the seconds pulses across the screen is the error in cycles per second, and whether the unknown is high or low is determined by the direction of drift. As an example, consider a constant unknown frequency of 60.3 cycles controlling a horizontal sweep which moves from left to right across the oscilloscope screen. Successive seconds pulses do not appear at the same point in this case but drift to the right and appear again at approximately the same point after about 3 seconds. After 10 seconds and three excursions across the screen, the pulse appears at exactly the same point. The frequency of drift across the screen is then 3/10 cycle, indicating that the unknown frequency is 60.3 cycles. The method is applicable, with pulses as received, to frequencies as high as 200 cycles, and can be extended to frequencies of several thousand cycles by using a pulse-sharpening circuit arrangement. Constant frequencies differing only a small amount from a whole-number value can be measured very accurately. For example, consider a frequency of 100 cycles; if, after three hours, the pulse returns to the same point on the oscilloscope screen the 100 cycles is in error by 1/10,800 cycle, or is accurate to about 1 part in 1,000,000.

The seconds pulses may, if desired, be used to control a source of frequency, i.e., to keep a local source of frequency correct.

The local source of frequency is a vibrating system, such as a tuning fork, adjusted to vibrate any whole number (up to about 500) of cycles per second. The tuning fork is simply started in natural vibration and the short pulse received once a second keeps it vibrating. The tuning fork must be a persistent vibrator, which requires it to be one of low power loss. Filters may be used if necessary to separate the seconds pulses from the 440 cycles and 4000 cycles.

Part 3 - Standard Audio Frequency.

The two audio frequencies, 440 cycles per second and 4000 cycles per second may be used as standard frequencies by the methods described in this section. The presence of the seconds pulses does not interfere. They are in fact advantageous in counting the number of elapsed cycles or elapsed time, and serve as a station guide or finder during the quiet portion of the 1-minute announcement period.

Since the audio frequencies are not broadcast for one minute of every five, it is desirable for some purposes to use a local oscillator operating continuously and check it as often as desired against the 440 cycles or 4000 cycles.

From the standard audio frequencies, any desired frequency may be measured. Using any receiving set capable of receiving one of the carrier frequencies, the standard audio frequencies are delivered at the output terminals of the set. One of these frequencies may be used for comparison with a local frequency, thus accurately measuring the latter, for control of some type of frequency standard, or for production of an accurate standard of time rate. By the use of frequency multipliers or dividers to step up or down either the incoming standard frequency, the local frequency, or both, measurements may be made very conveniently as well as accurately. The cathode-ray oscilloscope is a useful instrument in most of the methods. It may be used as a measuring device, an indicator of wave form, a fading indicator, and an indicator of which of two frequencies is the higher. Separation of the two audio frequencies in the output of the radio receiver is not particularly difficult and may be done to a great extent, without additional equipment, by using a selective radio receiver. Tuning the receiver slightly high or low will cause 4000 cycles to predominate while exact tuning to the carrier frequency largely eliminates the 4000 cycles. Complete separation of the frequencies may be had by using a Wien bridge, a wave filter, or a selective audio-frequency amplifier. One of the latter two devices is usually desirable in order to minimize interfering electrical noise. Automatic volume control is an advantage in reducing fluctuations of amplitude and phase of the received audio frequencies. Other effective filters are: a tuning fork, a vibrating steel reed, a synchronous motor-generator. Magnetostriction bars are good filters for higher frequencies, and piezoelectric quartz plates are very good for radio frequencies.

The following list gives a number of basic methods which have been found practicable.

Methods of Utilizing Received Audio Frequency

A. Checking a frequency.

1. Comparison of received and local frequencies, by timing change of cathode-ray oscillograph pattern.

    a. Direct comparison.
    b. Use of harmonic amplifier, to step up.
    c. Use of frequency divider, to step down.

2. Comparison, by recording both frequencies with a recording oscillograph.

    a. Direct comparison.
    b. Use of harmonic amplifier, to step up.
    c. Use of frequency divider, to step down.

3. Comparison, by recording beats on a graphic recorder.

    a. Direct comparison.
    b. Use of harmonic amplifier, to step up.
    c. Use of frequency divider, to step down.

4. Counting of beats between harmonics.

5. Calibration of a frequency-indicating device.

B. Control of a source of frequency.

1. Tuning fork.
2. Audio-frequency oscillator.
3. Radio-frequency oscillator.

C. Production of a time rate standard.

In any of these methods, whether it will be more accurate and convenient to utilize the frequency directly or to use harmonics or subharmonics depends upon the magnitude and character of the frequency to be checked or controlled, the equipment available, and the circumstances of the radio reception. For some purposes a combination of two or more methods is useful.

In methods A, either high or low standard frequencies may be produced by using harmonics or subharmonics and amplifying as desired. Standards of low audio frequency (e.g., 60 cycles per second) are easily produced by operating a synchronous motor on the amplifier output, with a-c generators of the desired frequency mounted on the same shaft. Such a motor-generator outfit may be of simple and fairly cheap type; somewhat like an electric clock. A standard 60 cycles can also be obtained with vacuum tubes. First, 500 cycles is obtained from 4000 cycles by frequency division. Then 60 cycles is obtained as the difference frequency between the standard frequencies of 500 and 440 cycles.

It is convenient in many cases to multiply or divide, add or subtract, harmonics, fractional frequencies and fractional harmonics of one or both of the standard audio frequencies. In this way one can arrive at another standard audio frequency which may be more useful. Some frequencies available in this manner may be expressed as $\frac{440\ K_1}{K_2}$ and $\frac{4000\ K_3}{K_4}$; and the sum and difference of these values where K_1, K_2, K_3, and K_4 are integers (1, 2, 3, 4, etc.). A few of the frequencies that can be derived are 88, 110, 220, 330, 440, 550, 660, 800, 1000, 1600, 2000, 3200, 4000, 5000, 8000, 10,000, 16,000, 20,000 cycles per second. By using K values up to 10 and by further divisions, multiplications, additions, and subtractions of derived standard frequencies one may obtain a standard audio frequency of any integral number of cycles per second.

Useful audio frequencies for general measurement and calibration work are 500, 1000, and 10,000 cycles per second. These frequencies can be derived from 4000 cycles. Frequency dividing equipment may be used to obtain 1000 and 500 cycles, while 10,000 cycles may be obtained as the tenth harmonic of 1000 cycles. A regenerative modulator type of frequency divider (see reference on page 29 line 15) is in some cases more suitable than the commonly used multivibrator. Its main advantage is that no output is obtained during absence of the controlling frequency. A single-tube, self-starting, non-oscillating circuit arrangement of this type can be used to obtain 2000 and 10,000 cycles from the 4000 cycles. This equipment can be followed by another single-tube circuit arrangement for supplying 1000 and 500 cycles.

Addition and subtraction of frequencies is done by use of the beat principle. A particularly useful device for doing this is the ring modulator bridge which may be built up with small dry-disc rectifiers of the instrument type (see reference on page 28 line 17). Its main output is the sum and difference of the two input frequencies. A filter may be used in the output to select one of the two predominent frequencies.

In frequency comparisons, if the received standard frequency is sufficiently free from fluctuations of amplitude or phase, it is generally found advantageous to make the comparison at some harmonic. For example, consider the use of method A1 in checking a local frequency of 60 cycles at its 74th harmonic (4440 cycles). Two frequencies are applied to the two pairs of plates of a cathode-ray tube and their frequency difference is determined by timing the shift of the pattern on the screen through one or more complete cycles. A high accuracy of comparison, better than a part in 500,000 in this case, may be secured by timing and determining the difference frequency over a period of about 20 seconds. One must be sure that there is no fading or other fluctuation in the received standard frequency when high-accuracy short-time measurements are made.

The greater the fluctuations of the received standard frequency, the lower must be the harmonic at which the observations are made and the longer the time required for the determination. Fortunately, such longer time of observation tends to eliminate any error in the result due to the fluctuation. The better the accuracy required, the longer must be the time of observation.

The use of the cathode-ray oscilloscope has a number of advantages in this as in all the other methods. It simplifies the differentiating of amplitude variations and interfering noise from phase changes. Also, if a linear sweep circuit controlled by the local frequency is used, one can tell readily whether the local frequency is higher or lower than the standard modulation frequency. If the oscilloscope beam is swept from left to right and the standing wave moves to the left the local frequency is low; if the standing wave moves to the right the local frequency is high.

In method A2, use is made of any type of recording oscillograph that may be available. It may, for example, be a photographic film recorder, or a rotating drum with a pen recording on paper. A requirement is that the time displacement be sufficient to separate the individual cycles so that the record can be readily analyzed. In this method the two frequencies are recorded simultaneously on the same graphic record, which permits a direct comparison by means of measurements of the photographic or other trace. If the speed of the recorder will not give sufficient time displacement, the frequencies can be stepped down to a desired value by means of a frequency divider.

An alternative method is to drive a recorder drum with a synchronous motor operated from the local frequency (or one of its harmonics or subharmonics). In one mode of use the drum carries a raised thread or spiral, and the paper driven by any desired means at some known speed passes the drum. A record is made by causing a spark, controlled by one of the standard frequencies (or one of its harmonics or subharmonics), to jump from the spiral thread through the paper and to a straightedge on the other side of the paper. The type of record depends on the speed of the drum, and the frequency of the spark. The method is useful for recording over a long period of time, and for some types of low-frequency records the spark may be replaced with a mechanical printing arrangement.

In method A3, the frequency difference between the standard and the local frequency is measured by combining the two, amplifying the beat frequency, and rectifying by means of a detector (e.g., copper-oxide rectifier or diode detector). A double-diode triode tube is convenient for both the amplifying and rectifying. A d-c meter can be used as a visual indicator, and a relay can be used to operate a counter. The direct voltage output can also be recorded on paper with a graphic recorder. If the rate at which the recorder paper moves is controlled by a synchronous motor, or some type of time marker is used, a very satisfactory measure of the frequency difference can be made. This method is limited to small frequency differences. If audio frequencies are compared directly rather than by their harmonics, the method requires the operation of the equipment for a considerable time.

In method A4, the beats can be counted by the aid of either aural or visual indication. A combination of the two means is often very convenient. Very great accuracy can be obtained by using harmonics such as to make frequencies of the order of 100,000 cycles per second. Broadcast radio frequencies can be checked by using harmonics of 10 kc/s which is derived from 4000 cycles.

Measurements can be made over any convenient period of time (up to 4 minutes), counting the difference frequency (beats) during the time interval chosen. The precision of such measurements, expressed as a fraction, is $\frac{n \Delta t}{t}$ where n is the beat or difference frequency in cycles per second, t is the time during which beats are counted, and Δt is the error $\pm$ in measuring t. For example, if the difference frequency is of the order of 1 cycle per second and is counted over a period of 5 seconds and the time measurement is accurate to $\pm$ 0.1 second, the accuracy of the beat frequency measurement is 1 part in 50.

The accurate control of a source of frequency (B in above list) involves the use of an automatic means of keeping a local source of frequency in agreement with the received standard audio frequency or a harmonic or subharmonic. Where the local source of frequency is a mechanical device, such as a tuning fork or synchronous motor-generator, its inertia is useful in carrying along through periods of rapid fluctuation of amplitude or phase of the received frequency. Any local source can usually be so designed as to operate through considerable fading or phase shifts of the received frequency.

If the local source is a 440-cycle or 4000-cycle tuning fork it can be driven directly from one of the received frequencies. In this application it is necessary that the adjustment of the fork be such that its natural frequency is in agreement with the driving frequency within rather narrow limits. In one particular installation it was found that the fork had to be in agreement with the received frequency within a few parts in 10,000. These limits depend in any particular case on such factors as the driving voltage and the mass of the fork.

One of the standard audio frequencies can similarly be used to control a multivibrator or other type frequency divider at the fundamental or a submultiple frequency. The multivibrator frequency can be multiplied by means of tuned harmonic amplifiers to higher frequencies as desired. While it is also possible to multiply the standard audio frequency by means of harmonic amplifiers to radio frequencies and control a radio-frequency oscillator, this is not commonly done because the fluctuations could be much greater than when starting with a standard radio frequency.

A simple means of producing a time rate standard (method C) from the received standard audio frequency is to use a simple a-c generator of any desired frequency mounted on the same shaft with a synchronous motor driven by an oscillator which is checked from time to time against the received frequency. Such a generator can operate an electric clock. Thus may be provided a standard of time rate for short periods, as well as of frequency, of an accuracy hitherto not generally available to laboratories.

Part 4. Standard Musical Pitch.

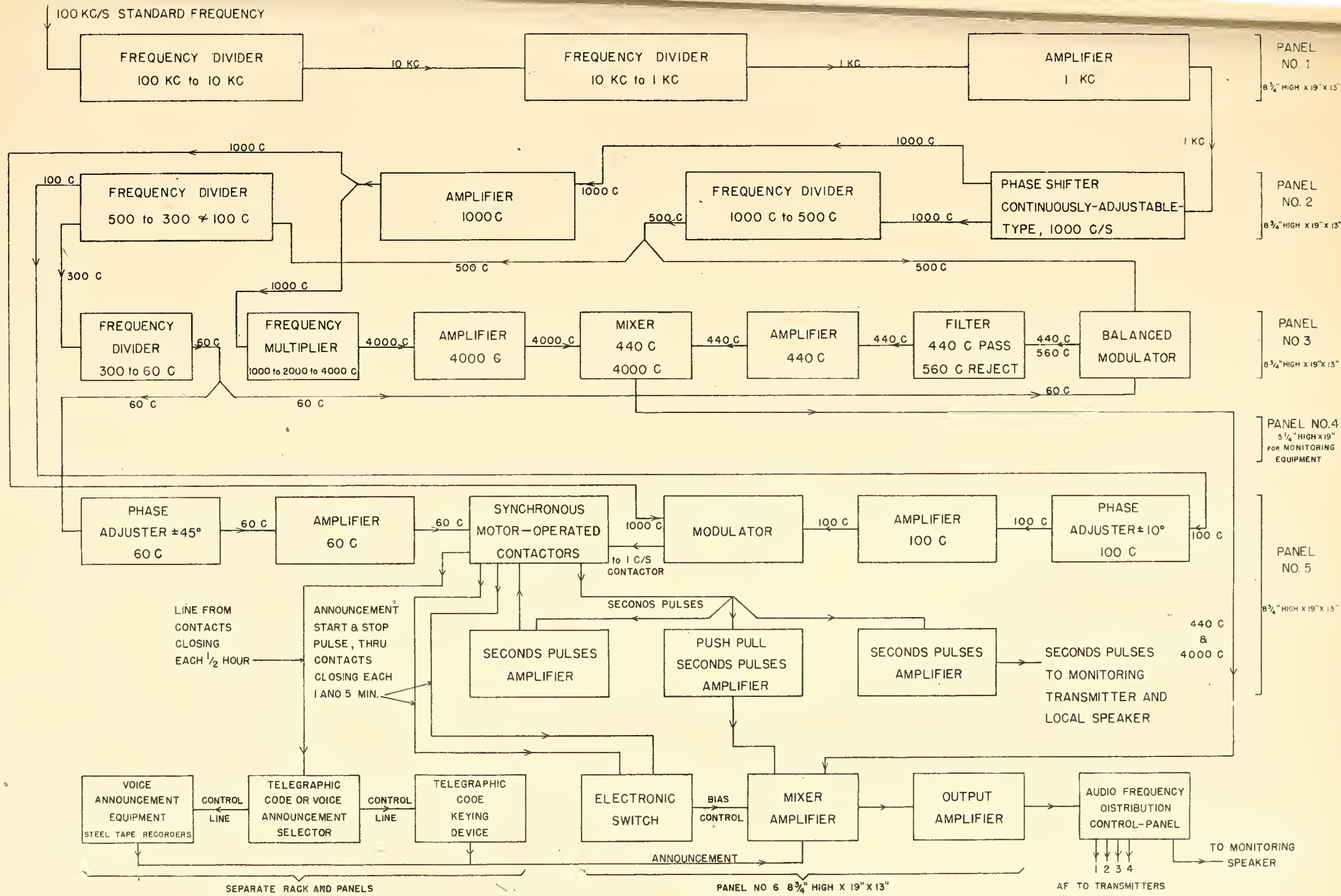
The continuous 440-cycle broadcast may be received with a high-frequency "short-wave" or "all-wave" radio receiving set. The radio carrier frequencies (2.5, 5, 10, or 15 megacycles per second) are much higher than the frequencies on which the usual broadcast entertainment programs are given. The purchaser of a radio should be sure that its tuning ranges do include 5.0 megacycles as well as the other high frequencies.

The "all-wave" receiving sets have a number of scales usually marked in megacycles for the higher frequency scales. The scale should be set for either 2.5, 5, 10 or 15 megacycles in order to receive the standard musical pitch broadcast.

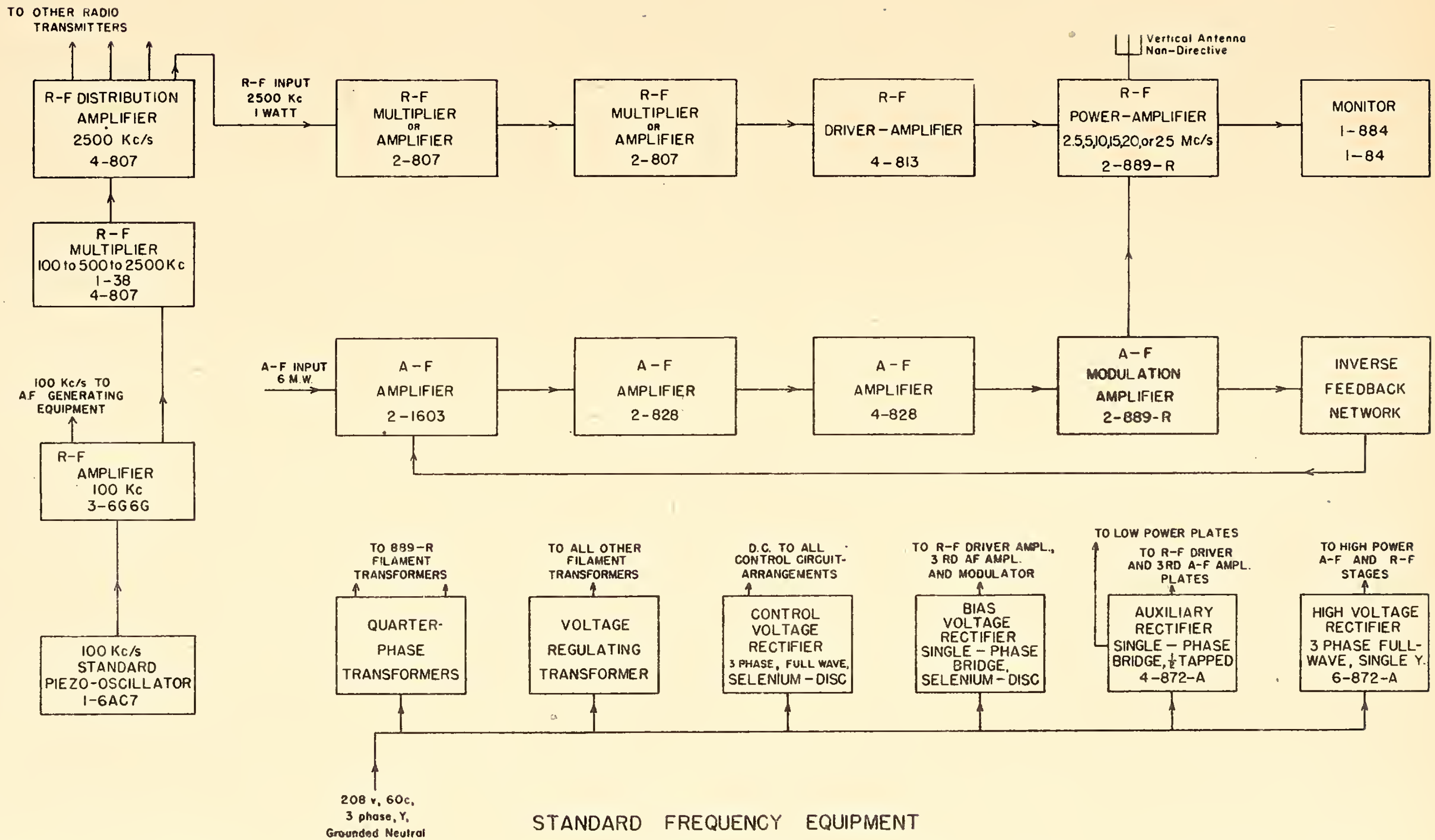
In order to receive this broadcast, considerable care must be used in the tuning of the radio receiver because a slight adjustment of the radio receiver at high frequencies changes the tuning by a much larger amount than at lower frequencies. The standard "A" tone (440 cycles per second) from the transmitter may not be as loud as the program usually received from stations in the broadcast band. In fact at certain times during the day or night, difficulty may be experienced in satisfactorily receiving the broadcast, because of "static", electrical noise from electrical devices, and other types of interference present at the receiving location.

To facilitate the reception of the standard "A" tone, the following suggestions are given. Turn on the radio receiver and, after allowing a few minutes for it to warm up, adjust the dial to the setting for one of the carrier frequencies. The volume control should be turned up. The calibration marked on the dial of the receiver may be in error by one or two divisions. To locate the stations, slowly adjust the dial of the receiver from two or three divisions below the desired frequency marking on the dial to the same amount above. If the note of 440 cycles per second is heard, adjust the dial very carefully to give the loudest signal and then adjust the volume control to give the desired volume of loudness. If no signal is heard, raise the volume control setting and vary the dial as before.

In some radio receivers the 440-cycle tone may be received at a setting other than the 2.5, 5-, 10-, or 15-megacycle points marked on the dial. This is merely an incident of the construction of the radio receiver. It is usually more satisfactory to employ the setting which is nearest to 2.5, 5, 10, or 15 megacycles.



BLOCK SCHEMATIC OF WWV's
AUDIO FREQUENCY, TIME INTERVAL, AND
ANNOUNCEMENT CONTROL EQUIPMENT.
Fig. 4.



STANDARD FREQUENCY EQUIPMENT
AND RADIO-TRANSMITTERS AT WWV

BLOCK SCHEMATIC OF ONE UNIT.

Fig. 5.

Besides its use for musical purposes, the 440-cycle frequency may be used for measuring audio frequencies by the methods described in Part 3 above.

If the received signal is seriously marred by any sort of fading or static or other interference, it may nevertheless be used as an accurate standard by providing a stable audio-frequency oscillator, adjusting it to zero beat with the received 440-cycle signal, and then utilizing the oscillator as the source.

Part 5 - Station Equipment at WWV.

Figures 4 and 5 are block schematic diagrams showing the arrangement of apparatus, as used at the radio transmitting station, which provides the standard frequency and standard time interval broadcast.

WWV'S frequencies and time intervals are controlled by a 100 kc/s standard frequency piezo-oscillator. It is one of seven separate units used in maintaining the national standard of frequency. Each oscillator's frequency is determined by continuous and automatic comparisons with the group and with time signals. The average frequency value is based upon and agrees precisely with the average U. S. Naval Observatory time signals. The broadcast time-interval indications agree precisely with the average Navy time signals and are more uniformly spaced.

All audio frequencies, time intervals, and announcements are supplied by the specialized equipment indicated in figure 4, and controlled by a standard frequency of 100 kc/s. Frequency dividers are of the regenerative-modulator type.

All radio frequencies are likewise controlled by the same standard frequency of 100 kc/s. In figure 5 the radio-frequency control equipment, and one of the four high-frequency high-power radio transmitters are diagrammatically shown.

Part 6 - References.

Further information on frequency measurements is given in the articles which are listed below in chronological order. This is not a comprehensive bibliography, but merely presents selected articles which are helpful. Except where noted, they are not issued by, and are not available from, the National Bureau of Standards. These publications can be consulted in public libraries which maintain files of periodicals or copies may be secured from the publishers at addresses given in the following list:

Annalen der Physik.
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Bell System Technical Journal. 195 Broadway, New York, N.Y.
Communications. (Radio Engineering now included with other publications

and called Communications). Bryant Davis Publishing Co., Inc., 19 East 47th St., New York, N.Y.
Electronics. McGraw-Hill Publishing Co., Inc., 330 W. 42nd St., New York, N.Y.
Electric Journal. 530 Fernando St., Pittsburgh, Pa.
Experimental Wireless & The Wireless Engineer, or the Wireless Engineer and Experimental Wireless. See Wireless Engineer below.
General Radio Experimenter. 30 State Street, Cambridge, A, Mass.
Hochfrequenztechnik und Elektroakustik.
Journal of the Optical Society of America (formerly Journal Optical Society of America and Review of Scientific Instruments). American Institute of Physics, 57 East 55th St., New York 22, N.Y.
Journal of the Institution of Electrical Engineers, Savoy Place, Victoria Embankment, London, W.C.2, England.
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Physics. American Institute of Physics, 57 East 55th St., New York 22, N.Y.
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Physikalische Zeitschrift.
Proceedings of the American Academy of Arts & Sciences. Library of the American Academy of Arts & Sciences, 28 Newbury St., Boston, Mass.
Proceedings of the Institute of Radio Engineers. 330 West 42nd St., New York, N.Y.
Proceedings of the Physical Society. 1 Lowther Gardens, Exhibition Road, London SW7, England.
Proceedings of the Royal Society. Harrison & Sons, Ltd., 44-47 St. Martin's Lane, London, W. C. 2, England.
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Review of Scientific Instruments. American Institute of Physics, 57 East 55th St., New York 22, N.Y.
Wireless Engineer, Illffe & Sons Ltd., Dorset House, Stamford St., London, S.E.1, England.

Such papers as are issued by the National Bureau of Standards can be purchased from the Superintendent of Documents, Government Printing Office, Washington, D.C., at the prices stated. The prices quoted are for delivery in the United States and possessions and in certain other foreign countries which extend the franking privilege. For delivery to countries other than those, remittance should be increased by one-third to cover postage. Remittances should be made to the "Superintendent of Documents, Government Printing Office, Washington, D.C."

Serial letters and numbers are used to designate Bureau publications.

S, "Scientific Paper", is used for reprints from the "Scientific Papers of the Bureau of Standards" (Sci.Pap.BS). This series was superseded by the "Bureau of Standards Journal of Research" in 1928. RP, "Research Paper", designates reprints of articles appearing in the "Bureau of Standards Journal of Research" (BS J. Research) and the "Journal of Research of the National Bureau of Standards" (J.Research NBS), the latter being the title of this periodical since July 1934 (volume 13, number 1).

In each reference below, unless otherwise indicated, the first number (underscored) is the volume of the periodical; the numbers following indicate pages and the year of publication. Names of periodicals abbreviated can be found in full in the list of addresses above.

The piezoelectric resonator. W. G. Cady. Proc.I.R.E. 10, 83-114 (1922).

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Radio-frequency standards. R. C. Hitchcock. Elec. J. 24, 430-438 (1927).

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