THE STATUS OF FREQUENCY STANDARDIZATION*

By

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Summary—*The measurement of frequency, hitherto of laboratory interest only, has become of first-rank importance in reducing radio interference. This has come about through the increasing use of all available radio channels particularly at broadcasting and higher frequencies. While an accuracy of one half per cent was satisfactory five years ago, accuracies a thousand times as good are now sought.*

The piezo oscillator is meeting the needs of this situation in large part. Much effort is being devoted to making the piezo oscillator as constant as possible. Commercially available piezo oscillators, without temperature control, are generally reliable to about 0.03 per cent, just barely enough to meet the Federal Radio Commission's requirement of one-half kilocycle. In order to reach greater accuracy, considerable work is being done on the primary standards of frequency, to insure the highest constancy and accuracy. The Bureau of Standards and other organizations are engaged on a cooperative program to attain an accuracy of 0.001 per cent. Comparisons with other nations show that the national laboratories of the larger countries are already in agreement to about 0.003 per cent.

Temperature controlled piezo oscillators will probably allow the holding of station frequencies so close that several stations can broadcast on the same frequency without heterodyne interference. Use of these or equivalent devices is vital to the maximum utilization of the very high frequencies; the separation of 0.1 per cent between high-frequency stations which is practicable in the immediate future is largely determined by frequency variations, and can be reduced as practice improves.

Introduction

RADIO manufacturers, transmitting stations, and standardization agencies have found it necessary to increase their accuracy of frequency measurement progressively during the past four or five years. This need has come about through the increasing use of the available radio channels and particularly through the development of broadcasting and of high-frequency transmission. While an accuracy of one-half per cent was satisfactory five years ago, it is now necessary to give consideration to accuracies a thousand times as good. It is not merely a question of measurement. Frequencies of transmitting stations

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must be actually held constant with very great accuracy. This is becoming more and more important as the available radio channels become saturated. The maximum number of communications can be packed into the radio spectrum only if each stays within its own channel, as any wandering due to inaccurate frequency adjustment causes interference with the communication on the adjacent channel.

Interference due to frequency variations is perhaps now the main source of interference, as far as technical (apparatus) causes of interference are concerned. Receiving sets are now so well designed that other sources of interference can be tuned out.

Piezo Oscillators

The advent of the piezo oscillator has met the needs of the situation in part. The device is a readily available standard, in terms of which frequencies may be measured to any desired precision (in the sense of fineness of adjustment). The *accuracy* with which frequencies may be thus made available is the subject to which this discussion is mainly devoted. Since piezo oscillators may be used for frequency comparison with practically unlimited precision, the question of their accuracy depends essentially on their constancy, and on the accuracy and constancy of the basic standards in terms of which they are standardized.

When the piezo oscillator was introduced, two or three years ago, it was quite commonly thought that it was an invariable standard of frequency. It has, however, been found that there are a number of factors which introduce variations in the frequency of the electromotive force produced by a vibrating quartz plate, and also in the frequency of response of a piezo resonator. These factors are the temperature, the particular method and details of the mounting of the quartz plate, the circuit constants of the associated circuits, and the methods of coupling between the circuit in which the quartz plate is inserted and the necessary auxiliary and measuring circuits. It is not true that highly accurate comparisons can be made by sending a quartz plate in the mail from one laboratory to another. The effects of the circuit constants may vary the frequency produced by a piezo oscillator several parts in 1000, and therefore a complete piezo oscillator must be sent for accurate comparisons. If it is desired to make measurements to as great an accuracy as one part in 10,000, it is necessary that the voltages used in the piezo oscillator be carefully measured and that the circuit arrangements and voltages be always the same in use as under the conditions of original calibration. This has been proved by special experimental trials of the effects of different circuit details on the frequency, by theoretical studies, and by the results of actual trial in practice. To carry the accuracy still further, to one part in 100,000, it is necessary not only to control carefully the circuit constants but also to keep the quartz plate at constant temperature.

Constancy and Accuracy of Standards

In order to secure maximum coherence of the results of frequency measurements, and minimum interference between stations adjusted thereby, it is necessary that all measurements be made in terms of the same primary standard, provided that standard has the two requisite properties, accuracy and constancy. Of these two, constancy is by far the more important, since the outstanding need is that the results of frequency measurements agree with one another, regardless of where or when made. If all should be 0.1 per cent different from the actual absolute value there would be no serious practical consequences. but if different laboratories or stations should have standards differing by 0.1 per cent there would be hopeless confusion and interference. This is not to say that absolute accuracy of the primary standard is unimportant; the highest accuracy must be sought, but this is less urgent than the maintenance of a standard of high constancy.

The official primary standard for the United States is that maintained by the Bureau of Standards. During the past four years the Bureau has steadily improved the constancy and accuracy of this standard by continuous research. In order to have a primary standard adequate to the present and the immediate future, the Bureau determined last year to establish and maintain a standard which should be constant to one part in 100,000, or 0.001 per cent. Such accuracy is difficult to attain in almost any line of physical measurement. The work is being carried on with the cooperation of other Government Departments and the various commercial organizations which have had experience in establishing frequency standards or constructing piezo oscillators of great constancy. Four organizations (the General Electric Company, Westinghouse Company, Navy

Department, and Bureau of Standards) have constructed temperature-controlled piezo oscillators which are intercompared and kept under observation at the Bureau. These are also compared against other standards of the Bureau, including quartz plates, tuning forks, and a special frequency meter. Absolute measurements of their frequencies, against time standards, are made by three organizations, the Navy Department, Bell Telephone Laboratories, and the Bureau of Standards.

The absolute measurement of frequency is a most interesting subject, but in this paper I will only be able to mention it briefly. Since frequency is the reciprocal of time, an absolute frequency measurement is a comparison against a standard of time. Ideally, this should be made as directly as possible against the primary time standard, the rotating earth. In practice, measurements are made against a standard clock, permitting frequency measurements in terms of the mean solar second. The measurements are usually made with the aid of an intermediate device (tuning fork, alternator, or oscillator) which produces an audio frequency, this being measured in terms of the clock. The comparison between the audio frequency and the radio frequency of the standard under measurement is made by a step-up process, such as the use of a harmonic amplifier[1] or cathode-ray oscillographs[2].

The measurement may be made even more directly in terms of the time standard by methods which have recently been worked out to eliminate the intermediate audio-frequency device. Such methods have been devised by the National Physical Laboratory in England, the Naval Electrotechnical Institute in Italy, and by the Bell Telephone Laboratories[3] in the U. S.

International Frequency Comparisons

Since both high- and low-frequency signals can be received over large portions of the world, it is of the greatest urgency not

[1] Frequency Measurement in Electrical Communication.—Horton, Ricker, and Marrison. *Trans.* A.I.E.E., **42**, p. 730; 1923.

A Self-Contained Standard Harmonic Wavemeter.—D. W. Dye. *Phil. Trans.*, Roy. Soc. London, **224**, p. 259; 1924.

Establishment of Radio Standards of Frequency by the Use of a Harmonic Amplifier.—Jolliffe and Hazen. Bureau of Standards Scientific Paper No. 530. 1926.

[2] Primary Radio-Frequency Standardization by Use of the Cathode-Ray Oscillograph.—Hazen and Kenyon. Bureau of Standards Scientific Paper No. 489, 1924.

[3] Precision Determination of Frequency. Horton and Marrison. Proc. I.R.E., **16**, p. 137; February, 1928.

merely that all U. S. radio be on a single frequency basis, but that this be true of the whole world. The international aspect of this is being cared for by the national standardizing laboratories of the various nations through intercomparisons of frequency standards. The Bureau of Standards has been particularly active in initiating and directing this work.

International comparisons of any physical quantity can be made by sending the standards of that quantity successively to the laboratories of the different nations. In the frequency comparisons that method has been followed with one exception. About five years ago it appeared that greater accuracy might possibly be obtained by another method, namely, the simultaneous measurement in the various laboratories of the frequencies of waves transmitted from stations of sufficient power to be received simultaneously in many nations. In 1924 such a set of comparisons was organized by the Bureau of Standards and measurements were made in the national laboratories of England, France, Italy, Germany, and the United States. The results of such comparisons extending over a number of weeks were only fairly satisfactory. The accuracy of measurement was not as good as had been hoped. The result, briefly, was to show an agreement between the various countries within about two parts in 1000. The methods used, and independent evidence of various kinds, were such that it was certain that the standards used in each of these countries were more accurate than this. The observed differences were therefore due in large part to the methods of measurement.

From the foregoing experience it was concluded that the more common method (actual transportation of standards from one laboratory to another) used in connection with other physical quantities should be considered anew. Just at that time, about four years ago, enough had been learned of the possibilities of piezo oscillators and piezo resonators to make it appear that they offered particular advantages as portable standards. Measurements upon piezo-electric devices therefore offered a method which might be superior to the scheme of measuring simultaneously the frequencies of transmitted waves. The first attempt of this kind was an informal series of measurements made in several national laboratories by W. G. Cady, Professor at Wesleyan University, Middletown, Connecticut. He took a number of piezo resonators (not oscillators) abroad; the results

TABLE I

PIEZO OSCILLATOR B. S. 33465-D WITH QUARTZ PLATE NO. 15

Laboratory	Approx. date	Temp-erature deg. C.	Frequency	Minus Mean B.S.	Frequency	Minus Mean B.S.	Frequency	Minus Mean B.S.
Bureau of Standards	Dec. 1925	—	75.30	—	106.24	—	455.40	—
National Physical Laboratory, England	Feb. 1926	17.2	75.344	+0.038%	106.273	+0.031%	455.560	+0.016%
Telegraphie Militaire, France	July 1926	(22)	75.33	+0.020%	106.1	−0.132%	455.7	+0.047%
Istituto Elettrotecnico e Radiotelegrafico, Italy	Sept. 1926	26.5	75.347	+0.042%	106.200	−0.038%	455.474	−0.002%
Physikalisch-Technische Reichsanstalt, Germany	Feb. 1927	20.5	75.331	+0.021%	106.248	+0.008%	455.525	+0.009%
Bureau of Standards	July 1927	24.8	75.33	—	106.24	—	455.57	—
Bureau of Standards	Mean B.S.	(24.8)	75.315		106.240		455.485	

TABLE II

PIEZO OSCILLATOR B. S. 33465-C WITH QUARTZ PLATE NO. 16

Laboratory	Approx. date	Temp-erature deg. C.	Frequency	Minus Mean B.S.	Frequency	Minus Mean B.S.	Frequency	Minus Mean B.S.
Bureau of Standards	May 1926	—	75.037	—	105.870	—	455.833	—
Physikalisch-Technische Reichsanstalt, Germany	Dec. 1926	20.5	75.035	−0.009%	105.879	+0.007%	455.940	+0.023%
Istituto Elettrotecnico e Radiotelegrafico, Italy	Mar. 1927	16.5	75.090	+0.064%	105.952	+0.075%	456.152	+0.069%
Telegraphie Militaire, France	June 1927	(22.)	75.004	−0.051%	—	—	455.940	+0.023%
National Physical Laboratory, England	July 1927	19.3	75.054	+0.016%	105.891	+0.018%	455.930	+0.021%
Bureau of Standards	Dec. 1927	22.6	75.048	—	105.875	—	455.840	—
Bureau of Standards	Mean B.S.	(22.6)	75.042		105.872		455.836	

of his measurements are published in his article, "An International Comparison of Radio Wavelength Standards by Means of Piezo-electric Resonators."[4]

In December, 1925, the Bureau of Standards sent a piezo oscillator to Europe, sending it first to the National Physical Laboratory of England, which was to send it in turn to the laboratory of the Telegraphie Militaire in France, to the Naval Electrotechnical Institute in Italy, to the Physikalisch-Technische Reichsanstalt in Germany, and then to be returned to the Bureau. A second piezo oscillator was sent in July, 1926, in the other direction, i.e., beginning with the Physikalisch-Technische Reichsanstalt. It is to be noted that complete piezo oscillators were sent, not merely the quartz plates.

The measurements upon these two piezo oscillators, on account of the necessary delays in getting from one laboratory to another, were only completed in December, 1927. The results are given in Tables I and II.

These results show that piezo oscillators, even without temperature control, provide a far more dependable method of making international comparisons of frequency standards than simultaneous measurements of station frequencies. The indicated differences between the various laboratories have a maximum of eight parts in 10,000; the net result is to show an agreement by this method which may be summarized as a few parts in 10,000. It was uncertain as a result of this work whether the observed differences were due to variations in the piezo oscillators used as the means of comparison or to actual differences in the basic standards of the different countries.

The same method was used, viz., the sending of piezo oscillators, to make comparisons between the frequency standards of the United States, Canada, and Japan. Early in 1927 a piezo oscillator was sent to Canada, was there measured by the Radio Service of the Department of Marine, then returned and measured again by the Bureau of Standards. The results were of the same order as those obtained in the European comparisons, and were considered by the Canadian administration as giving a comparison of standards to as great an accuracy as their measurements permitted. The Bureau of Standards sent the same piezo oscillator in March, 1927, to Japan. The average of the Japanese values differs from the Bureau of Standards

[4] Proc. I.R.E., 12, p. 805, Dec. 1924.

TABLE III

Piezo Oscillator B. S. 33465-E with Quartz Plate No. 12

Laboratory	Approx. date	Temperature deg. C.	Frequency	Minus B. S.	Frequency	Minus B. S.	Frequency	Minus B. S.
Bureau of Standards	Jan. 1927	—	75.32	—	106.26	—	455.86	—
Radio Service, Canada	Feb. 1927	22	75.27	−0.07%	106.16	−0.09%	455.93	+0.02%
Bureau of Standards	Mar. 1927	23.5	75.32	—	106.26	—	455.86	—
Ministry of Communications, Japan	July 1927	24	75.32	0.00%	106.24	−0.02%	455.85	0.00%

Note.—This piezo oscillator has not yet returned from Japan.

measurements by only one part in 10,000. The detailed results are given in Table III.

Piezo oscillators with temperature control began to be constructed in 1927, and a great increase of the possible accuracy of the comparison of standards of different laboratories was thus presented. As I was going to Europe in the summer of 1927 for the Bureau of Standards, an opportunity was afforded to use one of these instruments for comparisons with the standards of the national laboratories of Europe. It was hoped that by taking this improved instrument to the European laboratories a frequency comparison could be obtained that would surpass the previous ones in accuracy. I accordingly had the pleasure of making frequency measurements, all of which were very satisfactory, at the National Physical Laboratory in London, at the laboratory of the Telegraphie Militaire under General Ferrie in Paris, at the Italian Navy Laboratory in Livorno, Italy, and at the Physikalisch-Technische Reichsanstalt in Berlin. I wish to acknowledge the splendid cooperation given me in each of these laboratories by my collaborators, Dr. D. W. Dye at the National Physical Laboratory, Prof. R. Jouaust in Paris, Prof. G. Vallauri in Livorno, and Dr. E. Giebe at the Reichsanstalt. The measurements were made in July and August.

The frequencies of the piezo oscillator were measured at the Bureau of Standards before I left the United States and again after my return. The instrument contained two quartz plates in a thermostatically-controlled heated enclosure, the quartz plates being kept at a temperature of 46 degrees C. Instruments were provided to insure that filament and plate voltages were always the same. The frequencies of both quartz plates were approximately 200 kilocycles.

It was interesting to find that in all the laboratories the same general method is used for frequency measurements of high precision. Typically, there are three generators placed in the laboratory about ten feet apart; one is the piezo oscillator under measurement, one is the auxiliary oscillator or heterodyne, and the third is the standard instrument against which the piezo oscillator is to be measured. There is coupled to each of these a single circuit which contains a receiving set with telephone receivers connected to it. The method of measurement is in all cases some variation of the simple procedure of listening for the frequency difference between the auxiliary generator and the piezo oscillator, and by one process or another reducing this difference to zero, and then adjusting to equality with the auxiliary generator the standard in terms of which the piezo oscillator is being measured (or else determining the difference between the standard and the auxiliary generator).

TABLE IV

SPECIAL TEMPERATURE-CONTROLLED PIEZO OSCILLATOR WITH QUARTZ PLATES *Y* AND *Z*

Laboratory	Date 1927	*Y*		*Z*	
		Frequency	Minus Mean B.S.	Frequency	Minus Mean B.S.
Bureau of Standards	June 15	200.122	—	200.142	—
National Physical Laboratory, England.	July 14	200.118	0.000%	200.128	−0.006%
Telegraphie Militaire, France	Aug. 4	200.134	+0.008%	200.149	+0.004%
Istituto Elettrotecnico e Radiotelegrafico, Italy.	Aug. 16	200.119	0.000%	200.137	−0.002%
Physikalisch-Technische Reichsanstalt, Germany.	Aug. 31	200.131	+0.006%	200.152	+0.006%
Bureau of Standards	Nov. 16	200.115	—	200.138	—
Bureau of Standards	Mean B.S.	200.118		200.140	

The results, shown in Table IV, justified every hope. The differences between the different laboratories in these measurements ranged from zero to five parts in 100,000, the average of the departures from the mean being three parts in 100,000. This agreement is indeed as good as the degree of certainty of the national standards. It is concluded that by using a portable temperature-controlled piezo oscillator in which the currents through the circuits are always adjusted to the same value, it was possible to get a 10-fold increase of accuracy over that attained with the simpler type of piezo oscillator used in the previous comparisons. This assurance as to the accuracy of the frequency standards available in the larger countries determined the action of the International Radio Conference in October, 1927, on the subject of frequency measurements, as expressed in Article 3 of the General Regulations of the International Radiotelegraph Convention.

The accuracy attained in these comparisons is not by any means the limit attainable. The instrument used in the comparisons was one upon which complete studies had not been made as to temperature equilibrium, frequency lag, and temperature coefficient of the quartz plate. No doubt as time goes on we can improve upon this. On the whole, however, I feel that it has been demonstrated that the several national laboratories are measuring frequencies with an accuracy satisfactorily in advance of the immediate requirements of radio practice. The standards of frequency of the larger countries agree sufficiently well to insure against interference provided the transmitting stations are accurately adjusted according to their national standards.

Applications in Broadcasting and High Frequencies

The developments in the accurate measurement of frequencies have their principal applications in those portions of the radio spectrum where the congestion of radio traffic is greatest, viz., broadcasting and high frequencies. The Federal Radio Commission requires every broadcasting station to operate within 0.5 kilocycle of its licensed frequency. At a frequency of 1500 kilocycles this means that the frequency must be maintained within 0.03 per cent. There were no means commercially available by which this could be done, a year ago. At the present time, using as a station frequency standard a piezo oscillator without temperature control but carefully operated, the requirement can just be met. To be certain of satisfactory operation, a piezo oscillator should be investigated over the range of temperatures at which it will operate, as sudden large changes of frequency with temperature occur in some of them.

The advent of temperature-controlled piezo oscillators opens up new possibilities. It is apparent, from the experience I have recounted, that these instruments can be relied upon, under conditions of practical use, to 0.003 per cent or better. At a frequency of 1000 kilocycles, this corresponds to a constancy of 30 cycles or better. In other words, two or more broadcasting stations using these devices could operate on the same frequency and remain synchronized so closely that there would be no audible beat note between their carrier frequencies. This is the only practical possibility at present available for eliminating heterodyne interference. Use of this plan may offer a way out of the hitherto insoluble problem of too many broadcasting stations. It is not an easily operated plan; it requires great care in operation of the piezo oscillators at all stations; but it seems to me at present the most practical of the various theoretically possible plans.

The increase in accuracy of frequency measurements has an application of at least equal importance in the use of very high fequencies. Since 0.03 per cent is about the limit of dependability of piezo oscillators without temperature control, it is not feasible at the present time to use narrower channels than 0.1 per cent. To illustrate, successive channels can be 10 000, 10 010, 10 020 kilocycles, etc. With a commercially available piezo oscillator used as a station frequency standard, the second of these channels could be reliably held within 10 007 and 10 013 kilocycles. Greater deviation than this would bring the transmission dangerously near the adjacent channels and cause interference. Thus, assuming the use of the best commercially available equipment and great care in the operation of stations, high-frequency channels cannot be spaced closer than 0.1 per cent at the present time.

More stations can be operated on the high-frequency waves almost in proportion to the increase in accuracy of the frequency control of transmitting stations. While it is true that there are other factors influencing the width of channel, e.g., selectivity of receiving sets, nevertheless for CW work it is likely that the channel width could be narrowed to something like 0.01 per cent if first-class temperature-controlled piezo oscillators, or apparatus of equivalent accuracy, were universally used in high-frequency stations. To illustrate again, at 10 000 kilocycles the channels would be 1 kilocycle apart, and the frequency of each would be maintained within 300 cycles. CW receiving sets can readily distinguish traffic with the minimum separation provided under such operation. For the whole frequency spectrum above 2000 kilocycles, this would mean that, in place of some 2000 CW station assignments possible under present conditions, about 20 000 could be accommodated.

Discussions

Henry Shore†: As Dr. Dellinger has pointed out, the second is the logical basis of our frequency measurement and standardization. Since this is so, it seems to me that any frequency standard should be directly and intimately related to the basis. Thus the frequency standard should be controlled by the clock or pendulum. A method of accomplishing this has been suggested by Dr. V. Bush of Massachusetts Institute of Technology.

The method consists of series of multivibrators interlocked and controlled by impulses from the standard time piece, the

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first multivibrator having a fundamental period of 2 cycles per second. The second multivibrator has a period of 40 cycles per second, the third a period of 1600 cycles per second and so on up the frequency spectrum. The clock impulses, furnished say by means of photocell, simply serve to maintain the fundamental frequency constant and do not drive the multivibrator units.

For a more detailed description of the multivibrator the excellent paper of J. K. Clapp, "Universal Frequency Standardization from a Single Frequency Standard," *Journal* Optical Society of America, **15,** No. 1, July, 1927, should be consulted.

G. W. Kenrick‡: Dr. Dellinger, in his interesting paper, has directed attention to the importance of the frequency standardization of broadcasting stations and suggested the use of standardized crystals at the stations to insure the constancy of the emitted frequency. I would like to direct attention to another possibility which suggests itself for holding these frequencies at such values as to insure suitable separations.

According to this plan as many stations as necessary would be established as standardization stations to transmit, on a radio channel, a standard frequency preferably equal to the desired frequency separation of the broadcasting stations or some exact sub-multiple thereof (let us say 10 kc. for example). These signals could now be received at the various broadcasting stations; and, after demodulation, passed through sufficient stages of frequency multiplication to bring them into correspondence with the given broadcasting station's assigned frequency. Such frequency multipliers utilizing accentuated harmonics in vacuum-tube circuits and resonance phenomena are, of course, quite well-known to the present stage of the art. Prime harmonics, not readily obtainable by several stages of successive multiplication alone, are readily available by the introduction of sum and difference frequencies produced by the modulation of the output of the higher multiplier stages by that of the lower stages or the fundamental.

It will be noted that this method of standardization has the advantage that the requisite frequency separations are secured independently of the precision of the 10 kc. standard which, however, is a single standard and hence readily producible with a high degree of precision and constancy at some central point,

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such as the Bureau of Standards. In my opinion this method has a distinct advantage over the use of a large number of independently calibrated crystals maintained at broadcasting stations under conditions necessarily less rigorous than those to which a central standard could be subjected. It will be noted that a minute injury or disturbance in any of these secondary crystal standards will correspondingly produce interference, and not infrequent recalibrations would hence be desirable.

The production of suitable frequency multiplying sets for use in the method here described, particularly in the considerable quantity necessary for the equipment of all broadcasting stations, would seemingly be readily practicable at a per unit cost inconsequential in comparison to the total investment in even a small modern station. It will be particularly noted that, once adjusted to the proper harmonic, the standardization at each station (by dead beat methods) may be obtained without further adjustment of the apparatus and will be essentially independent of local conditions.

J. H. Dellinger: The work mentioned by Mr. Shore is an interesting addition to the work I mentioned on direct comparisons of radio frequencies with a time standard. I judge that the method is the one developed by the National Physical Laboratory. The use of multivibrators is not a good feature, as they are inferior to the harmonic amplifier.

The method Mr. Kenrick mentioned of holding broadcasting station frequencies on the licensed values is theoretically correct. However, outside of the difficulty of distributing the basic frequency to all stations, the most serious objection to the method is the requirement that every broadcasting station use a harmonic amplifier to compare its frequency with the lower frequency standard. This would introduce a complicated apparatus of laboratory type into every station; it is very unlikely that the station personnel would in all cases be competent to secure the desired results.