U. S. DEPARTMENT OF COMMERCE

NATIONAL BUREAU OF STANDARDS

WASHINGTON

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Letter
Circular
LC-645

METHODS OF USING STANDARD FREQUENCIES BROADCAST BY RADIO

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(Supersedes LC-567)

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METHODS OF USING STANDARD FREQUENCIES BROADCAST BY RADIO.

The National Bureau of Standards broadcasts standard frequencies and related services by radio. The transmitting station from which these services were transmitted was destroyed by fire November 6, 1940. A reduced service has been provided since then by temporary equipment in another building. This will continue for some months. As rapidly as possible the Bureau will establish a new station to provide more fully than in the past standard frequencies capable of being received satisfactorily at all times throughout the country. These will be transmitted on more adequate power, and several radio carrier frequencies will be used, in order to provide more certain coverage of all distances.

The service is continuous at all times day and night, except for the possibility of breakdowns of the temporary apparatus used in the next few months. The broadcast carries the standard musical pitch and other features. During the next few months there will be only one radio carrier frequency, viz, 5 megacycles (= 5000 kilocycles = 5 000 000 cycles) per second.

The standard musical pitch carried by the broadcast is the frequency 440 cycles per second, corresponding to A above middle C. This is accepted as standard pitch by the musical profession and the American Standards Association. It also serves as a standard audio frequency. In addition there is a pulse every second, heard as a faint tick each second when listening to the 440 cycles. The pulse lasts 0.005 second, and provides an accurate time interval for purposes of physical measurements.

The 440-cycle tone is interrupted every five minutes for one minute in order to give the station announcement and to provide an interval for the checking of radio measurements based on the standard radio frequency. The announcement is the station call letters (WWV) in telegraphic code (dots and dashes).

The accuracy of the 5-megacycle and the 440-cycle frequencies 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 440-cycle frequency 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 1-minute announcement interval, the 4-minute 440-cycle interval, and the 5-minute interval marked by the beginning and ending of the announcement periods are accurate to a part in 10 000 000. The beginnings of the announcement periods 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; this adjustment does not have the extreme accuracy of the time intervals, but is within a small fraction of a second.

The broadcast is from a 1-kilowatt transmitter. It is most useful for medium distances in the daytime and long distances at night. For reception in locations reasonably free from interference, it is receivable in the summer at all distances up to about 500 miles from Washington in the middle of the day. The distance range increases after dark; at night the broadcast is receivable generally throughout the United States (i.e., the 5-Mc carrier frequency; the 440-cycle tone is sometimes not receivable at night beyond about 1300 miles). Sometimes at night it may be difficult to receive either the 5 Mc or the 440 cycles at distances between about 50 and 500 miles while it is easy to receive them beyond 500 miles. In the autumn the daytime distance range will increase, rising to about 1000 miles in the winter.

Part 1A (page 3 hereof) gives methods of using the standard radio frequency, 5000 kc/s, for the calibration of standard oscillators in simple cases where the frequencies have such numerical values as to be readily checked directly. Caution is necessary in using these frequencies to avoid confusion between the carrier frequency and the two side frequencies due to the 440-cycle modulation.

Part 1B (page 8) gives details for the checking of frequencies in the standard broadcast range, 550 to 1600 kc/s. The discussion is divided into three sections, progressing in difficulty of measurement. Section I deals with only two frequencies, 1000 and 1250 kc/s; very little apparatus is required for measurements at these frequencies. Section II gives the method of measurement, using an auxiliary generator, for frequencies which are multiples of 50 kc/s. Section III gives the method of measurement for any broadcast frequency (multiples of 10 kc/s).

Part 2 (page 14) 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 not capable of giving absolute time, as needed in navigation, for example, for which astronomical observations or the Navy's time signals are required.

Part 3 (page 15) describes methods of using the 440 cycles as a standard audio frequency. 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 21) 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 23) 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 a million.

Part 1A. Checking Standard Oscillators.

Method of Measurement.- While the standard frequency emissions may be used for many standardization purposes, the most common use is to determine accurately the frequency of a standard oscillator. The apparatus necessary is (1) the oscillator, (2) a continuously variable radio-frequency generator which is approximately calibrated, (3) a variable audio-frequency generator, and (4) a radio receiving set. A frequency meter of the resonance type is also useful but it is not essential. It is desirable that the receiving set have automatic volume control. A simple regenerative receiving set will suffice. There are some difficulties to be guarded against when using a superheterodyne receiving set if it does not have sufficient radio-frequency amplification; it may respond to a station frequency at two points, one of which is the nominal station frequency and the other either plus or minus twice the intermediate frequency of the receiver away from the nominal frequency. As the receiver will respond to the harmonics of a local oscillator, and response will also be obtained when any of the harmonics beat with the intermediate-frequency oscillator of the receiver or its harmonics, a great multiplicity of response frequencies are obtained which make identification of the desired frequency difficult.

A good type of standard oscillator is the piezo oscillator. The fundamental frequency is fixed by the dimensions of the quartz plate used. The usual vacuum-tube circuit arrangement in which the quartz plate is connected gives numerous harmonics for each fundamental frequency. The radio generator, which is continuously variable, can be adjusted to any frequency, and likewise gives a series of harmonics for each fundamental frequency to which it is adjusted. If the frequency of the radio generator is varied over a wide range, beat notes are produced at a number of settings of the generator by the interaction of various harmonics of the fundamental frequency of the piezo oscillator with a harmonic of the fundamental frequency of the generator. The beat notes may be heard in a telephone receiver suitably connected to the generator or to the piezo oscillator. Any frequency present in the piezo oscillator can beat with a corresponding frequency present in the radio generator, which makes it possible to set the generator at a number of frequencies which have a simple relation to the fundamental frequency of the piezo oscillator. Provided the harmonic relationship is known, measurements can be made at a great number of frequencies in terms of a single standard frequency.

If f is the fundamental frequency of the piezo oscillator which is being used and F the fundamental frequency of the auxiliary generator which gives zero beat, then

$$af = bF$$

where a and b are integers (1, 2, 3, 4, etc.).

The procedure is simplest when the ratio of the received radio frequency to the nominal frequency of the piezo oscillator to be standardized is a fairly small integer, less than 100. For instance, secondary standards whose fundamental frequencies are 50, 100, 200, 500, or 1000 kc/s can be measured very simply in terms of the 5000 kc/s and these secondary standards may be advantageously used in turn to calibrate other apparatus. It is, however, possible to use the 5000 kc/s, with auxiliary apparatus, to establish accurately any desired frequency.

Examples of Measurement Methods.- Suppose it is required to measure the frequency of a piezo oscillator, the approximate frequency of which is 700 kc/s, in terms of the 5,000-kc standard frequency.

If the radio generator is set at 100 kc/s, the 50th harmonic (5000 kc/s) will beat with the 5000 kc/s, and the 7th harmonic (700 kc/s) will beat with the fundamental of the piezo oscillator.

The 5000-kc standard frequency is received first and identified with the receiving set in the generating condition. The radio generator is then turned on and adjusted to near 100 kc/s. This should give a beat note with the frequency generated by the receiving set. The regeneration of the receiving set is then reduced until the set just stops generating. A beat note should then be heard which will in general be of less intensity than that previously heard. This is the beat between the 50th harmonic of the radio generator and the frequency of the incoming wave. This beat note should be reduced to zero frequency by adjusting the radio generator. For most precise work, this adjustment should be made by using a beat-frequency indicator or other means of indicating exact zero beat. A simpler and equally accurate substitute is to bring in a tuning fork as described below. However, for a simple discussion of the steps involved in the measurement, it will be assumed that an accurate zero-beat setting is obtained.

The radio generator is therefore precisely adjusted so that it has a frequency of 100 kc/s. Without changing its adjustment, couple the piezo oscillator to it loosely. A beat note should be heard in the telephones in the output of the piezo oscillator unless the frequency given by the piezo oscillator is an exact multiple of 100 kc/s. Suppose, for example, it is 700.520 kc/s. In this case a beat of 520 cycles per second will be heard. To determine the value of this note, the audio generator must be used.

The frequency of the beat note and the frequency of the audio generator may be compared by using single phone units from each source and rapidly interchanging them at the ear. If sufficient intensity is available from the two sources then the two audio frequencies will combine and beats may be heard by the ear when the audio generator is closely adjusted. For exact zero beat the frequency of the adjustable audio generator gives the difference in frequency between the 7th harmonic (700 kc/s) of the generator adjusted to 100 kc/s and the fundamental of the piezo oscillator.

Fig. 1 gives a diagrammatic representation of the frequencies used. It is necessary to determine whether the piezo-oscillator frequency is higher or lower than 700 kc/s. This can be done by varying the frequency of the radio generator. If increasing the frequency of this generator results in decreasing the beat note, then the piezo oscillator frequency is higher than the reference frequency, that is, the audio frequency is to be added to 700 kc/s. If the reverse is true, then the audio frequency is to be subtracted.

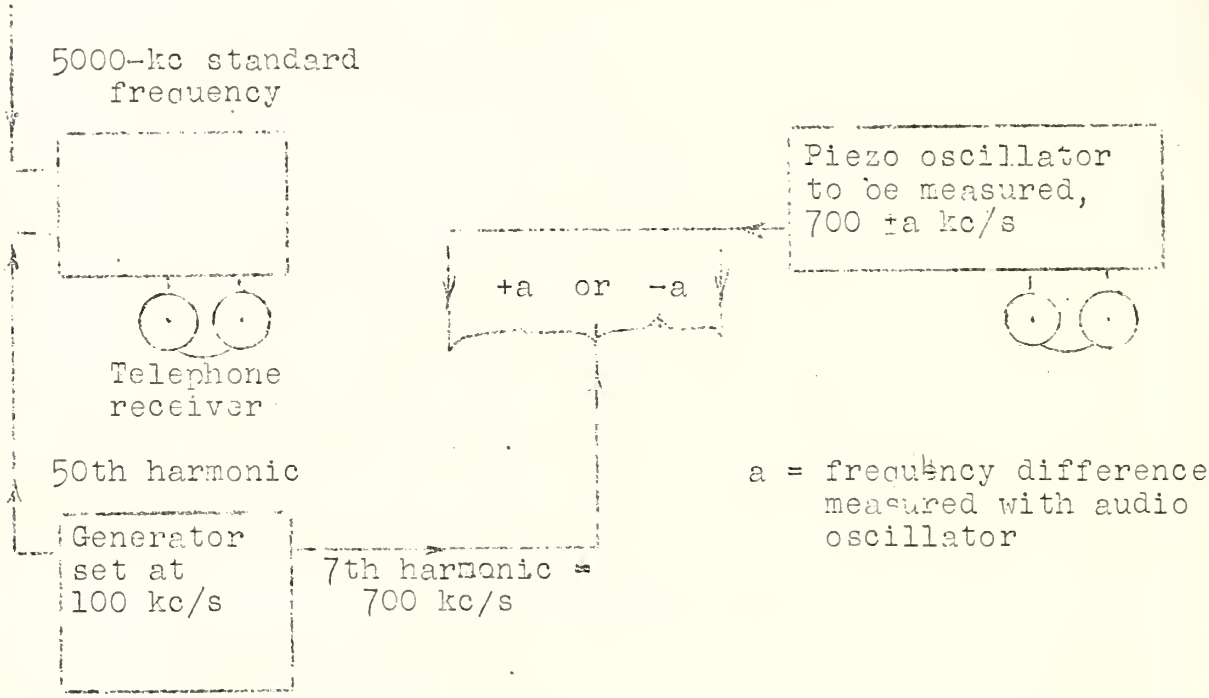

Fig. 1.

Use of Audio-Frequency Note in Measurement.- A change in the method described above which does not require a beat indicator, is to adjust the radio generator to have a known frequency difference with the incoming wave by means of matching with that of a tuning fork of known frequency such as 1000 c/s. This method is more complicated in calculation because a record must be made of four factors, (1) as to whether the radio generator was adjusted higher or lower than zero beat, (2) the frequency difference, (3) the harmonic relation between the standard frequency and the radio generator frequency, and (4) the harmonic relation between the radio generator and the piezo oscillator. The harmonic relations, however, come in to any method of measurement of this kind. The measurements involving the use of the tuning fork for adjusting the generator to give a beat note 1,000 cycles below the 5,000-kc signal would be made as follows, and are shown diagrammatically in Fig. 2. Set generator from approximate zero beat at 100 kc/s to 99.98 kc/s. The 50th harmonic is 99.98 x 50 = 4,999.0 kc/s (beats with 5,000 kc/s in receiver which is not oscillating and gives a 1000-cycle note). The 7th harmonic of the generator (99.98 x 7 = 699.86 kc/s) may now be heard beating in the telephones of the piezo oscillator which is known to be approximately 700 kc/s. If this value were exactly 700, a note of 700.000 - 699.860 kc/s or 140 c/s would be heard. However, the beat note produced is matched with a corresponding note from the audio generator. If the piezo oscillator had the frequency of 700.520 kc/s as assumed previously, the audio-frequency note measured would have been 700.520 - 699.860 = 0.660 kc/s or 660 c/s.

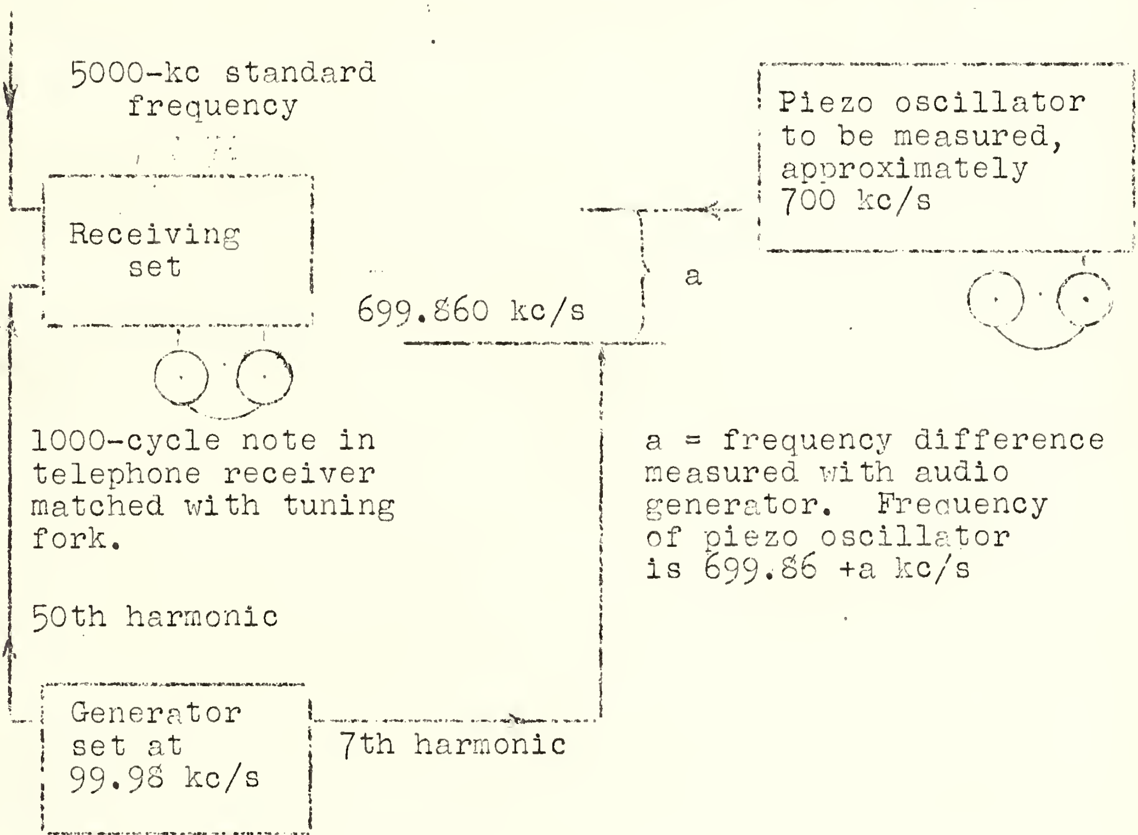

Fig. 2.

Whether to add or subtract the audio-frequency note of 660 c/s to the known frequency of 699.860 kc/s would be decided as follows when the radio-frequency generator was set lower than the standard frequency. If lowering the frequency of the radio generator increases the beat note (660 c/s in this case), add the beat note frequency, or if increasing the frequency of the radio generator decreases the beat note, add the beat note frequency.

The measurement could also be made by adjusting the generator to 100.020 kc/s using the 1000-cycle tuning fork, as in Fig. 3. The 50th harmonic is 100.020 x 50 = 5001 kc/s which beats with the standard frequency of 5000 kc/s and produces a 1000-

cycle note. A certain audio-frequency note is produced in the telephones of the piezo oscillator, which is matched with a similar note from the audio oscillator as before. If lowering the frequency of the radio generator reduces the audio-frequency note heard, subtract it from the known frequency of 700.140 kc/s, or if increasing the frequency of the radio generator increases the audio note, subtract it. The audio-frequency note heard with a piezo oscillator having the assumed frequency would be 380 c/s, hence 700.140 + 0.380 = 700.520 kc/s.

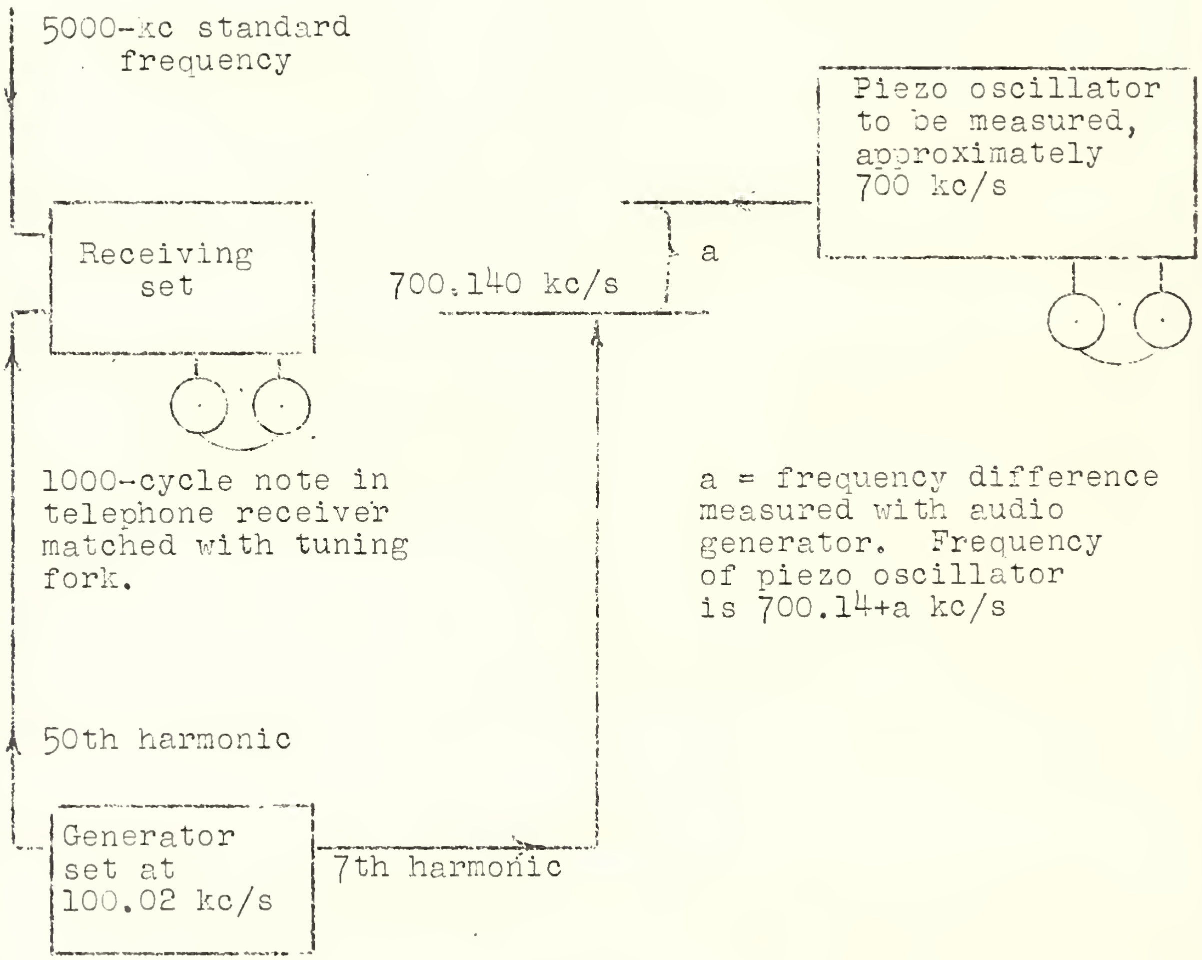

Fig. 3.

Part 1B. Checking Frequencies in the Standard Broadcast Range, 550 to 1600 kc/s.

I. Integral Submultiples of Standard Frequency.

The frequencies which are integral submultiples of the standard frequency are most easily measured. For the standard frequency of 5000 kc/s there are only two standard broadcast frequencies, 1000 and 1250 kc/s, which bear this relation. If a 1000-kc oscillator, whether a transmitting set or frequency standard, is coupled to a radio receiver tuned to 5000 kc/s at a time when the standard frequency is being received, a heterodyne note will be produced which is equal to the frequency difference between the 5th harmonic of the 1000-kc oscillator and the standard frequency. Assuming that the nominal value of the 1000-kc oscillator is known, all that remains in order to measure the frequency accurately, is to determine the frequency of the beat note and whether the frequency is higher or lower than the standard frequency. This is done when the radio receiver is not in the generating condition. The most convenient method, if the beat note is in the audible range, is to match it with a known audio frequency produced by a calibrated audio oscillator. The direction of the deviation is most easily determined by making a slight change of known direction in the unknown frequency. If an increase in the unknown frequency increases the frequency of the beat note, the unknown frequency is high. If an increase in the unknown frequency decreases the frequency of the beat note, the unknown frequency is low. Conversely, if a decrease in the unknown frequency increases the frequency of the beat note, the unknown frequency is low, and if a decrease in the unknown frequency decreases the frequency of the beat note, the unknown frequency is high. If it is impossible to vary the unknown frequency in a known direction, then an auxiliary generator or a cathode-ray oscillograph may be used. If the beat frequency to be measured is below the range of available measuring equipment it is necessary to provide a carrier for this frequency. This is done by making the radio receiver generate and adjusting the resulting beat note so that it is approximately 1000 c/s. A fluctuation in the amplitude of this 1000-cycle note, which has a frequency equal to the frequency difference between the two radio frequencies, will then be heard. If it is only desired to readjust the unknown frequency to agreement with the standard signal, it is a simple matter to adjust to zero beat. The same method can be used for a frequency of 1250 kc/s. Precaution must be taken to make it possible to combine the frequencies with approximately equal intensity. Some difficulty in this respect may be expected if measurements are made when the transmitter is operating unless the harmonics are very completely suppressed.

A station frequency monitor which utilizes a piezo oscillator having a frequency of 1000 or 1250 kc/s can be measured or adjusted to frequency in a similar manner. If the radio transmitter is operating, the measurement can be made indirectly in terms of the transmitter in the following manner. Measure the frequency of the radio transmitter in terms of the 5000 kc/s and simultaneously read the frequency as indicated by the frequency deviation meter on the monitor. The two frequencies should agree. If they do not, adjust the frequency monitor until the deviation meter indicates the correct frequency deviation. It may be desirable to measure the frequency monitor directly against the standard frequency at a time when the radio transmitter is not operating.

If the frequency monitor is of the type which is adjusted to exactly 1000 or 1250 kc/s, the measurement can be made the same as in the case of the radio transmitter. However, if the monitor is set high or low by 500 or 1000 c/s, it will be necessary to make use of an audio oscillator to determine the value of the audio beat frequency. In the case of a monitor which has a frequency of 999.500 or 1000.500 kc/s, the beat note to be measured would be 2500 c/s. As five cycles variation in the beat note is only 1 part in 10^6, any audio oscillator which would be constant to 5 or 10 c/s would be adequate. In the case of a monitor which has a frequency of 999.000 or 1001.000 kc/s a 5000-cycle note would be produced. Similarly for 1250 kc/s, audio-frequency beat notes of 2000 and 4000 c/s would have to be measured. The general relation is that the audio-frequency note produced by heterodyning the monitor frequency and the 5000-kc standard frequency is equal to the product of the number of cycles the monitor is set high or low and the ratio of 5000 to the nominal value of the monitor.

II. Measurements with Auxiliary Generator for Frequency Multiples of 50.

Measurements of any of these frequencies require the use of an auxiliary generator in addition to the high-frequency receiver. The auxiliary generator may be a piezo oscillator or it may be a manually controlled oscillator. If a piezo oscillator of the desired frequency is available, it is desirable to use one. In this case a distorting amplifier is necessary in order to bring out the harmonics so that the beat against the standard frequency can be easily heard. This piezo oscillator should be provided with a fine adjustment of frequency so that it can be readily adjusted to agreement with the 5000-kc standard in the manner previously described. After this is done the monitor or radio transmitter can be measured in terms of harmonics of the auxiliary generator. If a manually controlled generator is used, the $\frac{L}{C}$ ratio must be low so that the frequency can be easily adjusted to zero beat with the standard frequency, and readily held on that frequency.

There are two main factors which determine the frequency to which the auxiliary generator should be adjusted. The first is that its frequency must have an integral relationship with the standard frequency and the nominal value of the frequency to be measured. The second is that the harmonic which is heterodyned with the standard frequency must be of sufficient intensity to produce a beat note which is easily recognized. Taking both factors into account the best result is attained if the frequency of the auxiliary generator is the highest common factor of the standard frequency and the frequency to be measured. The following table indicates the broadcast frequencies which can be measured in terms of the 5000-kc standard frequency broadcast by means of a high-frequency radio receiver and an auxiliary generator. It will be understood that the table gives all broadcast frequencies which are multiples of 50, but does not indicate more than one generator frequency for these frequencies except for 1000 and 1500 kc/s.

Broadcast Frequencies Measurable with Auxiliary Generator

	Frequency of Auxiliary Generator in kc/s			
	500	200	100	50
Broadcast	1000	600	700	550
	1500	800	900	650
Frequencies,		1000	1100	750
		1200	1300	850
kc/s		1400	1500	950
		1600		1050
				1150
				1250
				1350
				1450
				1550

As an example of this method of measurement, assume the frequency of the radio transmitter to be 1150 kc/s. The radio receiver, in the generating condition, is tuned until the 5000-kc standard frequency is heard. The auxiliary generator, set on approximately 50 kc/s, is then turned on and the frequency varied until a second audio frequency is heard on the output of the high-frequency receiver. If the radio receiver is then adjusted so that it does not generate, the auxiliary generator can be set to zero beat with the standard frequency signal. If the radio receiver is again made to generate, the auxiliary generator can be easily set to agreement with the standard frequency as previously explained. The rough adjustment to zero beat must be made when the radio receiver is in the non-generating condition, otherwise there is danger of setting to zero beat between the two audio frequencies or harmonics of the audio frequencies. If a piezo oscillator is used, this precaution is unnecessary. A detector-amplifier is set up so as to receive portions of the outputs of the auxiliary generator and the 1150-kc radio transmitter, Fig. 4. The output of the amplifier will give the audio beat-frequency between the 23d harmonic of the auxiliary generator and the 1150 kc/s of the radio transmitter. If this audio frequency is reduced to zero as indicated on a visual beat indicator the transmitter frequency will be in exact agreement with the standard frequency. One person can make this adjustment, as an aural indication may be used for the auxiliary generator and a visual one for the transmitter adjustment.

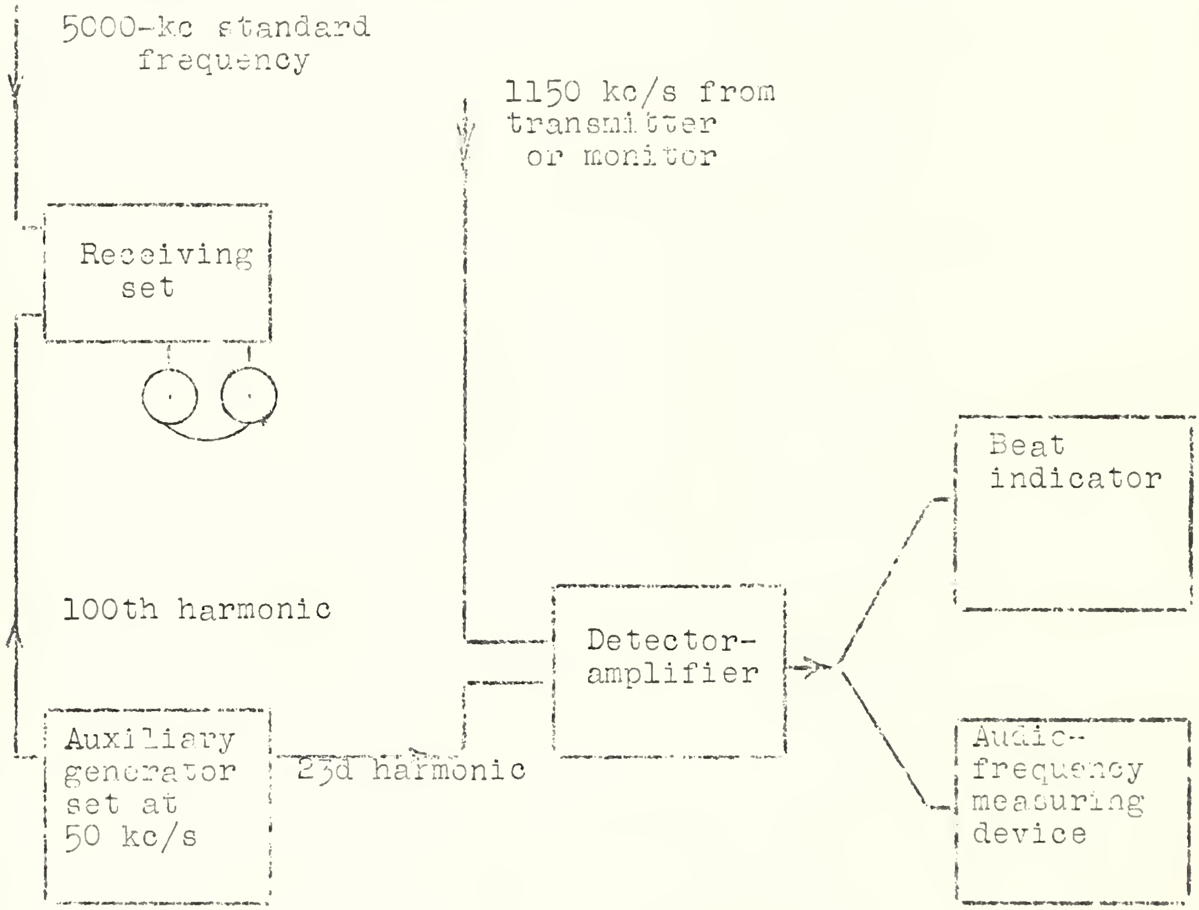

Fig. 4.

If a piezo oscillator is used as the auxiliary generator, it need only be checked against the standard frequency at intervals.

III. Measurement of Any Broadcast Frequency.

The methods of measurement given in the preceding paragraphs are applicable to twenty-two of the frequencies in the standard broadcast band of frequencies. The highest common factor of 5000 and the remaining broadcast frequencies is 10. The frequency of the auxiliary generator must therefore be

10 kc/s if the other broadcast frequencies are to be checked readily in terms of the 5000 kc/s. The beat note between the 500th harmonic of the 10-kc generator and the 5000-kc standard would not be loud enough to be heard distinctly. The simplest solution, therefore, is to set the auxiliary generator on 100 kc/s and let it control a 10-kc multivibrator. The beat against the standard frequency could then be heard easily and the harmonics of the 10 kc/s would heterdyne equally well with frequencies in the broadcast band. It is evident that with this equipment all standard broadcast frequencies can be checked against the 5000-kc standard frequency, Figure 5.

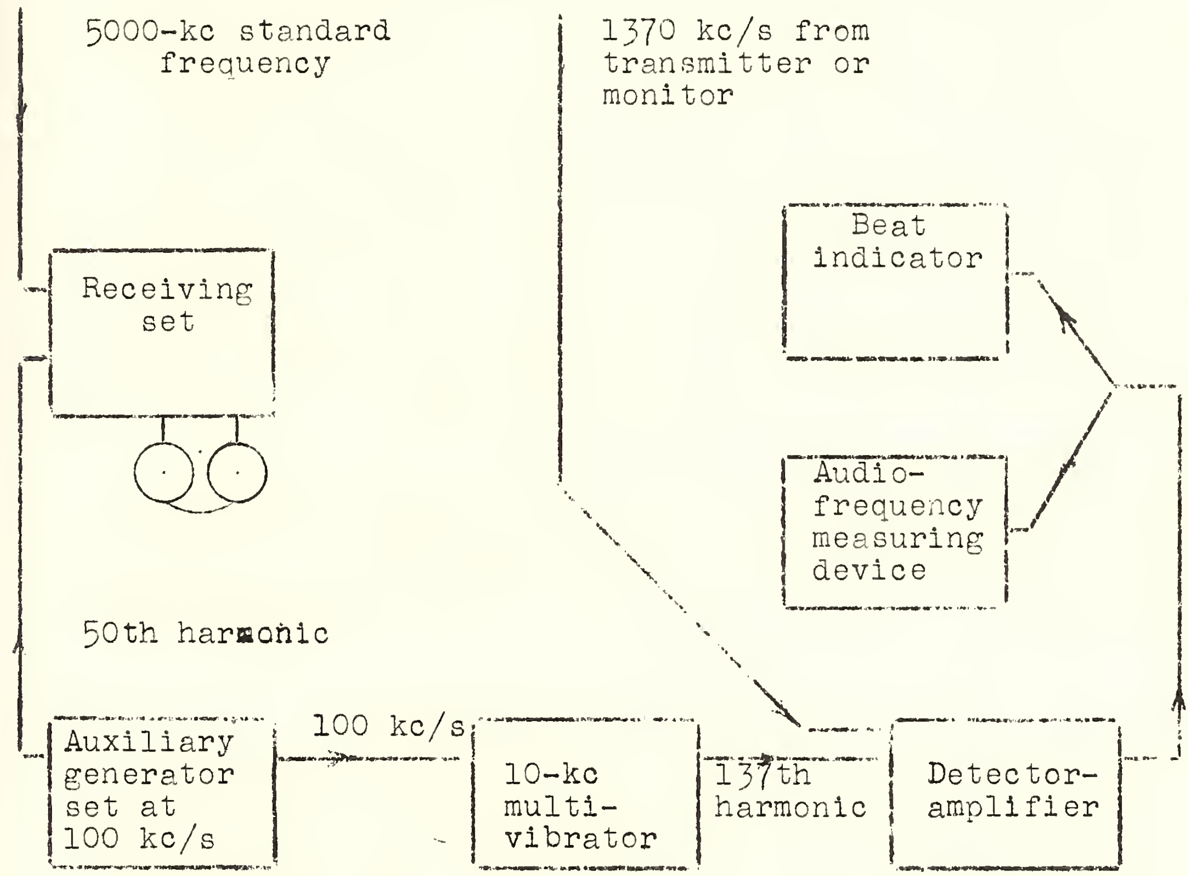

Fig. 5.

There are some cases in which a frequency can be measured by more than one of the methods indicated. The question arises as to the advantages and disadvantages of the various possibilities or as to how existing equipment might be brought into use. The first method is applicable to only two frequencies. It provides the most accurate check for frequencies which are very near the harmonic value. For monitors, however, which are set high or low by 500 or 1000 c/s, the audio frequency which must be measured is so high that it is very difficult to determine its value. This method is further handicapped by the fact that if the measurements are made in the transmitting station when the power amplifier is operating, the harmonic which is picked up on the receiver may be so strong that it will block the receiver. If that is the case it would be necessary to locate the receiver at some distance from the transmitter and use a line between transmitter and receiver.

The second method requires an auxiliary generator and detector-amplifier in addition to the equipment used in the first method. A small error may be introduced in this method in the adjustment of the auxiliary generator. If a piezo oscillator is used this error is negligible. The error is much greater if a manually-controlled oscillator is used. In either case, however, it should not be more than a few parts in a million. This method is applicable to 22 of the broadcast frequencies, and is much more satisfactory for checking monitors which are set off-frequency because the audio frequency to be measured equals the amount the monitor is set high or low. If a harmonic amplifier is coupled to the auxiliary generator so that sufficient voltage is provided, the measurement of the monitor can be read directly on the visual indicator provided with that unit.

It is necessary to use the third method in checking the remaining 84 broadcast frequencies. This method requires a high-frequency receiving set, auxiliary generator, 10-kc multivibrator, detector-amplifier, and audio-frequency measuring equipment. The accuracy of this method is the same as of the second method.

Part 2. Standard Time Intervals.

As previously stated, the standard one-second intervals provided by the pulses each second are accurate to better than 0.000 01 second, as sent out from the transmitter. Taken over a longer period of time, the percentage accuracy increases in proportion to the number of seconds duration of the time interval considered, up to a limit of one part in 10 000 000. That is, under ideal receiving and measuring conditions one could measure a time interval of 100 seconds or longer to better than a part in 10 000 000. However, measurements to 0.000 01 second are difficult and a longer time interval than 100 seconds would ordinarily be required to obtain a certainty of one in 10 000 000.

For high accuracy the radio receiver should have constant supply voltages and be accurately tuned. A carrier intensity meter or tuning indicator, (such as the 6E5 tube), is desirable for detecting fading. Automatic volume control is helpful. A piezoelectric filter or an audio-frequency filter having a narrow band width is not desirable as it tends to reduce the amplitude of the received pulse; also, audio-frequency circuits having a very long time constant will give the impression of a weak signal or a low percentage of modulation. An oscillograph is required to make time measurements to 0.001 second or less. An oscillograph with a suitable viewing screen is helpful in determining whether consecutive pulses have the same wave form and whether high accuracy is possible.

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 in consistent sequence from one broadcast to another.

The seconds pulses are also usable as a basis of measuring frequencies. One method of using them is to control the vertical deflection of a cathode-ray oscillograph with them and use for the horizontal deflection the frequency which is to be measured (or a harmonic or subharmonic thereof). The frequency of the drift of the seconds pulses across the screen of the oscillograph is the error in cycles per second. Another method is to record the seconds pulses on a moving-film type of oscillograph along with a timing line from the frequency which is to be measured.

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.

Part 3. Standard Audio Frequency.

The standard musical pitch, 440 cycles per second broadcast as described in Part 4, may also be used as a standard frequency by the methods described in this section. The presence of the seconds pulses does not interfere with the use of the 440 cycles. 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 440 cycles is off 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-cycle broadcast.

From the standard audio frequency, any desired frequency may be measured. Using any receiving set capable of receiving 5000 kc/s, the standard audio frequency is delivered at the output terminals of the set. This frequency may be used for comparison with a local frequency and 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 harmonic amplifiers or multivibrators 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 oscillograph 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.

In any of the methods it may be found worth while to eliminate fading trouble by using an auxiliary oscillator whose frequency is occasionally made precisely equal to (or an exact multiple of) the received frequency by setting to zero beat between the two fundamentals or two harmonics.

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 multivibrator, 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 multivibrator, 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 multivibrator, to step down.

4. Counting of beats between harmonics.

B. <u>Control of a source of frequency.</u>

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

C. <u>Production of a time rate standard.</u>

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.

The effects of fluctuations of amplitude and phase of the received audio frequency may be markedly reduced by the use of automatic volume control and filters. Filters also have the advantage of minimizing interfering electrical noise. An effective filter for 440 cycles per second is a combination of low-loss condenser and coil, preferably parallel-tuned between ground and grid of an audio-amplifier stage. 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.

When multiplying from 440 c/s it is necessary to use very selective apparatus to remove 440-cycle sidebands from the output of the multiplying device. For this purpose a quartz plate filter (at 44 kc/s or 55 kc/s, for example) is very good.

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.

It is convenient in many cases to add or subtract a known frequency from the received 440 cycles per second or a harmonic thereof, or from the local frequency to be compared therewith. The advantage is that the frequencies to be compared can be made even multiples or submultiples of each other. The frequency added or subtracted should be small compared with the frequency being measured, and the accuracy of its value should be known. For example, a frequency of 13333 cycles per second can be compared directly against 440 per second on a cathode-ray oscillograph, by subtracting 133 cycles from it and using thirtieth harmonic of 440. Addition or subtraction of frequencies is done by the use of the beat principle. It is sometimes advisable to employ filters also.

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 such as 11,000 or 99,000 cycles per second. For example, consider the use of method A1. The 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, for example, may be secured by timing for 3 minutes when the comparison is made at 440 cycles per second, but may be secured by timing for only a few seconds when the comparison is made at 100,000 cycles per second.

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.

It may be desirable to multiply either the incoming standard frequency, the local frequency, or both. Frequencies can be multiplied quite simply by means of tuned harmonic amplifiers. Another means is the use of frequency doublers utilizing two tubes connected with their grids in a push-pull arrangement and their plates in parallel. It is convenient to have the incoming 440-cycle frequency control a multivibrator and step up in frequency from that.

The use of the cathode-ray oscillograph has a number of advantages in this as in all the 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 oscillograph 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 of the 440 c/s, the received signal can be stepped down to a desired value by means of a multivibrator.

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 there is a raised thread or spiral on the drum, and the paper passing at a known speed past the drum; a record is made by causing a spark, controlled by the 440-cycle frequency (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, the number of spiral threads on 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 differences 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.

When it is desired to check a local frequency which is lower than 440 c/s (e.g., 60 c/s), one procedure is to multiply the local frequency up to a frequency which can be compared directly with the standard modulation frequency or some harmonic of it. In the case of 60 c/s it would be divided by 3 and multiplied by 22, in one or two steps, which would give an output of 440 c/s. The received standard 440-cycle frequency could conceivably be multiplied by 3 and divided by 22 so as to be compared directly against 60 c/s, but this would result in a lower accuracy of comparison or would require a longer time to make a measurement. Since frequency multiplication is easier than frequency division, a more convenient method of accurately measuring 60 c/s is to multiply it to to 1320 cycles per second. The proper harmonic is selected from a multivibrator controlled from the 60 c/s, or two stages of frequency multiplication are used. The resulting 1330-cycle frequency is then compared against the third harmonic of the standard 440 cycles per second.

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 multiplying the standard 440 c/s to 11 kc/s and using harmonics of its output in conjunction with a calibrated audio oscillator.

Measurements can be made over any convenient period of time (up to four 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 ± 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 ±0.1 second, the accuracy of the beat frequency measurement is 1 part in 50.

To obtain greater accuracy in a given length of time, the frequencies can be multiplied and the difference frequency measured at a higher harmonic.

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 tuning-fork it can be driven directly from the received 440-cycle frequency. 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.

The standard audio frequency can similarly be used to control a multivibrator 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 would 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 not generally available to laboratories hitherto from any service.

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 frequency (5 megacycles per second) is much higher than the frequencies on which the usual broadcast entertainment programs are given. The broadcast receiving sets sold previous to about 1933 will not receive this high frequency, but part of those now being sold will do so. The purchaser of a radio should be sure that its tuning ranges do include 5.0 megacycles.

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 5 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 5 megacycles. 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 or 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 of 4.1 as well as 5.0 megacycles. This is merely an incident of the construction of the radio receiver. It is usually more satisfactory to employ the 5.0 than the 4.1 setting.

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.

The 5-megacycle carrier frequency can of course be used as a standard radio frequency. When there is uncertainty as to whether the carrier or one of the side-frequencies is being used, this can be checked by observation during the 1-minute announcement which is given every 5 minutes. If it is desired to reduce the side-frequency beats this can be done with a simple low-pass filter; another method is to use a 440-cycle band-pass filter, connected in an inverse-feedback circuit from the radio receiver output, to modulate the screen grid of a r-f tube in an auxiliary 5000-kc piezo oscillator.

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. 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 the following addresses:

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Electronics, McGraw-Hill Publishing Co.,Inc., 330 W. 42d 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 St., Cambridge, A, Mass.
Hochfrequenztechnik und Elektroakustik. Akademische Verlagsgesellschaft MBH, Leipzig, Germany.
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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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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.

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