Some Developments in Common Frequency Broadcasting *

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This paper describes the results of the simultaneous operation of radio stations WHO and WOC broadcasting the same program on a common frequency using independent crystal controlled oscillators. These stations had previously been compelled to share time on 1000 kc and each is now able to render full time service.

The exceptional stability of the crystal controlled oscillators used at each station is described. Since even these oscillators require occasional readjustment to maintain them in isochronism, a monitoring receiver was established midway between the stations and the resultant program is sent back by wire line to WOC to provide an indication for readjusting its frequency to exact isochronism with WHO. An audio oscillator used to modulate the carriers in the monitoring receiver provides a tone independent of the program for the guidance of the operator. Curves are presented showing the quality impairment caused by different degrees of isochronism and signal strength ratios.

The improvement in distant reception with simultaneous operation is reported and an explanation given. The impaired reception in the area midway between the stations and outside their normal service range is shown to be a function of the degree of modulation of each transmitter, of the field strength ratio and of the audio phase angle and independent of the carrier phase at the transmitters. It is pointed out that reception equal to that from either station alone may still be obtained in this area by the use of a simple directive antenna.

The marked increase in the service rendered by these stations through simultaneous operation is indicative of the improved service that can be rendered to urban areas by common frequency broadcasting. Although it is probable that the high powered station on a cleared channel will remain the best means of affording a high-grade service to a metropolitan area while also rendering an acceptable service to large rural areas, common frequency broadcasting now appears to offer definite means by which to provide an improved coverage to a number of noncontiguous communities.

THE development of chain broadcasting and the congestion in the broadcast frequency range has naturally led to a consideration of the possibilities of operating a group of stations on a single frequency.[1,2] The possible usefulness of such a system has resulted in a number of attempts to secure the additional coverage offered by the simultaneous operation of two or more stations broadcasting the same program on a common frequency. This problem has been attacked in two different ways.

* Presented at Sixth Annual Convention of I. R. E., June 4–6, 1931. Published in Proc. I. R. E., 19, 1347–1369; August, 1931.

[1] DeLoss K. Martin, Glenn D. Gillett, and Isabel S. Bemis, "Some Possibilities and Limitations in Common Frequency Broadcasting," *Proc. I. R. E.*, **15**, 213–223; March, 1927.

[2] Charles B. Aiken, "The Detection of Two Modulated Waves which Differ Slightly in Carrier Frequency," Proc. I. R. E., January, 1931; B. S. T. J., January, 1931.

In one case, a control frequency has been transmitted either by wire line or radio to each station and a frequency multiplier used to develop directly the carrier frequency which was to be transmitted from the station. This method has met with some success both here and abroad. It was used in this country for the commercial operation of WBZ-WBZA [3] and in Germany the Postal authorities have operated several stations experimentally with equipment developed by the Telefunken G.m.b.H. and the C. Lorenz A.G.[4,5] Both the WBZ-WBZA and the Telefunken systems used a high control frequency which was particularly suitable for transmission over open wire lines while the Lorenz system used a lower control frequency which was suitable for transmission over cable circuits as well. Three stations located at Berlin, Stettin, and Madgeburg, respectively, are now in commercial operation on a common frequency using control equipment manufactured by the Lorenz firm.[6] In Sweden the postal authorities have developed a similar system of frequency control capable of using either a high or low standard frequency interchangeably. This system was used in placing the broadcast stations at Malmo and Halsingborg in commercial operation on a common frequency in the latter part of 1929.[7] Intensive development work on similar systems is under way in the United States. The National Broadcasting Company has in operation in its network, two groups of two stations each, which are being operated synchronously using a standard reference frequency transmitted between stations over telephone circuits. The Bell System has developed a common frequency broadcast system using a standard reference frequency suitable for transmission over telephone circuits. This system has been given a practical test in coöperation with the Columbia Broadcasting System. It will shortly be commercially available.

The other method of attack has been to derive the carrier frequency at each station from an independent oscillator. In England,[8,9] electrically driven tuning forks have been used to supply an audio frequency of high stability from which the carrier frequency has been derived by means of frequency multipliers. With this equipment it has been possible to maintain the derived carrier within a few cycles per second of

[3] Frank B. Falknor, "A History of Synchronization," *Citizens Radio Call Book Magazine and Technical Review*, **12**, 38–40; March, 1931.
[4] W. Hahn, *Funk*, **35**, 247–248, 1928.
[5] W. Hahn, *Die Sendung*, **5**, 430–432, 1928.
[6] F. Gerth, "A German Common Frequency Broadcasting System," *Proc. I. R. E.*, **18**, 510–512; March, 1930.
[7] Erik Esting, *Elektroteknik*, pp. 109–112, June 7, 1930.
[8] P. P. Eckersley, "The Operation of Several Broadcasting Stations on the Same Wave-length," *Jour. I. E. E.*, 1929.
[9] P. P. Eckersley, "The Simultaneous Operation of Different Broadcast Stations on the Same Channel," *Proc. I. R. E.*, **19**, 175–194; February, 1931.

isochronism [10] and this has been sufficient to permit a satisfactory service to be rendered to the territories immediately adjacent to each station. As will be shown in detail later there is a substantial difference between the service range of a station operating in almost perfect isochronism with the other stations in the common frequency broadcast system and that of a station which is more than a small fraction of a cycle per second out of isochronism. In this country "matched crystals" and other means of independent frequency control have been tried but the frequency stability of the best equipment available in the past has fallen far short of that required for the satisfactory operation of the stations on a common frequency.

In the spring of 1930 the Central Broadcasting Company of Iowa found itself in the possession of a concrete example of the need for the simultaneous operation of two stations on a common frequency in that its stations WHO and WOC were compelled to divide time equally on 1000 kc. so that the Davenport and Des Moines areas each received service from its local station but half the time. These stations are 153 miles apart and either could be depended upon to render a high-grade service only within a radius of about fifty miles of the station. It was felt that with the simultaneous operation of both stations, each of these areas would receive full time service from its local station.

The Central Broadcasting Company presented its problem and asked for equipment capable of maintaining the carriers of these two stations within the limits of isochronism required for their simultaneous operation. Bell Telephone Laboratories therefore undertook the necessary development work.

The degree of isochronism required for the various conditions existing under the different types of common frequency broadcast systems is in fact a fundamental question that must be answered before any logical delineation of the problem can be attempted. Unfortunately there exists no similar condition in ordinary human experience from which a valid analogy can be drawn, so that the *a priori* assumptions which have been used in the preliminary theoretical discussions of the various phases of this problem have of necessity been based primarily upon personal opinion and the resultant conclusions have quite naturally varied between extremely wide limits.

The problem had been studied intensively during the preliminary field tests of common frequency broadcasting which were made in the fall of 1929 in coöperation with the Columbia Broadcasting System us-

[10] The term "isochronous" has been used instead of "synchronous" in order to exclude the concept of identity of phase which is usually included in the meaning of the latter together with the meaning of identity of frequency which is common to both words.

ing stations WABC and WCAU. It proved to be very difficult to get accurate and consistent data from such field observations without a very extensive series of tests because the fortuitous variations in the transmission medium continually altered the test conditions. These were especially troublesome since the frequency difference between the carriers is but one of the two independent variables of primary importance which affect the quality of the program received at any given point, the other being the ratio of field strength received from the two stations at the point in question.

It was therefore necessary to set up in the laboratory apparatus which would simulate as closely as possible the conditions existing in the field but with all the variables under definite control Two identical miniature transmitters were modulated by the same program. The modulated carriers were then attenuated through independent transmission paths and received by a high-quality detector. The layout of the apparatus is shown schematically in the block diagram of Fig. 1.

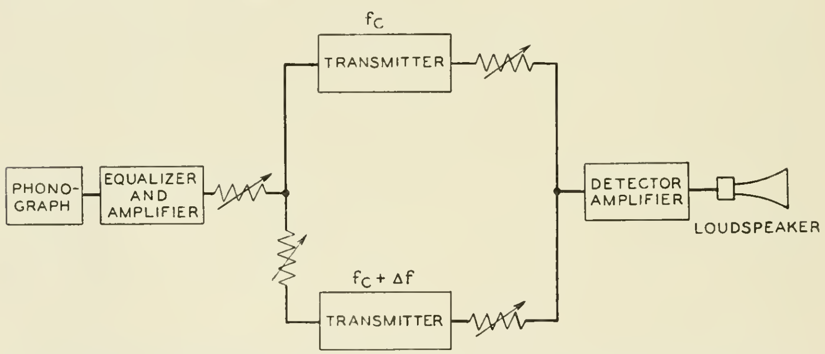

Fig. 1—Block diagram of apparatus set-up for determinations of quality impairment with different degrees of isochronism and field strength ratios.

It will be seen that with this equipment the signal strength received at the detector from either station may be varied independently so that any desired signal strength ratio may be obtained. The frequency difference, Δf, was fixed directly by the adjustment of the carrier frequencies of the two transmitters to the required degree of isochronism. These transmitters, operating at a frequency of approximately 50 kc. were quite stable and capable of accurate adjustment.

The over-all audio-frequency transmission characteristic of the whole system was even better than is available in the better commercial radio receivers. The observers were engineers well acquainted with the effects to be expected and whose judgment was extremely critical. Tests were made with material consisting of both musical and talking programs and, while the effects are more noticeable with musical programs due to the presence of sustained tones, the difference was not marked. The observers compared the quality of the program received from the two stations with varying field strength ratios and degrees of carrier isochronism with that received from one of the stations transmitting alone. The change from the test condition to the reference condition could be made at will and the gains of the various circuit elements were adjusted so that the apparent program level was the same under the two conditions. Each test covered a considerable period of time and the curves shown in Fig. 2 mark the field strength ratios at

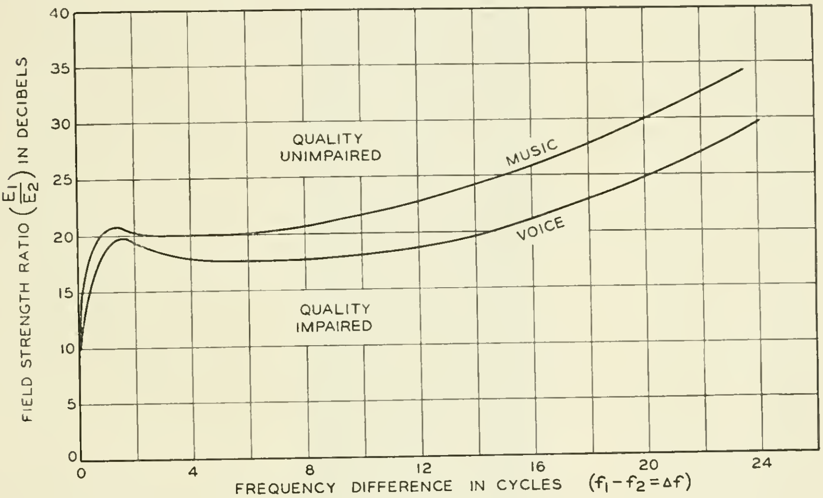

Fig. 2—Quality impairment vs. the frequency difference f_1-f_2 and field strength ratio E_1/E_2. The curves mark points where the quality impairment was just perceptible.

which the observers could not distinguish between the test and reference conditions. The data shown are therefore believed to be distinctly conservative and to represent a criterion much more severe than any which will be encountered in commercial operation. These results are also in agreement with the experimental data that were obtained from our field tests and also check closely the data obtained by the engineers of the British Broadcasting Company in similar field tests in England.

It will be noted that when the frequency difference is very small, closely approaching isochronism, unimpaired reception is assured provided the field strength ratio is at least 10 db but that as soon as the frequency difference is at all appreciable the required field strength ratio for ordinary programs rises sharply to about 20 db and is approximately constant within the range from 1 to 10 cycles per second.

Our field strength distribution surveys and studies have shown that, for 5-kw stations separated by two or three hundred miles, a field strength ratio of 20 db is obtained only at points well within the normal service area of the station. On the other hand the limits of the 10-db ratio lie for the most part outside the normal service range of the station. Thus if such a station is to be operated on a common frequency chain, the carriers must be maintained approximately in isochronism if a large portion of the listeners within the normal service range of the station are not to receive a seriously impaired program. If approximate isochronism is maintained, the service area of each of these stations should not differ materially from that which selective fading and interference would establish for that station transmitting alone.

In order to maintain unimpaired reception in the region where the field strength ratio is between 10 and 20 db, it is necessary that the stations be operated so that their carriers are not permitted to differ in frequency by more than one cycle in 10 seconds and this demands a frequency stability of an entirely new order of magnitude for commercially available independent oscillators. However, at the time that this development was undertaken for the Central Broadcasting Company, previous tests had shown that a newly developed crystal controlled oscillator unit designated as the No. D-90684 oscillator-amplifier possessed an exceptional frequency stability for commercial equipment and that minor modifications would give it the stability required for the simultaneous operation of a small group of stations on a common frequency.

It was therefore planned to replace the existing crystal control equipment by one of these new units located at each station and supplemented by a monitoring receiver located midway between the transmitters.

The No. D-90684 oscillator-amplifier is a relay rack mounted assembly consisting of a shielded unit containing a constant temperature oven and a crystal oscillator, an amplifier having a maximum power output of thirty watts, and the necessary power control equipment. The amplifier tubes, instruments, and controls are mounted on the front of the panels as is shown in Fig. 3 and all other apparatus is mounted in the back and enclosed by a metal locker. The assembly of the various components inside the locker is shown in Fig. 4. The power equipment is placed in the lower part, the constant temperature oven and crystal oscillator unit is mounted on slides in the middle compartment, while the upper shielded section isolates the buffer and output stages from the rest of the transmitter. The door of the locker is fitted with safety switches which automatically disconnect all high voltages from the equipment before the door can be opened. It was a simple matter to install one of these compact self-contained units adjacent to each transmitter to replace the existing crystal control equipment as the source of the carrier frequency. A corner of the operating room at station WOC is shown in Fig. 5, with a part of the radio transmitter at the extreme right and the oscillator-amplifier mounted adjacent to it. The author is holding the crystal oscillator and constant temperature oven, and over his head to the left is the loud speaker through which the program from the monitoring point is received.

Fig. 3—Front view of crystal controlled oscillator-amplifier unit.

The extraordinary frequency stability of these units has not been obtained through any radical change in design but has come rather as a result of the refinement of all the component elements to form a coördinated unit. A clamped crystal has been used in an improved type of holder, designed to maintain a constant pressure on the crystal and at the same time to prevent any lateral movement which would cause a change in the crystal frequency. The crystal and its holder are mounted in an oven fitted with an improved thermostat capable of maintaining the temperature of the crystal constant within extremely narrow limits. This constant temperature oven is built as an integral part of the oscillator, which has been designed to work the crystal under the conditions of optimum stability.

The oscillator and crystal are carefully shielded and isolated from the output stage by several buffer stages in order to prevent any change in the load conditions from being reflected back to the oscillator and thereby changing its frequency. Careful tests in the laboratory have shown that the output power could be varied from zero to full load without affecting the frequency within the limits of observation, which

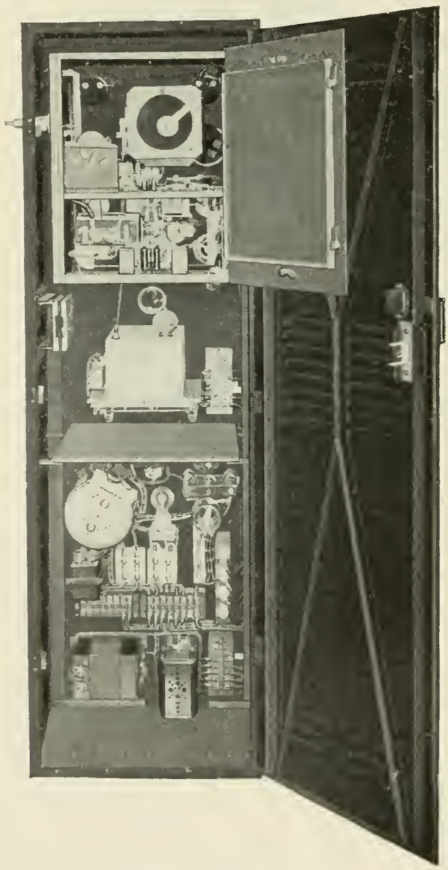

Fig. 4—Rear view showing interior of oscillator-amplifier unit.

were about one part in a hundred million. It is relatively insensitive to changes in filament current, though this is maintained constant within narrow limits by a ballast lamp. Since a change of one per cent

Fig. 5—A corner of the operating room at station WOC.

in the plate voltage causes an immediate change in the frequency of about one part in fifteen million and an ultimate change of about one part in two million, the crystal oscillator is now being operated from batteries.

Since even with these oscillators absolute isochronimc sannot be maintained indefinitely without readjustment, WHO was chosen as the reference frequency station and WOC was provided with means by which its carrier frequency could be brought into exact isochronism with that of WHO. In order that the operator of WOC could easily determine the degree of isochronism, a monitoring receiver was set up at a point midway between the stations and the program received there was transmitted back to station WOC by wire line. A departure of the two stations from isochronism is shown by a slow variation in the level of the program received and the operator can then make the adjustment necessary to restore the stations to isochronism. The nicety of this adjustment can best be appreciated by the fact that a complete revolution of the control dial varies the carrier frequency at WOC by but one part in a million.

It was found difficult at times to determine the beat frequency resulting from a lack of isochronism on account of the masking effect of the rhythm or beat of a musical program. The receiver was therefore equipped with a small audio-frequency oscillator which was arranged to modulate completely the incoming carriers received from the two stations. These combined modulated carriers are detected in the usual way and the output from the receiver is then an audio tone, the level of which is directly proportional to the resultant of the combined carriers. This tone overrides the program and is transmitted back to the station where even very slow changes in its level are easily detected by the operator. This also has the advantage that the degree of isochronism can be determined before any program is broadcast and that any necessary readjustment to restore isochronism can be made during silent periods in the program. This tone is required only at the time of adjustment, and relays at the monitoring point have been arranged for remote control from station WOC by which the audio oscillator can be turned on whenever desired. These relays also permit the operation of either of two receivers and permit the setting of the gain of either receiver at the proper level for day- or nighttime reception. The control panel at the station, shown in Fig. 6, is equipped with supervisory signal lamps which indicate the position of these relays.

The equipment at the monitoring point, shown in Figs. 7 and 8, is mounted on a single relay rack and includes the loop antenna which has been made sufficiently unidirectional to permit the obtaining of an exact balance between the signal strengths received from the two stations. The two radio receivers with their associated audio oscillators and the relay control panel complete the equipment at the monitoring point. The rack is arranged for the complete enclosure of all the equipment by means of dustproof can covers which also serve to prevent any accidental disturbance of the settings and adjustments.

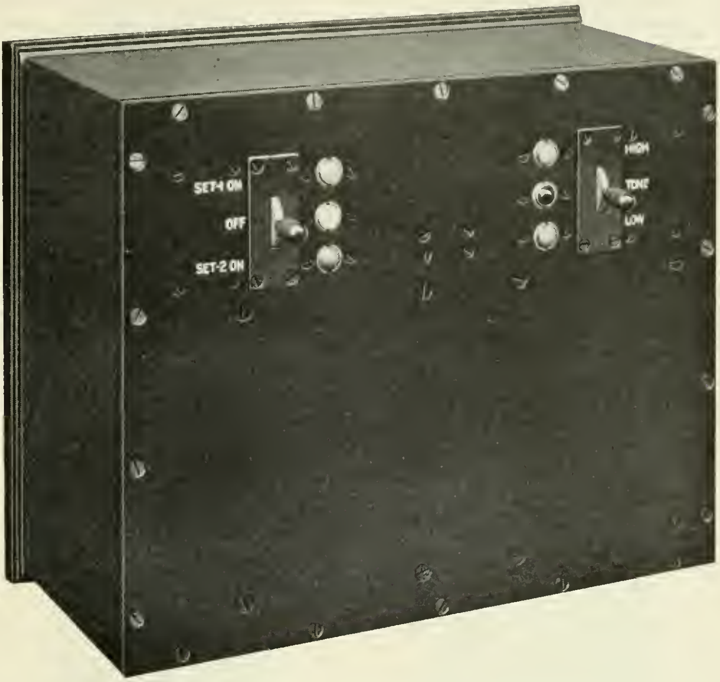

Fig. 6—Control panel for remote control of the monitoring point receivers.

With this equipment in commercial operation, a checking of the frequency every ten minutes in connection with the regular routine inspection of the transmitter has been sufficient to maintain the carriers within an average of two cycles per minute of absolute isochronism. Departures from isochronism of this order of magnitude are not detectable within the normal service area of either station.

While with an installation of this type one is primarily concerned with frequency stability rather than permanence of calibration, the Laboratories have measured the frequency of these stations periodically. It was found at the time of the installation, after the reassembly of the equipment subsequent to its shipment from New York, that the frequency was about two cycles per second different from that measured before shipment. Measurements since that time have shown that the frequency has varied over a period of time between seven cycles above the assigned frequency and seventeen cycles below it. It is known, however, that these variations were primarily due to the

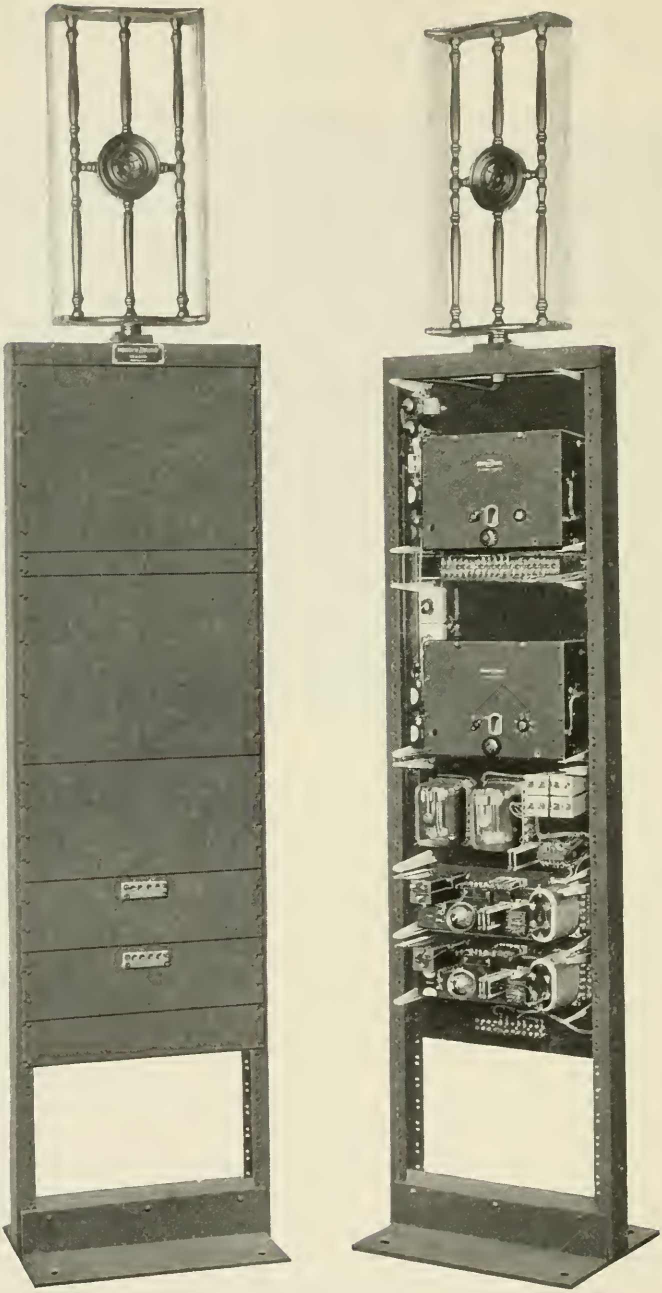

Fig. 7—Remote controlled monitoring point receivers.

Fig. 8—Can covers removed from rear of monitoring point receivers to show the location of the receivers and remote control relays.

variations in plate voltage at WHO, which were permitted in the interest of economy, since the ensuing variations of the two carriers were still far within the requirements of the Federal Radio Commission.

More recent measurements made on a similar unit installed in a broadcast station where precautions have been taken to insure the application of a constant plate voltage to the oscillator have shown a frequency variation of less than five cycles per second from the assigned value over a period of several weeks.

Before approval was sought from the Federal Radio Commission for the full time simultaneous operation of these stations on a common frequency, careful surveys of the areas served were made by the engineers of the Federal Radio Commission, the Department of Commerce, the Central Broadcasting Company, and Bell Telephone Laboratories during their simultaneous operation on an experimental basis during the early morning hours in order to determine the nature of the service being rendered. Nearly three thousand miles were covered by the radio test cars during these tests. Upon completion of these surveys the Federal Radio Commission immediately granted permission for the simultaneous operation of WHO and WOC during regular broadcast hours.

These surveys showed that the service rendered by the simultaneous operation of these two stations was substantially twice as great as the service given on a shared time basis. The normal service area of each station was maintained and the nighttime reception at points over a hundred miles distant from either station was improved by the partial elimination of rapid and selective fading as well as by an increase in the average field strength received.

This improvement in distant reception was confirmed by the letters received in response to requests, made during the tests, for reports as to the quality of reception. In making these requests, the nature of the distortion that might be experienced was carefully described and it was especially emphasized that mere reports of reception would be of no value and that the information desired concerned the quality of the program received during the simultaneous operation of the stations as compared to that from either one alone. Several hundred replies were received from outside the State of Iowa beyond the normal service range of either station. These were almost unanimous in reporting better reception with simultaneous operation. The reports received from distant points during the first year's commercial operation are in full accord with these test data. This improvement apparently occurs wherever marked selective and general fading is experienced in the reception of either station alone.

It has been generally accepted that fading, commonly experienced in the nighttime reception of programs from a distant station, is due to the arrival of the signals along at least two different paths. In the mathematical analysis of this problem it will be convenient to represent each portion of the carrier which arrives at the receiving point via an independent path as a vector of constant amplitude and random phase variation. It will then be possible to represent the fading signal received from a single station as the sum of at least two such vectors. It is then logical to assume that the signal received from two distant stations operating on approximately the same frequency is the summation of at least four of these vectors of constant amplitude and random phase relation. This assumption of random phase relation is valid for any of the common frequency broadcast systems now being developed commercially either here or abroad. If the carriers are derived directly from a reference frequency transmitted via wire line circuits to the several stations, the slight phase variations caused by temperature and humidity changes are sufficient to cause the phases of the derived carriers of the different stations to vary in a fortuitous manner. Furthermore, even if the carriers of two stations were held exactly in phase at their respective antennas, or at some point midway between the transmitters, the variations in the path-lengths of the waves arriving at any given distant point would be sufficient to cause a random phase variation. It is helpful in the mathematical analysis to assume also that these vectors are of equal amplitude. While this is not strictly true in all cases, our field observations have shown that it is the limit which tends to be approached as the distance from the stations is increased.

With these assumptions it can be shown mathematically [10] that the probability P_2, that the ratio of the sum of two vectors to their absolute sum will be less at any instant than a given value λ, is given exactly by the expression

$$P_2 = \frac{2}{\Pi} \sin^{-1} \lambda.$$

For larger values of "n," the exact expression is difficult to evaluate but a close approximation to the probability P_n for "n" vectors is afforded by the expression given below:

$$P_n = \frac{12n^2 - 6n + 1}{12n} \lambda^2 - \frac{12n^2 - 18n + 13}{24} \lambda^4 + \frac{12n^3 - 36n^2 + 55n}{72} \lambda^6 - \frac{12n^4 - 60n^3 + 155n^2}{288} \lambda^8 + \frac{12n^5 - 90n^4 + 350n^3}{1440} \lambda^{10} - \frac{12n^6 - 126n^5 + 646n^4}{8640} \lambda^{12}$$

[10] See Lord Rayleigh's, "Scientific Papers," Vol. 6 section on "Flights in 1, 2, and 3 Dimensions," and also section on "Random Unit Vibrations."

This probability of the sum of "n" vectors being less than any given percentage of the absolute sum of "n" vectors has been computed by means of these expressions for the cases corresponding to the distant reception of 1, 2, 3, and 5 stations. The results of these computations have been plotted in Fig. 9.

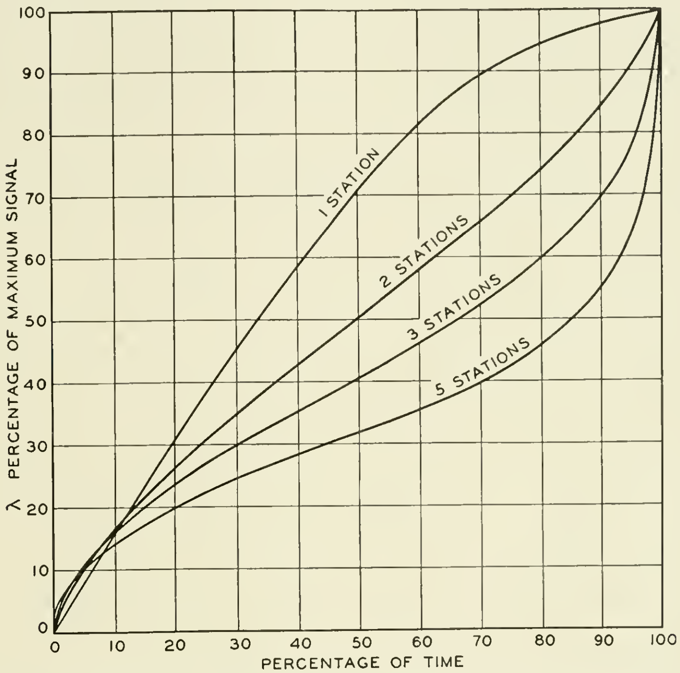

Fig. 9—Curves showing the probability that the instantaneous sum of the signals from a number of distant stations will be less than any given percentage, λ, of their absolute sum.

There are two aspects of these curves which are of especial interest in connection with this problem. First it will be noticed that as the number of stations is increased the percentage of time that the signal fades below a small value such as 5 per cent of its maximum should be decreased. Thus the percentage of time that bad quality will be received due to the elimination of the carrier should be noticeably reduced as the number of stations is increased. Also it will be noted that a rapid reduction in the percentage of time that the signal approaches the maximum should occur as the number of stations is increased. This serves to emphasize the second aspect of the problem, i.e., the level of the signal received should remain near the mean for a much larger percentage of the time as the number of stations is increased. Thus a distant listener can set his receiver so that a normal level should be obtained for a much larger proportion of the time as the number of stations is increased. As an example, let us consider the proportion of the time that the level of the received program should lie between the limits of 25 and 50 per cent of the maximum signal; for one station it should be but 17.5 per cent while for two stations it should be 32.5 per cent, for three 45 per cent, and for five 55 per cent of the total time. A further development of the probability integral given above has shown that not only should the proportion of the time that a normal program is received increase, but that the instantaneous rate of fading should also de-

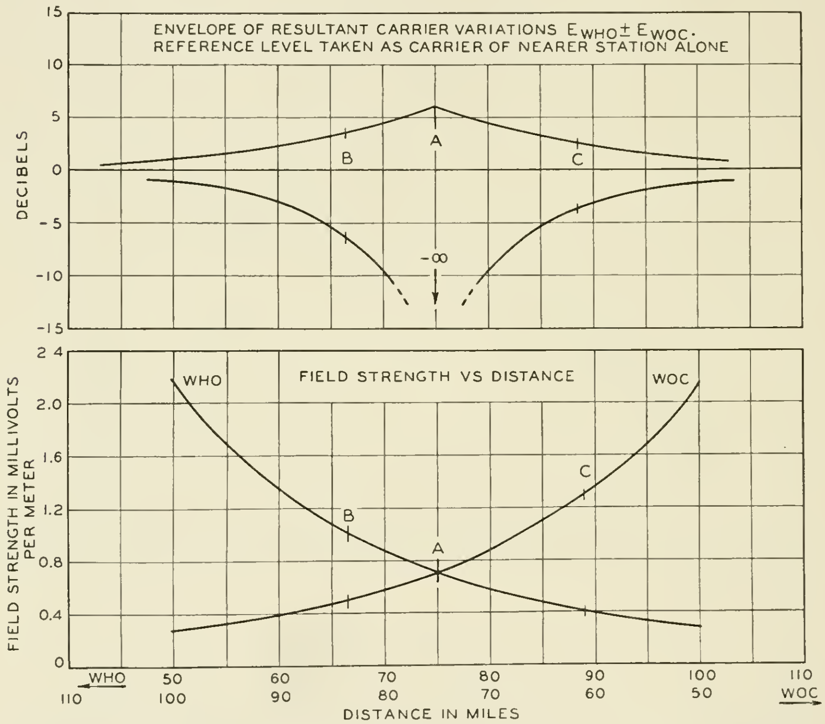

Fig. 10—Smoothed curves of field strength vs. distance for stations WOC and WHO, fc = 1000 kc and the envelope of resultant carrier variations for $E_{WOC} \pm E_{WHO}$.

crease as the number of transmitting stations is increased. This is important because the sensitory reaction to fading, within ordinary limits, apparently depends more upon the rate of change of program level than it does upon the absolute total volume change. Since the same arguments apply equally well to each of the individual frequencies comprising the side bands, it can be seen that the general tendency of increasing the number of isochronously operated stations is to improve markedly the satisfactoriness of the program received at a point distant from all the stations of the chain.

On the other hand in a small area midway between the stations, which received but a mediocre service originally since it lay outside the normal service area of either station, the reception with simultaneous operation was somewhat further impaired. The conditions that exist in this no-man's land between any two stations operating on a common frequency seem worthy of a detailed consideration, especially since wide publicity has been given to the misconception that the maintenance of the carrier in perfect synchronism at the transmitters would entirely eliminate this area of impaired reception. It will be shown below that fundamentally the degree of isochronism merely determines the rate at which alternate strips of bad and good quality reception are swept across this territory. The attainment of exact isochronism would only mean that these strips would tend to be fixed in space and that a certain proportion of the listeners would then receive bad quality all the time instead of getting their share of the good with the bad.

A smoothed curve of the daytime field strengths from WOC and WHO existing in the middle area on a line between the stations is shown in the lower part of Fig. 10.[11] The range of variation that the

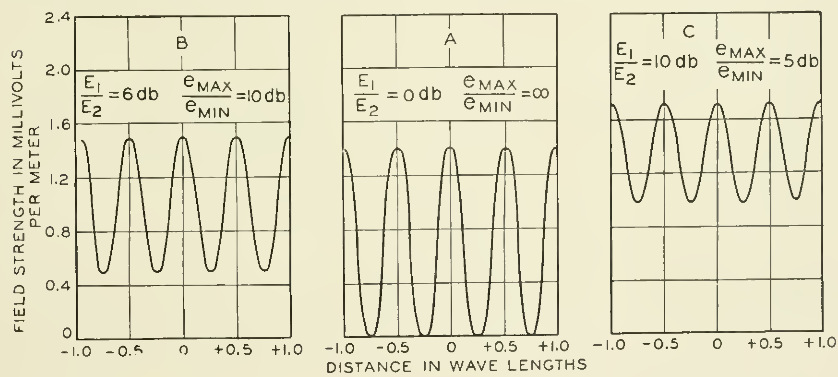

Fig. 11—Enlarged sections of the points *A*, *B*, and *C* of Fig. 10 showing in detail the resultant carrier variations with distance.

resultant carrier level will undergo as the carriers pass in and out of phase is shown in the upper part for the corresponding points along this line. In Fig. 11 enlarged sections showing in detail the variations

[11] These curves are based on field strength measurements made by Radio Inspectors J. M. Sherman and H. T. Gallaher of the Department of Commerce, and furnished through the courtesy of Mr. H. D. Hayes, U. S. Supervisor of Radio, Chicago, Ill.

of the resultant carrier level with distance are given for the point of equal signal strength *A* and for the points *B* and *C* where the field strength ratio is 6 and 10 db, respectively. Any departure from isochronism will have the effect of making these points of maxima and minima move along this line in space at the rate of one-half wave-length per cycle difference in frequency.

Now since the side band frequencies must perforce differ in wavelength from the carrier, they will arrive at any given point out of phase with the carrier, the amount depending on the distance from the transmitter and the side band frequency. Thus the side bands will not for the most part be in phase opposition at the same points in space as are the carriers, and distortion will result from the elimination of the carrier while strong side band components are present. The magnitude of this distortion is primarily a function of the existing field strength ratio between carriers and, while the distortion occurs for only a small proportion of the fading cycle, it is extremely objectionable where the field strengths approach equality. Here the carrier is almost entirely eliminated momentarily and the resultant program consists mainly of second harmonics and other distortion products.

It is entirely outside the scope of this paper to attempt to present a complete analysis of this problem but an effort has been made to indicate the quantitative results that may be expected by selecting a few typical examples. The signal being detected has been assumed in all cases to consist of the ordinary carrier and double side band transmission. The theoretical work which follows has been based upon the use of a square-law detector as being representative of the majority of the existing receivers. In order to avoid undue complexity the curves have been computed for a single frequency audio signal.

In a square-law detector distortion appears primarily in the form of second harmonics and the ratio of these to the fundamental has been taken as a measure of the distortion present under the varying conditions of reception that may exist in the middle area between the stations. There are so many variables concerned in this problem that it is necessary to hold first one and then another fixed while different aspects of the situation are studied.

The first set of curves, Figs. 12, 13, and 14, shows the conditions which exist at the point directly between and equidistant from the two stations when the audio signal supplied to the two transmitters is exactly synchronized, i.e., the audio phase angle $\beta = 0$. With this variable fixed the curves in each successive figure of the series have been plotted for successively decreasing signal strength ratios in order to show the effect of the varying radio phase angle with different degrees of modulation. It will be seen from these curves that making the modulation of the two carriers equal effects a tremendous reduction in the amount of distortion present in the hollows of the fading cycle that occur when the carriers approach phase opposition, i.e., $\gamma = 180$ degrees. Also it will be seen from a comparison of the family of curves for 100 per cent and 50 per cent modulation ($M_2 = 1$ and $M_2 = 0.5$),

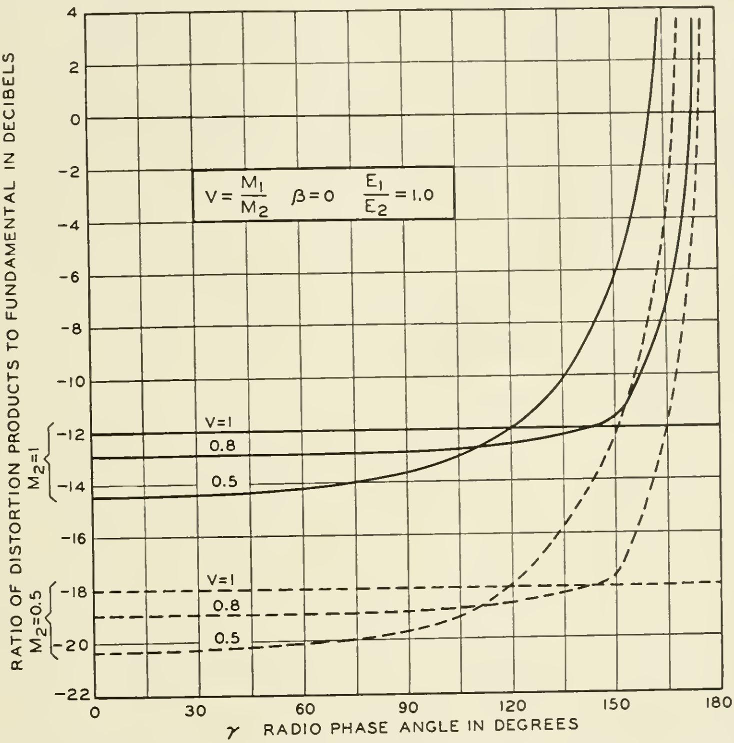

Fig. 12—Ratio of distortion products to fundamental for the point directly between and equidistant from the two stations, with varying carrier phase angle, γ, and different degrees of modulation of the two carriers, ($V = M_1/M_2$), where the audio phase angle $\beta = 0$ and the field strength ratio $E_1/E_2 = 1$.

that a reduction in the degree of modulation of both carriers by 6-db effects an equal reduction in the amount of distortion. Furthermore, a comparison of the curves in the successive figures will show how rapidly the maximum distortion due to the unequal degrees of modulation of the two carriers is reduced as the field strength ratios diverge from unity.

In the second series of curves, Figs. 15, 16, and 17, the effect of varying the carrier phase angle is shown for different representative values of audio phase angle while the degree of modulation of the carriers is fixed and equal and the field strength ratio is given a different

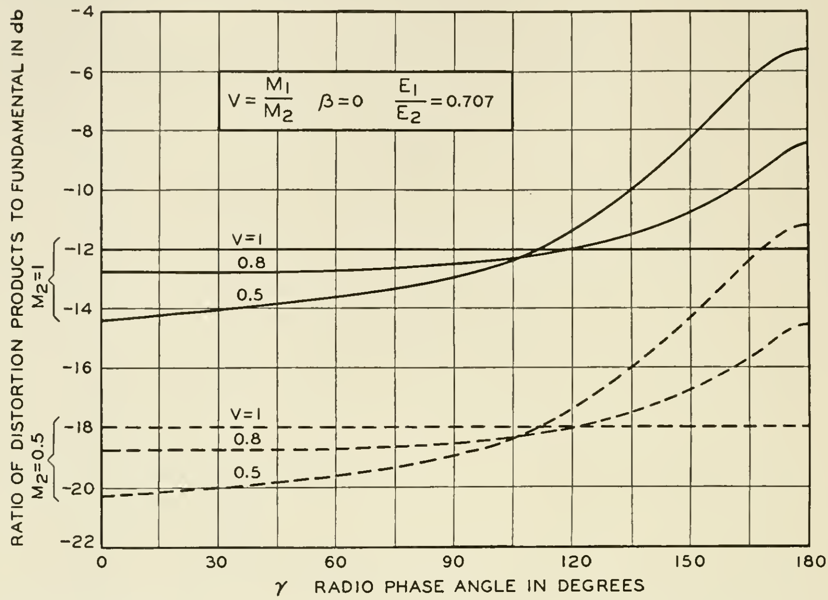

Fig. 13—Same as for Fig. 12 except that the field strength ratio $E_1/E_2 = 0.707$.

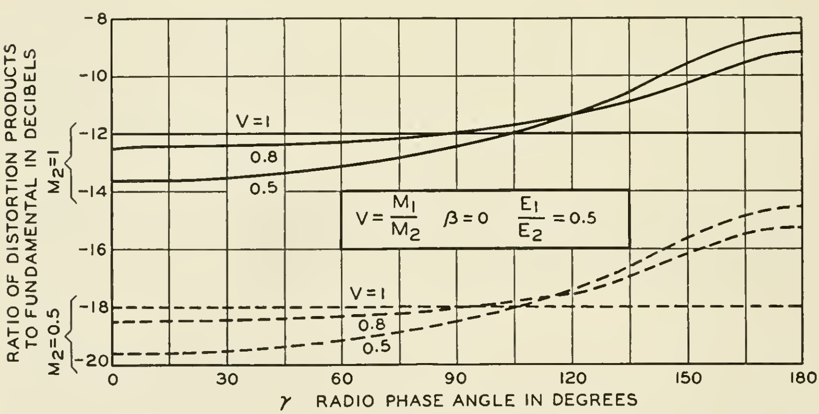

Fig. 14—Same as for Fig. 12 except that the field strength ratio $E_1/E_2 = 0.5$.

value in each successive figure. Here the marked increase in the amount of distortion present as the audio components depart from synchronism and the carriers approach phase opposition is most striking. Also the rapid decrease in the amount of distortion present as the field strength ratio diverges from unity is noteworthy where $\beta \neq 0$.

The distortion for values of $\beta = 0$ and equal degrees of modulation ($V = 1$) remains constant in both these series of curves because this is the limiting case and is the distortion that would result from the re-

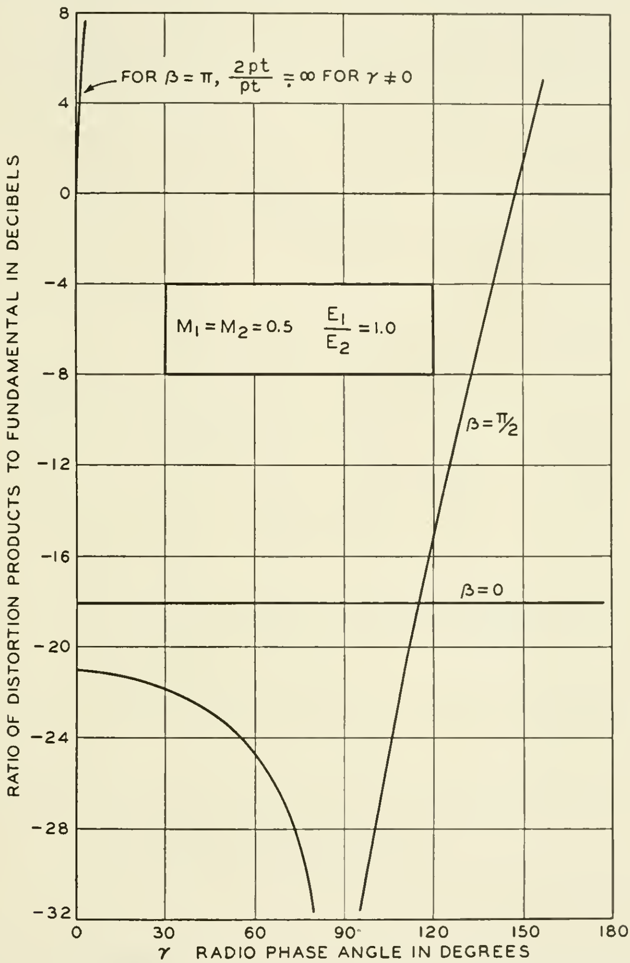

Fig. 15—Ratio of distortion products to fundamental with 50 per cent modulation of each carrier for varying audio and radio phase angles, β and γ respectively, where the field strength ratio $E_1/E_2 = 1$.

ception of a similar program from but a single station. This fact affords a basis for comparison in considering the additional distortion that results under certain conditions from the simultaneous operation of two stations. While the distortion products loom large in proportion to the fundamental at times, these are also the times when the fundamental is fading out and the actual magnitude of the distortion products is not large.

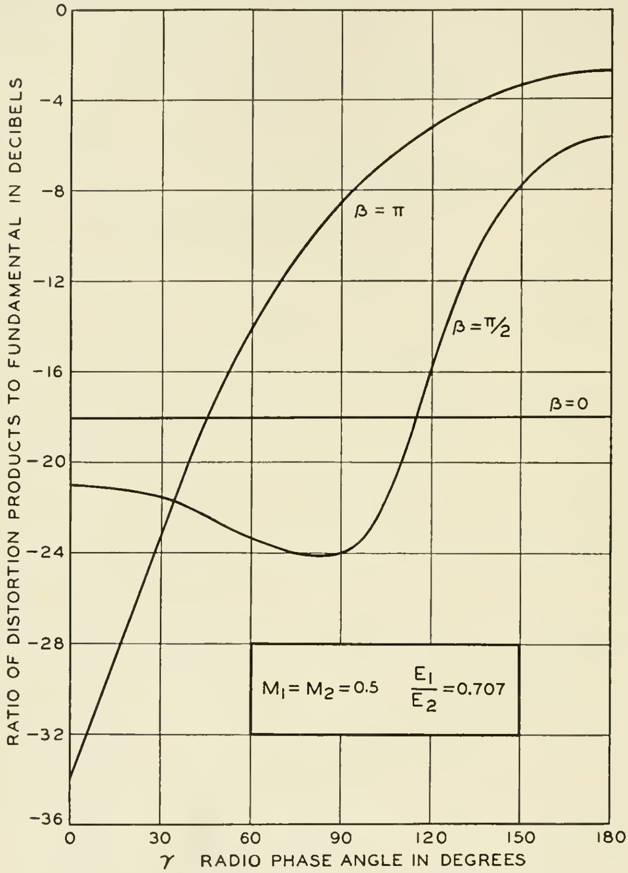

Fig. 16—Same as in Fig. 15 except that $E_1/E_2 = 0.707$.

In practice, broadcast programs do not consist of a single frequency but represent instead a complex frequency distribution. The distortion resulting from the reception of such a program therefore represents a general average of all the different conditions shown in the curves given above. These are averaged in the final analysis by the listener, whose ear is far from linear in its response and whose judgment is affected by his personal opinions and past experience. We have therefore considered it futile and perhaps misleading to attempt to present any graphical summation of the effective distortion present in the reception of an ordinary broadcast program under such conditions. On the other hand these theoretical studies were undertaken in order to explain certain phenomena observed during the preliminary field tests as the degree of modulation and the field strength ratio were varied. The actual results have been quite closely corroborated by the conclusions reached from a study of these single frequency curves which have been of great value in obtaining a physical picture of the conditions that exist in this middle area.

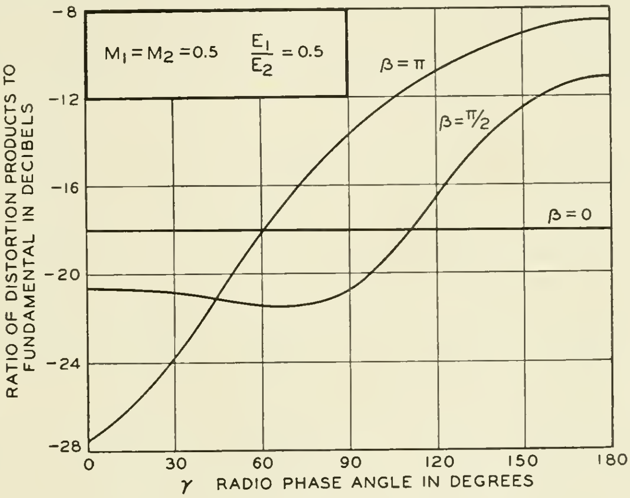

Fig. 17—Same as in Fig. 15 except that $E_1/E_2 = 0.5$.

These curves have been limited, for the sake of simplicity, to the consideration of the conditions at the points in the middle area equidistant from the two stations. It will be seen from these curves for this limited case that if, with equal degrees of modulation, each individual frequency component of the program could be synchronized at the two transmitters no additional distortion would be caused at these points by the isochronous operation of the two stations. But for points not equidistant the audio phase angle will not be zero even though it is maintained so at the transmitter and the magnitude of this divergence from synchronism will be different for each audio frequency and for each separate point in space. The magnitude of this divergence increases rapidly as the distance to the respective stations becomes more unequal. Furthermore, the problem of maintaining in synchronism every component of the broad frequency spectrum required for program transmission appears to offer tremendous technical difficulties.

It seems especially questionable whether such synchronism is necessary since tests in this area have shown that the use of a simple directive antenna capable of moderate discrimination against the weaker of the stations at the point in question is sufficient to render the reception at least comparable to that from either station alone. A loop antenna grounded at one side instead of the center was found to be very effective.

Population studies made in connection with the field surveys show clearly how marked is the improvement in the service rendered by these particular stations under simultaneous operation as compared with operation on a shared time basis. On a shared time basis a population of approximately 1,000,000 received adequate service from these stations but half the time, the value of which was greatly impaired by its intermittent character. With simultaneous operation the service area of each station receives full time service. No accurate estimate can be made of the number of people in the middle area, and outside the normal service range of either station alone, whose reception has been further impaired by simultaneous operation. The importance of this effect can, however, be estimated from the fact that but 60 complaints of impaired reception were received by these stations in the first 35 days of simultaneous operation during the regular hours and that the total for the first year is less than one hundred.

The marked increase in the service rendered by these stations through simultaneous operation is an indication of the possibilities of the improved service that can be made available to urban areas by the use of isochronized transmitters for the broadcasting of a common program. Although it is probable that the high powered station on a cleared channel will remain the best means of affording a high-grade service to a metropolitan area while also rendering an acceptable service to large rural areas, common frequency broadcasting now appears to offer a definitely useful means by which to provide an improved coverage to a number of noncontiguous communities.

In conclusion, the author wishes to acknowledge his especial indebtedness to the following members of Bell Telephone Laboratories: to Mr. G. R. Stiblitz for the development of the probability curves, and to Mr. C. B. Aiken and Mr. R. J. Jones for their preparation of the distortion curves as a part of their general mathematical study of the problem.