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Frequency Determination

By JAMES K. CLAPP

ONE need be only a casual reader of current radio literature to know that the precision determination of frequency is a most important engineering problem. The growing economic, political, and social significance of all radio channels is requiring an increasingly precise distribution of services over the useful frequencies of the spectrum. Already the Federal Radio Commission requires that the broadcasting station's carrier frequency at the high-frequency end of the band be maintained within three parts in 10,000, and one of the constantly-repeated suggestions to the Commission for the elimination of all heterodyne interference would, if put into effect, reduce that tolerance tenfold. What is more, the problem is international, which means that every radio-using nation must, in addition to using precise methods of frequency determination, maintain its working standards of frequency in agreement with those of the others.

A READER is likely to find the subject of frequency determination rather complicated unless he has an appreciation of the author's point of view. This article, although complete in itself, is the introduction for a series which will discuss the General Radio Company's attack upon the problem of standardization and precise determination of frequency. In addition to establishing a definite point of view the present article is general enough to enable one to fit into the picture the various systems that have been proposed and are now in use.

Mr. Clapp, a member of General Radio's Engineering Department, was the author (with L. M. Hull) of the paper on "Secondary Frequency Standards" appearing in the February Proceedings of the I. R. E.

It will be helpful to an understanding of what follows to realize that the precise determination of frequency is, essentially, the precise determination of a time interval. For example, the frequency of a commercial power supply may be 60 cycles per second, and the time required to complete a cycle is 1/60th of a second; the frequency of a clock's second hand is 1/60th of a revolution per second, and the time required to complete one revolution is 60 seconds; the rotational frequency of the earth is 1/24th of a revolution per hour, and the time required to complete one revolution is 24 hours. Frequency, then, is determined when the time interval is determined, and, what is more important, the standardization of a time interval at the same time establishes a standard of frequency. The two concepts are practically synonymous.

Various systems for the standardizing of a time interval have been proposed, among them some based upon the velocity of propagation of light in space, but the one generally used depends upon the high degree of uniformity in the rate of the earth's rotation upon its axis. It is argued that, theoretically at least, the rate of rotation can change from the effects of friction and variation in the earth's moment of inertia, but the probable deviation from absolute uniformity is said to be negligible, even over a period of a thousand centuries. Granting the possibility of a variation, the fact remains that the earth is a timekeeper many many times more reliable than the best man-built clock. The length of the Solar Day, as determined by the time between successive transits of the sun across the meridian of the observer, changes from day to day, and for everyday civil uses and for all non-astronomical scientific work as well, the standard interval is the Mean Solar Day, the average or mean of the length of all the Solar Days in the year. The second is a 1/86400th part of it.

Differing somewhat from this is the Sidereal Day which the astronomer defines as the interval between two successive transits of a particular "fixed star" across his meridian. The length of the Mean Solar Day bears an almost constant ratio to the length of the Sidereal Day and inasmuch as the former is an average not susceptible to measurement, all observatories check their clocks and radio and telegraphic transmission of time signals against astronomical determinations of the Sidereal Day.

As has already been pointed out, the universal acceptance of the Mean Solar Day as the standard time interval establishes the rotational frequency of the earth as the primary standard of frequency (1/86400th of a revolution per second) in terms of which all other frequencies must be expressed. But the frequency of this primary standard is so remote from any of the frequencies encountered in communications engineering that an intermediate or working standard is not only desirable but essential. It is the development of this working standard with a method of deriving from it all frequencies necessary for useful purposes that constitutes the so-called frequency determination problem.

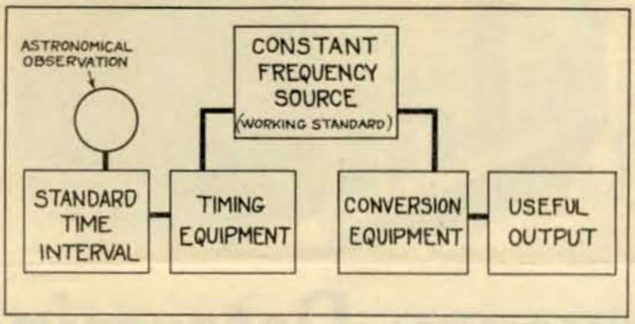

FIGURE 1. AN OUTLINE CHART FOR A PERFECTLY GENERAL FREQUENCY-DETERMINATION SYSTEM

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In any general frequency-determination system such as the one we are discussing here, there are three essentials which are shown graphically in the accompanying "flow chart" (Figure 1). Each of them presents a distinct problem.

First: there must be provided a generator whose frequency can be maintained constant for an indefinite period. "Working standard" is a better name for the source in a general system than the purely relative terms "primary" or "secondary" standard. If the timing equipment directly links the source with the astronomical determination of the Mean Solar Day, the term "secondary standard" might be suitable, but if the source were timed against a clock which was in turn checked against radio time signals, "tertiary" or some higher order might be the better descriptive term. Working standard is, therefore, perfectly general and includes:

(*1*) Pendulums
(*2*) Tuning forks
(*3*) Magnetostriction oscillators
(*4*) Piezo-electric oscillators
(*5*) Vacuum-tube oscillators of special construction

Any of these may be used as a working standard; which one is chosen is entirely a matter of system design. By careful control each of these may be made to maintain its frequency with little variation, although some are inherently more steady than others.

Second: there must be provided a means of timing the working standard for determining its frequency in terms of the standard time interval, an operation which generally involves counting the number of cycles completed by the working standard during the interval. When the frequency of the working standard is low, the counter may be a chronograph or a synchronous impulse motor and clock train connected directly to the standard, but a high-frequency standard may require an intermediate frequency-dividing link before a counting mechanism can be conveniently operated.

The clock-train counter is used in exactly the same manner in the timing equipment as it is in a time-keeping clock. In the latter it serves to count the number of impulses of the pendulum (or balance wheel) for comparison with the number of impulses counted by a standard clock in the same interval. The chronograph, as its name implies, records graphically the impulses from the working standard and a time standard for comparison.

A working standard of high frequency (100 kilocycles, for example) could not operate directly an electro-mechanical counter, and intermediate frequency-dividing equipment is, therefore, essential. Several such schemes are in use, but almost all make use of some kind of generator, the fundamental frequency of which is low enough to operate the counting mechanism. A harmonic of the generator is either synchronized with or monitored against the frequency of the working standard, which is then known to be an integral multiple of the frequency driving the counter. Most of the devices mentioned in the next section are suitable for use as frequency dividers as well as frequency multipliers.

Third: once a working standard has been set up and timed against the standard time interval there remains the problem of deriving from it a sufficient number of useful frequencies. It cannot be expected to furnish them all, but enough should be available to make possible accurate interpolations. This may be accomplished by frequency multipliers and dividers of several kinds: some are capable of holding themselves in synchronism and others require manual monitoring. The list of suitable devices includes:

(*1*) Mechanical methods
(*2*) Quiescent harmonic amplifiers
(*3*) Controlled distorted-wave generators
  (*a*) Relaxation oscillators
    (*i*) Neon tubes
    (*ii*) Multivibrators
  (*b*) Vacuum-tube oscillators

Necessarily limited by size and speed, mechanical devices are most useful at comparatively low frequencies

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A Better Frequency Meter for the Amateur

FIGURE 2 THE TYPE 558-P METER CONTAINS NO RESONANCE INDICATOR

BEFORE the amateur bands made necessary by the Washington Convention of the International Radio Telegraph Conference went into effect last January, wavemeters or frequency meters were not the absolute necessities that they are today. With not-too-tolerant commercial and military services in adjacent channels, services that are themselves required to hold closely to their assigned frequencies, it is little wonder that increased official emphasis is being laid upon the necessity of the amateur's keeping within bounds.

Realizing the necessity for such an instrument, the General Radio Company last July brought out the TYPE 558 Amateur-Band Wavemeter in which the accuracy of calibration was 0.25% over all five of the high-frequency bands. By the use of a tuning condenser designed to spread the band over the whole 180 degrees of the dial and by the addition of a specially constructed neon-tube resonance indicator, an instrument capable of unusually precise work was provided for the amateur. Later on the meters were calibrated in frequency instead of wavelength and the official title was changed to "Amateur-Band Frequency Meter."

Many users, inexperienced in making a frequency measurement upon an oscillator, failed to observe the one rule that must be followed when the meter circuit contains a resonance indicator: the coupling between the oscillator and the meter must be kept very loose. On many low-powered transmitters loose coupling could not be made to give an energy transfer sufficient to light the neon indicator. The coupling would then be tightened, but the frequency indicated by the meter might be considerably in error because of the mutual reaction of the meter circuit and the oscillator upon each other. The frequency meter could be made to give precise readings, but it had to be handled with care.

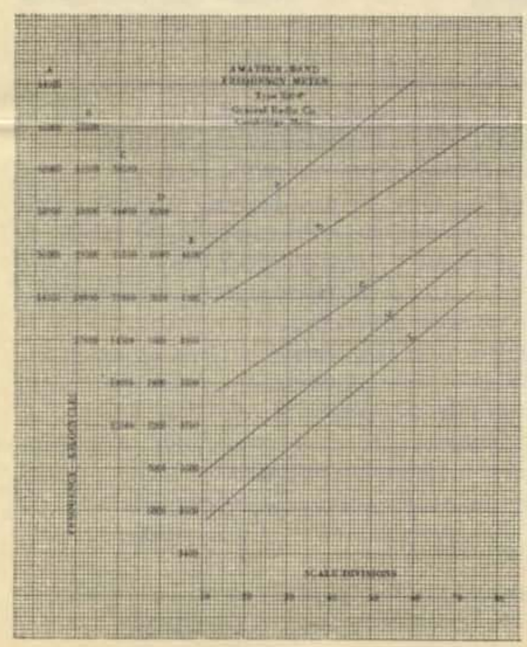

FIGURE 3. EACH INSTRUMENT IS INDIVIDUALLY CALIBRATED

In order to improve upon the amateur-band frequency meter and make it easier for the non-professional user to obtain high precision without in any way affecting its utility, the resonance indicator has been entirely removed from the instrument. This requires that some indirect method of indicating resonance be used, but a number of methods are available that are extremely sensitive and leave little to be desired in precision.

The best known of these is the so-called plate-reaction method. With loose coupling between the oscillator and the coil of the frequency meter, the plate-current meter of the oscillator will "kick" as the frequency-meter circuit passes through resonance. With some oscillators the current will increase, in others it will decrease, but the kicking point can usually be picked out with little difficulty and with much looser coupling than would be needed to operate a neon indicator. It may well be emphasized that a plate-current meter is not absolutely necessary in using this method. A flashlight bulb of the proper size may be used, and, especially when the filament is biased with an external battery, it is highly sensitive to small changes in the magnitude of the plate current.

The method recommended for use wherever it is possible (it always is possible in the amateur station) makes use of a monitor heterodyne oscillator. Although seemingly the method is little used outside the college and commercial laboratories it is one that deserves to be better known among amateurs. (See "Checking Tone and Wavelength of Transmitters" by James K. Clapp, *QST*, December, 1926.) Using the fundamental or a harmonic of the oscillating receiving set as the monitor, to beat with the fundamental or a harmonic of the transmitter, the fre-

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Frequency Determination

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where they can be made to perform satisfactorily. Most of them are synchronous motor-driven tone-generator systems and are capable of being designed to give nearly any ratio of motor to generator frequency.

The harmonic amplifier is designed to distort the wave-form of an alternating voltage impressed upon its input, as a result of which harmonics of the impressed voltage appear in the output circuit. It has the advantage of being quiescent; that is to say, when the applied voltage is removed, no voltage of any frequency appears in the output; the only possible output frequencies are, therefore, always integral multiples of the applied frequency. Any non-linear vacuum-tube amplifier is a harmonic amplifier, at least to a certain extent.

Relaxation oscillators utilize either the "cut-off" or the negative resistance characteristics of such devices as neon tubes, carbon arcs, and the usual forms of vacuum tubes to sustain oscillations in a circuit comprising a direct-current source, resistances, and condensers. The output of such oscillators is rich in harmonics. If a second oscillation of higher frequency be injected into the circuit, the relaxation oscillation may assume a frequency which is a submultiple of the injected frequency.

Although the neon tube is simplest, its control by the injected voltage is not as stable as that obtained from the multivibrator. The control of a multivibrator is not affected by variations in the magnitude or frequency of the injected voltage or the applied voltages on the tubes over reasonably wide ranges. This inherent stability of the system, together with the comparatively large output it is capable of delivering, makes it an excellent frequency converter for a multiplying or a dividing system.

By overloading, the output waveform of a vacuum-tube oscillator may be distorted to produce a relatively large number of harmonics, so that it may also be operated as a frequency multiplier or divider, under the control of an injected voltage; however, the control is less stable than that obtained in either type of relaxation oscillator previously mentioned.

The practical importance of the systems outlined above may be summarized by stating that each is capable of being operated in such a manner as to derive by frequency division, from a high-frequency working standard, lower frequencies which are suitable for operating a counting mechanism. Further, due to the large number of harmonic frequencies in the output, it is perfectly feasible to combine the functions of the conversion equipment with those of the timing system, in a single assembly, by frequency multiplication.

III

The foregoing outline has necessarily been brief, but it has emphasized most of the fundamental concepts involved in frequency measurements. Here it may well be pointed out again that the system under discussion has been a perfectly general skeleton upon which the elements of existing and proposed systems may be draped for easy classification. Most of the important system elements have been mentioned for the purpose of showing how they fit into the complete structure, but for detailed information on specific systems, the reader is referred to the papers and bibliographies appearing in the American and foreign technical periodicals (the *Proceedings of the I. R. E.*, in particular).

A Better Frequency Meter for the Amateur

(*Concluded from page 3*)

quency meter is next coupled rather loosely to it. As the frequency meter dial is swung past the frequency of the transmitter a change in the pitch of the beat note can be heard in the telephone receivers. The coupling between the transmitter and the frequency meter is then loosened until the variation in the beat note becomes almost inaudible. The setting of the frequency meter at which the beat note changes in pitch is the frequency of the transmitter. With this method it is possible to check the meter against standard frequency transmissions from such a station as WWV.

This raises the question of the accuracy of the Type 558-P Frequency Meter (the type number for the new meter without a neon indicator). Its calibration in the laboratory is made to within 0.25%, but how long that accuracy can be maintained depends in large measure upon the treatment that the instrument receives. The Type 224 Precision Frequency Meter costing ten times as much as the Type 558-P Meter is calibrated with the same accuracy, but it will retain that calibration longer and, because of its micrometer scale, be capable of a more precise setting than the little fellow. The Type 558-P Meter is carefully packed before shipment, and, if it is not roughly handled or subjected to extremes in temperature, the original calibration should hold closely. Even the calibration of the precision frequency meters is guaranteed for only six months; and it follows that the less sturdy amateur-band frequency meter should be checked by reference to the standard frequency transmissions or returned to the General Radio Company for recalibration at least that often.

There are five coupling inductors, four of which are wound on bakelite tubing threaded to insure that the spacing between turns remains fixed. The 5-meter inductor is a simple loop of heavy brass rod. The Type 558-P Frequency Meter is shipped in a strong packing case, in addition to the storage box supplied with the instrument. Each one is individually calibrated to within 0.25%.

Its price is $18.00, $2.00 less than the old Type 558 Neon-Tube Meter. The code word is WOMAN.