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Radio Telephone Service to Ships at Sea *

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The paper discusses the American end of the ship-to-shore radio telephone system and the connecting equipment on board the *Leviathan*. The most suitable wavelengths for this service are in the short-wave range, but the use of these wavelengths complicates the problem, since different wavelengths are required according to the distance of the ship from shore, the time of day, season of year, etc. The problem on shipboard is further complicated by the fact that the transmitting and receiving systems are necessarily near together and special precautions are necessary to take care of interference from the radio telephone transmitter and the radio telegraphic services. In addition to interference from these sources, there is a background of interference in the ships' electrical equipment, all of which necessitates a much more powerful land station than is necessary on shipboard.

In the present system, the shore transmitter has a power rating of 15 kw. and the ship transmitter of 500 watts. The shore transmitting station is located at Ocean Gate, N. J., and the receiving station at Forked River, N. J. At both of these locations, directive antennas are employed which cover the ships' lanes. The stations are connected by wire to the Long Lines toll office in New York, and the over-all control of the circuit is carried out from this point. Both the ship and shore transmitters are crystal controlled. The ship's receiver is highly selective and is of the double-detection type. Communication between the ship and the shore is carried out by use of a pair of frequencies, one for transmission in each of the two directions, separated from each other by about three per cent. Ships of a number of nations are being equipped with wireless telephone apparatus and as the service expands, it will undoubtedly be necessary to formulate a plan in which international agreement is reached on the allocations of frequencies for ship-to-shore telephony and telegraphy, in order that undue interference within the services themselves or between the two services shall not ensue.

IN view of the developments which have recently taken place in the field of ship-to-shore radio telephony, it would appear appropriate to review the state of the science and to discuss the problems which have arisen, the facilities which have been installed, and the general results obtained.

The ship-to-shore radio telephone system, which is here described, was opened for public service between the *Leviathan* and the United States on December 8, 1929. This was the first extension of the public telephone service to a ship at sea and enabled calls to be made between the vessel and any Bell System subscriber. The system as set up is intended primarily for giving telephone service to the larger passenger-carrying vessels as an extension to the wire network, and should be distinguished from the more simple uses which have been made of radio

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telephony in the marine field, such as that of enabling a coastal station operator to talk with coast guard vessels, fishing trawlers, etc.

This paper is concerned with the developments which have been carried out in the United States, including the establishment of transmitting and receiving stations on the New Jersey coast, the equipping of the *Leviathan* and the establishment of service to that ship.

It is significant of the wide-spread interest in this type of service that developments have also gone forward rapidly on the European side where the British, Germans, and French are preparing coastal stations and equipping some of the larger ships for public telephone service. The British have already initiated service to two of the White Star Liners, the *Olympic* and the *Majestic*, and before the summer is over it is likely that half a dozen of the larger transatlantic vessels will be undertaking this service, connecting with both the American and the European networks.[1]

Early Developments

Attempts to apply telephony in the maritime field date back to the pioneer work on radio telephony itself, but it was not until the application of the vacuum tube were developed that radio telephony for any service became finally practicable.

Following the long distance, point-to-point radio telephone experiments of 1915, there was carried out in the following year what is believed to have been the first trial of two-way radio telephony from the wire telephone system to a vessel at sea. This trial was conducted by Bell System engineers in cooperation with the Navy Department. On that occasion the Secretary of the Navy, in his office in Washington, carried on two-way conversations with the captain of the *U. S. S. New Hampshire* off Hampton Roads.

Following the further development of radio telephony during the War, there was undertaken, in the years 1920-1922, an extensive development of ship-to-shore radio telephony, looking toward the linking of ships at sea with the land line telephone network.[2] At that time there was built a coastal radio telephone station at Deal Beach, N. J., and several ships were equipped on a trial basis. Extensive engineering tests were made and a number of demonstrations carried out which proved the physical feasibility of establishing such connections.

While the trials were successful from the technical standpoint, the development was not carried into commercial use because the adverse economic conditions existing in the post-War period did not appear to

[1] Ship-to-shore telephone service is now given (July, 1930) from both U. S. and British shores to the Leviathan, Olympic, Majestic and Homeric.

[2] "Radio Extension of the Telephone System to Ships at Sea," by H. W. Nichols and Lloyd Espenschied, *I. R. E. Proceedings*, Vol. 11, 1923.

justify the initiation of the new service at that time. Furthermore, the waves in the range of 300–500 meters, which had been used in these early trials, were soon thereafter assigned for broadcasting.

In the last few years the whole outlook has changed considerably. The development of short-wave radio systems has greatly increased the message carrying capacity of the radio spectrum and has made it feasible to maintain communication over a greater range of distances than was previously practicable for ships. Transoceanic radio telephone services have been inaugurated, and with the large increase in steamship travel there has arisen a renewed interest in the extension of telephone service to ships at sea.

When it became evident that short-wave transmission might be

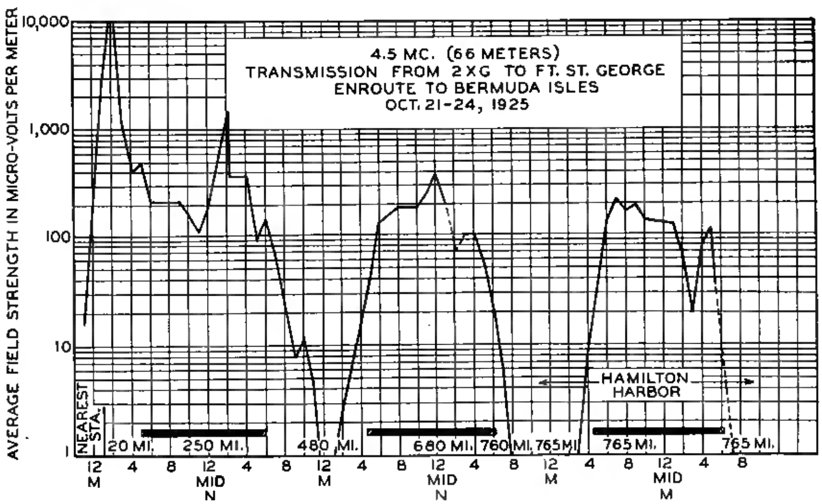


Fig. 1—Received Fields, New York-Bermuda Run 1925.

desirable for ship-to-shore telephone service, there was undertaken a program involving the measurement of the strength of the electric fields received aboard ship from a shore transmitter. This work was part of a general program intended to obtain fundamental data upon short-wave transmission, for purposes of point-to-point, as well as for ship-to-shore telephone services. The tests were first made in 1925 on vessels running between New York and Bermuda. Further measurements were made on other ships in subsequent years.

Fig. 1 is an example of the result of these earlier tests. Transmission was from Deal Beach on 4.5 megacycles (66 meters). The curve shows the relatively weak field which was received as the vessel left dock, due to the considerable stretch of land which intervened in the transmission path, the rise of the field to high values as the ship passed out of the harbor, and the gradual diminution as the vessel continued on her course. It will be observed that transmission on this frequency was effective at night all the way to Bermuda, but that during the daytime the transmission failed for distances greater than a few hundred miles. Corresponding measurements showed that daylight transmission could be secured by means of a higher frequency, such as 9 megacycles (33 meters). Measurements of this kind, supplemented by data obtained for a wide range of distances over land, and for transatlantic distances, have built up a fairly complete set of quantitative data on short-wave transmission over different distances and for various times of the day and year.

Along with this study of transmission conditions, there was carried on the development of short-wave apparatus technique for telephony. The first application was in the field of point-to-point transatlantic operation and the considerable art built up there, including the design of transmitters, receivers, directive antennas, and the working out of two-way operating methods, served as a very useful basis from which to develop the coastal and ship stations for the maritime system.

With this background of development, preparations were made to set up a two-way, short-wave radio telephone system for commercial service. This service was centered upon New York because of the large concentration of ocean-going traffic at that port.

The Technical Problem

One of the most important problems to be solved in the design of a short-wave system is that of determining the frequencies necessary for giving the service involved. The frequencies which are best suited to the different distances, time of day, and season of the year for transmission over the North Atlantic are indicated in the curves of Fig. 2. The curves for the greater distances refer to the transmission which appears to take place in the upper regions of the earth's atmosphere and is usually referred to as sky-wave transmission. Each of the sky-wave curves traces the optimum frequency-distance relation for the time of day and season of the year indicated. The curves merely give a general picture of the frequency relation and do not take account of other effects, such as fading, magnetic storms, etc.

The figure brings out very clearly the necessity for using a variety of wavelengths if the ship lanes are to be adequately covered. Fortunately, there is a considerable band on each side of the curves shown, in which good transmission can be obtained, and this enables one to choose a small number of frequencies in the short-wave range which are adequate to cover the conditions. Actually, it is found that a set of about four frequencies will suffice to cover the North Atlantic. For distances greater than a few hundred miles this characteristic obtains irrespective of whether the transmission is over water or over land, by reason of the fact that the transmission appears to take place in the upper regions of the earth's atmosphere.

Closer in to the transmitting station, however, there is the so-called surface component, the attenuation of which is much less over sea water than over land. It will be seen that the surface wave may be relied upon for distances of the order of 200–300 miles, for frequencies of about 4 megacycles. The transmission of this component is much more stable and reliable than is the transmission of the sky wave. It

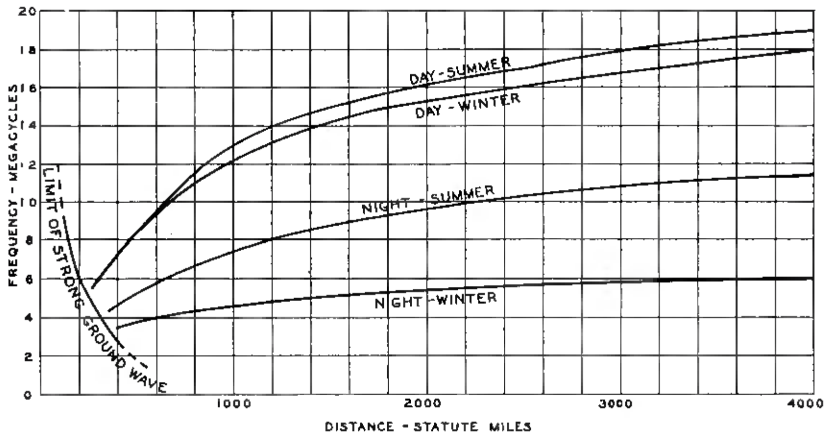


Fig. 2.—Distance-frequency characteristic.

seemed important, therefore, to utilize the surface wave to the maximum extent possible.

With this in mind, a series of transmission measurements was made over a stretch of water between New Jersey, Long Island, and Nantucket for the purpose of more accurately evaluating the effectiveness of the surface wave component, particularly in so far as it bears upon the question of how close to the water front the coastal station need be placed. Transportable transmitting and receiving stations were used in these tests. It was found that as the transmitting or the receiving station was moved away from the water front, the attenuation increased materially. For example, moving either terminal a mile back from the coast line increases the attenuation some 8 decibels at 4.5 megacycles. On the other hand, a narrow stretch of land, such as a sand bar, out a few miles from the coast, introduces relatively little loss.

These results indicate that if full advantage is to be obtained from the more reliable surface-wave component, the coastal station should be immediately upon the seacoast or a salt-water bay.

An important factor in connection with radio reception on shipboard is that of electrical interference. The modern steamship requires for its operation and its service a large amount of electrical machinery. In addition to this, it is equipped with various radio telegraphic services. The operation of all of this electrical equipment produces interference in a receiver which is much in excess of that normally encountered in a shore receiving station which can be so located as to be reasonably free from electrical disturbances. Furthermore, there is on the ship another source of disturbance which is due to

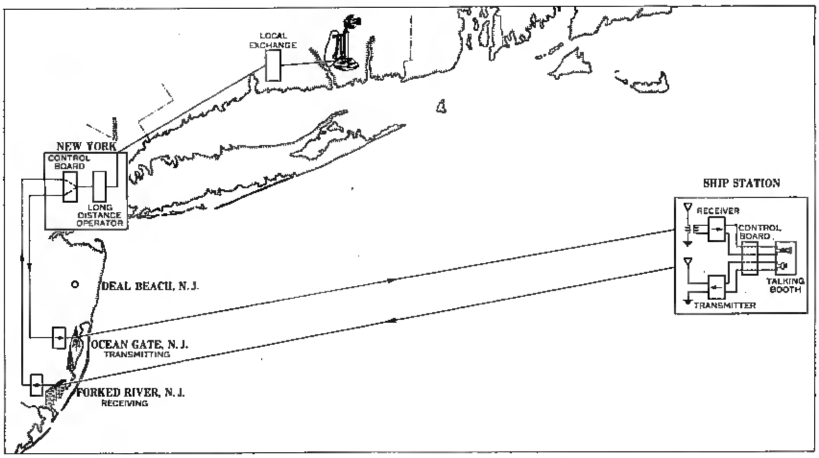


Fig. 3—U. S. coastal station, circuit between New York and ship.

charging and discharging of various parts of the rigging in the strong electromagnetic fields of the various radio transmitters. These various sources of disturbance were found in the earlier shipboard experiments and the high noise levels are, in general, the predominant factor in limiting the communication range. These factors made it desirable to employ at the shore end as powerful a transmitter as was available and to use whatever benefit could be obtained from antennas designed to be roughly directive along the transatlantic ship lanes. A transmitting set of the type used in transatlantic communication, but adapted for the ship-to-shore wavelengths, was therefore employed.

Since the shore receiver can be located in a comparatively quiet situation and since use can also be made of roughly directive receiving antennas, there is no advantage in transmitting as large an amount of

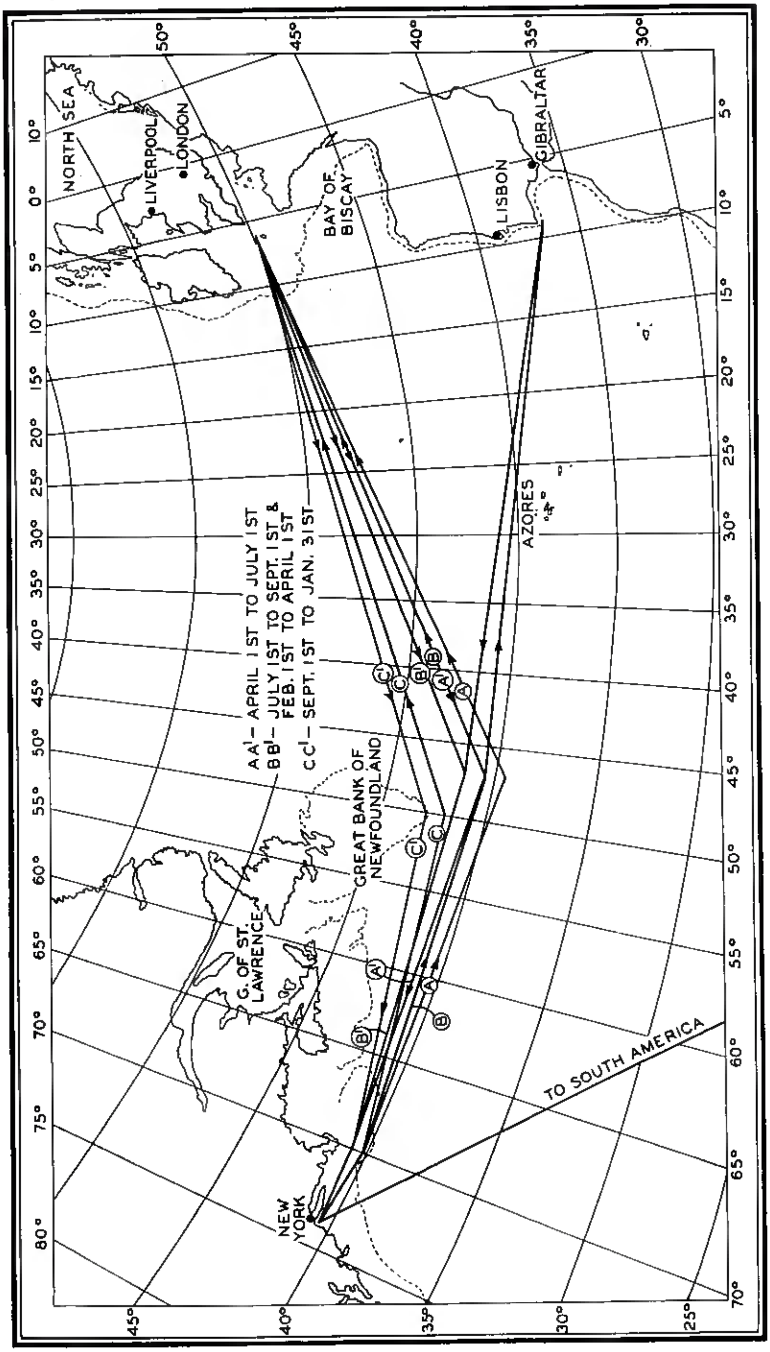


Fig. 4—North Atlantic steamship lanes.

power from the ship as from the shore. The actual power radiated by the *Leviathan's* transmitter is of the order of 500 watts. The shore receiver is of the type used on the transatlantic radio telephone circuits, working with a directive antenna. The arrangement provides a fairly well proportioned system, the channels being substantially equally effective in the two directions.

The Shore System

The general setup of the system is illustrated in Fig. 3. The coastal stations, sending and receiving, are located about 60 miles south of New York on the New Jersey shore, at Ocean Gate and Forked River. The course followed by the transatlantic ships is indicated on the map of Fig. 4. The directional bearing of this course and the directivity

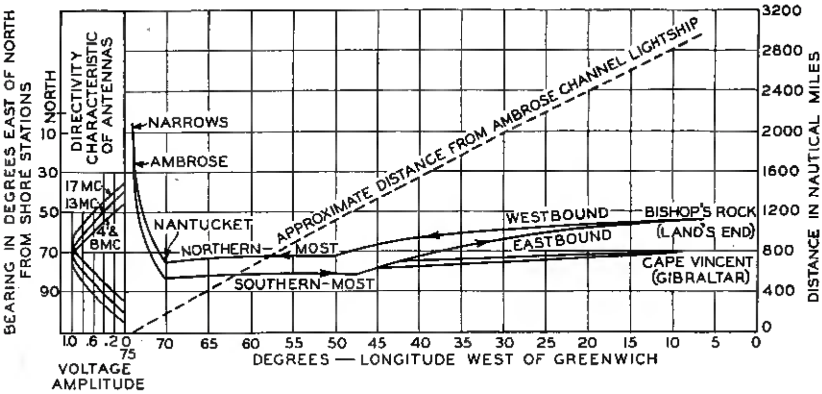


Fig. 5—Directional bearings.

characteristic of the New Jersey shore station antennas are illustrated in Fig. 5. It will be observed that the breadth of the transmitted beam is adequate to take care of the variation of the directional bearing of the course. For steamship routes other than the transatlantic, as for example the coastal route to the South, other antenna arrangements will be required.

In general, the whole coastal station, including the transmitting and receiving units, taken together with the wire line connections and control position in New York, is similar to one end of a transatlantic point-to-point circuit. The transatlantic facilities have been described in previous papers [3] and reference should be made to them for more detail than is given below. The transmitting set has been adapted to cover

[3] Papers on Transatlantic Telephone Service by Messrs. Miller, Bown, Oswald, and Cowan, presented at Winter Convention of the A. I. E. E., New York, N. Y., January 1930. Papers by Messrs. Bown and Oswald, *B. S. T. J.*, Apr. 1930.

the frequency range used in the service. It has a power of 15 kw. output of unmodulated carrier and is capable of delivering 60 kw. peak power. A photograph of a similar transmitter at Deal Beach, which is being used for this service pending the completion of the transmitting station at Ocean Gate, is shown in Fig. 6. The antennas are simpler

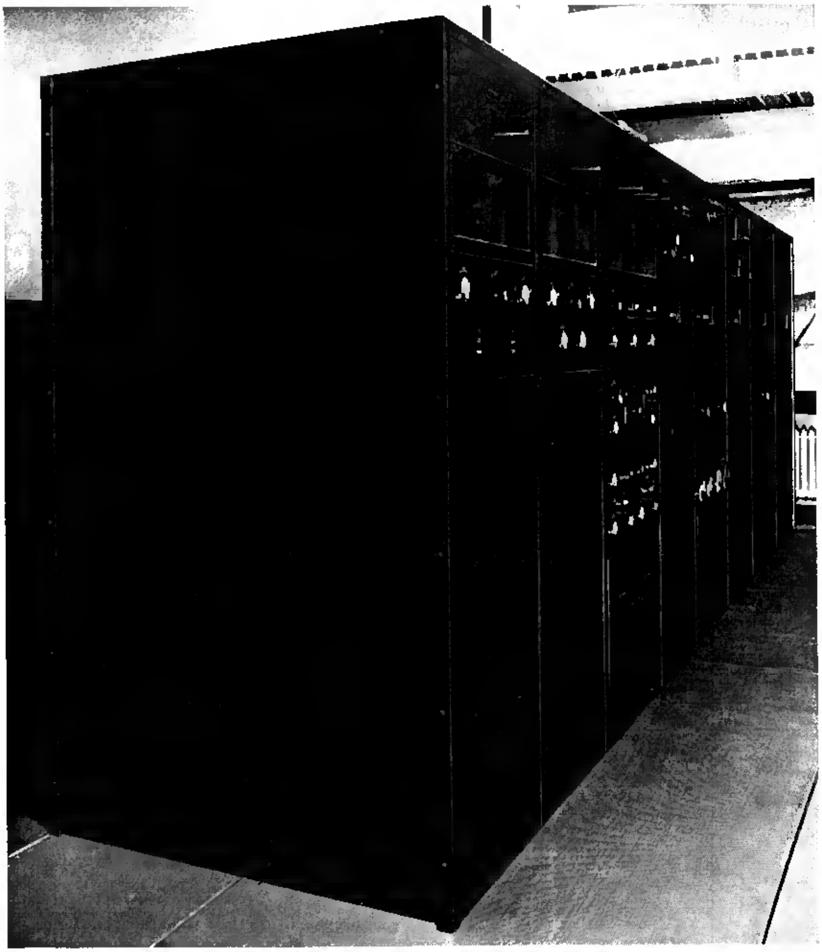


Fig. 6—Deal Beach transmitting set.

and less directional than those employed in the transatlantic circuit, and give a transmission gain of 8 to 10 db as compared with a single half-wave antenna.

The receiving station at Forked River has been in operation since the opening of commerical service last December. A photograph of the receiving set is shown in Fig. 7. The receiver is of the double-detection type, of high gain and selectivity, and employs screen-grid tubes. It is provided with automatic gain control. The apparatus shown includes not only the receiving set proper but also the equipment which is required for monitoring the circuit and for connecting with the wire

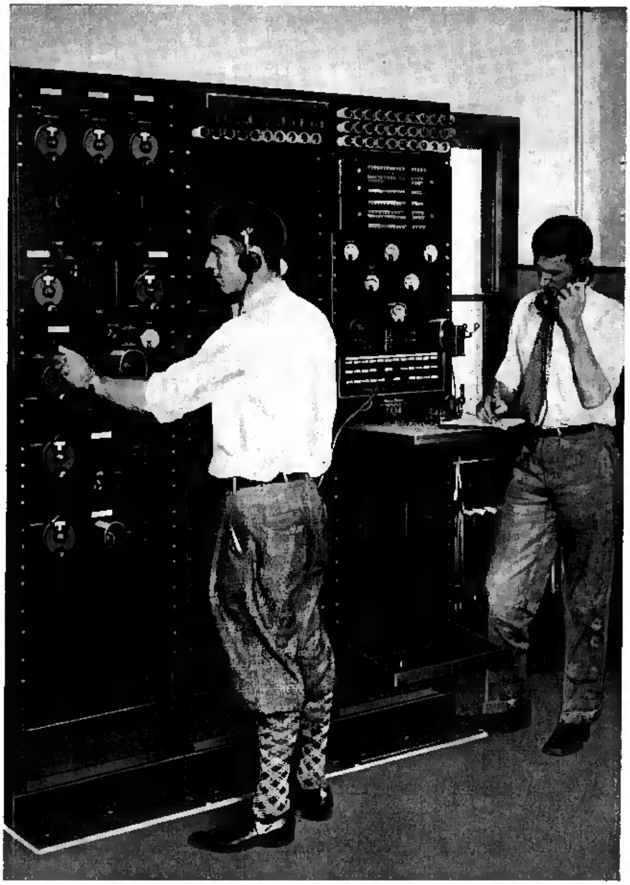


Fig. 7—Forked River receiving set.

line into New York. The receiving antennas are of the same general type as those used in the transatlantic system, which consist of a row of quarter-wavelength verticals connected alternately top and bottom by quarter-wavelength conductors. In the case of the longer wavelengths used in the ship-to-shore service, the vertical conductors are reduced in height and the horizontal links correspondingly elongated. A photograph of the station at Forked River and two of the antennas is shown in Fig. 8.

The control and operating terminal equipment in New York is identical with that in use on the transoceanic radio telephone circuits. The control positions, as they exist in the New York long-distance telephone building for both transatlantic and ship-to-shore circuits, are pictured in Fig. 9. These control positions have associated with them such things as voice-frequency repeaters, indicators of the volume being transmitted and received over the circuit, gain controls, monitoring and testing facilities, and voice-current operated switching devices. The latter prevent the speech received from the ship from being reradiated from the shore transmitting station and permit independent adjustment of amplification in the circuits leading to the transmitting and receiving stations. Thus, the volume sent to the

Fig. 8—Forked River station with antenna.

transmitting station may be kept substantially constant, despite variations in speech volume received from different land line subscribers and full modulation of the transmitter may be obtained for overriding noise on the ship. The function of the technical control operator is that of maintaining the circuit in the correct technical condition for talking. In general, it is the intention that the shore transmitting and receiving stations should function, as far as possible, merely as repeater stations, with the control of the over-all circuit from New York to the ship resting in the New York technical operator.

The circuit terminates as an operating facility before a traffic operator at one of the long-distance telephone boards. In Fig. 10 is shown an illustration of the traffic positions for the transatlantic radio telephone circuits, including, at the right, two positions devoted to the ship-to-shore service. The duty of one of these two girls is confined to the radio circuit itself in that she talks to the ship operator, passes and receives information as to calls, and is generally responsible for completing the connection between the ship circuit and the land line subscriber.

The adjacent operator is concerned more particularly with the land line subscribers, answering inquiries and recording calls outbound to ships and, in turn, getting in touch with and holding land line subscribers for inbound calls.

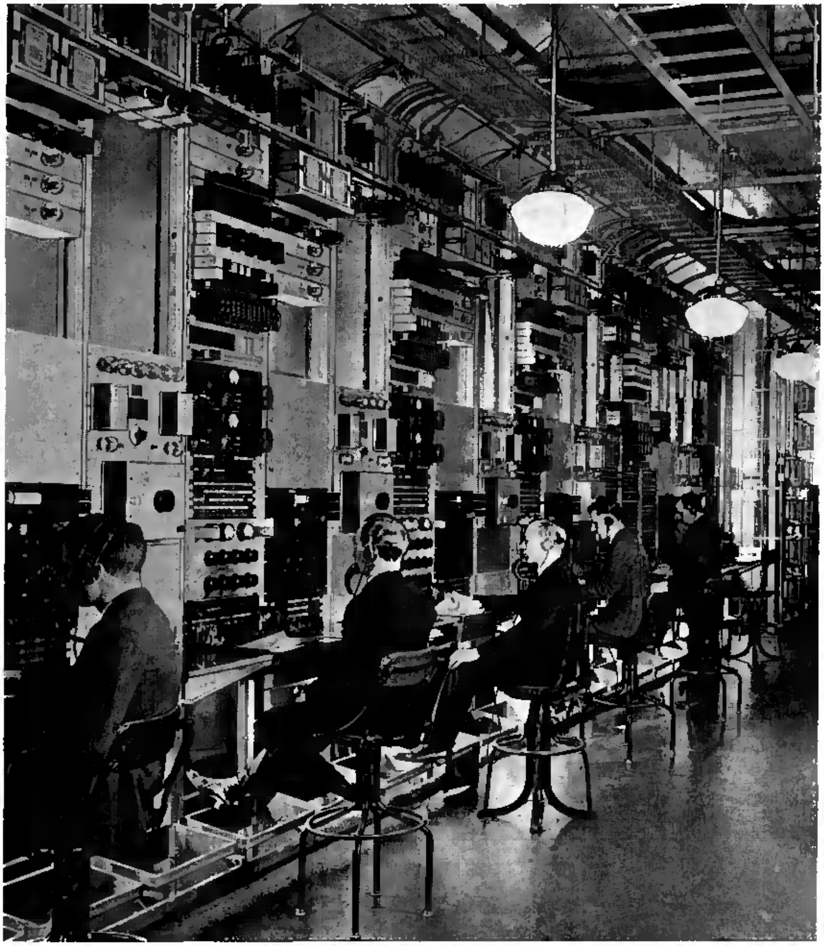


Fig. 9—New York technical control positions.

The Ship Station

The *Leviathan's* radio transmitter was designed to supply about 500 watts, 80 per cent modulated radio frequency power to an antenna at frequencies from 3 to 17 megacycles. To insure satisfactory operating conditions, the carrier frequency stability was made as good as that required for point-to-point service and the transmitter has been designed with the object of holding the frequency within 0.01 per cent. This facilitates the establishment of contact between the ship and shore and obviates the necessity for frequent retuning of the shore receiver. The background noise on the unmodulater carrier, due to commutator ripple, etc., is inappreciable and the audio-frequency characteristics from 200 to 2750 cycles is flat to within $\pm$ 2 db.

In addition to these electrical requirements, the mechanical design must be such as to withstand ship's vibration, permit easy access to the

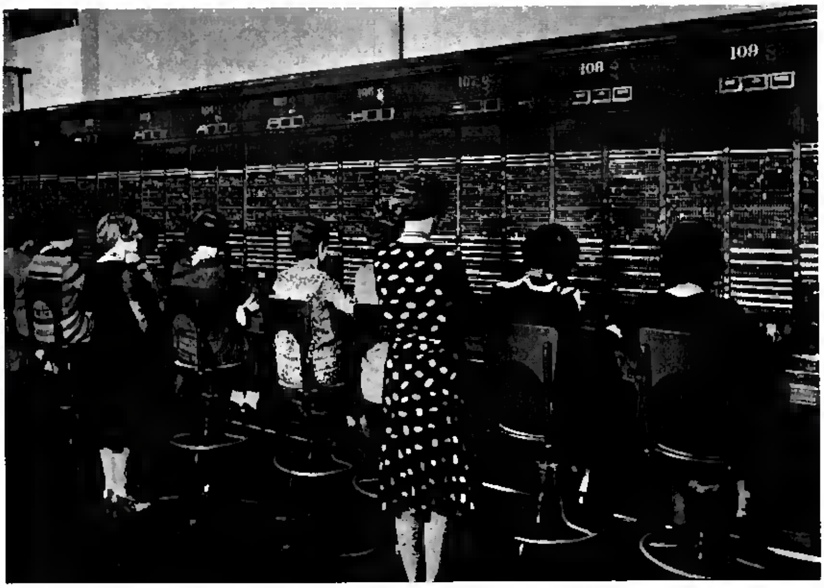


Fig. 10—New York traffic positions.

interior so as to facilitate wave change, and at the same time protect the operators from electrical shock.

The transmitter consists of a crystal oscillator and associated amplifiers. The crystal provides the necessary carrier frequency accuracy and stability and the amplifiers step up the power of the carrier to the desired level. Audio-frequency filters are placed in all voltage supply circuits to eliminate background noise. The modulation system with its associated transformers is designed to produce the requisite audio-frequency quality. A diagram of the circuit is shown in Fig. 11.

Very thorough electrical shielding is necessary between amplifier stages to prevent singing. This shielding makes the changing of coils, which is necessary for the changing of wavelengths, very unhandy, and hence the crystal control and amplifier system, except the last stage is provided in duplicate, one side being used for the longer and the other for the two shorter waves. Wave changing, except for the output circuit of the power stage, is then accomplished by connecting the proper amplifier to the power stage.

The quartz plates used in the crystal control system are circular, being approximately one inch in diameter, and are clamped rigidly in the holder. This clamping serves to prevent any change of frequency with mechanical vibration. The holder with its crystal is mounted in a small oven, the temperature of which is held constant at 50 deg. cent. to better than ± 0.1 deg. cent. The thermal system of this oven is so

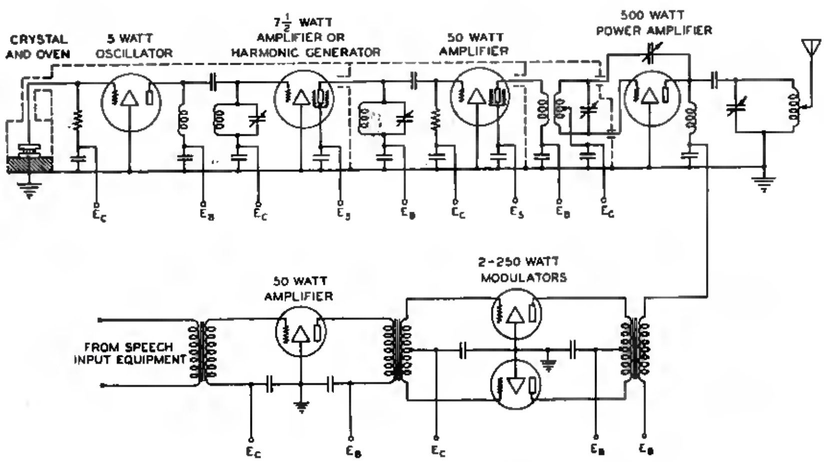


Fig. 11—Ship transmitter's schematic diagram.

designed that the change of internal oven temperature with temperature changes of the surrounding air is negligible.

As shown in the figure, the crystal is connected between the grid and filament of a 5-watt vacuum tube which, together with the parallel resonant circuit connected to the output of this tube, forms the crystal oscillator. The radio-frequency voltage developed by the crystal oscillator is applied directly to the grid of a 7½-watt screen-grid tube which can be used either as an amplifier or a frequency doubler. The output of this tube, except in the case of the higher frequencies, is applied directly to the grid of a 50-watt screen-grid amplifier. For the higher frequencies a second frequency doubler can be switched into the circuit. The output of the 50-watt tube is coupled through a balanced transformer to the final amplifier stage. The amplifier or frequency doubler stages are separately shielded and radio-frequency filters are provided in all power supply leads.

The power amplifier consists of an air-cooled, three-element, one-kilowatt tube. Neutralization is accomplished by the familiar balancing arrangement shown in the figure. The output circuit of this stage consists of a parallel resonant circuit with provision for tapping in the connection to the antenna.

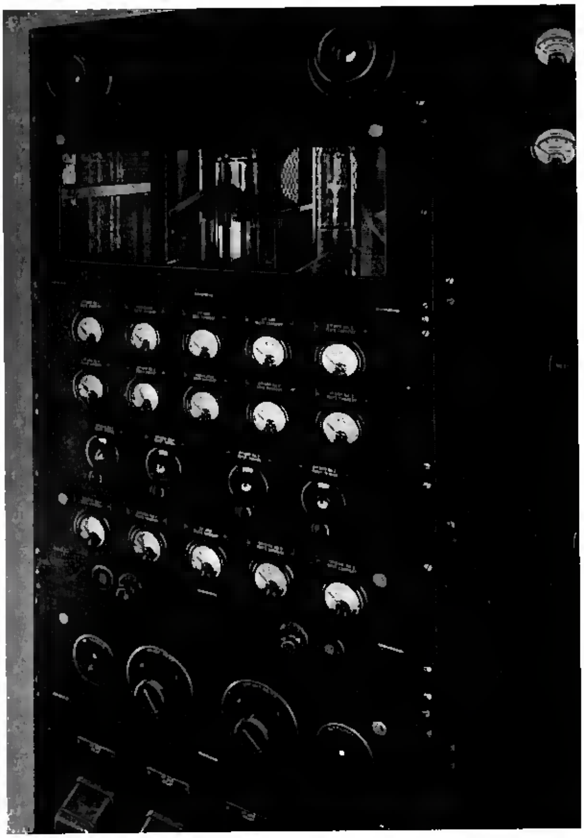


Fig. 12—*Leviathan* transmitter.

Modulation takes place in the plate circuit of the final amplifier stage, the plate current supply being fed through a special transformer, the secondary of which is connected to two 250-watt tubes connected push-pull and fed by a 50-watt amplifier.

The power supply is obtained from motor-generator sets operated from the 110-volt, d-c. ship supply. Protection of the operators and apparatus is provided by means of relays and contactors in the high-voltage supply circuits which prevent the high voltages from being applied if the filament or grid circuits are not closed or if the doors of the transmitter are open.

An illustration of the ship's transmitter is shown in Fig. 12. The picture is somewhat out of perspective owing to difficulty in taking the photograph in the limited space available on shipboard.

The receiving problem on shipboard is complicated by a number of factors. The transmitting and receiving frequencies must be within a few per cent of each other, if the best transmission conditions for the time and place are to be utilized and if the frequencies are to remain in the bands assigned internationally to the mobile services. This requirement, as well as the noise conditions on shipboard, calls for a receiver of high selectivity, which is obtained, in the present instance, by the use of a double-detection set. The over-all selectivity is accomplished both by having a number of highly selective circuits ahead of the first detector and by using tuned circuits in the intermediate frequency stages, the high-frequency selectivity being used primarily to prevent overloading of the first tube and the intermediate frequency circuits being used to obtain the final selectivity required.

A reduction of the disturbances due to stay noises and better discrimination against the transmitted carrier is obtained if the transmitting and receiving antennas are widely spaced. On the other hand, for operating reasons, it is desirable to have the transmitter and receiver located in the same room. In the case of the *Leviathan* installation, the transmitting antenna is located directly above the radio room, between the second and third stacks, and the receiving antenna is placed as far as possible behind the third stack. The receiving antenna is connected through a suitable step-down circuit to a shielded transmission line, the other end of which is connected to the receiver, the receiver itself being very thoroughly shielded to avoid direct interference from the transmitter. On account of limited space, only two antennas are provided to handle the four frequencies, each antenna representing a compromise between the most efficient antennas which could be put up to handle the separate wavelengths.

As stated above, the receiver itself is of the double-detection type, using heater type tubes throughout. Screen-grid tubes are used for the first detector and intermediate frequency amplifiers and three-element tubes in the remaining positions. A photograph of the receiver and associated voice-frequency equipment, as it is installed on the *Leviathan*, is shown in Fig. 13, and a diagrammatic representation of the receiver is shown in Fig. 14. The high-frequency selective system consists of four separately shielded tuned circuits, coupled by small capacities. The use of a screen-grid tube in the detector circuit gives a two fold advantage over the use of a three-element tube in that a higher input impedance is maintained at the higher frequencies and the necessity for neutralizing against the reaction of the beating oscillator on the input circuit is eliminated. The beating voltage is made of the order of 75 to 100 volts for the purpose of reducing the effective tube noise in the detector plate circuit. With this arrangement no d-c. plate voltage is ordinarily required. The screen voltage is 22

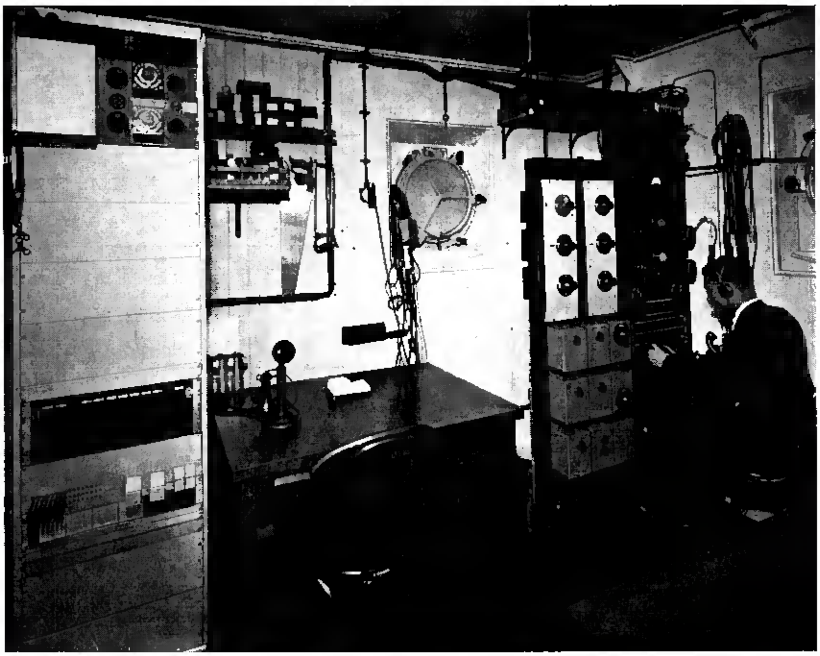


Fig. 13—*Leviathan* receiver.

volts. The output circuit is tuned to the intermediate frequency of 300,000 cycles and connection with the first intermediate amplifier is effected by means of a low impedance transmission line. The intermediate frequency amplifier stages are coupled by means of doubled tuned circuits. The use of properly designed circuits of this type makes it possible to obtain a high degree of selectivity against undesired frequencies while obtaining sufficient band width to maintain ease of tuning and to pass the desired frequencies. The second detector is of the conventional grid bias type. Automatic gain control is provided in which a certain amount of the carrier is taken at the end of the intermediate frequency stages, amplified and rectified. The resulting d-c. current produces a voltage drop across a resistance, which is applied to the grid of the first detector in such a manner that an increase in the intermediate frequency output brings about a reduction in the total set gain and vice versa. Manual gain control for following wide changes in the received fields is accomplished by variation of the voltages applied to the grid and the screen of the first detector.

The voice-frequency equipment, in addition to the desk telephone

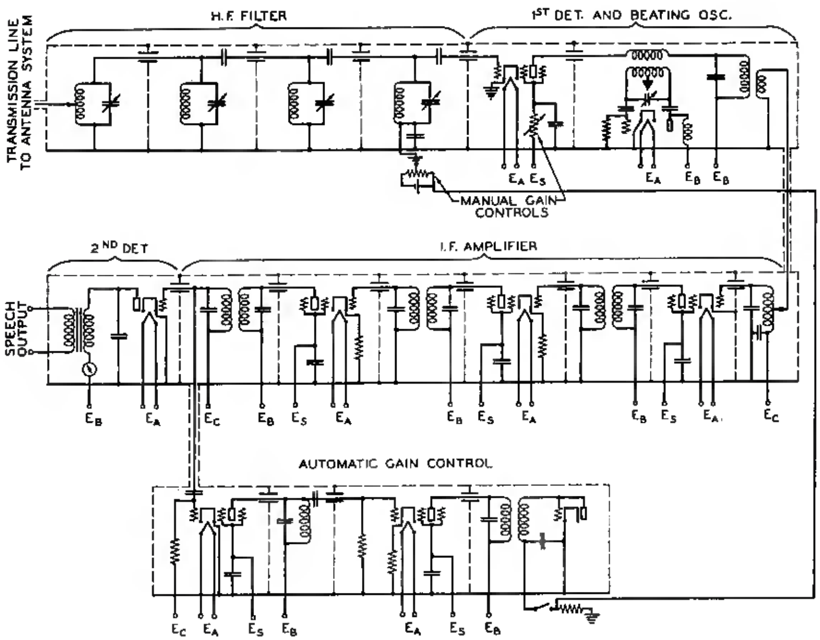


Fig. 14—Ship receiver schematic diagram.

set located in the subscriber's booth, comprises a technical operator's position located adjacent to the ship's receiver, and an attendant's desk located on a lower deck in a room adjacent to the subscriber's booth. The control equipment consists of repeaters, volume control devices, and volume indicators, by means of which the levels of the incoming and outgoing signals can be properly adjusted. Keys are provided which enable the technical operator to talk either over the radio circuit or to the ship subscriber. The booth attendant has facilities by which he can talk either to the subscriber or to the control operator and has a connection with the ship's telephone system for the purpose of locating persons on the ship and calling them to the radio telephone booth.

The subscriber's booth is provided with a desk telephone set having a high-grade transmitter. The outgoing and incoming circuits are shielded from each other and brought separately to the transmitter and receiver of the subscriber's set. An illustration of the subscriber's booth on the *Leviathan* is shown in Fig. 15.

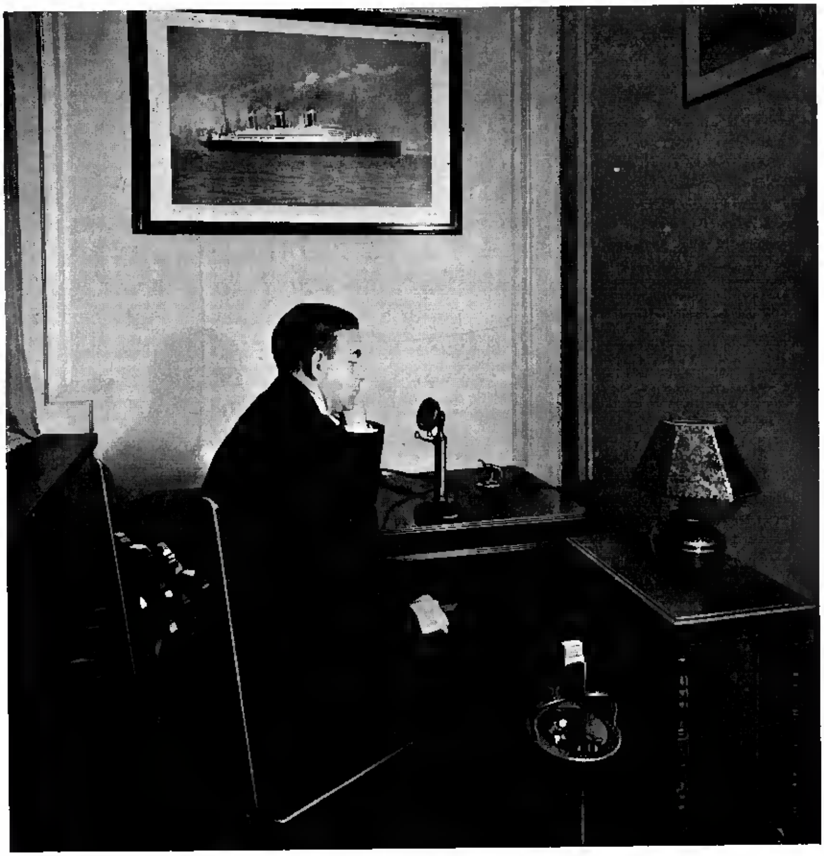


Fig. 15—Subscriber's booth on *Leviathan*.

The Wavelength Situation and Simultaneous Telephone and Telegraph Operation

Communication between ship and shore is carried out by the use of a pair of frequencies, one for transmission in each of the two directions, separated from each other by about 3 per cent. The specific frequencies which were first assigned by the Federal Radio Commission to the shore station and the *Leviathan* were necessarily chosen on more or less of a makeshift basis, in the absence of any comprehensive wavelength plan for this new service. The Commission has recently had under study the setting up of more adequate provisions for ship-to-shore telephone channels, whereby it is hoped a series of frequencies may be designated for telephone service exclusively and whereby there may be established the relation between the telephone and the telegraph frequencies necessary for the avoidance of interference between the two services. Especially is coordination of the two sets of frequencies necessary on the larger vessels, in order that simultaneous telegraph and telephone service may be given without mutual interference. On the larger liners simultaneous use of the radio telephone and radio telegraph service must be provided for. This means that the transmitters of both services must keep accurately on their frequencies and be free of spurious components, and that the receivers must be highly selective. It further entails that the transmitting and receiving frequencies in each of the two cases be so coordinated that the transmission frequency of one service does not lie too near the receiving frequency of the other, and bespeaks a considerable amount of mutual cooperation between the operating agencies involved. Difficulties of fitting in the two services were encountered in the early work on the *Leviathan* and, although the problem has not been worked out to final solution, sufficient progress has been made, in cooperation with the engineers of the Radio Corporation of America, to enable the telegraph and telephone services to be conducted simultaneously without undue interference.

In view of the fact that ships of a number of nations are already preparing to give radio telephone service on the transatlantic routes and with the probability of this service also extending to other parts of the world, it would appear to be a matter of importance that the whole question of marine frequency allocations be worked out in the near future not merely on a national but also on an international basis.

Transmission Results

The transmission results which have been obtained with the *Leviathan* on her first trip of commercial service are summarized in Fig. 16. It will be noted that practically continuous 24-hour communication was maintained for distances within 1000 miles of the shore, corresponding to two days out. The service at greater distances was more intermittent. This was largely due to the fact that during this first trip the effort was concentrated on covering reliably the more important nearer-in distances, and the ship was not prepared to transmit on frequencies above 8 megacycles. The service proved to be much in demand

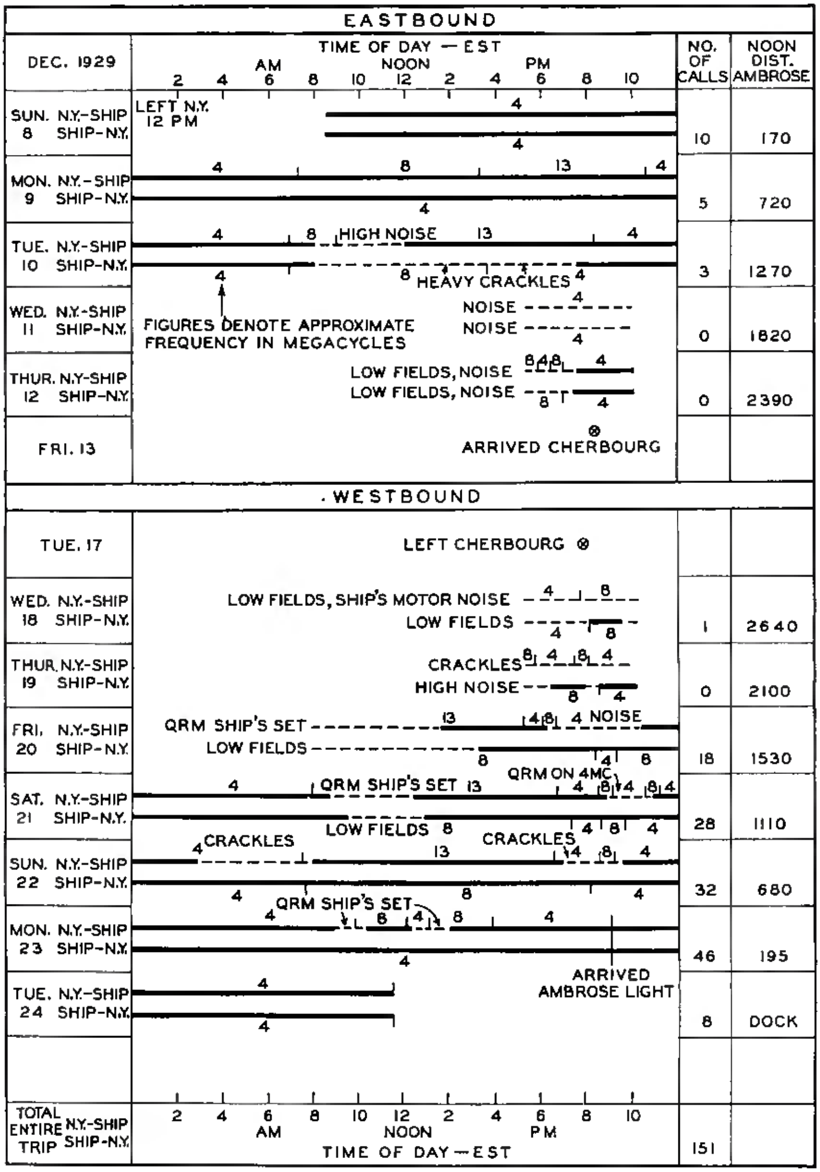


Fig. 16—Transmission results between *S. S. Leviathan* and New York.

by the passengers, as is indicated by the number of calls completed each day, particularly on the return trip. A similar number of test and demonstration calls was made during the voyage. The calls were completed without undue delay, there being only one ship involved, and a fairly high grade of communication was obtained.

In conclusion it will be realized that the solution of the techincal problem of ship-to-shore telephony is now well in hand and has been carried to the point of having proved the practicability of giving this service. Further problems are naturally arising in carrying the development into more general effect, particularly operating problems and those concerned with the international coordination of the service. The indications are that the larger transoceanic ships will be rather generally equipped for telephony and that the service will become one of permanent value in the maritime field.

A General Switching Plan for Telephone Toll Service

By H. S. OSBORNE *

This paper outlines a comprehensive plan for improved switching of long haul toll telephone traffic in the United States and Eastern Canada. A brief discussion is given of the methods of designing the toll plant to give adequate transmission efficiency for all connections established in accordance with this plan. This includes a new method of providing amplification at intermediate switching points replacing the cord circuit repeater method.

ON January 25, 1915, telephone service was, with due ceremony, inaugurated between the Atlantic and Pacific Coasts of this country. This occasion marked a great step forward both technically and commercially. Before that time, the limit of practicable telephone transmission had been about 1,500 miles. The transcontinental service was made possible by the completion of numerous important developments and particularly by the perfection of telephone repeaters and of means for applying them to long wire circuits.

Until then the Pacific States and their neighboring states had been isolated telephonically from the eastern and midwestern parts of the country. The demonstration of commercially practicable telephone circuits across the continent gave a great impetus to the idea of universal service, that is the provision of a telephone plant such that telephone service could be given at commercially attractive rates between any two telephones in the country.

In the fifteen years since the opening of the first transcontinental circuits, the ideal of universal service has to a large extent been realized. Practically all the telephones of the United States and a large part of Canada now have provision for connection with the countrywide toll telephone network, more than 99 per cent being included. To achieve universal service, however, involves a great deal more. Circuits must be provided in such numbers and so arranged that connections between any two telephones can be established quickly and without too many intermediate switching points. Also the telephone plant must be designed for such standards of transmission that these connections, when established, permit satisfactory conversation. In general, the technical advances which have been made during the last fifteen years to achieve the present standards of toll service have been described from time to time before the American Institute of Electrical Engineers, and it is not within the scope of this paper to review them.

* Presented at Convention A. I. E. E., Toronto, June 1930.

Associated with this development of the telephone plant has been a very rapid increase in traffic. Fig. 1 indicates this increase in the United States and Canada since 1915. A striking characteristic of this growth is that the increase has been much more rapid for the longest lengths of haul than for the shorter lengths of haul. For example, during the last five years in which the messages on lengths of haul up to 250 miles approximately doubled, the messages on hauls from 250 to 1,000 miles increased five times and those over 1,000 miles increased more than ten times. This characteristic is also

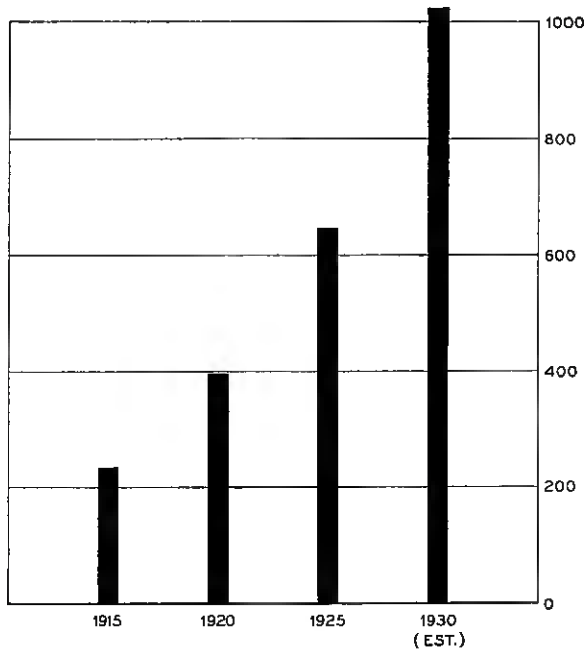


Fig. 1—Total toll messages in millions per year—Bell system.

illustrated in Figs. 2, 3, and 4 which show respectively the growth in the number of circuits between Toronto and Detroit 240 miles in length, Buffalo and Chicago 550 miles in length, and direct circuits from New York and Chicago to the Pacific Coast, averaging about 2,500 miles in length. This particularly rapid growth in very long haul traffic has made it practicable to establish a considerable number of long haul circuit groups and has greatly assisted in the problem of handling satisfactorily calls between widely separated points. It has led to the condition today in which 74 per cent of the long distance (Long Lines) messages are handled over direct circuits and 20 per cent with one intermediate switch.

The part of the business on which it is most difficult to give a high grade of service is naturally the scattering business between widely separated points. In these cases each item of traffic, that is the business between two specific points, is relatively small but the number of items of traffic is great. The number of messages involved in each item of traffic does not justify direct circuits and in very large

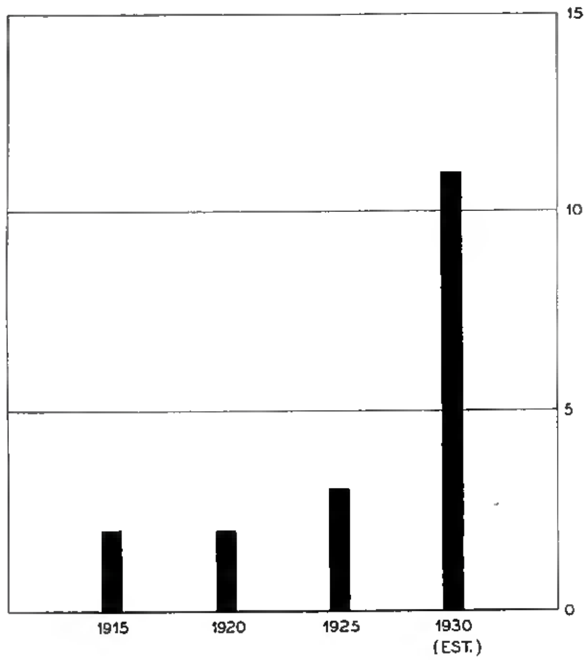


Fig. 2—Growth in number of toll circuits—Toronto to Detroit.

numbers of cases it is necessary, in order to provide a connection, to make more than one intermediate switch. This applies at present to six per cent of the long distance telephone business of the country. All measures of the quality of service—speed, accuracy and transmission—show that the difficulty of satisfactorily handling the service increases rapidly with the number of intermediate switches involved.

The development of the toll business has led to a great increase in the amount of business between large numbers of widely separated points. There has also been an extensive trend toward concentration of the plant used in handling the business in important toll offices and along important routes. The long haul toll business is now handled at about 2,500 "toll centers" out of approximately 6,400 central offices in the United States and eastern Canada. Furthermore, the technical developments in toll circuits have led to great increases in the numbers of circuits along a given route. The extension of the use of carrier telephone has increased the capacity of a 40-wire pole line from 30 circuits to 70 circuits. On the heaviest toll routes, moreover, circuits are now provided by means of toll cable construction, a single cable carrying 200 or 300 circuits. During the past year

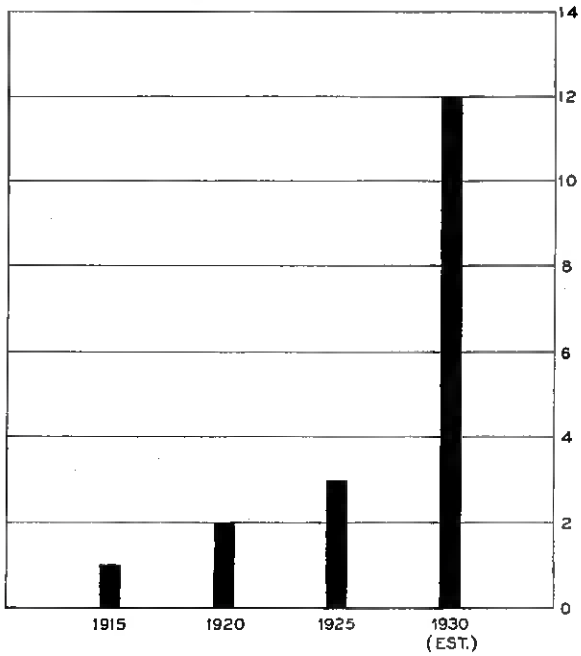


Fig. 3—Growth in number of toll circuits—Buffalo to Chicago.

or two the growth has been so rapid as to stimulate a very large amount of construction of underground toll conduit routes, providing in many cases for several thousands of telephone circuits on a single route.

General Toll Switching Plan

The conditions outlined above form the background which has made it both possible and important to adopt a new fundamental arrangement for the layout of toll plant and the routing of toll messages. This is called the "General Toll Switching Plan." The purpose of this plan is to provide systematically a basic plant layout designed for the highest practicable standards of service consistent with economy, including speed, accuracy and directness of routing between any two points in the country and suitable transmission standards. This involves the layout of the plant in such a manner as to limit as much as practicable the number of switches required for providing a connection between any two telephones and the establishment of standards of design and construction providing satisfactory transmission over any route thus established. The plan is, therefore, of particular

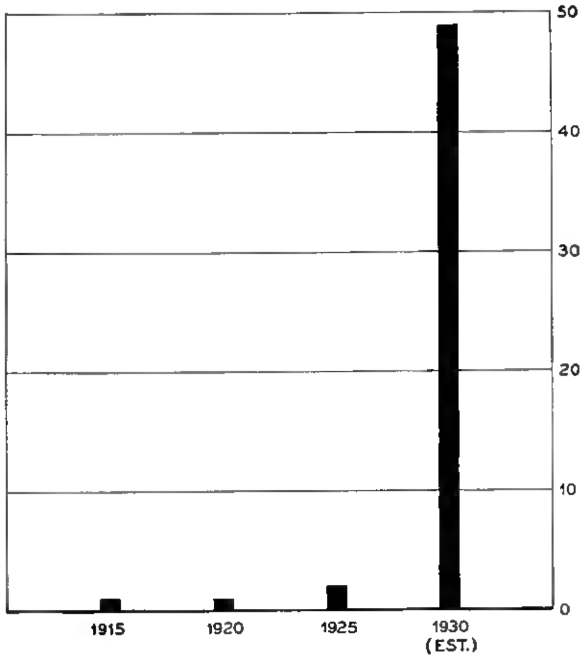


Fig. 4—Growth in number of toll circuits—New York and Chicago to San Francisco, Los Angeles and Seattle.

value in improving the service conditions of switched toll traffic, that is, traffic requiring the connection of two or more toll circuits.

The general features of the plan will be understood by reference to Figs. 5 and 6. Figure 5 shows the application of the plan to a limited operating area such, for example, as a State. Within the area are selected a small number of important switching points designated as "primary outlets." Each toll center is connected directly to at least one of these outlets and all primary outlets within the area are directly interconnected. This makes possible the interconnection of any two toll centers within the area with a maximum of two switches and within the part of the area served by one primary outlet, with a maximum of one intermediate switch.

The primary outlets were selected after a careful study of the present switching and operating conditions and the probable development of toll traffic within the various areas with a view to obtaining the minimum number of primary outlets capable of handling the traffic economically. The routings provided by the plan are supplemented by direct circuits, or by other routings where the amount of business justifies such additional circuits as indicated by the dashed lines in Fig. 5. In general the requirement is made that these supplementary routes shall be at least as satisfactory, both as regards

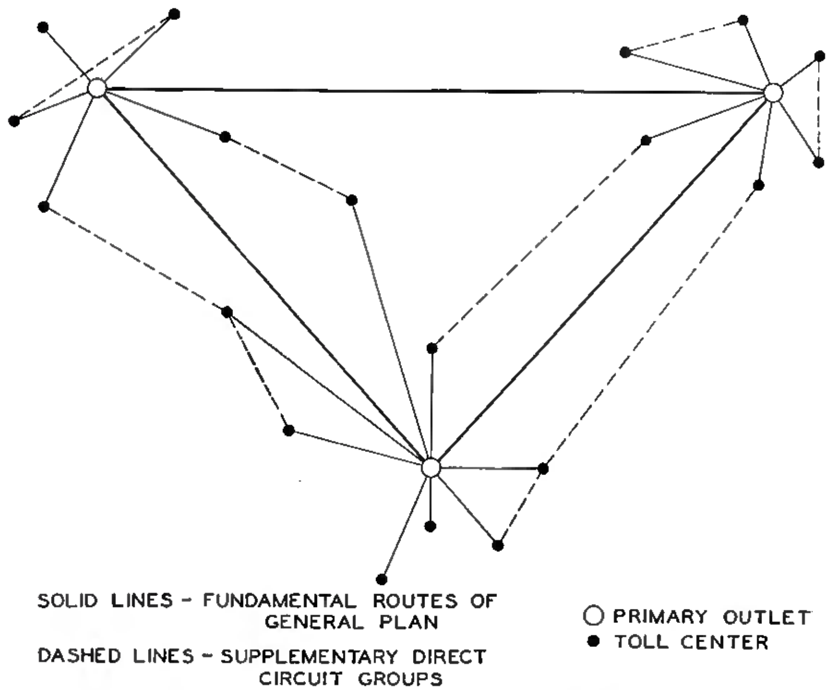


Fig. 5—General toll switching plan—application in local company area.

number of switches and transmission, as the routes provided by the fundamental switching plan. However, when the supplementary routes are used only as alternates to a primary routing they may be somewhat less satisfactory in these respects.

The tentative selection of primary outlets is shown in Fig. 7. It is interesting to note that it is found practicable to take care of switching for the 2,500 toll centers of the United States and eastern Canada by the establishment of approximately 150 of these as primary outlets.

For handling the business throughout the country eight of the primary outlets are designated as regional centers, which are indicated in Fig. 7. The method of routing calls is indicated by Fig. 6. Each primary outlet is connected with at least one regional center and with as many more as practicable. Each regional center is directly connected to every other regional center in the country. By this means, any one of the primary outlets, which are the 150 most important switching centers in the country, can be connected to any other primary outlet in the country with a maximum of two switches and within the area served by a regional center with a maximum of one intermediate switch. As an illustration of the concentration of switching which results, New York serves as regional center for the entire northeastern section of the United States and eastern Canada.

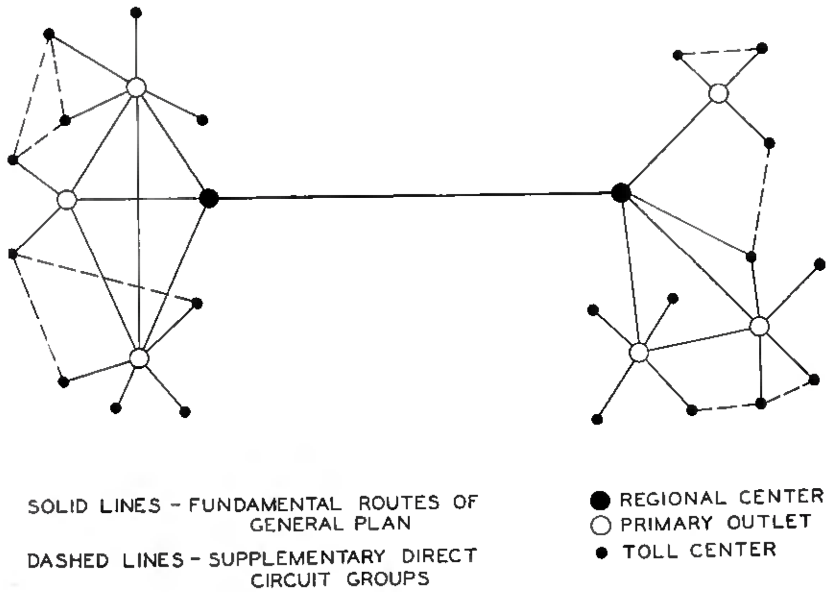


Fig. 6—General toll switching plan—illustration of interconnection of important switching offices throughout Bell system.

The extent to which intermediate switching is limited by the application of this plan is indicated by Fig. 8, which shows the maximum number of switches required under the plan between different types of toll centers. It is estimated that the percentage of long haul messages requiring more than one intermediate switch will, by means of this plan, be reduced by more than 50 per cent.

As an example of the benefit resulting from the adoption of this plan between two remote points, consider a connection which was requested between Pembroke, Ontario and St. Anthony, Idaho. Under the old routing instructions such a call required intermediate

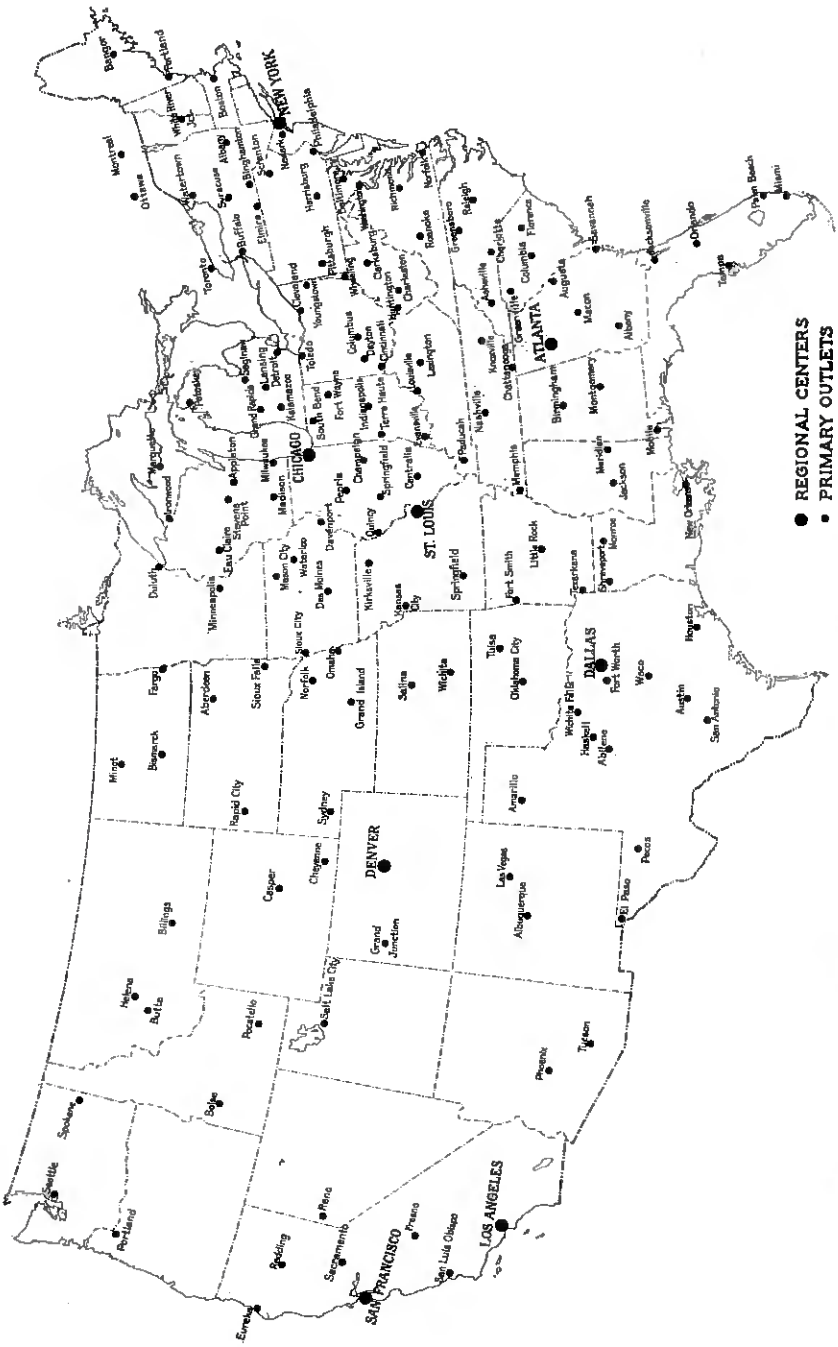


Fig. 7—General toll switching plan—location of points tentatively selected as regional centers and primary outlets in the United States and Canada.

switches at Ottawa, Toronto, Chicago, Denver, Salt Lake City, Pocatello and Idaho Falls, a total of seven. The chance of establishing such a connection within satisfactory limits of time was, of course, relatively small and the resulting circuit, when established, did not permit the conversation to be held. Under the general toll switching plan, this call will be routed with switches at Ottawa, New York, Denver and Pocatello, a reduction of three switches. Furthermore, the circuits involved in this connection will be designed with such transmission standards as to give satisfactory conversation.

	Same Regional Area				Another Regional Area			
To— / From	Regional Center	Primary Outlet	Toll Center Directly Connected to Regional Center	Toll Center Directly Connected to Primary Outlet	Regional Center	Primary Outlet	Toll Center Directly Connected to Regional Center	Toll Center Directly Connected to Primary Outlet
REGIONAL CENTER	0	0	0	1	0	1	1	2
PRIMARY OUTLET	0	1	1	2	1	2	2	3
TOLL CENTER (directly connected to Regional Center)	0	1	1	2	1	2	2	3
TOLL CENTER (directly connected to Primary Outlet)	1	2	2	3	2	3	3	4

Fig. 8—Maximum number of switches under general toll switching plan.

The routes provided by the plan for countrywide service are also supplemented by more direct routes of equivalent or better service characteristics in cases where the amount of business is sufficient to make this economical. Furthermore, the routes to regional centers are, in some cases, supplemented by alternate routes through what are called "secondary outlets." These are distinguished from the primary outlets in that they do not necessarily have direct circuit connections to all toll centers in their areas but serve a useful purpose as an alternate route for the toll centers connected to them.

The essential features of the general toll switching plan from the standpoint of the interconnection of the switching offices may be summarized as follows:

Regional Centers

Regional centers are switching offices strategically located to cover the various parts of the country and completely interconnected with direct circuits, thus forming the basis of a countrywide toll network.

Primary Outlets

Primary outlets are switching offices having direct circuits to one or more regional centers and each having direct circuits to all toll centers in the area for which it is the primary outlet. Also, each primary outlet is connected to every other outlet within as large an area as practicable, usually within a State.

Supplementary Offices
Secondary Outlets

Secondary outlets are switching offices having direct circuits to one or more regional centers and are intended primarily to furnish alternate routes for toll centers for reaching the regional centers, thus providing a greater degree of flexibility in the plant.

Secondary Switching Points

Secondary switching points are additional switching offices intended to provide routes which are more direct thus reducing back haul for intra-area business.

Transmission Considerations of General Toll Switching Plan

An important part of the development of the plan was the determination of proper transmission requirements such that any toll connection established in accordance with the plan would have satisfactory transmission efficiency.

Before the perfection of telephone repeaters, the provision of satisfactory transmission efficiency depended largely upon limiting the total attenuation loss of the complete circuit. At the present time the perfection of repeaters has practically removed that limitation. For example, the attenuation in a New York-Chicago circuit in cable is such that without the use of repeaters the ratio of input power to output power for speech currents transmitted over the circuit would be 10^{45}, while by the use of repeaters at the terminals and at 17 intermediate points the ratio actually is 10.

The removal of the limitation formerly set by circuit attenuation makes possible the increase of the efficiency of circuits to the limit determined by some other characteristic of the circuit. There are various things which under different conditions may determine this limit. One is the effect on transmission of echoes, namely, portions of the speech currents reflected back from the distant end of the circuit or from intermediate points. Another is the distortion due to the building up of greater transmission gain at certain frequencies than at others, which effect may result if repeaters introduce too great an amplification into the circuit. As an extreme case, this might result in a sustained oscillation or singing on the circuit. Other effects which may be important are those of crosstalk between telephone circuits, or of noise induced in the telephone circuits from outside sources, both of which are increased by increasing repeater gains. On the longer connections, echoes are almost always the controlling factor, whereas on the shorter connections, such effects as crosstalk, singing and noise generally are limiting. A reduction in any of these effects generally involves more expensive types of construction.

The difference between the attenuation loss of the circuit and the total transmission gain introduced into the circuit by repeaters is spoken of as the net equivalent. For long telephone circuits it is generally economical to provide sufficient repeater gain so that the circuit can be operated at the minimum net equivalent permissible, this minimum equivalent being determined by the transmission factors just mentioned. Therefore, in establishing satisfactory transmission efficiencies for the overall toll connections in accordance with the toll switching plan, each link must be designed on the basis of the minimum working net equivalent which it will contribute to an overall connection made up of several circuits switched together.

The establishment of satisfactory and economical transmission requirements for the toll circuits laid out in accordance with the plan involves the following steps:

a. The establishment of satisfactory overall net transmission equivalents.

b. The coordinated design of all classes of toll circuits, and of the subscribers' circuits, toll switching trunks and tributary trunks connected to them, in such a way that the desired overall transmission standards will be given at a minimum total cost when suitable transmission gains are provided by repeaters in the toll circuits and at toll switching points.

c. The economical and satisfactory distribution of transmission gain, permitting all toll circuits to be operated at their minimum net equivalents when this is desirable.

The overall transmission equivalents to be given under the plan are based on standards which have heretofore been used for a large part of the toll business but which it has been impracticable to meet in many cases between widely separated points. With the means now available for operating circuits at their minimum working net equivalents, it was found that satisfactory overall transmission equivalents could be provided under the plan even for the maximum number of switches using standards for the construction of toll circuits very comparable with those already applied to new circuits. Expressed in terms of the transmission reference standard, the plan set up gives a maximum of 25 db overall equivalent within one interconnected area (two intermediate switches) and a maximum of 31 db between any two telephones of the United States and eastern Canada.

In order to determine the most economical distribution of these overall equivalents, a study was made based upon the estimated total number of toll circuits of each class in 1932 and their distribution by length. It is also necessary to include the corresponding estimates for the plant between the toll office and the subscriber, the loss in this part of the plant being on the average about half of the overall net equivalent of the connection.

Based upon these estimates, it was possible to determine, by an economic study, the distribution of the overall minimum net equivalent between these various parts of the circuit which would give minimum total expenses. The toll terminal losses and the minimum net equivalents for toll circuits established in this way are shown in Fig. 9.

Classification of Toll Circuit Involved	Minimum Working Net Loss of Toll Circuit—db	Maximum Via Operating Equivalent —db	Transmission Margin—db
Toll Center to Primary Outlet	3.0	4.0	+ 1.0
Toll Center to Regional Center	3.5	4.0	+ 0.5
Primary Outlet to Regional Center	3.5	3.0	− 0.5
Regional Center to Regional Center	4.0	3.0	− 1.0*
Primary Outlet to Primary Outlet	4.0	3.0	− 1.0
Toll Center to Toll Center	6.0	6.0	—
Direct Toll Circuit (for terminal use only)	9.0	—	—
Toll Terminal Loss	7.0	—	—

* Circuits equipped with echo suppressors may be designed with greater negative margins.

Fig. 9—Transmission design data of general toll switching plan.

In addition to the circuits involved in multi-switch business, the studies connected with this plan necessarily include circuits used for terminal business only, and others for which switching is limited to a single intermediate switch at points where transmission gain is not required. These circuits are associated with the plan because the portions of the circuit between the toll center and the subscriber are common for these circuits and for circuits directly involved in the general plan. Design standards for these classes of circuits are also shown in Fig. 9.

Provision of Transmission Gain at Intermediate Switching Points

The third step mentioned previously is the determination of the best distribution of repeater gains to permit the individual circuit to be operated by itself or in conjunction with other toll circuits at approximately the minimum net equivalent as determined by the several effects mentioned previously. In so far as the gain of repeaters permanently inserted at intermediate points in a toll circuit is concerned, this is a matter of economical design of the circuit and has been adequately covered in other papers. We are interested here, however, in considering the provision of gain at the intermediate switching points when two toll circuits are connected together.

As indicated previously, echo effects are usually controlling on the longer connections, whereas crosstalk, singing and noise will usually control on the shorter connections. This is due to the fact that for the great majority of toll circuits the echo effects on individual circuits increase more rapidly with length than do crosstalk and noise. Singing tendencies also increase at a rapid rate with increase in length on two-wire circuits but tend to be independent of length on four-wire cable and carrier telephone circuits which are used to a large extent to provide the circuits between the primary outlets and regional centers and between the regional centers. Furthermore, when two or more toll circuits are connected together, the echo effects of the individual circuits add together almost directly, whereas the effects of crosstalk, singing and noise increase at a much less rapid rate. The result of these general considerations is that when a toll circuit is switched to another toll circuit, the overall combination can, in general, be operated at a lower net equivalent as determined by echo effects than the sum of the two circuits when operated individually in which case the minimum equivalent is determined by the crosstalk, singing and noise effects. Therefore, it is necessary in the case of connections built up by connecting together a number of toll circuits to introduce repeater gain at the intermediate switching points. If gain were not introduced at intermediate points, it would be necessary in order to obtain the same overall results on connections involving more than one toll circuit to design and build a considerably more expensive type of toll circuit plant in which the crosstalk, singing and noise effects would be greatly reduced.

In the past, gain was inserted at intermediate switching points by the use of cord circuit repeaters. These familiar devices consisted of telephone repeaters inserted in the cord circuits and associated by means of double plugs with the toll circuits and with individual balancing networks designed for each toll circuit. By this means intermediate gains of from 4 to 10 db were inserted at the switching points when connection was made between two toll circuits.

The use of cord circuit repeaters has been an outstanding element in the provision of improved transmission on switched connections. It has, however, some disadvantages which have increased in importance with the increase in transmission efficiency of circuits and with the rapid development of toll business. The routine for inserting the cord circuit repeaters when needed is necessarily somewhat cumbersome, involving considerable expense for operators' labor and for increased use of the toll circuits by operators. Furthermore, under practical conditions it was found to be not possible to insure that the cord circuit repeaters would always be used when required by the routing instructions.

Recent developments in the types of toll circuit have greatly increased the numbers of toll circuits provided with repeaters at their terminals as a part of the most economical design of a circuit. When such repeaters are available, the desired switching gain can be obtained by making use of the gain available in these repeaters. The great increase in the number of terminal repeaters required for other reasons, important reductions in the cost of repeaters and the savings of operators' labor and circuit time have made it practicable to adopt a plan of providing, at certain points, terminal repeaters for every circuit, thus doing away entirely with cord circuit repeaters at these points. With the terminal repeater arrangement, the insertion of transmission gain on switched connections is done automatically by taking out of each circuit on such connections a section of artificial line. This is, of course, the equivalent of increasing the gain of the terminal repeater.

Satisfactory transmission results for all connections under the general toll switching plan involve the insertion of repeater gain on all connections switched at important switching points. This will be carried out by the terminal repeater plan just described. The artificial lines or pads which are cut out of the circuit on switched connections have losses of from 1 to 4 db, depending upon the circumstances of each case. This means that when two toll circuits are switched together, from 2 to 8 db is automatically subtracted from the connection at each switching point. The arrangement is indicated schematically in Fig. 10. The design of each circuit must, of course, be such that when either end of the circuit is connected to a subscribers' station, the repeater gain at that end will not be greater than that permissible under the terminating condition, but that when two or more of such circuits are connected together for a long built-up toll connection, the complete circuit will operate at as nearly as practicable its minimum working net equivalent. While under these conditions the permissible values of the pads associated with the terminal repeaters naturally vary in individual cases, it has been found possible to work out for general use a series of values which should give satisfactory results. These are indicated in Fig. 11. It will be noted that these values are such that a circuit switched at both ends to other toll circuits is operated at either .5 db or 1 db less than its minimum working net equivalent, this deficit being made up by a corresponding margin at the ends of the circuit. For example, by reference to Fig. 11, it will be noted that whereas the design values of the three intermediate links of a five-link connection equate to 11 db, these links will contribute a total loss of only 9 db. On the other

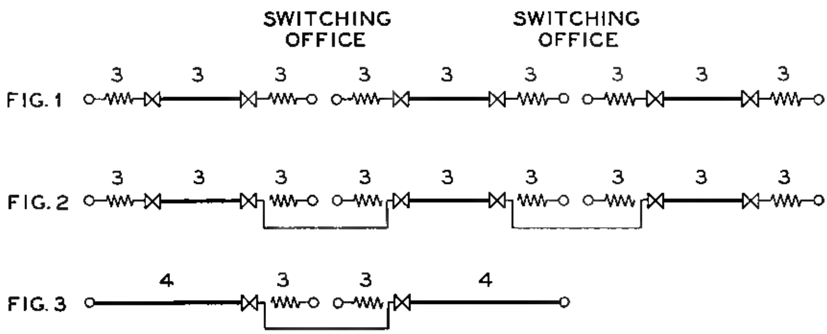


Fig. 10—Illustration of typical transmission data of terminal repeater—switching pad method of operation. Fig. 1—Circuits between switching pad offices in terminal condition. Fig. 2—Circuits of Fig. 1 interconnected at switching pad offices. Fig. 3—Connection between non-pad offices switched at pad office.

hand, the end links will contribute a total of 8 db, whereas their design values equate to only 6 db. The 2 db marginal deficiency in the intermediate links is compensated for by the 2 db marginal surplus in the end links. When intermediate links are used as end links in built-up connections, the switching pads at the terminating ends restore the necessary positive margins.

The design of the very long intermediate circuits, such as some of those connecting two regional centers, requires special consideration and treatment to meet the transmission requirements specified. By making use of a fundamental feature of four-wire circuits equipped with echo suppressors and by employing circuits with the highest velocities of propagation for this purpose, these circuits may be designed in practically all cases to contribute not more than the desired operating equivalent for an intermediate link. Four-wire circuits equipped with echo suppressors are unique in that at the longer circuit lengths the increase in minimum net equivalent with further increase in length becomes very slight.

Two general arrangements for removing the switching pads from and restoring them to the toll line circuits are available depending upon the type of switchboard facilities involved. Either arrangement

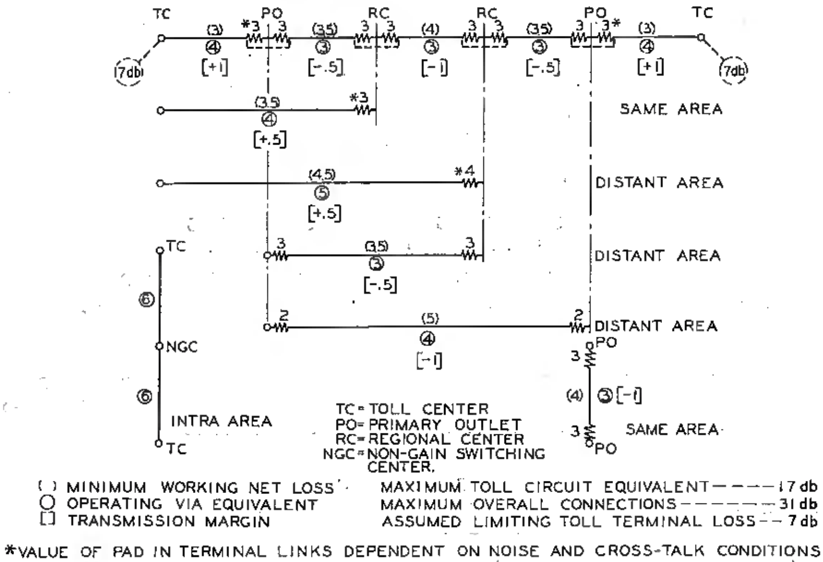


Fig. 11—Diagrammatic representation of transmission data for handling switched toll traffic under general toll switching plan.

requires the modification of both the toll line circuit and the switchboard circuits. One method controls the switching pad by a marginal relay in the sleeve of the toll line circuit. In the other arrangement, the pad is under the control of relays operated by battery supplied from a simplex bridge in the connecting circuits.

With the general toll switching plan the number of places in which switching gain is required is greatly limited, being, as pointed out above, a total of about 150 out of 2,500 toll centers. This number will be somewhat increased by secondary switching points in which it is found economical to insert switching gain in order to save the back-haul involved in following the routing provided by the plan. However, the net result is that under the toll switching plan the number of points at which switching gain is provided will be materially limited, with corresponding economies.

Programming the Establishment of the General Toll Switching Plan

The full application of the general toll switching plan involves a large number of individual rearrangements of plant layout, the establishment of certain new circuit groups and the rerouting of a considerable amount of switched business, the conversion of the switching offices to the terminal repeater arrangement, and the modification of the transmission requirements of certain of the circuits. The date at which these rearrangements will be completed is naturally different for different sections of the country and is determined by the regular program of plant additions and rearrangements to take care of increasing business and of needed service improvement. The existence of a comprehensive plan of this sort insures that the program of rearrangements as carried out will be along the lines of greatest economy and maximum improvement in service. The present plans of the telephone companies in the United States and Canada indicate that the plan as now established will be very closely approximated by the actual plant in the course of about five years.

Future View

Such a plan as has just been discussed is naturally not a static thing but is subject to continual modification to bring it into correspondence with changed conditions. In connection with such changes it is of interest to consider briefly the probable long time trend of the development of the plan.

One possible ultimate development would be the increasing connection of primary outlets to a single regional center so that ultimately only one regional center would be necessary. If this were to take place, the regional center would undoubtedly be Chicago. Fig. 12 is interesting as showing the extent to which the primary outlets already are connected directly with Chicago, over one half of them having such direct connection.

If Chicago ultimately became the only regional center, it would reduce the maximum number of switches to three. It seems evident, however, that such a plan would have many disadvantages. It seems clear that with such an arrangement, numerous secondary regional centers would be necessary to avoid uneconomical back-haul of large amounts of traffic, and the economies of such an arrangement do not look promising. Furthermore, it would lead to a tremendous congestion of through switching at one point, this congestion going far beyond the limits of economical concentration and leading to serious operating difficulties.

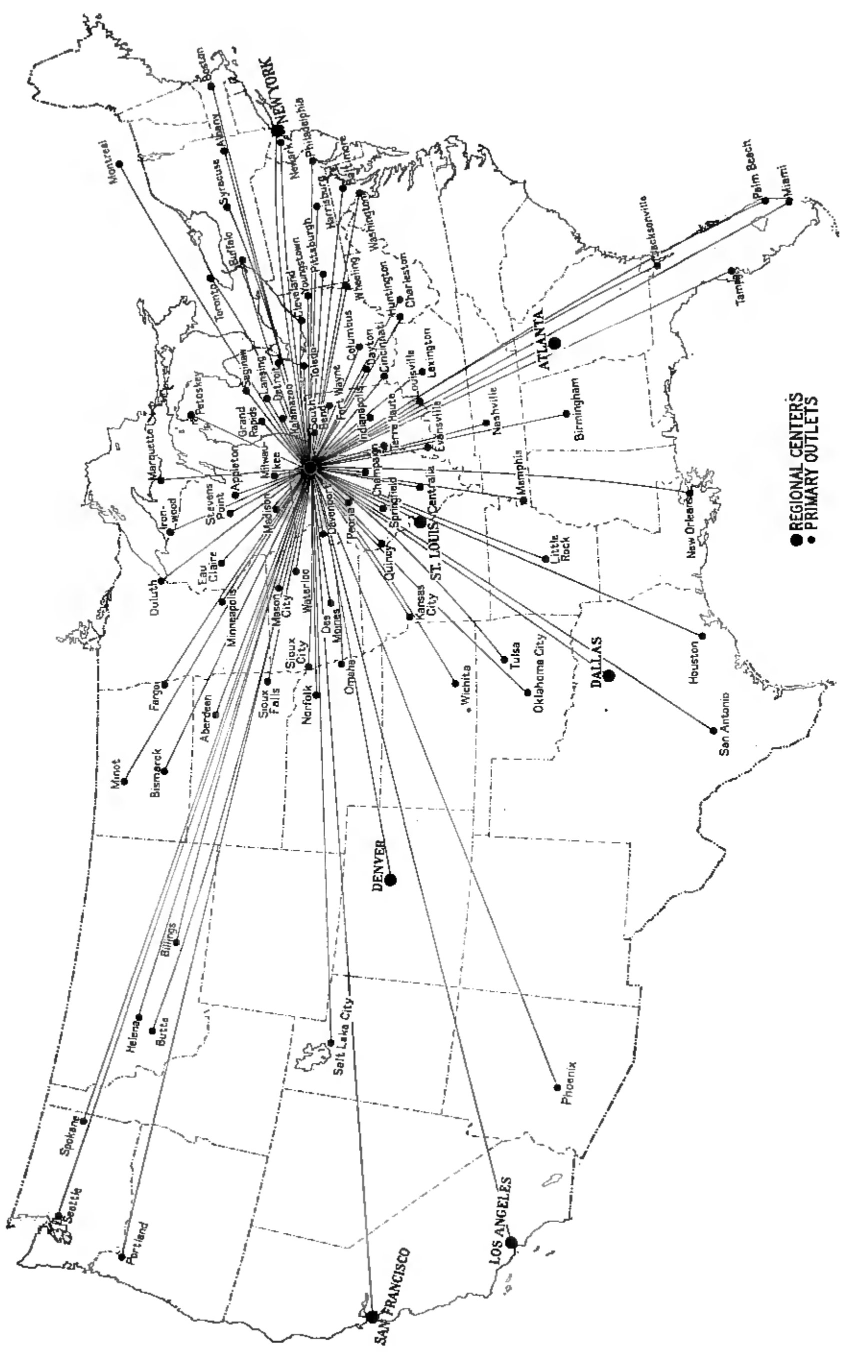


Fig. 12—General toll switching plan—number of primary outlets and regional centers having a direct circuit group to Chicago.

A second, and it is believed more promising general trend would result from the gradual increase in the number of regional centers as the continued development of business makes this economical. With this growth would come also a continued increase in the number of toll centers connected directly to a regional center. By this process there would be a continued growth in the number of toll centers which can be interconnected with a maximum of two intermediate switches, and it is possible that ultimately the primary outlets can drop out of the picture completely, giving a maximum of two intermediate switches for the entire country. While any such outcome is evidently many years away, it seems probable that it is along these lines the growth in development of the plan should be directed.

Although this direction of development avoids the congestion which would be brought about by the single regional center plan, even under this plan the rapidly growing amount of toll switching to be done in large metropolitan centers offers a very important problem for the future. Toll switching at these points is rapidly outgrowing the capacity of a single manual switchboard, as the switching of local calls did long ago. Equipment changes are being made which increase this capacity, but they can be but a temporary relief. Looking to the future, an increasing amount of the outgoing traffic will be handled by operators in the local central offices, reaching the toll line over toll tandem trunks. It is evident, however, that the ultimate solution of the problem will involve the use of machine methods for the selection of the toll line by the operators, as is now done in certain segregated toll tandem systems.

The entire trend of recent years is thus to decrease the differences between the handling of exchange messages and of toll messages. At the present time more than 95 per cent of the toll messages are completed while the subscriber remains at the telephone, with speeds of completion only slightly slower than those of exchange messages. Transmission standards, while naturally somewhat better for the shorter distances involved in exchange messages, are, nevertheless, rapidly becoming very comparable. The present view of trends for the future is for continuation of this process, perhaps even to the use of similar types of machine equipment at central offices for switching the various classes of messages.

The author gratefully acknowledges the assistance of many of his associates in the preparation of this paper, and particularly of Mr. J. V. Dunn.

Image Transmission System for Two-Way Television *

By HERBERT E. IVES, FRANK GRAY and M. W. BALDWIN

A two-way television system, in combination with a telephone circuit, has been developed and demonstrated. With this system two people can both see and talk to each other. It consists in principle of two television systems of the sort described before the June, 1927, Convention of the American Institute of Electrical Engineers. Scanning is by the beam method, using discs containing 72 holes, in place of 50 as heretofore. Blue light, to which the photoelectric cells are quite sensitive, is used for scanning, with a resultant minimizing of glare to the eyes. Water-cooled neon lamps are employed to give an image bright enough to be seen without interference from the scanning beam. A frequency band of 40,000 cycles width is required for each of the two television circuits. Synchronization is effected by transmission of a 1275 cycle alternating current controlling special synchronous motors rotating 18 times per second. Speech transmission is by microphone and loud speaker concealed in the television booth so that no telephone instrument interferes with the view of the face.

DURING the past few years, since the physical possibility of television has been established, the chief problems which have received attention have been those of one-way transmission. In particular, the experimental work in radio television has had for its principal goal the broadcasting of television images, which is inherently transmission in one direction. At the time of the initial demonstration of television at Bell Telephone Laboratories in 1927,[1] one part of the demonstration consisted of the transmission to New York of the image of a speaker in Washington simultaneously with the carrying on of a two-way telephone conversation. At that time it was stated that two-way television as a complete adjunct to a two-way telephone conversation was a later possibility. It is the purpose of this paper to describe a two-way television system now set up and in operation between the main offices of the American Telephone and Telegraph Company at 195 Broadway and the Bell Telephone Laboratories at 463 West Street, New York. It consists in principle of two complete television transmitting and receiving sets of the sort used in the 1927 one-way television demonstration. In realizing this duplication of apparatus, however, a number of characteristic special problems arise, and the paper deals chiefly with matters peculiar to two-way as contrasted with one-way television.

* Presented at June, 1930, meeting of A.I.E.E., Toronto, Canada.

[1] *Bell System Technical Journal*, October, 1927, pp. 551–652.

Physical Arrangement and Operation

The detailed description of the optical and electrical elements of the two-way television system will be more readily grasped if it is preceded by an account of the general arrangement of the parts and of the method of operation of the system from the standpoint of the user.

The physical arrangement of the two-way television system is shown by the pictorial sketch Fig. 1, and in the photographs Fig. 2 and Fig. 3. The terminal apparatus is largely concentrated into a booth,—the television booth—similar in many respects to the familiar telephone booth, and a pair of cabinets, which contain the scanning discs and light sources. As in the 1927 demonstration, scanning is performed by the beam method, the scanning beam being derived from an arc lamp whose light passes through a disc furnished with a spiral of holes and thence through a lens on the level of the eyes of the person being scanned. The light reflected from the person's face is picked up by a group of photoelectric cells for subsequent amplification and transmission to the distant point. The signals received from the distant point are translated into an image by means of a neon glow lamp directly behind a second disc driven by a second motor placed below the first and inclined at a slight angle to it. The two discs, which are shown in the center cabinet of Fig. 2, are of slightly different sizes; the upper one 21″ in diameter and the lower one 30″. They differ from the discs used in the earlier demonstration in that in place of the 50 spirally arranged holes formerly used, they carry 72 holes whereby the amount of image detail is doubled. While with the earlier "50 line" picture recognizable images of a face were obtainable, the aim in this new development was to reproduce the face so clearly that there would never be any doubt of recognizability, and so that individual traits and expressions would be unmistakably transmitted. This doubled number of image elements necessarily requires, for the same image repetition frequency (18 per second) twice the transmission band, or approximately 40,000 cycles as against 20,000 for the 1927 image.

The only part of the television apparatus visible to the user is the array of photoelectric cells which are in the television booth behind plates of diffusing glass. In addition to the photoelectric cells and their immediately associated amplifiers, the booth contains a concealed microphone and loud speaker. By means of these, the voice is transmitted to the distant station and received therefrom without the interposition of any visible telephone instrument which could obscure the face.

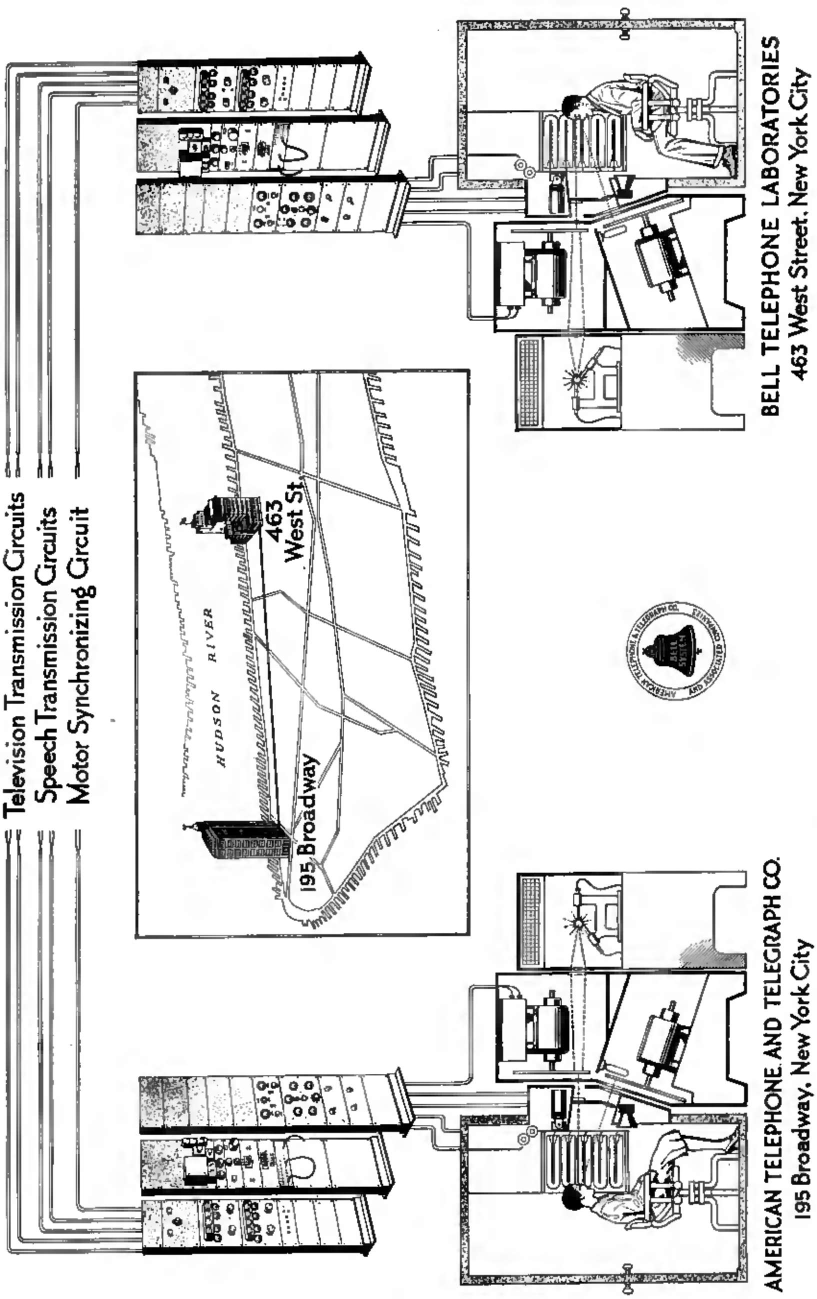


Fig. 1—Pictorial sketch of two-way television system.

From the standpoint of the user, the operation of the combined television and telephone system is reduced to great simplicity. He enters the booth, closes the door, seats himself in a revolving chair, swings around to face a frame through which the scanning beam reaches his face, and upon seeeing the distant person, he talks in a natural tone of voice, and hears the image speak. Conversation is carried on as though across a table.

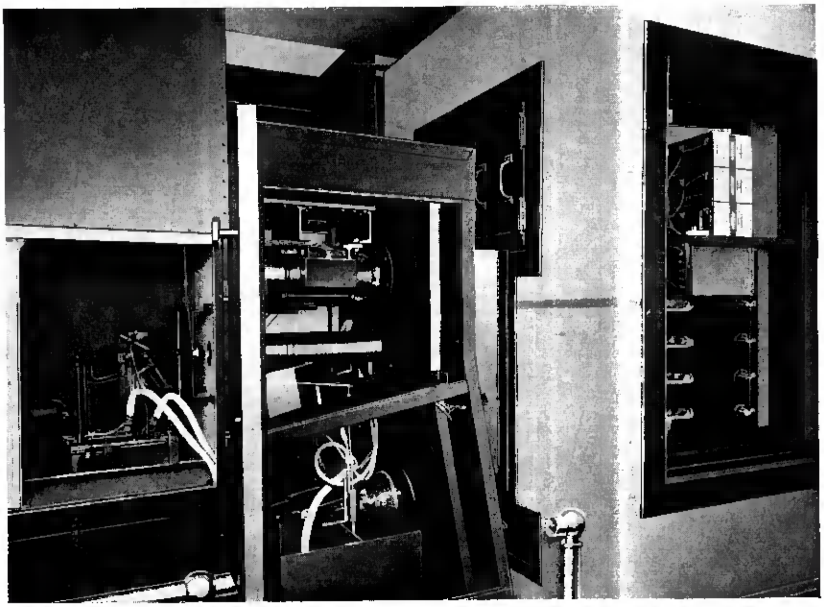


Fig. 2—The three major cabinets of the television-telephone apparatus.

Optical Problems

Some of the more special of the problems encountered in two-way television are primarily optical in character. The principal one is that of regulating the intensity of the scanning light and of the image which is viewed so that the eye is not annoyed by the scanning beam or the neon lamp image rendered difficult of observation. It has been necessary for the solution of this problem to reduce the visible intensity of the scanning beam considerably below the value formerly used and to considerably increase the brightness of the neon lamp.

The means adopted consists first, in the use of a scanning light of a color to which the eye is relatively insensitive but to which photoelectric cells can be made highly sensitive. For this purpose blue light has been used, obtained by interposing a blue filter in the path of the arc light beam, and potassium photoelectric cells specially sensitized to blue light and more sensitive than those previously used have been developed. The number of these cells and their area has also been increased over those used in the earlier television apparatus so that the necessary intensity of the scanning beam is decreased.

The second half of the problem, namely that of securing a maximum intensity of the neon lamp, has been attained by the development of water-cooled lamps capable of carrying a high current. The net result of the use of the blue light for scanning, of more sensitive photoelectric cells, and of the high efficiency neon lamps is that the user of the apparatus is subjected only to a relatively mild blue

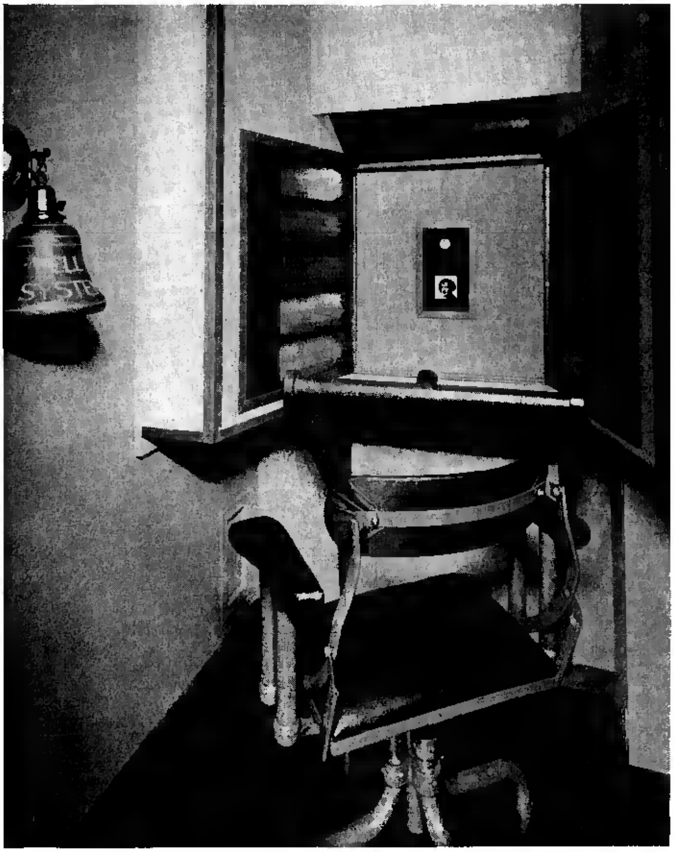


Fig. 3—Interior of the television booth.

light sweeping across his face, which he perceives merely as a blue spot of light lying above the incoming image. Figure 3 shows the interior of the television booth with the frame through which the observer sees the image of the distant person.

A second optical problem is the arrangement of the photoelectric cells required in order to obtain proper virtual illumination of the observer's face. As we have previously pointed out in discussing the beam scanning method,[2] the photoelectric cells act as virtual light sources and may be manipulated both as to their size and position like the lights used by a portrait photographer in illuminating the face. In the present case, it is desired to have the whole face illuminated and accordingly photoelectric cells are provided to either side and above. One practical difficulty which is encountered is that eyeglasses, which often cause annoying reflections in photography are similarly operative here. For this reason, it is important that the photoelectric cells be placed as far to either side or above as possible. The banks of photoelectric cells shown in Fig. 3 are accordingly much farther removed from the axis of the booth than were the three cells used in the first demonstration. In the position which has been chosen for the cells, reflections from eyeglasses are not annoying unless the user turns his face considerably to one side or the other.

The number of cells has been so chosen as to secure a good balance of effective illumination from the three sides and it has been found desirable to partly cover the cells on one side in order to aid in the modelling of the face by the production of slight shadows in one direction.

Another optical problem is the illumination of the interior of the booth. There must, of course, be sufficient illumination for the user to locate himself, and it is also desirable that the incoming image and the scanning spot be not seen against an absolutely black background. The illumination of the booth is by orange light, to which the cells are practically insensitive, and so arranged that the walls and floor are well illuminated. In addition to the wall and floor illumination, a small light is provided on the shelf bar in front of the observer so as to cast orange light on the front wall surrounding the viewing frame. This light contributes materially to reducing the glaring effect of the scanning beam, and to the easy visibility of the incoming image.

In addition to the optical features which are visible to the person sitting in the booth, there are very necessary optical elements which

[2] *Jnl. Optical Soc. of America*, March, 1928, p. 177.

have to do with the positioning of the outgoing and incoming images. A practical problem which is encountered when customers of various heights use the apparatus is that the scanning beam, if fixed in its position, would strike too high or too low upon many faces. In order to direct the beam up or down as is required, a variable angle prism, consisting of two prisms arranged to rotate in opposite directions,

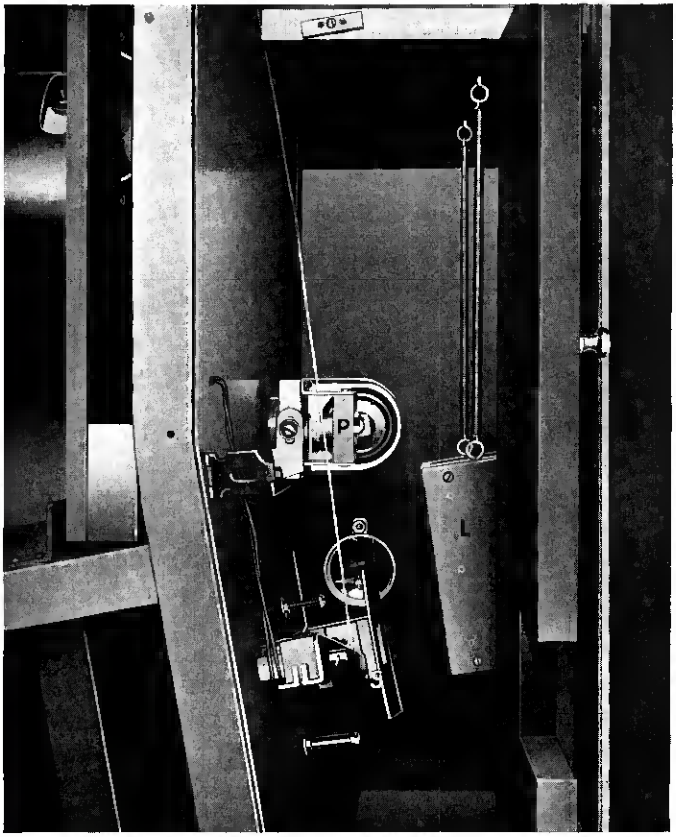


Fig. 4—Optical means for controlling heights of scanning and viewing beams.

is interposed in the path of the scanning beam. This prism, which lies directly in front of the projection lens used with the upper disc, is shown in Fig. 4 at *P*. Its rotation is controlled by a knob with a numbered dial. The exact position is determined by the operator by reference to a monitoring image which will be described below.

Another optical element which serves two purposes, is a large convex lens lying between the receiving disc and the observing frame, shown at L, Fig. 4. This lens is used to magnify the incoming image to such a size that the image structure is just on the verge of visibility, under which condition the face of the distant person appears as though he were approximately eight feet away. In addition to acting as a magnifier, this lens serves to position the incoming image to fit the height of the user. For, by raising or lowering it by means of a knob, the operator, using the information as to the observer's height obtained from the position of the scanning beam, locates the lens so that the virtual image appears in the proper position.

Photoelectric Cells and Associated Circuits

The photoelectric cells used in this apparatus are similar in shape to those used in the first demonstration, but somewhat larger. Each

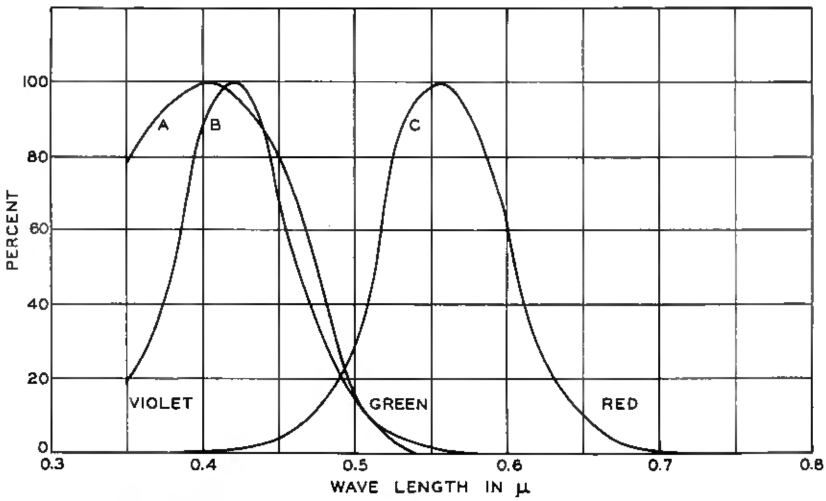


Fig. 5—*A*. Relative optical transmission of the blue filter through which the scanning beam passes. *B*. Relative sensitivity of the photoelectric cells to various parts of the spectrum. *C*. Relative sensitivity of the eye to various parts of the spectrum.

cell is twenty inches long and four inches in diameter, giving it an area of approximately eighty square inches for collecting light. The anode is made in the form of a hollow glass rod wound with wire. This construction prevents the electrical oscillations that would otherwise result from mechanical vibrations of the anode. The sensitive cathode consists of a coating, covering the rear wall of the tube, of potassium sensitized with sulphur.[3] This kind of cell is considerably more sensitive than the older type of potassium-hydride cell

[3] A. R. Olpin, *Phys. Rev.*, **33**, 1081 (1929).

while still having most of the sensitiveness in the blue region of the spectrum. Figure 5 shows the response of the photoelectric cells used to the various parts of the spectrum together with the transmission of the blue filter and the brightness of the various parts of the spectrum as evaluated by the human eye. The very great efficiency of the photoelectric cells and the inefficiency of the eye to the light used are apparent.

To amplify the photoelectric current, the cells are filled with argon at a low pressure. Photoelectrons passing from the sensitive film to the anode ionize the gas atoms along their paths and thus cause a greater flow of current. The ionization of the gas does not, however, instantaneously follow sudden variations of the true photoelectric emission from the sensitive film, that is, there is a time lag in the

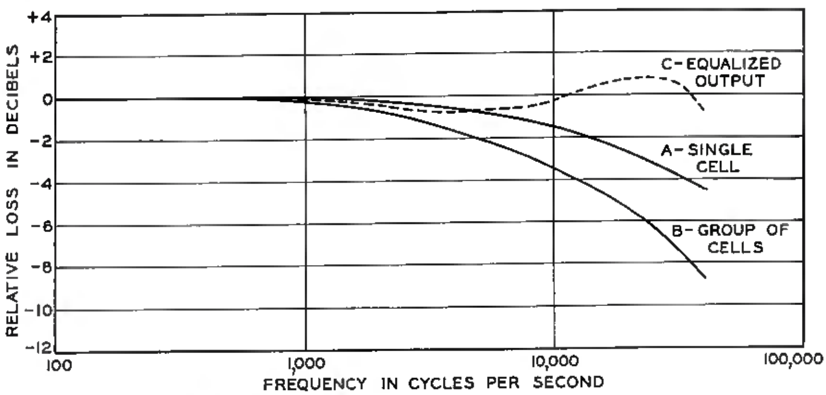


Fig. 6—Loss in response of photoelectric cells at high frequencies.

ionization of the gas and in the disappearance of ionization. This lag results in a relative loss and phase shift of the high frequency components of a television signal with respect to the low frequency components which become serious in the wider frequency range utilized in the 72 line image. The relative loss in output from a single large photoelectric cell at high frequencies is shown in decibles by curve A of Fig. 6.

In the television booth, the twelve large cells mounted in the walls of the booth present an area of approximately seven square feet to collect light reflected from a subject. To secure the desired effective illumination, the cells are mounted in three groups, comprising a group of five cells in each of the two side walls of the booth and a group of two cells in the sloping front wall above the subject. The twelve cells are enclosed in a large sheet copper box, provided with doors to each group. The cells of each group are connected in parallel through the input resistance of a two stage resistance-capacity coupled amplifier similar to those previously used. This raises the level of the signal to such a point that the output of the three amplifiers may be carried through shielded leads and connected in parallel to a common amplifier.

The metal anodes and lead wires of the cells in parallel in any one group give an appreciable capacity to ground, which results in a further loss in amplitude and phase shift of the high frequency components of the signal. The combined loss introduced by ionization of the gas in the cells and by capacity to ground is shown by curve *B* of

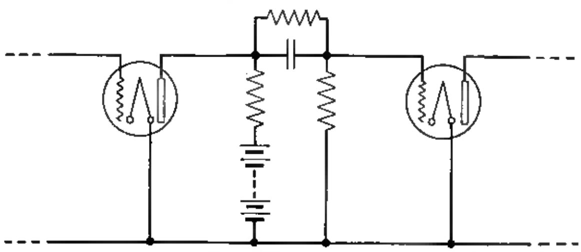


Fig. 7—Schematic of interstage amplifier coupling to equalize for the high frequency losses in the photoelectric cells.

Fig. 6. This combined loss is equalized by an interstage amplifier coupling, Fig. 7. The equalized output from the photoelectric cells is shown by curve *C*, Fig. 6.

Two-Way Image Signal Amplifiers

The vacuum tube system used to amplify the photoelectric cell currents in two-way television is patterned closely after that used previously in one-way television, and the description here will be confined chiefly to novel features. These new features are necessary to take care of the doubled frequency band which results when the scanning is done with a 72-hole disc rather than with a 50-hole one, and to provide sufficient power to operate the high intensity neon lamp which is essential to two-way television. Certain other new features have been introduced in order to simplify the apparatus and to reduce the maintenance required to keep it in good working condition.

The vacuum tubes which operate at low energy levels are the so-called "peanut" type, chosen because of their freedom from microphonic action and their low interelectrode capacities. Protection against mechanical and acoustical interference is secured by mounting these tubes in balsa wood cylinders which are loaded with lead rings and cushioned in sponge rubber. The tubes are electrically connected in cascade by means of resistance-capacity coupling, so that the whole amplifier system is stable over long periods of time and is also uniformly efficient over the required frequency band. Grid bias for the small tubes is supplied by the potential drop across a resistance in the filament circuit; the power requirements for the low level stages of the amplifier are filled by 6-volt filament batteries and 135-volt plate batteries, all located externally where they can be checked and replaced conveniently.

The amplifier system is divided into units of convenient size as shown in Fig. 8. Associated with each of the three banks of photo-

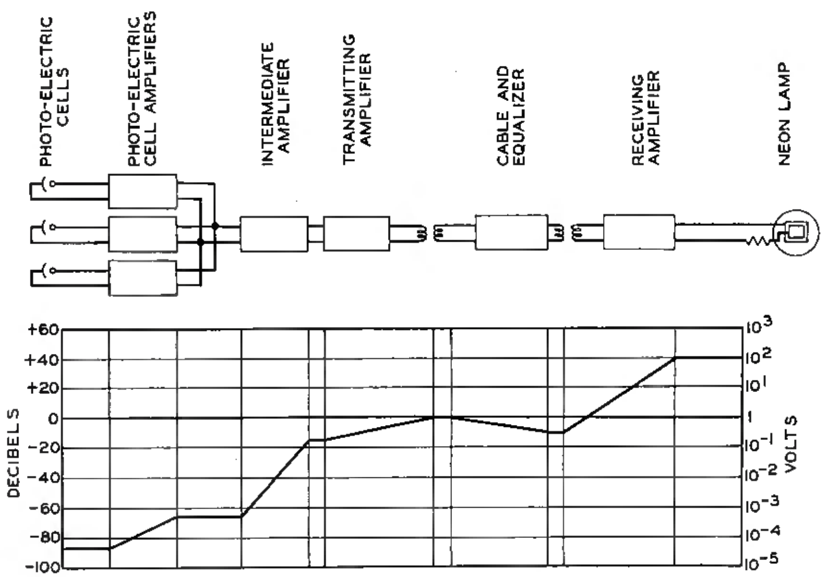


Fig. 8—Schematic diagram of the complete television channel and the relative voltage levels of the signal along the channel.

electric cells is a two-stage unit known as the photoelectric cell amplifier; the combined output of these three units is carried to a four-stage unit known as the intermediate amplifier whose output is of sufficiently high level to be carried outside the copper cell cabinet to the three-stage transmitting power amplifier on the relay rack. A four-stage unit known as the receiving power amplifier is also on the rack, and serves to amplify the signal from the other station to a level which will yield an image of satisfactory contrast when it is translated into a light variation by means of the neon lamp. The final stage of this amplifier consists of two special 250-watt tubes in parallel. These large tubes are used because their plate impedance is of the same order of magnitude as the impedance of the neon lamp, and because they will supply the necessary direct current to the neon lamp without overheating.

Figure 8 also shows what may be termed a voltage level diagram for the whole system. Ordinates on this diagram represent voltage amplitudes at the junctions between units of the system, and by themselves tell nothing at all about the power conditions in the system, since the impedances are not specified. It is interesting to observe that the signal voltage produced by the three banks of photoelectric cells has an effective value of about 50 microvolts across the 50,000 ohm input resistance; the transmitting amplifier delivers about 1 volt to the 125-ohm cable circuit, and the receiving amplifier delivers about 100 volts to the 1,000 ohm neon lamp circuit. The signal current through the neon lamp has an effective value about a thousand million times greater than that of the current variation in one of the photoelectric cells.

The most outstanding contribution to the development of television amplifiers is the combination of output and input transformers whose transmission characteristics are shown in Fig. 9, *A*, and whose impedance characteristics are shown in Fig. 9, *B*, and *C*. The exceptionally wide frequency range, corresponding to a ratio of limiting frequencies of 5,000 to 1, transmitted by these transformers is due largely to the use of chrome permalloy, a recently developed core material having very high permeability. The improved characteristics are also the result of refinements in design which involve the use of adjusted capacities and resistances to control the characteristics at the higher frequencies. Due to the fact that each terminated transformer looks like a resistance of 125 ohms over practically the entire frequency range of the image signal, it makes no difference in the form of the overall voltage amplification characteristic of the circuit whether the transformers are connected together directly or by means of the equalized cable circuit whose characteristic in shown in Fig. 10. Advantage of this circumstance is taken in providing switching means whereby each transmitting amplifier may be connected through a resistance pad to its local receiving amplifier, enabling a person to see his own image in the television booth, which is a convenience in making apparatus adjustments.

Transformers of this type must be carefully protected against magnetizing forces which might cause polarization of the core material. In order to keep the plate current of the final tube of the transmitting power amplifier from flowing through the winding of the output

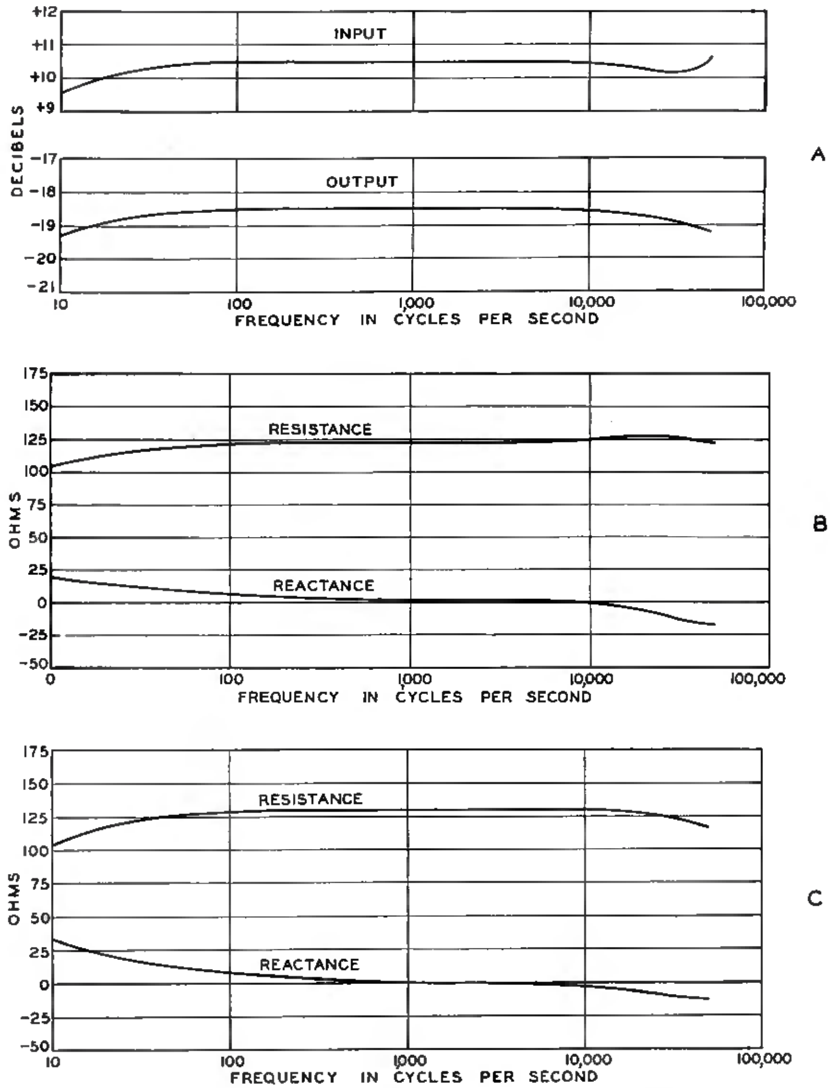


Fig. 9—*A*. Voltage ratio characteristics of W-7879 input transformer and W-7880 output transformers, each connected between its rated impedance. *B*. Impedance characteristic of W-7880 output transformer with 1765 ohm resistance load. *C*. Impedance characteristic of W-7879 input transformer with 20 mmf. capacity load.

transformer, the transformer winding is shunted by a battery and a resistance in series. The resistance is made high, so that the transmission loss due to bridging it across the circuit is small; the voltage of the battery is made equal to the potential drop across the resistance due to the plate current of the tube, so that the average voltage across both the battery and the resistance, and hence across the transformer winding, is zero.

A vacuum thermocouple is connected in series with the line winding of the output transformer, serving as level indicator for the transmitting amplifier. The level indicator for the receiving amplifier is

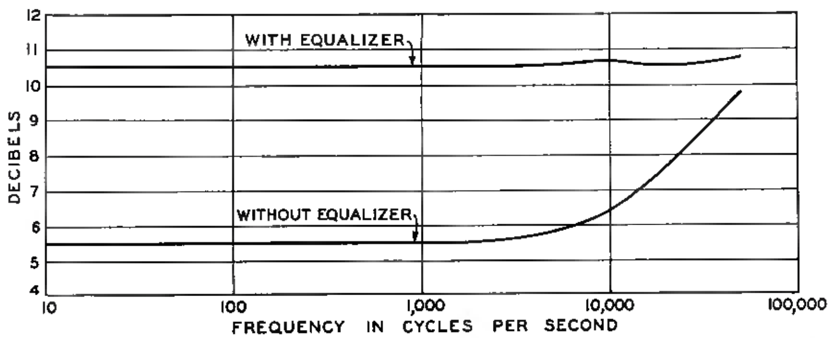


Fig. 10—Insertion loss characteristic of cable cricuits which transmit the image signal, measured between 125 ohm resistances.

a vacuum thermocouple in series with the grid resistance of the two 250-watt tubes.

The electrical control panels associated with one terminal of the television apparatus are shown in Fig. 11.

Transmission Circuits

Two special requirements for the two-way television transmission circuits are to be emphasized. The first, which has already been referred to, is the wide frequency transmission band, from 18 cycles to 40,000 cycles, which must have a high degree of uniformity of transmission efficiency and freedom from phase distortion. The second is the necessity for *two* circuits for the television images. This arises from the fact that the two parties to the conversation must both see and be seen at all times. There can be no interruption of one face by the other, comparable with the alternation of the role of speaker and listener in telephony which permits the use of a single circuit for ordinary speech communication.

The terminal stations of the two-way television system are connected by eight underground circuits, each consisting of 13,032 feet of No. 19 gauge and 390 feet of No. 22 gauge non-loaded cable. Two circuits are used for transmitting the image signals, two for the accompanying speech, one for the synchronizing current, two are used as

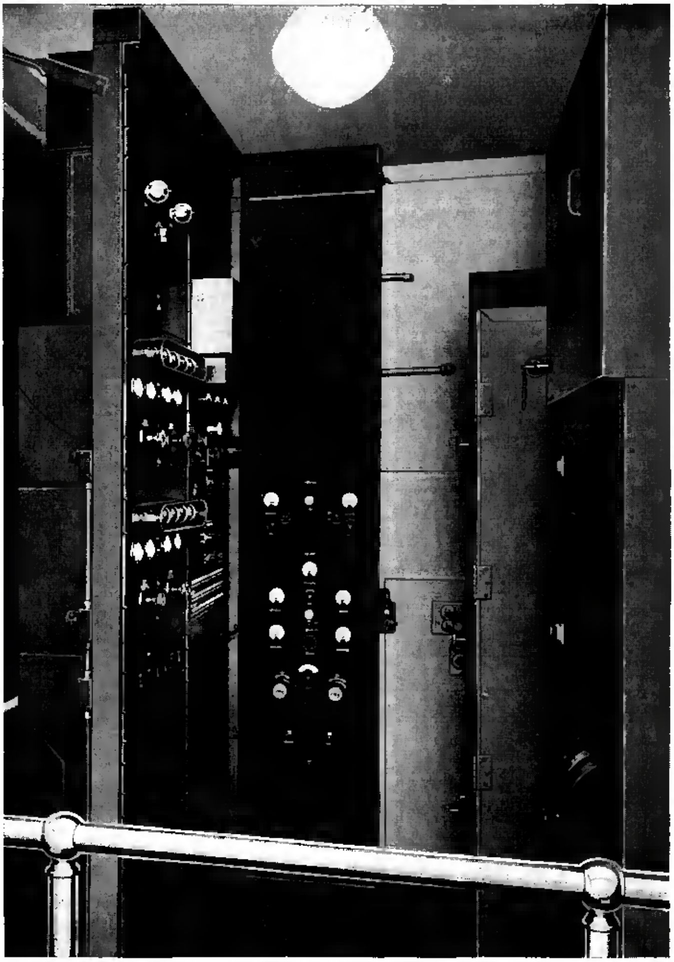


Fig. 11—Control apparatus panels associated with one terminal of the television apparatus.

order wires, and one is kept as a spare. All of the circuits have identical transmission characteristics, but equalization is necessary only on the two which carry the image signals. Figure 10 shows the insertion loss characteristic of each circuit, and also shows the insertion loss characteristic of the image circuits when the image line equalizers are included.

Although the distance between the stations is small the requirements of the television system from the standpoint of freedom from noise and other interference require that considerable care be given to the selection of the cable circuits used. All terminal connections are made through balanced repeating coils or transformers so that all of the circuits are balanced to ground. Also, in order to insure that the crosstalk between the various channels be unnoticeable the terminal equipment is so adjusted that approximately the same amount of power is transmitted by each circuit.

Neon Lamps and Associated Circuits

After amplification, the received television signal is impressed on the grids of two power tubes in parallel to furnish current for a neon receiving lamp. The terminal lamp circuit is shown in Fig. 12.

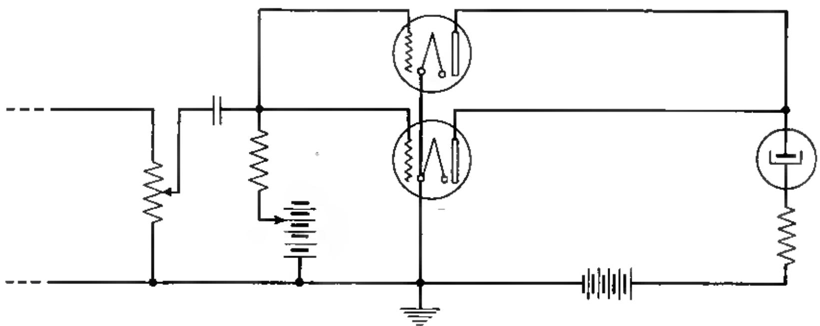


Fig. 12—Schematic of neon lamp circuit.

The grid bias of the two power tubes is varied by the operator to control the DC plate current, which replaces the original DC signal component suppressed at the sending end. The quality of the reproduced image is determined by the operator's control over the relative levels of the incoming AC signal and the restored DC current.

The television current from the power tubes is translated back into light by a water-cooled neon lamp designed to operate on a large current. The structural details of the lamp are shown in Fig. 13. Heavy metal bands attach the rectangular cathode to a hollow glass stem occupying the central portion of the tube. Water from a small circulating pump flows continuously through the glass stem and cools the cathode by thermal conduction through the metal bands. To reduce sputtering of the cathode and consequent blackening of the glass walls, the front surface of the cathode is coated with beryllium. This metal resists the disintegrating action of the glow discharge very satisfactorily and gives the lamp a prolonged life. Other metal surfaces in the tube are shielded from the discharge by mica plates; and

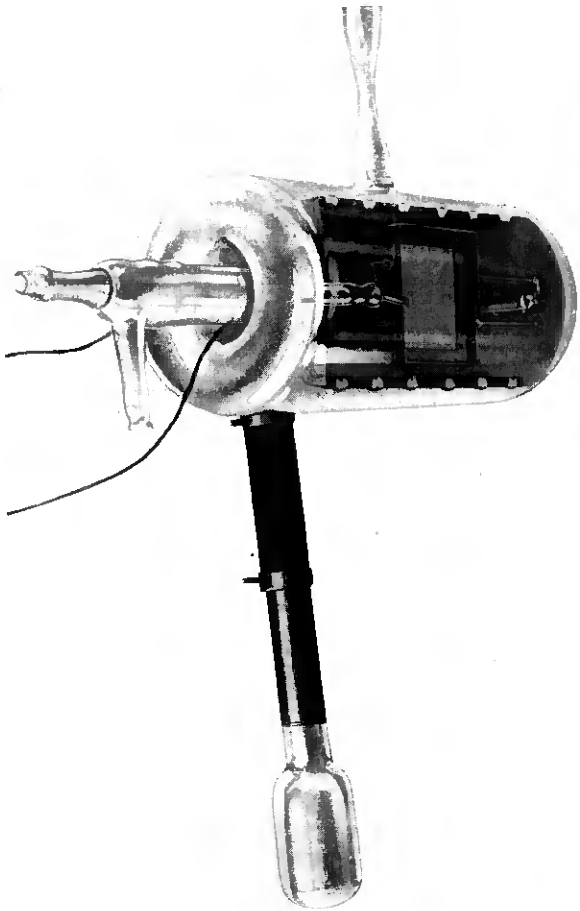


Fig. 13—Water-cooled neon lamp.

the discharge passes from the frame-like anode to the front surface of the cathode, covering it with a brilliant layer of uniform cathode glow.

Pure neon in a plate type of lamp gives a very inferior reproduction of an image. The impedance of the lamp is relatively high and comprises both a resistance and a reactance which vary with frequency. The variation in the impedance causes a relative loss in the frequency components of the signal and also introduces spurious phase shifts.

In addition, pure neon has an after-glow; the gas continues to glow for an appreciable time after current ceases to flow. This after-glow casts spurious bands of illumination out to one side of the brighter image details.

A small amount of hydrogen in the neon prevents such an afterglow; and at the same time improves the circuit characteristics of the lamp. The total impedance of the lamp is lower, making it a less influential part of the lamp circuit; and the resistance and reactance vary in such a manner that the phase shift is more nearly proportional to frequency (a phase shift proportional to frequency causes no distortion in the reproduction of an image). Other active gasses may be used with the neon to improve the operation of a television lamp, but one or two per cent of hydrogen is most satisfactory.

Since hydrogen is absorbed by the electrodes in a glow discharge, it slowly disappears from the neon during operation of the lamp. For this reason the lamp is provided with a small side reservoir of hydrogen. The lamp and the reservoir carry porous plugs immersed in a pool of mercury; and a flexible rubber connection permits the two plugs to be brought into contact at will. Minute quantities of hydrogen may be introduced into the lamp by simply bringing the two plugs into contact for a short time.

Even with this improvement the circuit characteristics of a lamp are not ideal. With power tubes it is usually desirable to include a fixed resistance in series with the lamp to prevent semi-arcing conditions. Such a resistance also makes the lamp a less influential fraction of the total circuit impedance.

Optical Monitoring System

In order to insure that the incoming and outgoing images are properly positioned, no matter what the stature of the person sitting in the booth, and that the images shall be of proper quality, it is essential to have some means for the operator to observe and adjust these images. The optical monitoring system provided consists of an outgoing monitor and means for adjusting the scanning beam, and an incoming monitor and means for adjusting the position of the viewing lens to suit the height of the sitter.

The outgoing monitoring system is the same as that used in the one-way television apparatus which has already been described. A small neon lamp (Fig. 14, at bottom of top disc) is placed behind the sending disc but displaced several frames from the aperture through which the arc lamp beam passes. By continuing the spiral of holes part way around it is possible to see the complete image from the auxiliary neon lamp, to which the outgoing signals are also supplied. In order to see this monitoring lamp from the operator's position, a right-angle prism and a magnifying lens are placed in front of the disc and the image is observed through an opening in the side of the motor cabinet. The

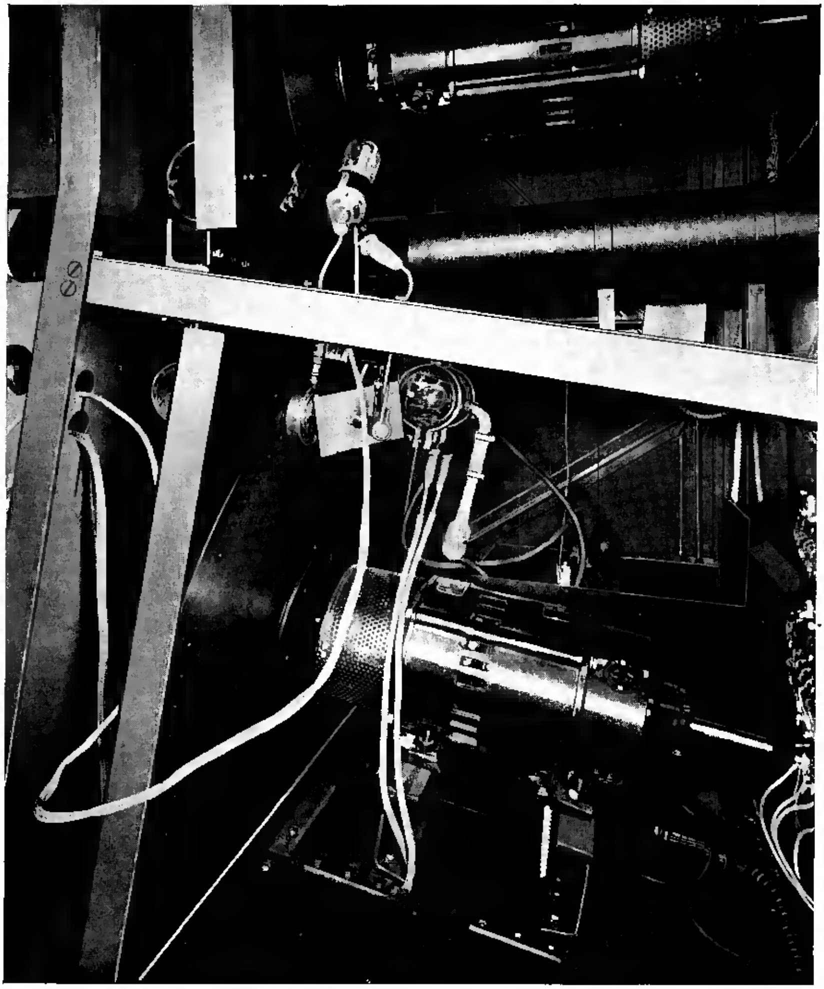


Fig. 14—Sending and receiving discs, with neon lamps and optical arrangements for image monitoring.

task of the operator is to direct the scanning beam up or down by means of the variable angle prism until the face of the person in the booth is centrally located. This adjustment is facilitated by a wire which passes across the image and is placed at the height at which the user's eyes should appear.

The height of the observer's eyes is an indication of the position which should be taken by the large magnifying lens *L*, and the operator, after having properly placed the scanning beam, reads the scale on the variable angle prism dial, and then sets the magnifying lens by turning its controlling knob to the same number. When both adjustments are complete, the person in the booth will not only be properly scanned but will be in the best position to see the image.

In order to monitor the incoming image, an optical arrangement is adopted by means of which light from the water-cooled neon lamp is taken off at the side and reflected through the disc and thence reflected again, as shown in Fig. 14 (top of bottom disc), through a second, lower, observing hole on the side of the motor cabinet. Because of the small area of the side view of the neon lamp, a lens system is inserted which focusses the image of the lamp at the place to be occupied by the pupil of the operator's eye. When the eye is properly placed, the whole of the lens area is seen filled with light and exhibits the incoming image.

In addition to the monitoring means just described, an additional view of the incoming image is provided by means of a 45° mirror which is carried on the back of a movable shutter which is shown at *S* in Fig. 4. This shutter carries an illuminated sign on the side turned to the user with the inscription "Watch this space for television image." The shutter with its sign covers the image until the adjustments just described are made, when it is dropped out of sight. While it is in place, the operator is provided with an additional monitoring image reflected from the 45° mirror. This view is, of course, in every respect identical with that which the user sees.

The function of the incoming monitoring system is primarily to enable the operator to set the electrical controls to give the proper quality of image. He also has another task which is that of properly framing the image. This he can do by turning the framing handle, which is described elsewhere, while watching the image from the 45° mirror. This framing operation is preferably performed not on a person sitting in the booth but upon some suitable object such as a mirror located upon the rear door of the booth. In order to make this framing adjustment, the operators at the two terminals set their scanning beam dials to predetermined positions such that the scanning beams place the framing mirrors at the lower edge of the scanning rectangles, the phases of the incoming discs are then shifted until the images of the mirrors are seen properly located in the incoming monitors.

Signalling System

In order to coordinate operations at the two terminal stations, an order wire system is provided. There are four telephone sets at each station; one on the attendant's desk in the ante-room, one concealed inside the television booth, one in the control room, and one at the control panels for the technical operator, who operates the small switchboard which is part of the system. Two of the underground cable circuits connect the two switchboards, so that there may be not more than two separate conversations between stations at one time. Ringing is accomplished by means of standard 20-cycle ringing current furnished by the Telephone Company.

During a demonstration, the attendants' telephones are connected permanently over one of the cable circuits. To relieve the operators of the duty of ringing each time the attendants wish to communicate, a push button and buzzer are provided at each attendant's desk, operated by the standard ringing currents simplexed on the synchronizing circuit. This arrangement leaves the operators free to manipulate the television apparatus.

The two order wire circuits are each simplexed to provide two additional circuits which operate signal lamps indicating to both operators when either chair in the television booths is occupied and turned in position.

Discussion

The primary objects in developing and installing the two-way television system have been two. The first was to obtain information on the value of the addition of sight to sound in person to person communication over the telephone. The second was to learn the nature of the apparatus and operating problems which are involved in a complete television-telephone service. While the installation is entirely experimental, it is being maintained in practically continuous operation for demonstration to employees and guests of the Telephone Company, and interesting data are being gathered on all aspects of the problem.

It may be said without fear of contradiction that the pleasure and satisfaction of a telephone conversation are enhanced by the ability of the participants to see each other. This is, of course, more evident where there is a strong emotional factor, as in the case of close friends or members of the same family, particularly if these have not been seen for some time.

Were the television apparatus and required line facilities of extreme simplicity and cheapness it would be safe to predict a demand for its early use. At the present time, however, the terminal apparatus is complex and bulky, and requires the services of trained engineers to maintain and operate it. In addition to the cost of the terminal apparatus there is the unescapable item of a many-fold greater transmission channel cost. Because of the wide transmission bands required for the television images, the inherent necessity for a television channel in each direction, and the extra channels for synchronizing and signalling, the total transmission facilities used in this demonstration are those which could, according to current practice, carry about fifteen ordinary telephone conversations. It is to be expected, of course, that development work will result in some increase in the efficiency of the transmitting channels and in simplifications of the terminal apparatus. It is conceivable, therefore, that our present conception of the cost of the whole system may ultimately be materially changed.

Synchronization System for Two-Way Television *

By H. M. STOLLER

In a previous paper presented before the June, 1927 Convention of the American Institute of Electrical Engineers, the method of securing synchronization of television signals was described as employed in the Bell System Television demonstration of April, 1927. The present paper describes the development of a new control circuit which is in use in the new two-way television system between the Bell Telephone Laboratories at 463 West Street and the American Telephone and Telegraph Company building at 195 Broadway, New York.

TELEVISION transmission requires not only synchronization of the transmitting and receiving equipment but such synchronization must be held to a narrow phase angle so that the scanning discs at the transmitting and receiving end will never depart more than a small fraction of a picture frame width from the desired position.[1] In the 1927 demonstration, 2125 cycle synchronous motors were employed with supplementary D.C. motors to facilitate starting. This plan required the use of vacuum tube amplifiers of large size in order to supply sufficient power to the synchronous motors.

Such high frequency synchronous motors, however, are inefficient and expensive, so that when designing the new system, it was desired to solve the problem of synchronization with simpler and cheaper equipment and in a manner which would require less attention in starting. It was particularly desired to employ a motor which could be operated directly from the 110 volt lighting circuit without any auxiliary "A", "B" or "C" batteries for the control equipment.

Description of Motor

Figure 1 shows a photograph of the new television motor and its associated control equipment.

The motor is a four pole compound wound D.C. motor with the following special features added.

1. An auxiliary regulating field, the current through which is controlled by the vacuum tube regulator.
2. A damping winding on the face of the field poles to prevent the field flux from shifting (Fig. 3).

* Presented at June, 1930, meeting of A.I.E.E., Toronto, Canada.

[1] These requirements are more fully discussed in a previous paper. (*Journal of the A. I. E. E.*, Vol. 46, page 940, 1927.)

3. Three slip rings are provided at points 120 electrical degrees apart for furnishing three phase power to supply plate and filament voltage for the regulating circuit.
4. A pilot generator of the inductor type is built into the motor frame and delivers a frequency proportional to the motor speed for actuating the control circuit.

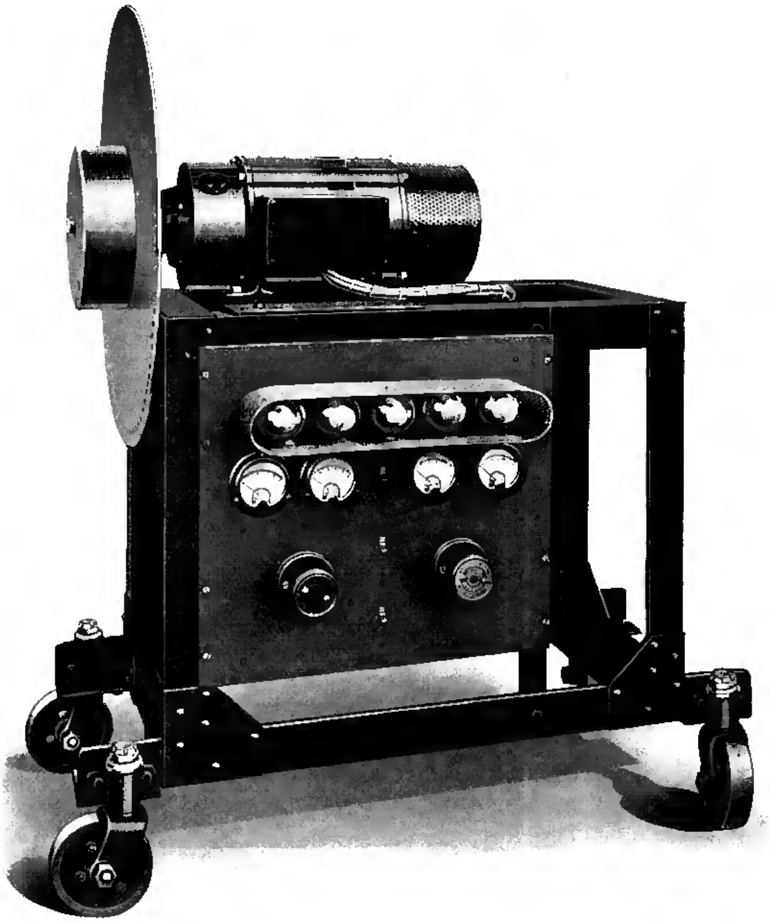


Fig. 1—New television motor and vacuum tube control circuit.

5. A hydraulically damped coupling is provided between the motor shaft and the scanning disc. (Fig. 4.)

The motor frame was made from a standard 36 tooth stator punching by cutting out three teeth per pole, thus forming four polar areas of six teeth each. The shunt, series and regulating fields enclose the entire polar areas. The damping winding consists of insulated closed turns of heavy copper wire distributed over the pole faces in the slots as shown in Fig. 3. It will be noted that this damping winding has no effect upon the flux through the poles as long as the flux density over the polar surface does not shift. In other words, the damping winding permits the total flux of the motor to increase or decrease as required by the regulating circuit but will oppose any tendency of the flux to shift back and forth across the pole face. As will be explained

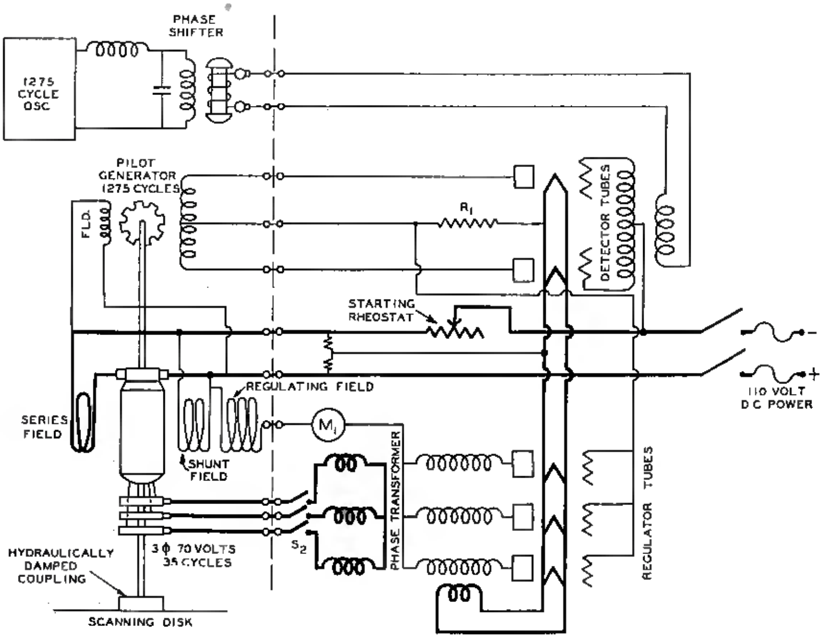


Fig. 2—Schematic diagram of control circuit.

later on, this feature is essential in order to prevent hunting or instability of the image.

The hydraulically damped coupling between the motor shaft and the scanning disc is also essential in order to avoid hunting. It employs flexible metal bellows filled with oil and connected by a small pipe equipped with a needle valve for adjusting the amount of damping. Figure 4 shows its construction. The scanning disc itself is centered on a ball bearing which allows the disc to rotate with respect to the shaft within approximately ± 5 degrees mechanical movement.

CONTROL CIRCUIT

Figure 2 shows a schematic diagram of the control circuit. When the motor is operating at full speed the pilot generator delivers approximately 1 watt of power at 300 volts, 1275 cycles to the plates of a pair of push-pull detector tubes. The grids of these tubes are supplied with an e.m.f. of the same frequency from an oscillator or other source of power having a sufficiently constant frequency. The amount of power required for this grid circuit is only a few thousandths of a watt. The detector tubes rectify the plate voltage producing a potential drop across the coupling resistance R_1. If the plate and grid voltages are in phase, so that the grids of the tubes are positive at the

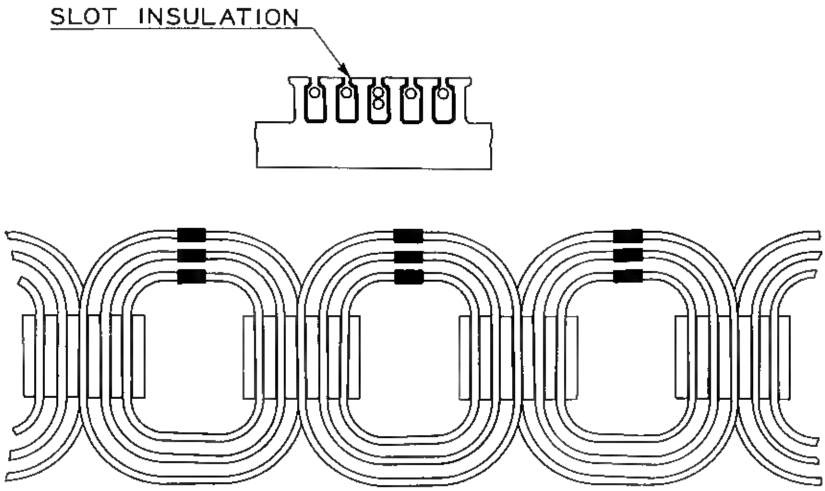


Fig. 3—Damping winding preventing shifting of field flux.

same instant that the plates are positive, the plate current will be a maximum. If the grid voltage is negative when the plate voltage is positive the plate current is practically zero, so that the magnitude of this current is a function of the phase relationship between the grid and plate voltages as shown in Fig. 5.

The voltage drop across the coupling resistance R_1 is applied to the grid circuits of three regulator tubes. These tubes derive their plate voltage supply from a three phase transformer fed with power from the three slip rings provided on the motor. These tubes act as a rectifier whose output is controlled by the potential impressed upon the grids from the coupling resistance R_1. The current of the regulator tubes is passed through the regulating field provided on the motor. This field is in a direction to aid the shunt field and series fields of the motor.

The operation of the circuit is as follows: In starting switch S_1 is closed which applies direct current to the shunt field and armature circuits of the motor. The motor accelerates as an ordinary compound wound motor. Switch S_2 is then closed applying three phase power from the slip rings of the motor to the transformer. As the speed of the motor approaches the operating point, the beat frequency between the pilot generator and the oscillator will cause beats in the current through the regulating field which are visible on the meter M_1. Let us assume that the field rheostat has been previously adjusted so that with

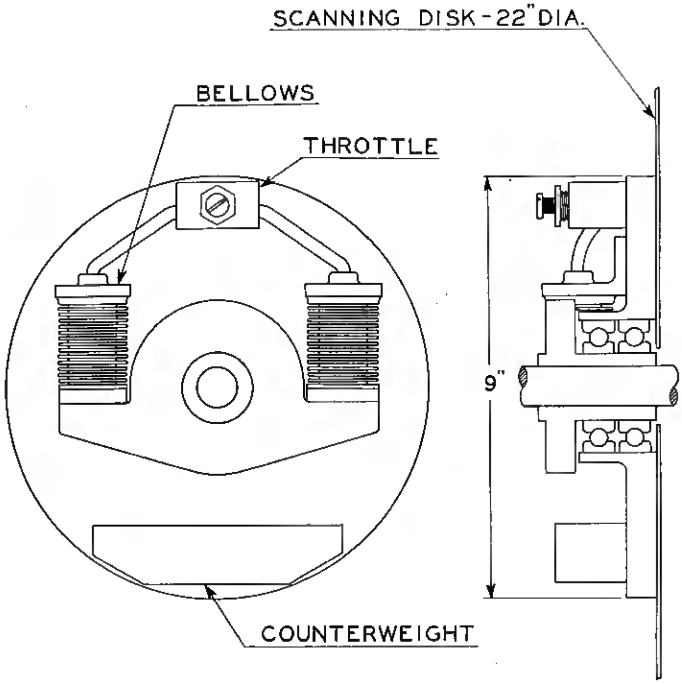


Fig. 4—Hydraulically damped coupling to prevent hunting of motor.

the shunt field alone the motor will tend to run slightly over the desired operating speed. When the exact operating speed is obtained, the beat frequency in the regulating field will be zero and as the motor tends to accelerate, the phase relationship between the pilot generator and the oscillator will reach a point tending to give maximum strength to the regulating field. When this point is reached, the acceleration of the motor will be checked by the increased field and the speed will tend to fall until the phase of the pilot generator with respect to the oscillator has shifted sufficiently so that the regulating field current is reduced to an equilibrium value, after which the motor continues to run at constant speed in accordance with the frequency of the oscillator.

Operating tests on the circuit show that the motor will hold in step over line voltage ranges from 100 to 125 volts and will be self-synchronizing over somewhat narrower voltage limits. Thus, under normal conditions all that is necessary from an operating standpoint is to close the switch and wait for the motor to pull into step.

Control Oscillator

The control oscillator is a standard type of vacuum tube oscillator having a frequency precision of the order of 1 part in 1000, when

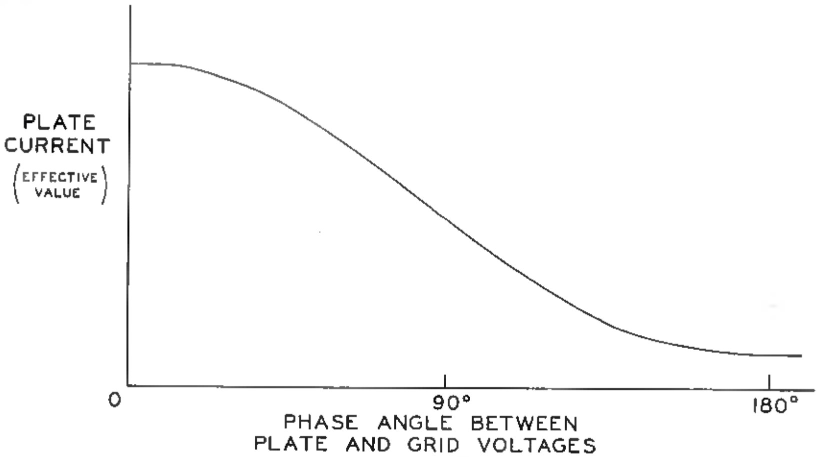


Fig. 5—Phase detector tube characteristic.

delivering the negligible output of .005 watts to the grid circuit of the detector tubes. This frequency is delivered directly to the motor circuits at one end of the line and is transmitted over a separate cable pair to the control circuits at the other end of the line. It was found that the detector tubes would operate successfully over a considerable variation in power level, provided the minimum oscillator output was sufficient.

An interesting alternative method was developed in which the synchronizing channel between stations may be omitted entirely, but this method was not used in the present system as the additional cost was not justified. The method, however, is described as it may prove of value if television transmission over long distances is considered.

Mr. W. A. Marrison in his paper "A High Precision Standard of Frequency," *Proceedings I. R. E.* July, 1929, described a crystal controlled oscillator which would maintain a precision as to frequency of 1 part in 10,000,000. This oscillator employs a quartz crystal as its primary means of control and by means of secondary circuits the natural period of the crystal, which is approximately 100,000 cycles, may be stepped down to lower frequencies which are more convenient for such purposes as motor control.

By this means, a frequency of the desired value may be obtained with a precision so great that the speed of the scanning discs under control of the above described circuit will be so nearly perfect that no synchronization channel at all is required. For example, if the period of observation of the television image is 5 minutes, the scanning disc will make 5300 revolutions when operating at a speed of 1060 r.p.m. Assuming a precision of control of 1 part in 10,000,000, the maximum error during the 5 minute interval will be 5300 divided by 10,000,000 or about 1/2000 of 1 revolution. Expressed in degrees on the periphery of the disc, this is equivalent to approximately 1/6 of 1 degree or since the width of the television image with 72 holes in the scanning disc is 5 degrees, the image will drift 1/30 of a frame width during the 5 minute interval. If the speed of the scanning disc at the other end drifts an equal amount in the opposite direction, the displacement of the television image will be only 1/15 of a frame width, which is a tolerable amount of drift.

From a practical viewpoint, however, it is apparent that the additional cost of very precise independent oscillators would be greater than the cost of providing the synchronization channel, except possibly for transmission over long distances.

Framing

Referring to Fig. 2, it will be noted that a phase shifter is provided between the oscillator and the input terminals to the control circuit. This phase shifter is designed with a split phase primary member producing a rotating magnetic field. The secondary member is single phase and is mounted on a shaft provided with a handle. By rotating the handle of the phase shifter in the desired direction, the frequency delivered from the phase shifter will be the algebraic sum of the frequencies of the oscillator plus the frequency of rotation of the armature of the phase shifter. It is, therefore, a simple matter for the operator at the receiving end to momentarily increase or decrease the control frequency and thus bring the picture into frame.

Discussion

During the development of the control system, one of the first difficulties encountered was hunting of the controlled motor. The problem of hunting, of course, becomes more difficult of solution the greater the precision of speed regulation desired and the greater the moment of inertia of the load connected to the motor, the latter statement applying only to controlled systems of the synchronous type. Since the moment of inertia of the scanning disc is large relative to that of the motor armature, it is seen that the conditions for securing stable rotation would be unfavorable in both the above mentioned respects if the scanning disc were mounted directly on the motor shaft. The hydraulically damped type of coupling above described was, therefore, inserted between the motor shaft and the scanning disc. It was found, however, that hunting still occurred. A further analysis of the problem showed that the axis of the field flux of the motor was shifting back and forth across the pole faces. The damping winding shown in Fig. 4 was then added with a marked improvement. It was also observed that a strong series field on the motor assisted in securing stability and it was, in fact, necessary to employ all three expedients to secure satisfactory performance. In the system as finally developed the television image, if disturbed by a momentary load such as the pressure of the hand against the disc, would come back to rest within approximately one second, there being two oscillations during this interval. In actual operation, it was found that the normal fluctuations in line voltage occurring on the commercial power supply produced no transients of sufficient magnitude to cause any objectional instability in the received image.

In conclusion, it should be pointed out that this type of control system could be equally well employed with larger motors for other applications requiring precise speed regulation. While the circuit described is applicable only to a direct current motor, a similar system may be applied to an alternating current motor substituting a saturating reactor in place of the regulating field winding in the manner described by the author in his paper[2] presented before the Society of Motion Picture Engineers, September, 1928.

[2] *S. M. P. E. Transactions*, Vol. 12, No. 35, page 696.

Sound Transmission System for Two-Way Television*

By D. G. BLATTNER and L. G. BOSTWICK

In this paper is described the speech transmission part of the two-way television system described in companion papers. The system is designed to produce the best possible illusion of face-to-face communication between speakers located at a distance. Some of the novel features of the system described include the use of distant pick-up transmitters and loud speakers concealed in the wall of the booth, also the use of heavy glass windows through which the scanning beam and the reproduced image are projected as a means of preventing the admission of noise into the booth.

IN the design of a sound transmission system to be correlated with a visual system, the requirements as to perfection of results desired are no more stringent than for other high grade sound reproducing systems[1] that have been described in the literature from time to time. Rather in this case the peculiarities of the system are largely those incidental to the adaptation of old technique to meet new conditions.

The principal limitation of the sound system imposed by the visual system is that the user be relieved of all necessity of holding a telephone in close proximity to the head. Such a limitation is highly desirable in order to secure the most natural pose of the features and the most satisfactory scanning. Obviously, the best way of meeting this limitation is by the use of telephone instruments of the type adapted for picking up and reproducing sounds at a distance. The use of such instruments has the further advantage that they can be located near the vision screen and so reproduce any peculiarities in tone quality that would result if the speaker were actually located at the position of the image. Of, course, the sharpness of this perspective effect obtained is influenced by the loudness of both the original and the reproduced sounds but the matter of location of instruments is also very important.

It would thus seem that the use of distant pick-up and distant projecting instruments offers certain rather fundamental advantages but it is also true that it presents certain other disadvantages. One of the disadvantages is that the distant pick-up microphone gives less output than a close-up device because of the reduced sound pressure on the diaphragm; also a sound producing device to give suitable reception

* Presented at June 1930 meeting of A. I. E. E., Toronto, Canada.

[1] "Public Address Systems" by J. P. Maxfield and I. W. Green in A. I. E. E., Feb. 14, 1923. Also "High Quality Recording and Reproducing of Music and Speech" by J. P. Maxfield and H. C. Harrison in A. I. E. E., Feb. 1926.

at a distance must be supplied with a higher transmission level than would a close-up instrument. It thus becomes necessary to provide for greater gain in transmission and greater electrical power capacity than would be required were the instruments held close to the head. The use of the more elaborate transmission facilities is in itself disadvantageous but it also tends to increase the feed-back from the loud speaker to the microphone; also the effect of any noise at the microphone position or at the listening position tends to interfere more seriously with the successful conduct of conversation. In the design of the two-way television system recently installed between the Bell Telephone Laboratories at 463 West Street and the American Telephone & Telegraph Co. at 195 Broadway in New York City, it was felt that it would be possible to overcome these technical objections to the distant type instruments and that the advantages mentioned would justify any measures necessary to do so.

The question of instruments was solved by the use of the Western Electric 394 condenser type transmitter [2] and a dynamic direct radiator loud speaker. The transmitter is one of the type generally used for phonograph and sound picture recording and for other purposes where good quality, high stability and quietness of operation are essential. The direct radiator type of loud speaker was used instead of the usual horn type because of the limited mounting space available. It consists of a dynamic structure with a rigid duralumin diaphragm about 3″ in diameter flexibly supported at the edge and radiating directly into free air. While such a structure is not highly efficient and permits of only a small sound power output these considerations are of secondary importance in this case. The instruments were located in the front wall of the booth about 2′ from the position of the user and adjacent to the viewing screen in order to enhance the perspective as described above, the microphone being above and the loud speaker below as shown in Fig. 1. These instruments were (in this particular case) connected into a four-wire circuit although in certain cases it might be desirable to use a 2-wire circuit. Such a change would of course be entirely feasible. The remainder of the apparatus used consisted of amplifiers located at the transmitting end of each channel and an attenuator at the receiving end, the two ends being connected by means of a loop of approximately 3 miles of non-loaded non-equalized cable. The amplifiers and the attenuators were each readily adjustable so that the sounds of different speakers could be reproduced at the optimum loudness. Observation of the performance of the system was made possible in each of the control rooms by means of a monitoring head

[2] E. C. Wente in *Physical Review* of May 1922.

type receiver bridged across the mid-point of an attenuator tying the two channels together. The attenuation used in the monitoring circuit was such as to give no audible feed-back in either booth. The results obtained with this set-up were considered satisfactory from the standpoint of both volume and quality. Ready recognition of familiar

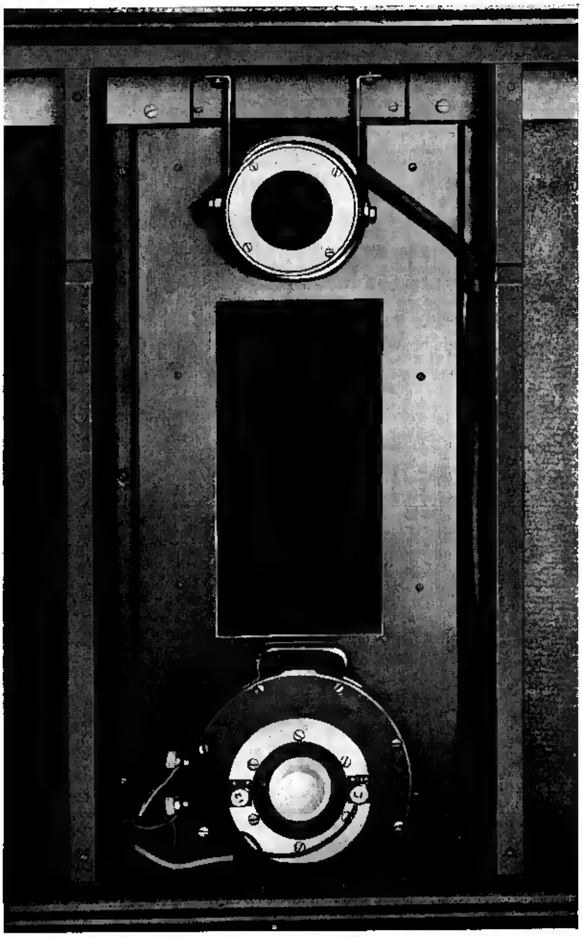


Fig. 1—Microphone and loud speaker in position above and below television scanning and viewing aperture.

voices and the association of the source of the reproduced sounds with the image were the usual occurrence. Figure 2 shows in block form the complete circuit set-up and Figure 3 shows the combined response frequency characteristic of the microphone, amplifier and loud speaker.

The ordinates of this curve represent variations in sound pressure from the loud speaker for constant pressure on the transmitter diaphragm. These data were obtained with the loud speaker located in a heavily damped room. The measurements were made on the sound axis at a distance of 2′, representing the relative position of the observer under conditions of actual use.

In setting up such a system the chief consideration is in regard to the acoustic feed-back from the loud speaker to the microphone and in this connection the design of the booth is an important factor. The booth must necessarily be so shaped that the user, looking at the viewing screen, can be satisfactorily scanned and the light reflected from

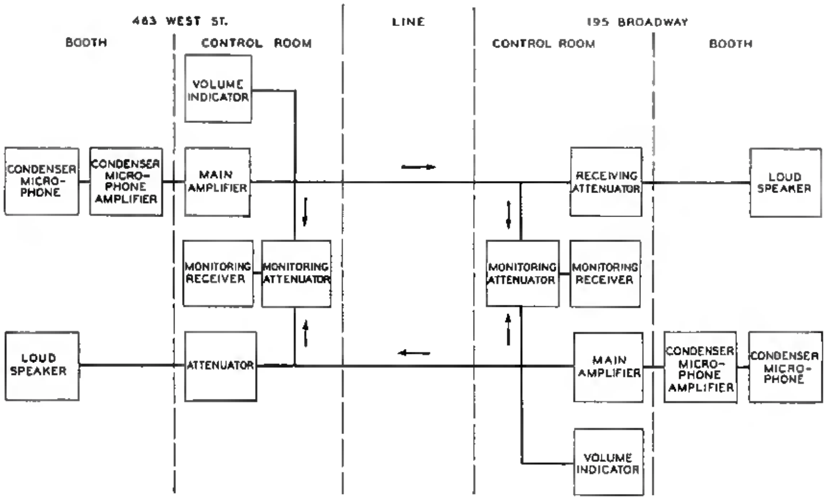


Fig. 2—Circuit diagram for sound transmission system for two-way television.

the scanned areas will strike the banks of photoelectric cells required for the reproduction of the visual likeness. This requires that the person scanned be located in close proximity to the scanning disc and to the photoelectric cells as well as to the microphone and loud speaker. Such an arrangement is objectionable from an acoustic standpoint in that in the present state of development the cells are necessarily large and poor absorbers of sound. They thus tend to cause part of the sound output from the loud speaker to reflect back into the microphone. If the sound so reflected or fed back is equal or greater in magnitude than the original sound picked up and is of the proper phase relation, the system will "sing" and the sound system become of no practical use. A further effect of the design of the booth is that as a closed cavity, it tends to cause sounds of a certain pitch range to be accentuated. To reduce these effects as far as possible, the television booths were made as large as other considerations would permit and all surfaces were covered where possible with acoustic absorbing material. They have a floor area of about 35 sq. ft. and are about 8 ft. high. Because of the increased transmission required for the proper interpretation of sounds in the presence of noise, the booths were made of heavy masonry material to insulate the user and the microphone from the noise incidental to the rotating parts of the television apparatus. It was thus necessary to project the scanning beam and to view the illuminated image through a window located in the front wall. The microphone and the loud speaker were fitted into this wall, which was then covered over with a thin screen to improve the appearance as

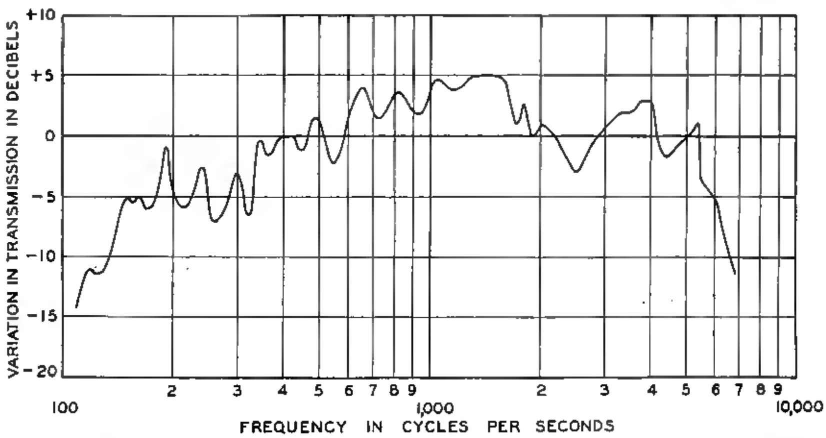


Fig. 3—Response frequency characteristic of microphone, amplifier and loud speaker.

shown in Fig. 3 of companion paper, "Image Transmission System for Two-Way Television." These means effectively reduced the noise in the booth to an unnoticeable amount and reduced reflection effects to the extent that the average speaker talking in a conversational manner could be reproduced at a loudness best suited to the general effect. The optimum loudness seemed to be about the same as would be obtained from the speaker direct at a distance of about 10 feet, the apparent distance between the image and the observer. At this loudness the gain of the amplifiers was 12 db less than that required to cause singing.

While the system demonstrated was operated over a distance of only a few miles, it will be appreciated that the same terminal facilities might have been used over much greater distances. Thus for the first time in the history of electrical communication it can be said that complete freedom of exchange of both visual and aural expression between distant users of the telephone has been made possible.

Transmitted Frequency Range for Telephone Message Circuits

By W. H. MARTIN

IN the Bell System the general objective which has been set up for the transmitted frequency range for new designs of telephone message circuits is a range having a width of 2,500 cycles, extending from about 250 cycles to about 2,750 cycles. In determining the frequency range of such a circuit, the cutoff points are taken as those at which the attenuation reaches a value 10 db greater than that at 1,000 cycles.

This frequency range for design is taken in general as applying to the overall transmission characteristic of the circuit between the terminal central offices of a connection. Where such offices are connected by a direct trunk this frequency range applies to the individual trunk. Where two or more trunks are used in tandem the frequency range of the overall connection will tend to be somewhat less than that of the component parts. For this reason then, to meet the specified range for an overall multi-switch connection, it will be necessary to have the frequency ranges of the trunks which are used as parts of built-up connections, somewhat greater than the specified range for the overall circuit.

In view of the relatively lower cost of toll switching trunks and other similar trunks from toll offices to local central offices, it is desirable that these terminal circuits have a broader frequency range than that specified above, so as to avoid their narrowing the range transmitted by the toll trunks with which they are connected.

It may be stated that the general purpose in working to the transmitted frequency range given above is that each individual trunk should have a frequency range at least as great as that specified and that the frequency ranges of those trunks which are frequently used as parts of built-up connections should be somewhat greater than the specified range.

In setting up the requirements for the various transmission characteristics of telephone message circuits, the aim is to arrive at the combination of requirements which will give the most economical telephone system for furnishing the desired grade of transmission service. Since the effects of many of the factors entering into the determination of this ideal are not susceptible to definite evaluation, the selection of a requirement such as that for the transmitted frequency range, is necessarily a matter of judgment, taking into account the various factors involved.

In Figure 1 are given the results of recent tests showing the effect upon articulation of varying the upper and lower cutoff frequencies of a circuit similar to the Master Reference System for Telephone Transmission. These results apply to the condition of no noise and the received volume at the optimum value. It will be noted from the curve for the variation of the upper cutoff frequency, that the rate

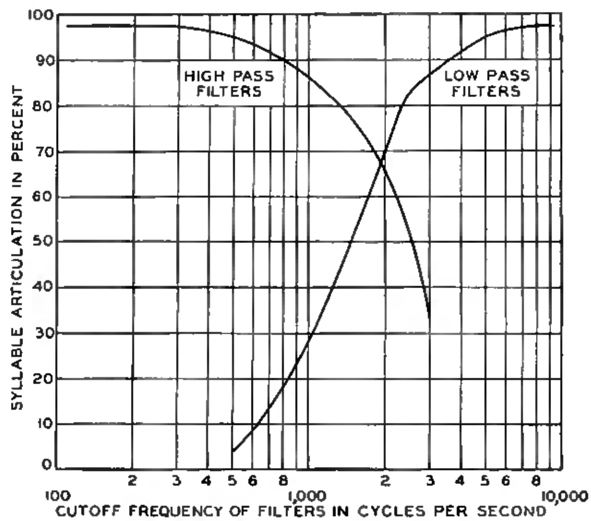
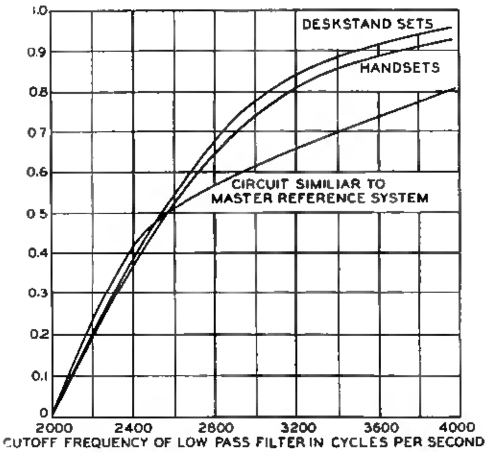


Fig. 1—Syllable articulation of circuit similar to master reference system at optimum received volume under quiet conditions.

of growth is relatively slower above 2,500 cycles than below, and that the total gain in going from this point to infinity is relatively small. Figure 2 shows on a somewhat different basis the upper part of this curve and also, for comparison, corresponding data for circuits having commercial terminal apparatus of the types used in the Bell System. The ordinates for these curves are the ratios of the increase in articulation in going from an upper cutoff frequency of 2,000 cycles to some higher point, to the total change in articulation in going from 2,000 cycles to infinity. For example, referring to the curve for the effect of upper cutoff frequency on articulation of the Master Reference System, it is seen that the articulation for the 2,000-cycle point is 70 per cent, for the 3,000-cycle point is 87 per cent and for infinity is 97 per cent. Increasing the cutoff from 2,000 to 3,000 cycles gives a growth in articulation which is 17/27, or .63, of the total increase in articulation which would be obtained in going to a cutoff of infinity. The values for the other curves of Figure 2 are obtained in a corresponding manner, it being appreciated that the articulation values with commercial instruments are lower than those for the Master Reference Circuit. This method of plotting the results has the advantage of showing the rate of growth of articulation for the three kinds of circuits on a comparable basis.



Ordinate is: $\frac{A_f - A_{2000}}{A_m - A_{2000}}$

Where A_f = the syllable articulation with a low pass filter of cutoff frequency f.

A_{2000} = the syllable articulation with the 2000 cycle low pass filter.

A_m = the syllable articulation obtained with no filters.

Fig. 2—Syllable articulation of telephone systems at optimum received volume under quiet conditions.

It is seen from the curves of Figure 2 that raising the upper frequency limit from 2,000 to 2,500 cycles gives about one-half of the total increase which would be obtained in going to an infinite cutoff and raising to 2,750 cycles gives for the commercial instruments about two-thirds of the increase in articulation which would be obtained in going to an infinite cutoff. These curves do not indicate any particular cutoff frequency as a stopping point for commercial circuits but it is considered that going as far as about 2,750 cycles is justified. While there is some articulation advantage in going further, observations of the number of repetitions occurring in conversations over circuits having different cutoff frequencies have indicated but little reduction in repetitions by going beyond about 2,750 cycles with commercial types of terminal sets.

For the lower end of the range, the lower cutoff frequency curve of Figure 1 shows little effect on articulation of cutoffs below 400 cycles.

The selection of the 250-cycle point for the specified frequency range is on the basis of maintaining reasonable naturalness.

It has been found that with present commercial station sets little is gained either in intelligibility or naturalness by extensions of the transmitted frequency range beyond the limits which have been set. This range, moreover, permits effective utilization, particularly from the standpoint of intelligibility, of the capabilities of much better station instruments even if this improved apparatus should approach the ideal in performance. With such terminal apparatus, major extensions beyond the upper frequency limits give improvements from the standpoint of naturalness largely as the result of better reproduction of the fricative consonants and of some of the incidental sounds which accompany speech. The extension necessary to effect a material improvement in this respect is a matter of a thousand cycles or more, rather than hundreds of cycles. It has been considered that such an extension for message circuits is not now justified.

Further in this connection, it must be borne in mind that an extension of the transmission range will in general increase the amount of noise on the circuit and magnify the crosstalk problem. For transmission systems such as carrier and radio where the noise may be assumed to be uniformly distributed over the sideband range, the added noise may be particularly important. Also a widening of the range increases the difficulties of securing proper impedance balances and of equalizing amplitude and phase distortion.

On the basis of these considerations, it has been decided that new designs of telephone message circuits for the Bell System should have an effective transmission band width of at least 2,500 cycles, extending from about 250 to 2,750 cycles. Furthermore, this band width will be made greater in those cases where this can be accomplished without material increase in costs.

Some Recent Developments in Long Distance Cables in the United States of America

By A. B. CLARK

THE transmission history of long distance circuits, and particularly long distance cable circuits, has been one of continually improving standards. It has also been one of continual reduction of circuit costs. These have resulted largely from new developments to which have been added economies resulting from heavy growth and improved engineering.

To put it another way, present-day circuits are capable of transmitting a kilocycle of frequency range more cheaply than those of earlier days. As the cost per kilocycle of band width has been reduced, part of the cost reduction has naturally been used in furnishing telephone customers wider-band and generally better telephone circuits.

The accompanying chart is of interest in comparing the transmission frequency characteristics of what were considered good telephone circuits some time ago with what are considered good telephone circuits today and what are proposed for the future. At the left of the chart are shown various types of circuits which have been in use or proposed for New York-San Francisco service, a distance of a little over 3,000 miles. The original loaded transcontinental line, which remained in service from January 25, 1915, until April, 1920, when it was unloaded, gave a band width of only about 900 cycles.* The non-loaded circuit was better, giving about 1,800 cycles. The modern carrier telephone circuit is better still, giving about 2,700 cycles. The extra-light loaded type of cable circuit (H-44, which has been the standard loading system for long distance use for some time) will give a band even wider, extending up to at least 3,000 cycles.

At the right of the chart are shown typical characteristics for New York-Washington (about 225 miles) two-wire cable circuits with various loadings. The now obsolete heavy-loaded system, H-245, gave an effective range of 1,400 cycles, the medium-heavy loaded or H-174 gave 1,900 cycles while a new system which is being considered, called B-88, will give about 2,700 cycles. (At the present time H-174 two-

* The limiting frequencies are taken as those at which the loss is 10 db greater than the loss at 1,000 cycles.

wire circuits are restricted to shorter lengths, the curve being given simply for comparative purposes.)

In addition to this matter of frequency band width, there has been improvement in the 1,000-cycle efficiency of long distance circuits and also improvement with respect to noise and crosstalk. The original loaded transcontinental circuit, for example, gave, during good weather,

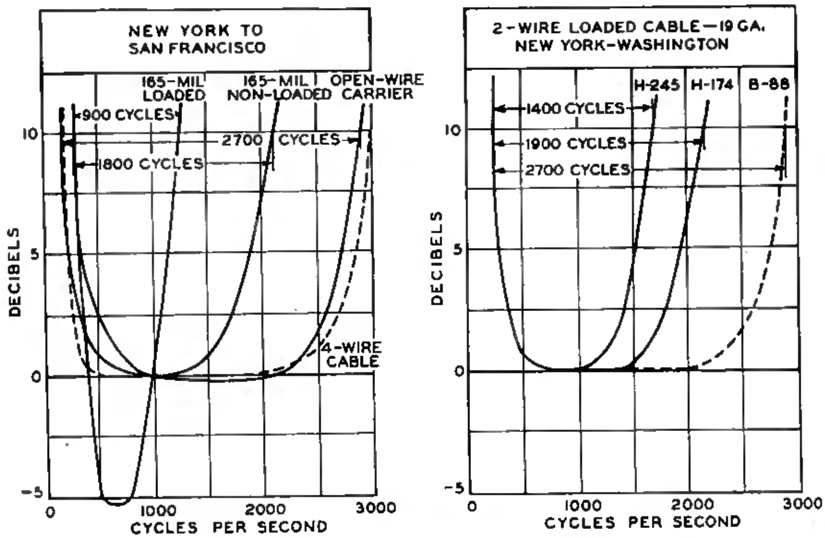


Fig. 1—Transmission-frequency characteristics of representative types of telephone circuits.

a 1,000-cycle transmission loss of about 20 db with a variation from this of at least 10 db during bad weather. The non-loaded circuit gave about 12 db during good weather with smaller variations. With both of these circuits the noise was somewhat in excess of 1,000 noise units. The carrier and cable systems compare very favorably with non-loaded voice-frequency circuits in the matter of transmission loss and are much quieter.

With the two-wire cable circuits shown, the H-245 circuit gave about 12 db loss at 1,000 cycles, the H-174 circuit 10 db loss and it is expected that the B-88 circuit will give about 9 db loss at 1,000 cycles. All of the cable circuits are strikingly quiet as compared with older type voice-frequency open-wire circuits. The cable circuits are also considerably better from the standpoint of crosstalk.

It is of interest to consider the effect on service of the change in standards of toll circuits as illustrated by the characteristics of the above circuits. One way of indicating this is by the repetitions occurring per unit time in commercial conversations. Assuming present commercial telephone instruments, typical terminal circuit and room noise conditions, following are some estimates on this basis:

Circuit	Repetitions per 100 Seconds
Loaded New York-San Francisco circuit	3
Non-loaded New York-San Francisco circuit	2
Carrier circuit, New York-San Francisco	1
H-44 cable circuit, New York-San Francisco	1
H-245 cable circuit, New York-Washington	1½
H-174 cable circuit, New York-Washington	1¼
B-88 cable circuit, New York-Washington	1

Short Cable Circuits

Consideration is now being given to giving up the H-172-63 two-wire circuits in favor of B-88-50 and H-88-50 two-wire circuits. H-172–63 four-wire circuits were given up some time ago. With the new two-wire circuits the important line constants and circuit characteristics are given in the following table.

H-88-50 loading is being considered particularly for those repeater sections less than about 40 miles in length while B-88-50 loading is being considered particularly for repeater sections whose lengths are greater than about 45 miles. For intermediate repeater section lengths the choice of loading will be dictated by various considerations applicable to the particular circuit layout involved.

With either of the above two-wire circuits, the following transmission results are anticipated:

> Circuits for terminal business up to about 250 miles in length to have a working net loss at 1,000 cycles of about 9 ± 2 db. The frequency range to extend from about 250 cycles to some frequency between 2,750 cycles and 3,000 cycles. Crosstalk between circuits to exceed 1,000 units in only about 1 per cent of the combinations. Noise measured at the receiving end of the circuit, including "babble," * less than 200 units.
>
> Circuits for "via" business to be limited to lengths in the neighborhood of 100 miles so that adding a circuit link of this type to a built-up connection will not, in general, add more than about 2 or 3 db to the overall loss.

* Babble is the name given to the effect produced by a number of different circuits crosstalking into a particular circuit at a given time and producing an unintelligible murmur.

Long Cable Circuits

Present plans are to retain H-44-25 four-wire circuits for the intermediate and longer distances. This type of circuit is well known so it is unnecessary to go into its characteristics. With the idea of transmitting frequencies up to about 3,000 cycles with very little evidence of phase distortion, phase correctors are being considered for very long circuits of this type, say, circuits exceeding 1,000 miles in length.

Characteristic	*H*-88-50	*B*-88-50
Conductor gauge	No. 19 B. & S.	No. 19 B. & S.
Side circuit cable capacitance per mile	0.062 microfarad	0.062 microfarad
Phantom circuit cable capacitance per mile	0.1 microfarad	0.1 microfarad
Inductance of loading coils on side circuits	88 milhenries	88 milhenries
Inductance of loading coils on phantom circuits	50 milhenries	50 milhenries
Spacing of loading coils	6,000 feet	3,000 feet
Nominal cutoff frequency of side circuit	4,000 cycles	5,600 cycles
Nominal cutoff frequency of phantom circuit	4,200 cycles	5,900 cycles
Nominal velocity of propagation of side circuit	14,000 mi. per sec.	10,000 mi. per sec.
Nominal velocity of propagation of phantom circuit	15,000 mi. per sec.	10,600 mi. per sec.
Nominal impedance of side circuit	1,110 ohms	1,560 ohms
Nominal impedance of phantom circuit	670 ohms	940 ohms
1000-Cycle attenuation of side circuit at 55° F.	0.36 db per mile	0.28 db per mile
1000-Cycle attenuation of phantom circuit at 55° F.	0.30 db per mile	0.24 db per mile

Importance of High Velocity Circuits in Cable

Echo suppressors have proven quite effective in reducing the echo effects on long distance circuits. For very long distance cable circuits, however, echo is still a matter for concern, particularly with losses held down to figures such as those given in the paper by Mr. H. S. Osborne entitled "A General Switching Plan for Telephone Toll Service."

When cable circuit lengths become very great the actual delay suffered by the speech waves in traveling from end to end of the circuit becomes important quite apart from echo. We must look forward to the time when a subscriber in San Francisco will talk by cable across the United States to New York, then by cable and open wire to Newfoundland, by submarine cable to England and then by a long cable circuit, let us say, to Constantinople; in other words, a 10,000-mile circuit length. The highest velocity long distance cable circuits in use today will give, for conversations over such a circuit, about ½-second delay in going from one end to the other so that when one subscriber speaks the other's reply cannot possibly reach him in less time than one second. This is quite a long time interval. By utilizing speaking tube delay circuits, connections have been set up involving delays as great as this. Conversations are possible over circuits with such delays but the delay is a serious interference particularly when voice-operated devices are added which tend to lock out portions of the conversations.

It is thus evidently important to seek higher velocity circuits.

Telephone Carrier in Cable

In seeking ways for obtaining high velocity circuits in cable in an economical manner, consideration has been given to the proposition of applying telephone carrier to long distance cables. For large groups of long distance circuits it appears likely that a carrier-frequency range can be advantageously used in cables, as wide or wider than the frequency range which has been exploited on open-wire lines. Experimental work on systems of this kind is actively under way at the present time.

The higher frequencies involved together with the accompanying attenuations and increased coupling between circuits introduce some very interesting and unusual noise and crosstalk problems, as well as problems of equalization and maintenance of transmission stability. Also, there are interesting economic problems of conductor size and type, loading versus no loading, repeater spacing, etc.

It is interesting to note that if non-loaded circuits are utilized, a velocity of transmission of about 100,000 miles per second would be obtained while with loaded circuits a velocity perhaps half as great. The non-loaded setup in particular would, therefore, provide circuits whose velocity, like open-wire circuits, would be great enough to leave no question of obtaining satisfactory conversations over any world-wide telephone network. It is too early, however, to predict just what the outcome of this development may be.

Phase Distortion in Telephone Apparatus *

By C. E. LANE

This paper shows that if, over its transmitting range, the phase shift, B, in radians, of a four-terminal network may be written $B = a_0 + a_1\omega$ ($\omega = 2\pi x$ frequency in cycles per second), there is no phase distortion if $a_0 = N$, N being any integer. However, there is a delay, for any signal, given by $dB/d\omega = a_1$ (seconds). If N is not an integer, there is a delay, a_1, and in addition a distortion, which distortion, generally for speech and music, may be neglected. Typical phase characteristics for lines, filters and all-pass networks are shown. In general over their transmitting range, such phase characteristics which usually are curved, may be regarded as the sum of two characteristics, a straight line having a slope corresponding to the minimum slope of the original and which introduces a delay without distortion and a curved portion to which all of the distortion of the signal may be ascribed. Oscillograms are given showing the distortion for a loaded line and for band filters for a signal which is of the form $y \sin(\omega_0 t + \theta)$ between $t = 0$ and $t = T$ and zero for all other time. A description is given of the means employed for reducing the amount of phase distortion in telephone cable and in low-pass filters in circuits used for program transmission and regular telephone service. Also, phase distortion in repeaters and transformers is described. Brief reference is made to the problem of phase distortion in telegraph, picture transmission, and television circuits.

THE effects of amplitude distortion in the transmission of signals has been taken into consideration in the design of telephone systems for some time. Recently [1] increasing attention is being given to the phase changes which waves undergo in the process of their transmission. The necessity of this is, on the one hand, due chiefly to the use of long distance telephone systems involving greater lengths of loaded cable and numerous filters and repeaters in tandem, and, on the other hand, due to the demand for improved performance. One place where better quality has become particularly desirable is in circuits for interconnecting broadcasting stations.

This paper will present some general considerations of the relation between the phase characteristics [2] of telephone apparatus and signal distortion,[3] show the types of phase characteristics that most frequently require consideration and discuss the manner in which the amount of phase distortion is controlled. Brief reference will also be

* Presented at New York Section, A. I. E. E., May 1930.

[1] At the end of this paper, a bibliography is given containing references to previous publications on this subject.

[2] For a definition of phase characteristic see Appendix I. The "insertion" phase characteristic and "image transfer" phase characteristic are defined there.

[3] A companion paper by J. C. Steinberg deals specifically with the effects of phase distortion on the quality of speech and music. Another companion paper by H. Nyquist and S. Brand treats of the measurement of phase distortion.

made to phase distortion in systems for transmitting other than telephone signals.

Interpretation of Phase Distortion

Telephone systems must be so designed that the received signal approximates in wave form the sent signal within limits found by experience to be tolerable. We are here concerned primarily with the departure of the received signal wave from the sent signal [4] which may be attributed to the phase characteristic [5] of such networks as lines, filters, repeaters, etc. which go to make up the complete system. Such distortion is called phase or delay distortion. The reason for the term, delay, will appear later. We shall summarize here some of the more general conclusions of the effect on signals of certain phase characteristics and discuss the validity of these conclusions in Appendix II.

If the phase characteristic of any network is of the type shown by any of the dotted lines in Fig. 1 the received wave will be an exact copy of the sent or reference wave (assuming no amplitude distortion). In the case of Fig. 2 the received wave differs from the reference wave only in that it is reversed in sign which is equivalent simply to reversing the terminals of the load. *In both cases the received wave is delayed with respect to the reference wave by a time interval that is given by the slope of the phase characteristic or $dB/d\omega$.* If B is in radians, and $\omega = 2\pi f$, where f is the frequency in cycles per second, the delay will be in seconds. There is no distinction in effect between the phase characteristics for any of the dotted lines and furthermore they are identical with any such solid broken line as that shown. Since this is true we may completely represent any of the phase characteristics of Fig. 1 if we choose by the single line passing through zero in which case the delay is B/ω.

If the phase characteristics are straight lines and intersect the vertical axis at odd multiples of $\pi/2$ the received wave may be obtained from the reference wave first by delaying it by $dB/d\omega$ and then shifting the phases of all its steady state sinusoidal components as obtained by Fourier Integral or Series analysis by $\pi/2$.

If the straight line phase characteristics intersect the ordinate at intermediate values the received wave may be said to be the sum of

[4] See Appendix I. If one desires to be specific the sent or reference wave in the case of considering image transfer phase shift may look upon as the current entering the network and in the case of insertion phase shift the current through the load with the network omitted; and the received wave the current through the load in either case with the network in place.

[5] In actual apparatus certain general types of phase characteristics are associated with certain attenuation characteristics. For this reason it is difficult to separate to the extent one might sometimes desire the effects of the two types of distortion, attenuation and phase.

two parts as follows: The first part is an exact copy of the original wave modified in amplitude by a factor cos a_0 and delayed by $dB/d\omega$. The second part is obtained from the original wave by shifting all of the

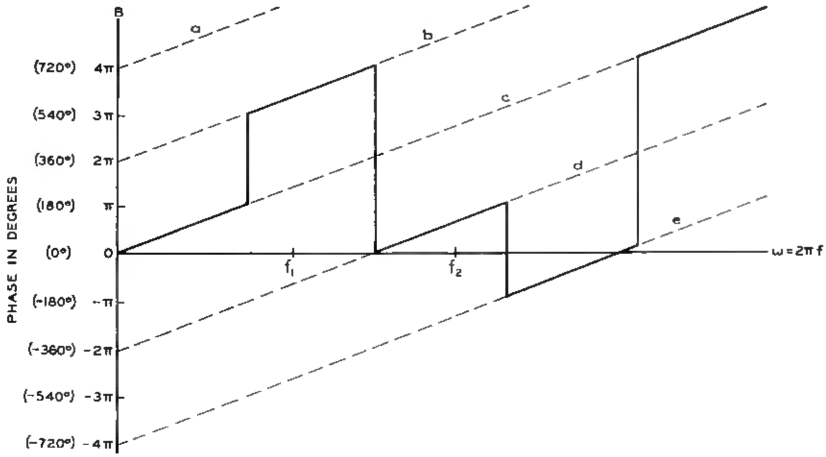


Fig. 1—Phase characteristics which introduce no distortion.

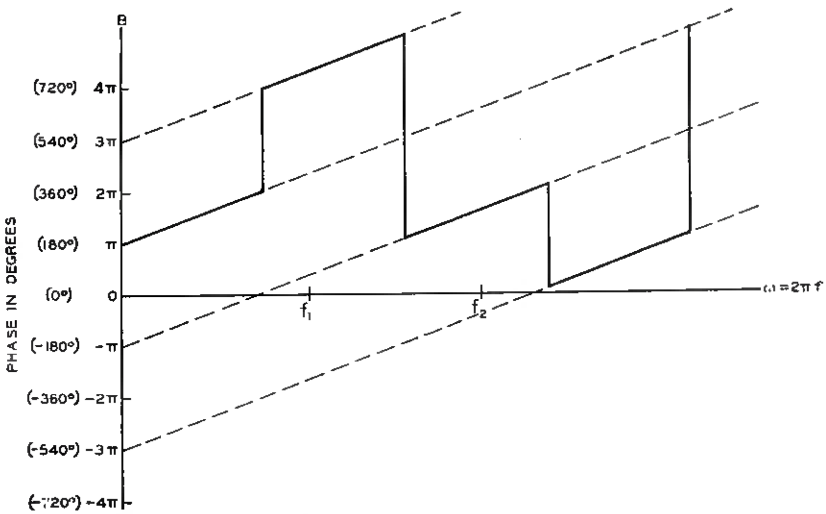


Fig. 2—Phase characteristics which introduce no distortion equivalent to those of Fig. 1 with connections to the load reversed.

components of the original by $\pi/2$, multiplying the result by sin a_0 and then delaying by $dB/d\omega$. a_0 is the value of the angle at the point of intersection of the vertical axis.

An important point to note here is that if a given signal has all its *important frequency components* falling in a region between f_1 and f_2 either because of the nature of the signal or as a result of attenuation in the system we are only interested in the phase characteristic in that region. *Thus for such a signal a sufficient condition for negligible phase distortion is that the phase characteristics be like those in Fig. 1 and Fig. 2 between f_1 and f_1 only.*

The phase characteristics actually found in telephone apparatus that frequently must be considered may for convenience be classified as follows: (1) those typical of the low pass filter and the loaded line,

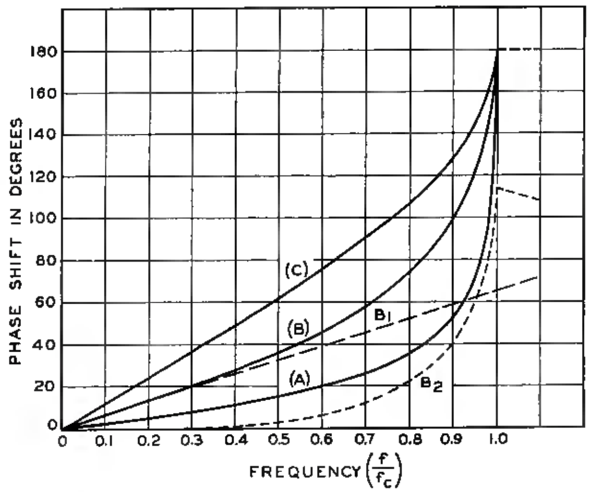


Fig. 3—Image transfer phase characteristics of typical low-pass filter sections. Same as insertion phase characteristic except in neighborhood of f_c. Curve C resembles closely the phase characteristic of a loaded line.

(2) those of band pass filters, (3) those of high pass filters, and (4) those of all pass networks.[6] The attenuation of all of these networks is fairly constant and small in the transmitting range.

The solid curves of Fig. 3 show the image transfer phase characteristics of typical low pass filter sections having a cut-off frequency f_c. The significance of these different type sections will be discussed later. The curve, C, resembles closely the phase characteristic of a loaded

[6] An interesting type of insertion phase is that obtained when these four types of apparatus are terminated over a considerable portion of their transmitting range in impedances that differ radically from their image impedances. The wavy phase curves obtained may be said to be chiefly responsible for the so-called reflection effects thus obtained though here too the attenuation plays an important part. If the attenuation in the network is large as in a line this waviness due to miss-match tends to disappear and the phase characteristic resembles closely in general shape that which would be obtained if no miss-match occurred.

line.[7] These curves as well as those in the following three figures are for non-dissipative networks terminated in their image impedances. However, the insertion phase characteristic with dissipation and the usual terminations, i.e. a resistance of fixed value, would not noticeably

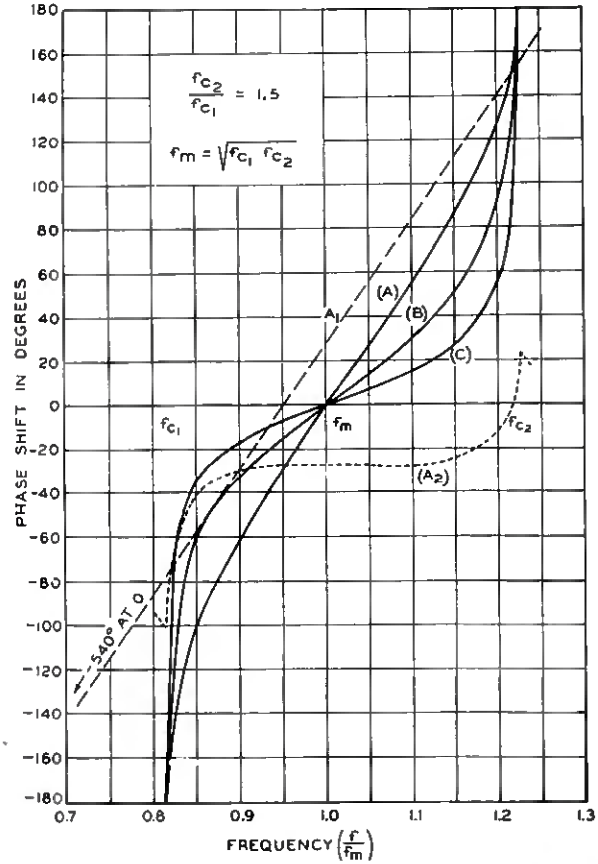


Fig. 4—Image transfer phase characteristics of typical band-pass filter sections

be different in most of the transmitting range. For filters in the latter case in the neighborhood of f_c the slope would be modified so as to remain finite. This will be discussed further in the next section.

The curves of Figs. 4 and 5 show respectively the image transfer

[7] It will be noted that the second derivative of these low pass filter phase curves are positive at all frequencies. However, special sections exist for which this is not true and such sections are occasionally used as discussed later where it is desirable to keep the characteristic as a whole nearly straight over a wider frequency range but low pass filters when considered as a whole generally have phase characteristics of the type shown.

phase characteristics for typical band pass and high pass filter sections. The curves of Fig. 6 are for all-pass lattice type network sections. The frequency f_r is the resonant or anti-resonant frequency of the series arms and cross-arms of the network.

The above four figures show that the phase characteristics are curved in every case over a considerable portion of the transmitted frequency range.[8] A curved phase characteristic like that shown in Fig. 3, curve B, for example, may be represented as the sum of a distortionless phase characteristic, B_1, of the type shown in Fig. 1 and another curved one, B_2, which is the difference between it and the

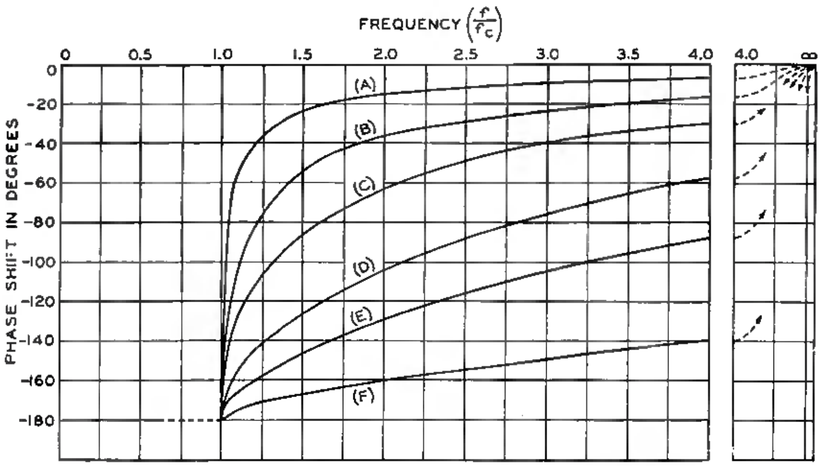


Fig. 5—Image transfer phase characteristics of typical high-pass filter sections.

original,[9] i.e., $B = B_1 + B_2$. The slope of the straight line characteristic is the minimum slope of the original, i.e. the slope at very low frequencies. B_1 introduces at all frequencies a definite delay without distortion given by its slope. B_2, to which no delay as a whole may be ascribed may be called the phase distortion characteristic of the network, and its derivative $(dB/d\omega)_f - (dB/d\omega)_{min}$. the *delay distortion characteristic* or simply the *delay distortion*. This procedure is equivalent to regarding the low pass filter as consisting of two parts in tandem the first part introducing a delay without distortion and the second part a distortion. If, after subtracting such straight line portions from low pass filters the remaining curves are the same, the phase

[8] In discussing the phase characteristics of filters only the characteristics in the transmitting range are considered, since in general the frequency components in this range only contribute noticeably to the received signal.

[9] See Appendix II.

distortion would be the same even though the delays might be different due to different slopes of the subtracted portion.[10]

In the case of the band pass filter of Fig. 4 a distortionless portion may be subtracted having the slope of the original at the mid-frequency but only for special cases will it be tangent to the curve. Fig. 4 shows curve A broken into two parts a distortionless part A_1 giving delay and a part A_2 responsible for the distortion, i.e., $A = A_1 + A_2$. It is doubtful if effects of A_2 on speech and music would be noticeably different than any other curve obtained by adding a constant angle to it at all frequencies. This type of variation occurs to the same ex-

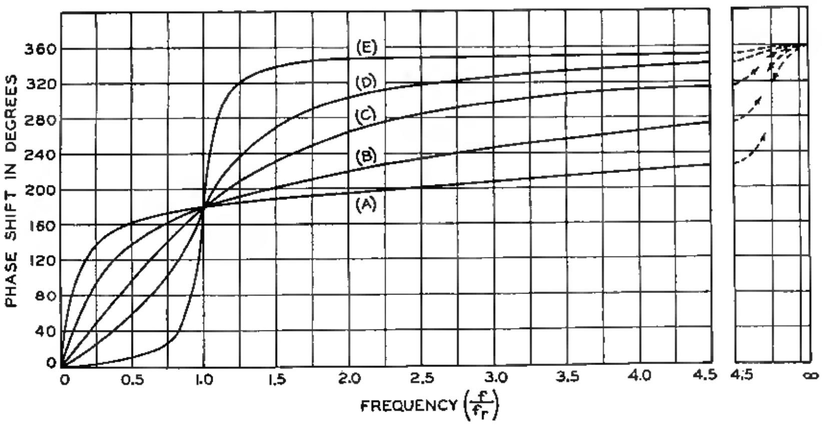


Fig. 6—Image transfer phase characteristics of typical all-pass lattice type network sections.

tent in apparatus observed to produce negligible phase distortion as where distortion is apparent. It is for this reason that the slope of the phase curve rather than the curve itself is generally taken as the criterion for determining the amount of phase or delay distortion in a network. In other words if two phase curves give the same $dB/d\omega$ or delay characteristics (sometimes called "envelope" delay characteristics) they are regarded as introducing the same phase distortion particularly for speech and music though such an assumption is not rigorously true.

In the case of the high pass filters and all pass networks of Figs. 5 and

[10] This procedure of breaking the phase characteristic into two parts one part introducing no distortion but a delay T_0 given by the minimum slope in the transmitting range and another part responsible for the distortion is perfectly rigorous, but it *must not* be interpreted to mean that for a signal starting at $t = 0$ absolutely nothing will be received before $t = T_0$. In the first place there is generally a small amount of energy outside the transmitting range that will come through earlier and in the second place, unless the residual phase characteristic is of a kind that can be produced by physical apparatus the distortion characteristic alone will cause the received wave to differ from zero prior to $t = T_0$.

6 the minimum slopes are zero hence no delay can be subtracted which applies to the signal as a whole.[11]

In order to observe the effects of phase distortion in some simple cases [12] we shall show oscillographs of some sent and received non-periodic waves. These waves are of the type that are zero up to time $t = 0$, take the form $y \sin(\omega_0 t + \theta)$ between $t = 0$ and $t = T$ and are zero for all future time.[13] A *Fourier Integral* analysis of these waves would show they contained energy over the entire frequency range, though most of it is confined to frequencies in the neighborhood of f_0 where $f_0 = \omega_0/2\pi$.

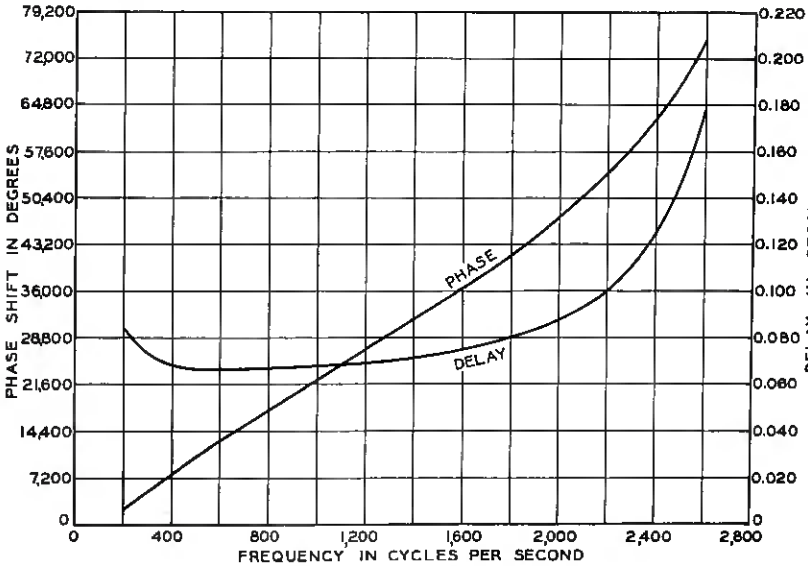


Fig. 7—Insertion phase and delay characteristics of a 600 mile length of medium heavy loaded cable (including repeaters).

Such waves as these are elementary waves which can readily be produced in the laboratory and the effects of distortion on them observed or in special cases the effect may be calculated.

[11] This assumes of course that energy falls in the frequency range where the slope approximates zero. If such were not the case for a particular signal a definite delay could be ascribed given by the minimum slope in the range where the frequency components of consequence fall.

[12] The effect of phase distortion on speech and music signals is discussed in the paper by J. C. Steinberg already mentioned.

[13] It is of interest to note that any complex wave which is zero at all times prior to $t = 0$ and also at all times after $t = T$ may be regarded as the sum of such finite components as these. Analyze it by means of *Fouriers Series* as though it repeated itself as a steady state wave for all time. Then multiply all of the steady state sinusoidal components by zero for all time prior to $t = 0$ and after $t = T$ retaining only the portion for the interval of time T. The resultant simple components will add up to give the original complex wave. After distortion the distorted components will add up to give the distorted wave as a whole.

Fig. 7 is the insertion phase and delay characteristic of a 600 mile length of medium heavy loaded cable including repeaters. This cable has a theoretical cut-off of about 2500 cycles. Fig. 8 shows the distortion for two simple waves [14] of the above type, for one $f_0 = 1000$ cycles and for the other $f_0 = 1500$ cycles. The oscillographs show as, predicted, that practically nothing in either case is received until after the time given by the minimum value of $dB/d\omega$, i.e. .0654 seconds. After this time a distorted form of the sent wave occurs. Since for $f_0 = 1000$ most of the energy of the wave as analyzed by the Fourier Integral method of analysis falls in the neighborhood of 1000 cycles

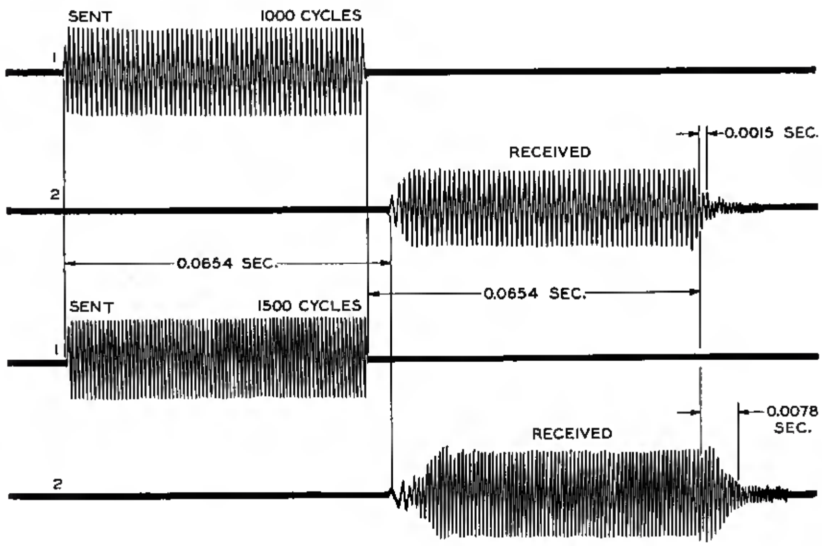


Fig. 8—Distortion resulting from 600 mile length of cable of Fig. 7 for signals of the form $y \sin \omega_0 t + \theta$ between $t = 0$ and $t = T$ and zero for all other time.

where the delay characteristic is reasonably constant this wave is not distorted much. In the case for $f_0 = 1500$ cycles a larger portion of the energy falls in the neighborhood of 1500 cycles where the delay characteristic is changing more rapidly and it is therefore distorted more. $(dB/d\omega)_{f_0} - (dB/d\omega)_{\min.}$ may be taken as a fair measure of the distortion of such simple waves although higher derivatives are also involved.

Fig. 9 shows the insertion delay characteristic for a system consisting of four band filters in tandem. The attenuation characteristic is also

[14] Reproduced from the paper by Sallie P. Mead, loc. cit.

shown. Fig. 10 shows oscillographs for waves of the above type for f_0 = 260, 300, 480 and 680 cycles per second. Notice that the distortion is much greater where f_0 falls near the edges of the transmitting band, although in every case the wave starts noticeably building up at about .0109 seconds after $t = 0$ for the sent wave. This is the value of $(dB/d\omega)_{\text{min.}}$ in the transmitting range of the filters. In both Figs. 8

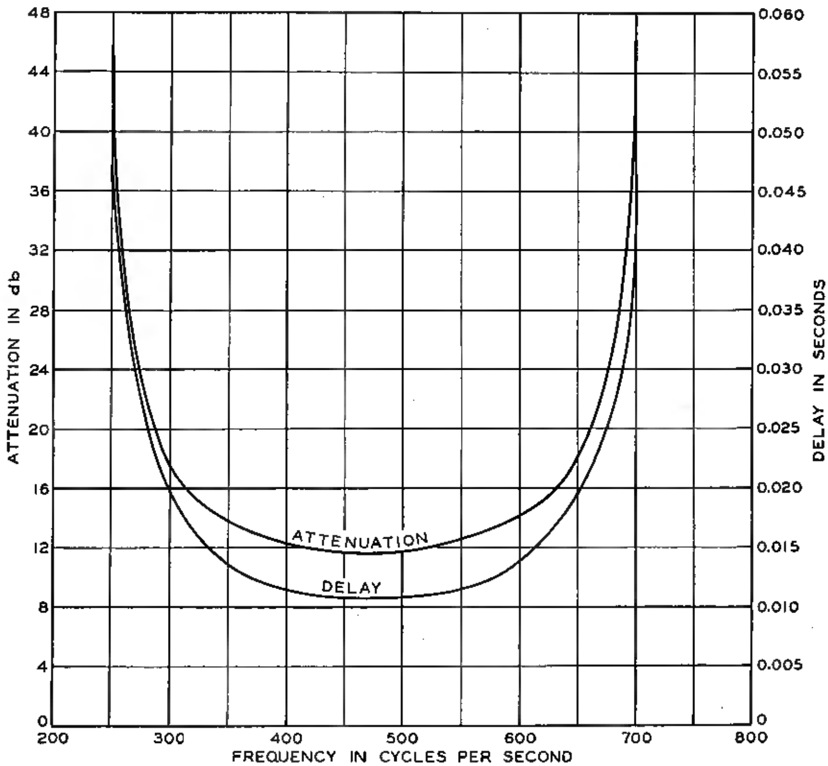


Fig. 9—Insertion delay and attenuation characteristics of 4 band-pass filters in tandem.

and 10 some of the distortion may be ascribed to attenuation although the *elongation effect* is primarily due to phase distortion. It is this elongation effect that is noticeable to the ear in speech and music.

Phase Distortion and Its Correction

This section of the paper will contain a more specific discussion of the phase characteristics of apparatus and the means employed for keeping phase distortion within desirable limits.

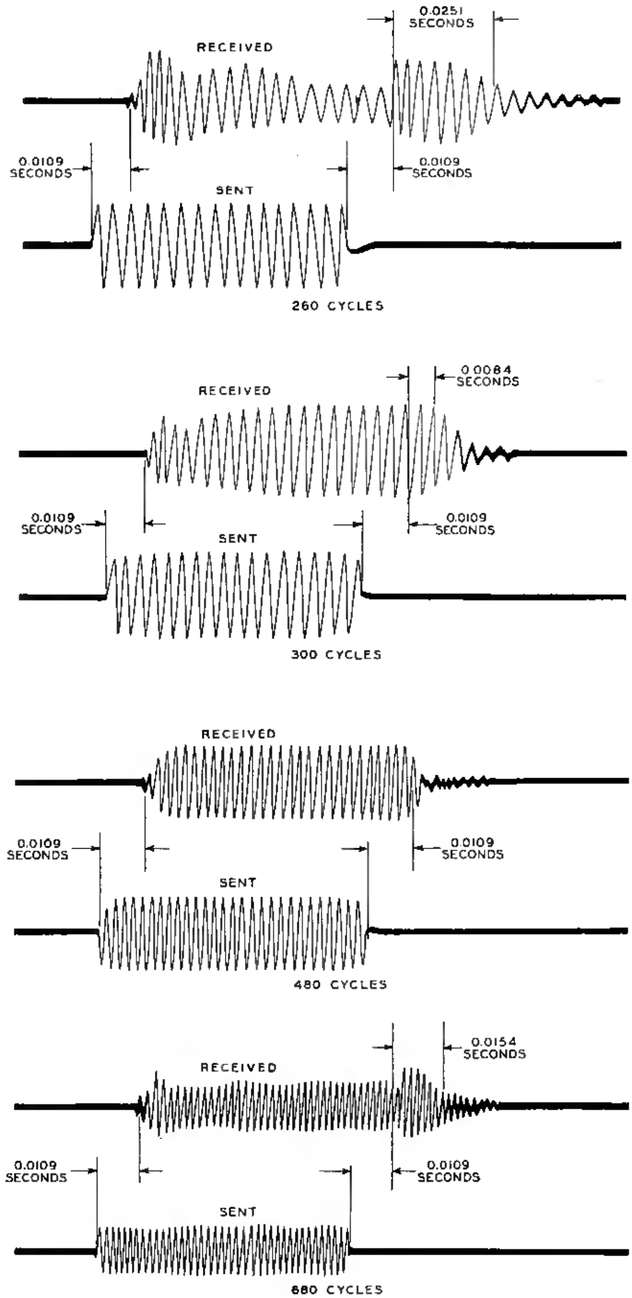


Fig. 10—Distortion resulting from four band filters of Fig. 9 for signals of the form $y \sin \omega_0 t + \theta$ between $t = 0$ and $t = T$ and zero for all other time.

1. *Telephone Cable.*—Two of the cases where phase distortion in telephone cable has been considered objectionable will be discussed: (1) In the newly developed high quality cable circuit for transmitting programs to and between broadcasting stations [15] which circuit is

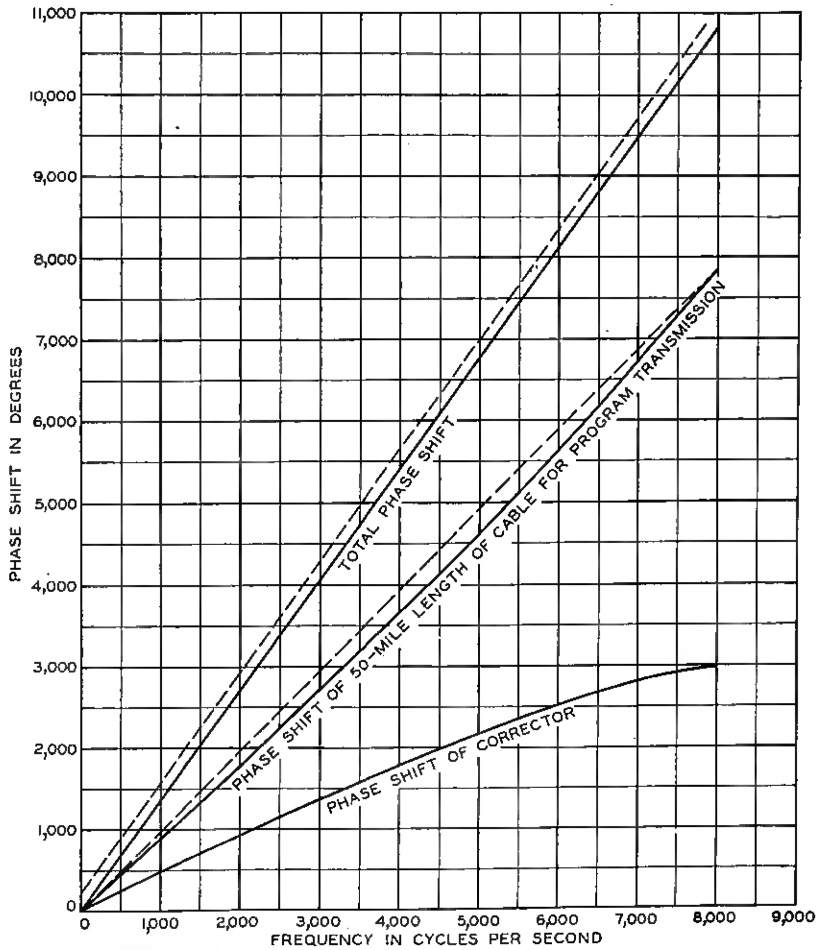


Fig. 11—Insertion phase characteristic of a 50 mile length of cable for program transmission. Also, phase characteristic of a phase corrector for this cable and for the sum of the two

designed to transmit with negligible amplitude and phase distortion all frequencies between 50 and 8000 cycles and (2) a proposed cable

[15] Long Distance Cable Circuit for Program Transmission, A. B. Clark and C. W. Green, to be presented at Summer Convention *A. I. E. E.*, Toronto, June, 1930. This cable consists of No. 16 gauge copper wire with 22 millihenry loading coils spaced every 3000 feet.

circuit [16] for regular long distance telephone message service designed to transmit with negligible distortion frequencies between 200 and 3000 cycles.

Fig. 11 shows the insertion phase characteristic of a 50 mile length of the cable for program transmission (exclusive of repeater). The broken line is drawn to bring out more clearly the curvature in the

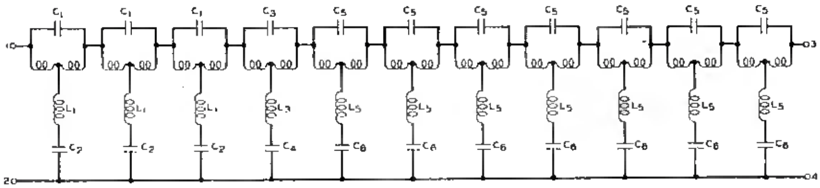


Fig. 12—Schematic of the phase corrector for a 50 mile length of cable for program transmission.

phase characteristic. Fig. 12 shows a schematic of the phase corrector used to correct for a 50 mile length of this cable. The insertion phase characteristic of this corrector as well as that of both the cable and corrector combined are also shown in Fig. 11. It will be noticed that a

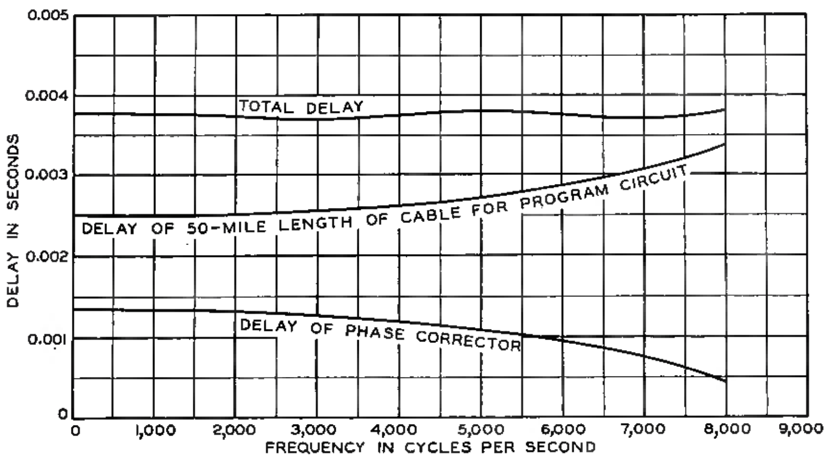


Fig. 13—Insertion delay characteristics corresponding to phase characteristics of Fig. 11.

single phase corrector consists of eleven sections, seven of one kind, three of another, and one of a third. Each section contains one two-terminal inductance coil and one three-terminal coil with mutual between the two windings and also two condensers. Fig. 13 gives

[16] This cable consists of No. 19 gauge copper wire with 44 millihenry loading coils spaced every 6000 feet.

dB/dω for the cable, the phase corrector, and the two combined. A 50 mile length of corrected cable gives a delay of .00375 seconds. A 3000 mile length [17] of this cable such as would extend from coast to coast would give a delay of .225 seconds, with a difference between the

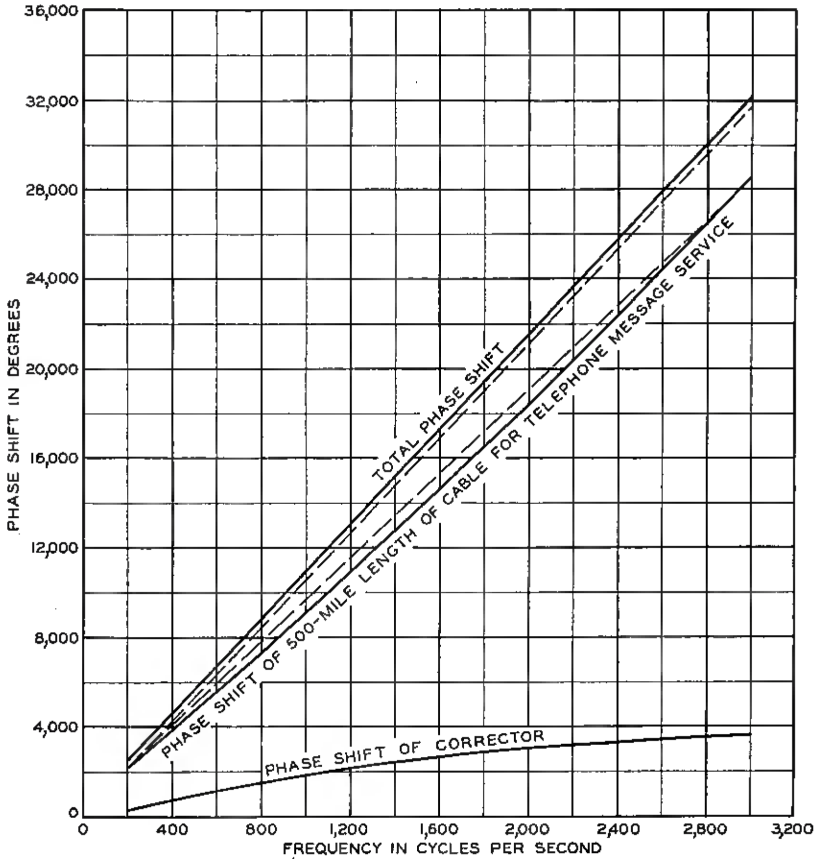


Fig. 14—Insertion phase characteristics of a 500 mile length of cable for telephone message service.

minimum and maximum value of .006 seconds in the corrected range. Without correction this difference would have been .055 seconds.

Figs. 14, 15 and 16 correspond respectively to the previous three but are for a 500 mile length of the cable for regular telephone message service. The total delay for 500 mile length of this cable after correc-

[17] In designing apparatus going in long distance circuits in general the parts are so designed that if a circuit 3 or 4 thousand miles long is used the total accumulated distortion due to either amplitude or phase will be within tolerable limits.

tion is .029 seconds. A 3000 mile length would give .174 seconds delay. The difference after correction for 3000 miles between minimum and maximum value of $dB/d\omega$ is .007 seconds and before correction .035 seconds. This phase corrector (for 500 miles) consists of 12 sections, 8 of one kind and 4 of another. Each section contains four condensers and two four-terminal inductance coils with mutual between windings. Both this phase corrector and the previous one are formed by connecting together such all-pass network sections as to give the phase characteristic desired. In the first bridge T-sections are used and in the second lattice type.[18] The former are more economical when unbalanced apparatus may be used, though similar phase characteristics may generally be obtained with either.

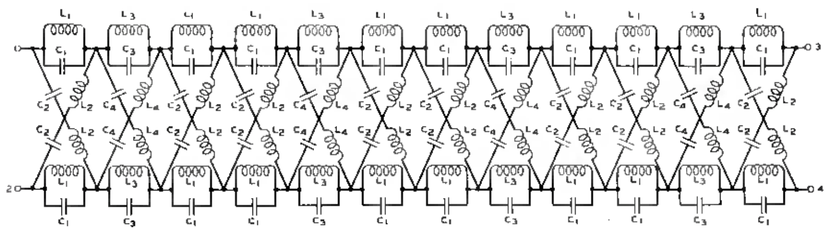


Fig. 15—Schematic of the phase corrector for 500 mile length of cable for telephone message service.

2. *Filters.*—The following factors influence the phase distortion in filters: (1) The width of the frequency band transmitted, (2) the amount of discrimination between transmitted and attenuated regions (corresponds to number of filter sections), (3) the rate at which the attenuation rises at the edges of the transmitting band, (4) the types of filter sections used, (5) the number of filters in tandem, (6) the amount of reflection due to impedance mis-match near the edges of the transmitting bands, and (7) the amount of dissipation in the filter elements.

The insertion phase characteristics of Fig. 17 and the insertion delay characteristics of Figs. 18 and 19 are for two low pass filters [19] of the usual type. As will be seen from their attenuation characteristics (insertion loss) each gives a discrimination of about 35 db, although the second requires an additional section in order to provide the rapidly

[18] Nyquist, U. S. patents Nos. 1,675,460 and 1,735,052 and Zobel patent No. 1,701,552; Maximum Output Network for Telephone Substation and Repeater Circuits, by G. A. Campbell and R. M. Foster, *Trans. A. I. E. E.*, Vol. 39, pp. 231–280.

[19] This note explains symbols used in these three figures and also the following three. Z_I is the image impedance. Z_0 for a low pass filter is the value of Z_I at zero frequency and for a high pass filter at infinite frequency. Q is the ratio of the coil reactance to its effective resistance. Dissipation in the condensers is considered negligible. For a filter section having an attenuation peak at frequency, f_∞, and a cut-off at, f_c, "a" is the ratio f_∞/f_c for a low pass filter and f_c/f_∞ for a high pass filter.

rising attenuation at the edge of the band. These curves show that the delay distortion in the transmitting band is increased by increasing the slope of the attenuation curve at the cut-off although the minimum value—i.e. the delay which applies to the signal as a whole, does not increase appreciably. The effective band width transmitted depends upon both the delay and attenuation characteristics since especially

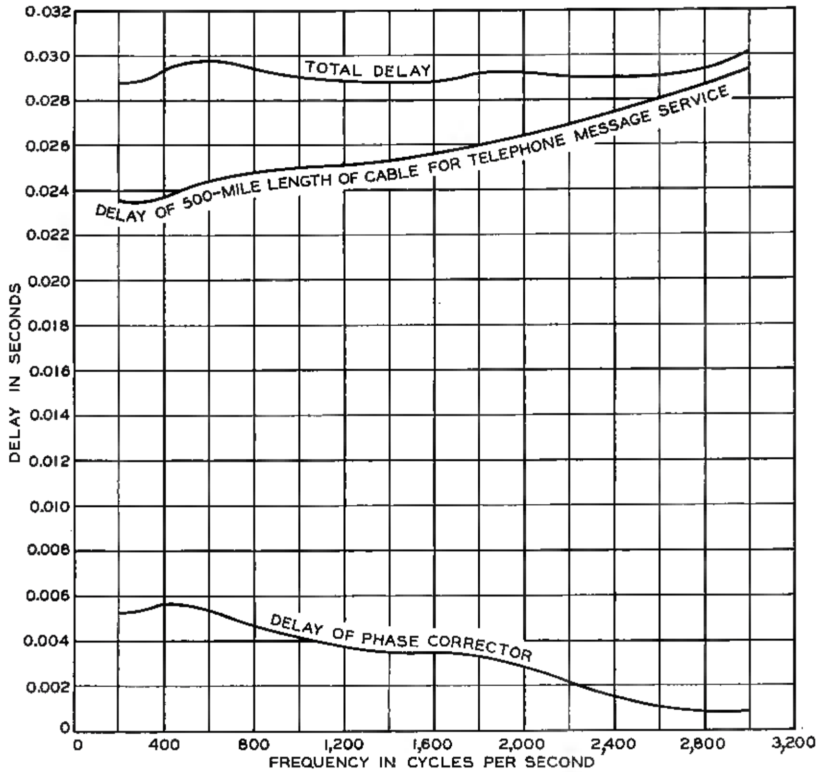


Fig. 16—Insertion delay characteristics corresponding to the phase characteristics of Fig. 14.

for a number of filters like these in tandem the delay of the frequency components of the wave near the cut-off may be so great that these components contribute little to articulation. Therefore in the design of filters a proper balance must be determined between the rate of attenuation and the delay distortion. A more complete discussion of the relation between delay, attenuation, and the effective cut-off is given in the paper by J. C. Steinberg.[20] When low pass filters are to be designed with sharper cut-offs from the standpoint of both delay and attenuation, there are two ways in which this is usually done, one

[20] Loc. cit.

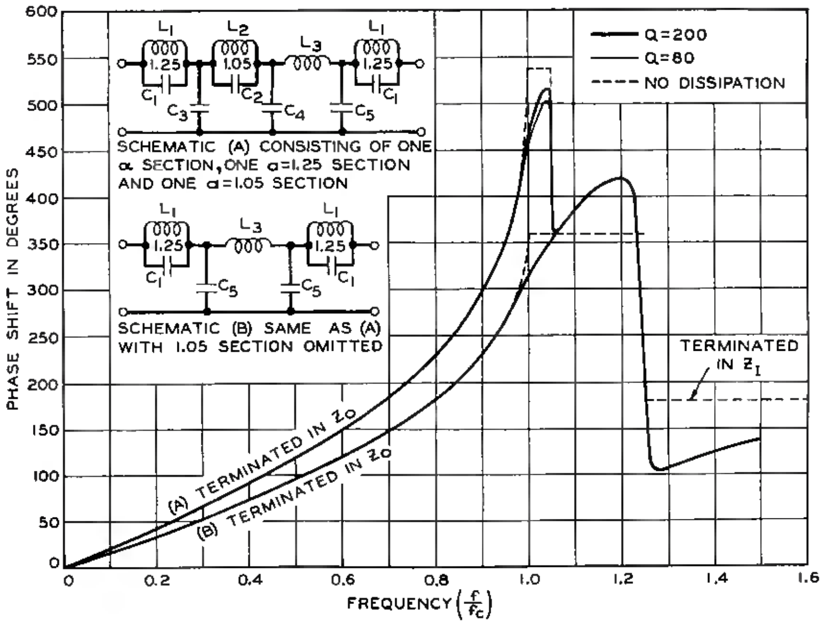


Fig. 17—Insertion phase characteristics and schematics of low-pass filters. (*A*) For a filter consisting of 3 full sections, one section having no attenuation peak, one with a peak at $1.25f_c$ and another at $1.05f_c$. (*B*) Same as (*A*) with the 1.05 section omitted.

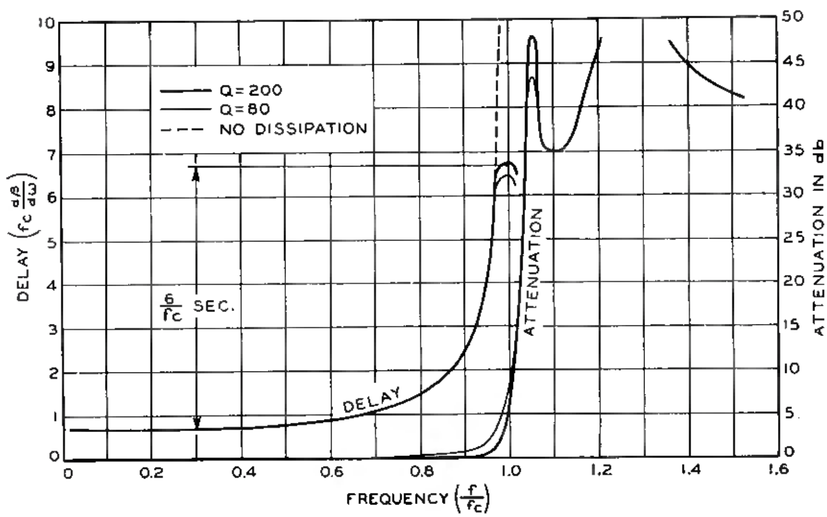


Fig. 18—Insertion delay and attenuation characteristics for filter *A* of Fig. 17.

is the use of a few filter sections of a type different from the usual types above having phase characteristics with a negative second derivative rather than positive so that the combination will postpone the occurrence of phase distortion until very near the theoretical cut-off and the other is the addition of all pass network sections which accomplish the same general result.

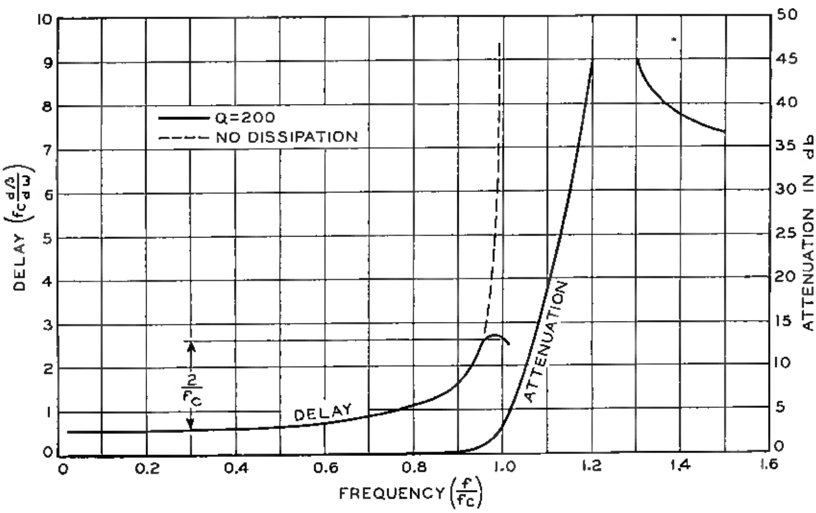


Fig. 19—Insertion delay and attenuation characteristics for filter *B* of Fig. 17.

One other point should be noted here. The shape of the insertion phase curve as shown at the cut-off frequency owes its departure from the image transfer phase shift without dissipation shown by the dotted line more because of the reflection than dissipation. The value of the Q so long as it is within the usual range makes little difference.

Figs. 20, 21 and 22 correspond to those of 17, 18 and 19 but are for high pass filters. High pass filters introduce no initial delay to signals as a whole. The distortion of the signal is dependent upon sharpness of cut-off, Q etc. just as for low pass filters.

Band pass filters give an initial delay defined by the shape of the phase curve. Other factors remaining the same this delay as well as the amount of phase distortion is inversely proportional to $f_2 - f_1$ the band width in cycles and is independent of the position of the band on the frequency scale. The effect of reflection, dissipation, sharpness of cut-off, etc., are about the same at the lower cut-off as for a high pass filter and at the upper cut-off as for a low pass. As already noted one distinguishing feature of the phase characteristic of a band pass filter

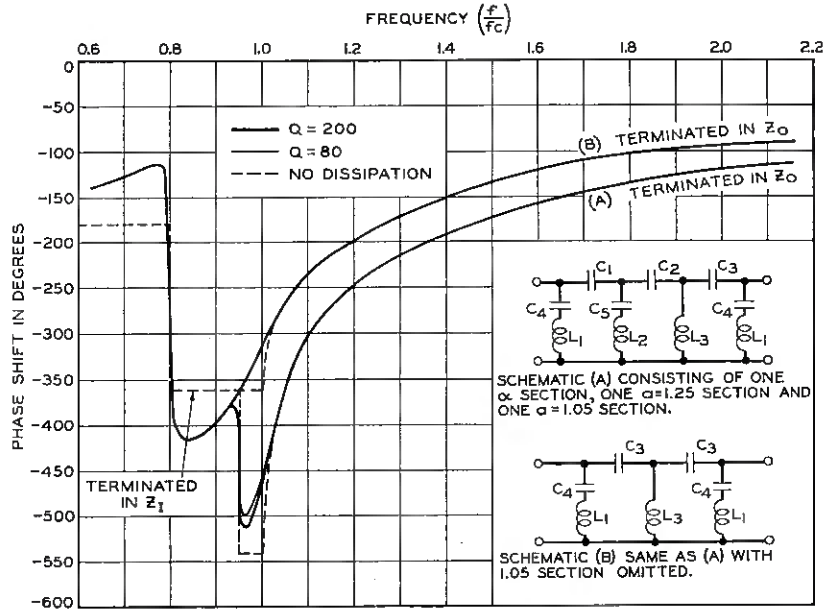


Fig. 20—Insertion phase characteristics and schematics for high-pass filters. (*A*) For a filter consisting of 3 full sections, one section having no attenuation peak, one with a peak at $1/1.25f_c$ and another at $1/1.05f_c$. (*B*) Same as (*A*) with the $1/1.05f_c$ section omitted.

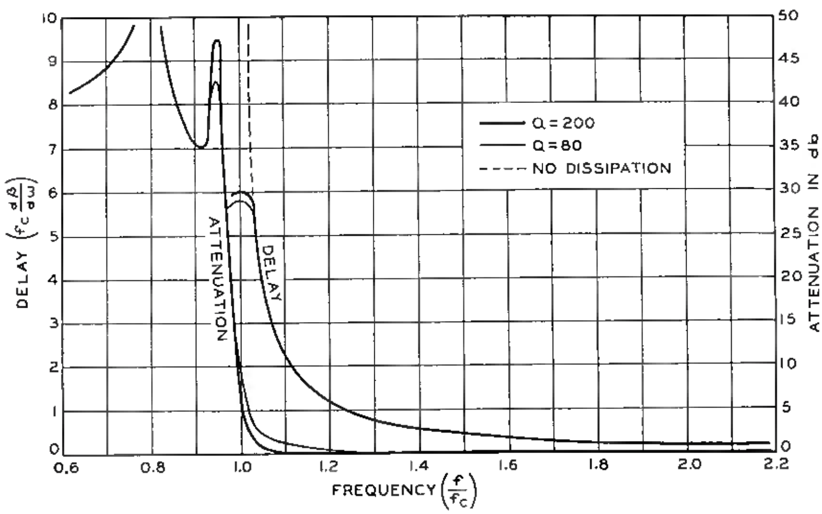


Fig. 21—Insertion delay and attenuation characteristic for filter *A* of Fig. 20.

is that the straight portion of the phase curve may if extended intersect the vertical axis at any point and does not like the low pass filter pass always through $N\pi$.

As an example of a condition where it has been found necessary to take phase into consideration in designing low pass filters let us consider the case of line filters used in open wire circuits transmitting simultaneously both programs for broadcasting and carrier telephony. Here as many as 40 or 50 filters may be used in tandem.

Fig. 23 shows the measured delay and attenuation characteristics

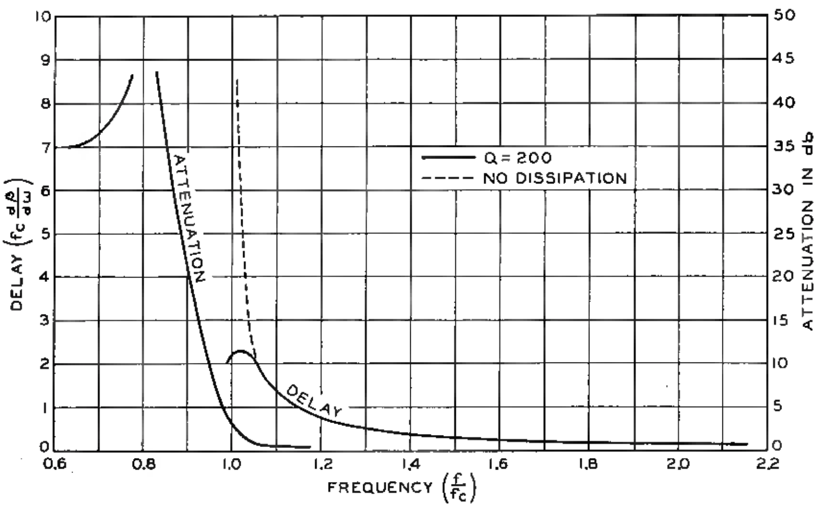


Fig. 22—Insertion delay and attenuation characteristic for filter *B* of Fig. 20.

for 25 of the present 5000 cycle quality line filters now in use, these filters being connected in tandem. The circuit is so designed that it practically equalizes up to 5000 cycles for the attenuation distortion. When a number of these filters are used in tandem as in the longest "hook ups" the phase distortion of these filters is somewhat noticeable but not seriously so and their effective cut-off is appreciably lowered because of this phase distortion.[21]

Fig. 24 gives the calculated delay and attenuation of twenty-five 8000 cycle low pass line filters connected in tandem. This filter is being considered for use in place of the 5000 cycle line filter of Fig. 23. The delay for 25 of these filters in tandem is approximately constant up to 7500 cycles (within .001 seconds). The attenuation is also constant up to this frequency. The attenuation

[21] J. C. Steinberg, loc. cit.

distortion between 7500 and 8000 cycles is purposely left uncorrected so that if these filters are used when a number of them are connected in tandem on a line, the effective cut-off will be lowered therefore eliminating the effects of any accumulating delay over this range. Thus for short distances 8000 cycle quality will be realized, and for very long circuits 7500 cycle quality, and for intermediate lengths something in between. In any case the effects of delay distortion will be negligible. Special filter sections are used in order to meet the unusual delay and attenuation requirements. The same results could

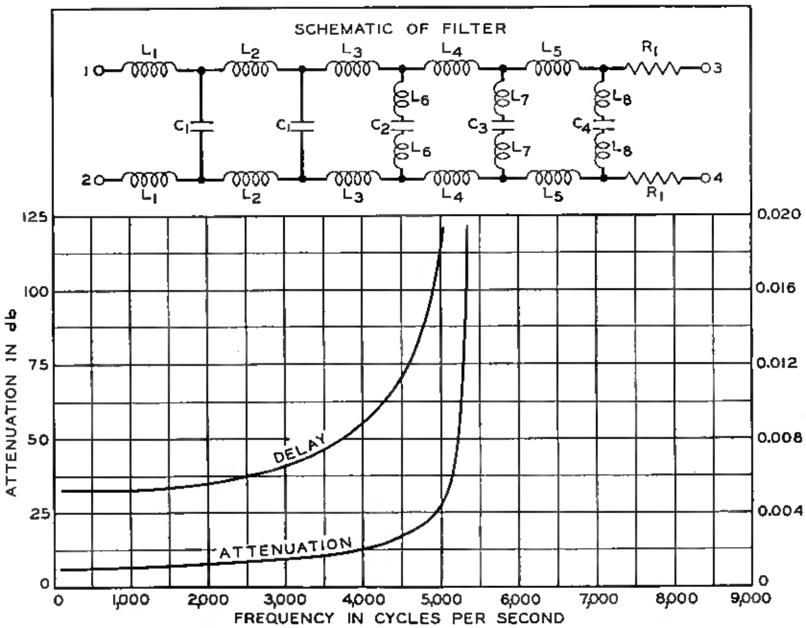


Fig. 23—Schematic, insertion delay and attenuation characteristics of twenty-five 5000 cycle low-pass line filters connected in tandem.

have been obtained using the usual type sections like those used in the 5000 cycle filter and then correcting for phase by an all-pass structure. Such a method would have resulted in a somewhat more expensive filter and one giving more overall delay.

3. *Repeaters.*—The chief sources of delay in telephone repeaters are the transformers. However, some additional low frequency delay is caused by shunt retard coils and series condensers. This is kept within negligible limits by using large values of both. Conversely inductance in series and capacitance in shunt cause high frequency delay but this effect can easily be made negligible in any frequency range in which one is interested. Fig. 25 is a schematic of the telephone repeater

used in the cable circuit previously referred to for program transmission. A repeating coil and input transformer at its input and the output transformer at its output are shown. These will be discussed in the next paragraph.

4. *Transformers.*—As an example of phase distortion in transformers we shall consider those shown in the telephone repeater of Fig. 25. Here, the phase shift of a small number of transformers would be of little importance but where a large number are connected together as in long toll circuits their effect cannot be overlooked. The delay caused by a transformer is similar to that of a high-pass filter. The

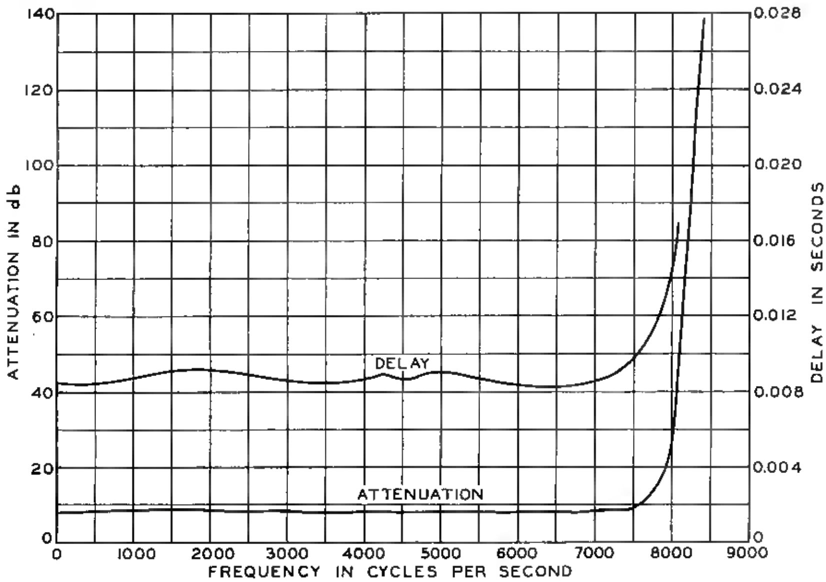


Fig. 24—Insertion delay and attenuation characteristics of twenty-five 8000 cycle low-pass line filters connected in tandem.

insertion phase characteristics of these three transformers between impedances for which they were designed are shown in Fig. 26 and their insertion delay characteristics, $dB/d\omega$ in Fig. 27. It will be noticed that practically all of the delay occurs below 100 cycles. The three together give at 40 cycles a value of $dB/d\omega$ of .0008 seconds. 25 sets would give .020 seconds delay. Experience has shown that this amount of delay for speech at low frequencies is negligible whereas at high frequencies such would not be the case.[22]

5. *Attenuation Equalizers.*—Attenuation equalizers introduce some phase distortion but the amount is so small that it can generally be

[22] At high frequencies $(dB/d\omega)_{max.} - (dB/d\omega)_{min.}$ must generally be kept under .005 to .010 seconds if its effect can be neglected for speech.

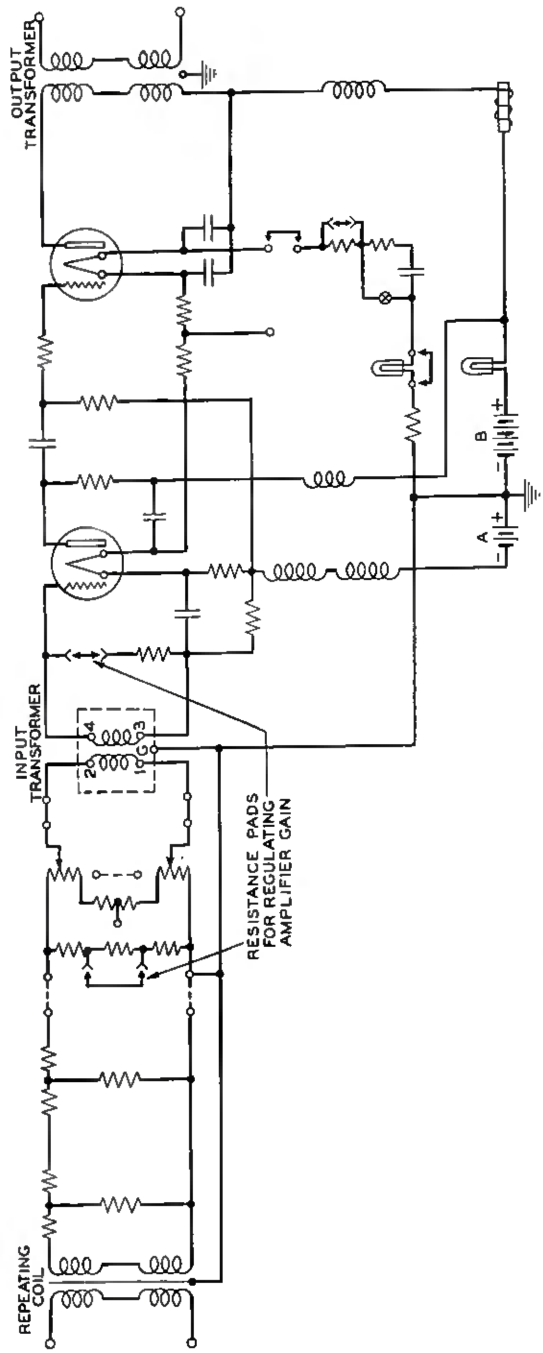


Fig. 25—Schematic of repeater used in the cable circuit for program transmission.

neglected. The presence of such equalizers in the circuit for program transmission did not influence the design of the phase correctors. However in considering the design of the equalizers the particular structure used was chosen on the basis of its giving a minimum amount of phase distortion.

Phase Distortion in Other Communication Systems

Phase distortion has for some time been considered a real problem in submarine cable telegraphy. If the highest reversal frequency of a telegraph signal is f_v it has been found expedient to correct for both

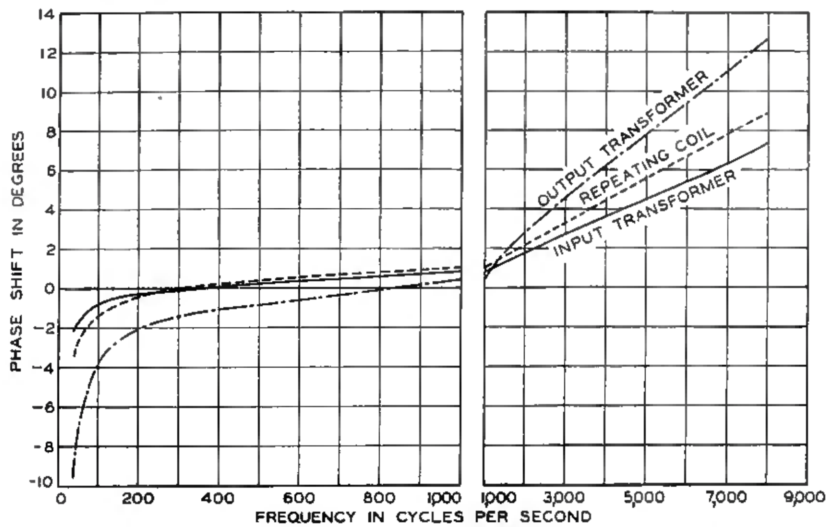


Fig. 26—Insertion phase characteristics of repeating coil, input transformer and output transformer used in repeater shown in Fig. 25.

amplitude and phase distortion over a frequency range of from zero to between 1.4 and 1.6 f_v. More phase distortion can be tolerated when the signal is read by the operator from a siphon recorder slip than for automatic printing. In the case where f_v is 60 cycles per second a 45° departure (at 60 cycles) from the low frequency characteristic if continued as a straight line it has been found in some cases to cause errors to be printed.

While no two telegraph cables are alike all except very short ones require that some means of phase correction be incorporated in the terminal apparatus. Although the general principles of correction have been investigated mathematically and the results have been very useful as a guide in indicating the relative effects of factors involved, the practical solutions so far have been largely empirical. This is due to the comparative simplicity of the experimental method. The results of a number of adjustments in the terminating apparatus may be observed experimentally while one is investigated mathematically. This is due to the fact that one can tell, using an oscillograph, from the direct observation of the received signal when a proper adjustment is reached. It is not necessary, as in telephony, to make complete

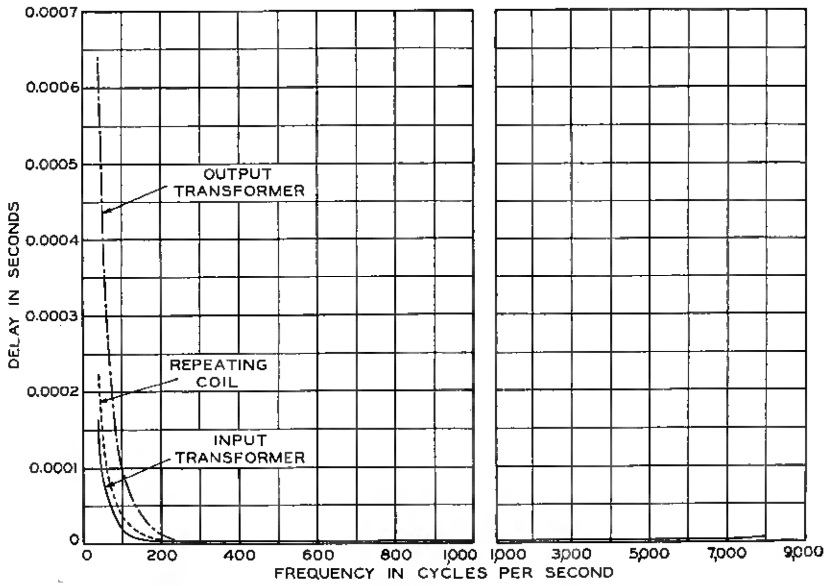


Fig. 27—Insertion delay characteristics corresponding to the phase characteristics of Fig. 26.

articulation tests or a large number of single frequency measurements. The advent of the continuously loaded cable made possible by the use of permalloy has simplified the problem. A discussion of detailed methods of phase correction in telegraph cable cannot be gone into here. Circuits in general use have been described in previous publications.[23]

Two other important places where it has been necessary to control phase distortion are (1) in circuits for picture transmission [24] and (2)

[23] The Loaded Submarine Cable, O. E. Buckley, *Bell Sys. Tech. Jour.*, July, 1925; High Speed Ocean Cable Telegraphy, O. E. Buckley, *Bell Sys. Tech. Jour.*, April, 1928; The Application of Vacuum Tube Amplifiers to Submarine Telegraph Cables, A. M. Curtis, July, 1927; Automatic Printing .for Long Loaded Submarine Telegraph Cables, A. A. Clokey, *Bell Sys. Tech. Jour.*, July, 1927; J. R. Carson (U. S. Patent 1,315,539) and R. C. Mathes (U. S. Patent 1,311,283).

[24] Transmission of Pictures over Telephone Lines, H. E. Ives, J. W. Horton, R. D. Parker and A. B. Clark, *Bell Sys. Tech. Jour.*, April, 1925.

television circuits.[25] The necessity in both cases is similar. In picture transmission the frequencies between 900 and 1700 cycles were involved and a maximum departure for the system as a whole of $dB/d\omega$ from a constant value of .0005 seconds in this frequency range was found permissible. In television it was considered desirable to transmit frequencies over the range from 10 cycles to 20,000 cycles such that the value of $dB/d\omega$ as a function of frequency was constant about $\pm$.00002 seconds over all but the lowest part of the range. There at the very lowest frequency $\pm$.001 seconds was considered permissible.

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Appendix I

Phase Shift Defined

Networks with a pair of input terminals and a pair of output terminals such as lines, filters, equalizers, phase correctors, transformers, etc., are designed to work between a source of e.m.f. E_a, of impedance Z_a, and a receiving device of impedance, Z_b. The source of e.m.f. is generally spoken of as the generator and the receiving device as the load. Such a network, N, connected to a generator and a load are shown in Fig. 28. Terminals 1 and 2 are the input terminals and 3 and 4 the output terminals.

For any frequency let $Z_a = W_a$ be the image impedance[26] at ter-

[25] Production and Utilization of Television Signals, F. Gray, J. W. Horton and R. C. Mathes, *Bell Sys. Tech. Jour.*, October, 1927; Wire Transmission Systems for Television, D. K. Gannett and E. I. Green, *Bell Sys. Tech. Jour.*, October, 1927.

[26] The image impedance at either end of a four terminal network is given by the square root of the product of two impedances at that end, one measured with the opposite end short circuited and the other with it open circuited.

minals 1 and 2 and W_b at 3 and 4. For these terminating conditions let the input current be I_a' and the output current I_b'. The image transfer constant, θ, of the network then is

$$\theta = \log_e \frac{I_a'}{I_b'} \sqrt{\frac{W_a}{W_b}}. \tag{1}$$

Let

$$\theta = A' + jB' \tag{2}$$

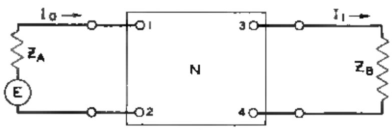

Fig. 28—Network connected between a generator of impedance Z_a and a load of impedance Z_b.

A' is the real part of the image transfer constant and B' is the imaginary part. We have

$$\frac{I_a'}{I_b'} \sqrt{\frac{W_a'}{W_b'}} = e^{\theta} = e^{A'} \underline{|B'}. \tag{3}$$

B' is the *image transfer phase shift* of the network.[27] Its value as a function of frequency gives the *image transfer phase characteristic* of the network.

There is another type of phase shift of more frequent use. Let I_b be the current through the load before insertion of the network, i.e., when the generator and load are connected directly together or connected together by means of an ideal transformer of the best turns ratio. Let I_b'' be the current through the load with the network in place as shown in Fig. 28. Then

$$\frac{I_b}{I_b''} = e^{A''} \underline{|B''} \tag{4}$$

B'' is the *insertion phase shift.*[28] It will be noted that when the terminating impedances are the image impedances that B' and B'' are the same.[29]

In most practical cases the phase shifts as defined above are determined for pure resistance terminations hence the phase shifts may equally well be said to relate the applied voltage to the received current. The angle of lag of the received current is regarded as positive.

[27] 20 $\log_{10} e^{A'}$ gives the image transfer loss in decibels.
[28] 20 $\log_{10} e^{A''}$ gives the insertion loss in decibels.
[29] The term insertion loss and insertion phase shift is here extended to include cases where apparatus is designed to work between resistance impedances of different values.

Appendix II

Analytical Discussion of Phase Characteristics

By means of the Fourier Integral any signal or wave whatever may be regarded as the sum of an infinite number of steady state sinusoidal frequency components which have existed and will exist for all time. Their amplitudes are infinitesimal and they are separated by differentially small amounts in their frequency spectrum. The finite wave is the sum of the infinitesimal components and is determined by their relative amplitudes and phases. The general Fourier Integral for the wave I_a may be written

$$I_a = \int y \cos (\omega t + \theta) \, d\omega, \tag{5}$$

where $\omega = 2\pi f$, f being the frequency. y and θ are functions of ω. If the amplitude is altered by a constant factor at all frequencies there is no amplitude distortion. For the purpose of discussing phase distortion we shall assume this factor unity. Let the angle be modified by any network by an angle B which is a function of frequency. The expression for the received wave will then be

$$I_b = \int y \cos (\omega t + \theta - B) \, d\omega. \tag{6}$$

Let us assume a simple case where B is proportional to frequency, i.e.

$$B = a_1 \omega. \tag{7}$$

Then

$$\begin{aligned} I_b &= \int y \cos (\omega t + \theta - a_1 \omega) d\omega \\ &= \int y \cos (\omega (t - a_1) + \theta) d\omega \\ &= \int y \cos (\omega t' + \theta) d\omega, \end{aligned} \tag{8}$$

where

$$t' = t - a_1. \tag{9}$$

This then is identical with the original wave form but occurs at a time a_1 later given by

$$\frac{B}{\omega} = \frac{dB}{d\omega} = a_1. \tag{10}$$

Such a phase curve then gives no distortion but a *delay*.[30]

The phase characteristic of a low pass filter or cable in the transmitting range may be written

$$B = a_1 \omega + a_2 \omega^2 + a_3 \omega^3 \cdots. \tag{11}$$

[30] It can be readily seen that for any portion of the phase characteristic we may have $B = a_1 \omega \pm N\pi$. N is an integer where N is even the results will still be the same as for $N = 0$ since $\cos (N\pi + \theta) = \cos \theta$. If N is odd the only difference is a change in sign of I_b.

We may consider the signal as operated on successively by different portions of the phase characteristic. The first term $a_1\omega$ delays the signal without distortion by time a_1, the remaining terms distorting it.

The phase characteristic of a constant K band pass filter and those derived from it may, in the transmitting range, be written

$$B = a_1(\omega - \omega_m) + a_2(\omega - \omega_m)^2 + a_3(\omega - \omega_m)^3 \cdots. \qquad (12)$$

Let $a_0 = a_1\omega_m$. a_1 again defines delay of the signal without distortion provided $a_0 = N\pi$. If $a_0 \neq N\pi$ there is a delay a_1 and in addition every component is shifted through an angle a_0 and then distorted by the remaining terms. Let us see what the constant phase shift a_0 of itself does to the signal.

We may write

$$I_b = \int y \cos(\omega t + \theta - a_0)d\omega \qquad (13)$$

or

$$I_b = \cos a_0 \int y \cos(\omega t + \theta)d\omega + \sin a_0 \int y \sin(\omega t + \theta)d\omega. \qquad (14)$$

The wave resulting from this distortion only may be resolved into two components one undelayed and exactly like the original but modified by the amplitude factor $\cos a_0$ and another which may be derived from the original by shifting all of the components through an angle $\pi/2$ and modifying by a factor $\sin a_0$.

The phase characteristics of a high pass filter may be written

$$B = a_1^1\omega^{-1} + a_2^1\omega^{-2} + a_3^1\omega^{-3} \cdots. \qquad (15)$$

Here there is no term producing a delay without distortion to the signal as a whole nor is there a constant term producing a constant phase shift at all frequencies as in band filters. The distortion depends upon the values of a_1a_2 etc.

The phase characteristic of an all pass network may in the lower frequency range be represented by the same expression as for the low-pass filter and in the upper frequency range as for the high-pass filter but no such series as above will cover the entire range.

Measurement of Phase Distortion *

By H. NYQUIST and S. BRAND

This paper deals with the measurement of phase distortion or delay distortion and is particularly concerned with measurements on telephone circuits. For this purpose, use is made of a quantity defined as "envelope delay," which is the first derivative of the phase shift with respect to frequency. Various methods for measuring this quantity and the principles on which they are based are discussed, the details of the measuring circuits being omitted and sources of further information referred to when possible. Data are included which give the measured envelope delay-frequency characteristics of several kinds of telephone circuits.

At an early date in the use of long loaded telephone circuits, certain disturbing effects at high frequencies were noticed which have been known as transients.[1] It was found that on such circuits, even when the attenuation was very carefully equalized within the transmitted range, these transient effects still persisted and were made worse. It was realized that these effects were due to phase distortion or delay distortion, that is, the resultant effect of phase shift varying with frequency in a peculiar manner. It was also determined that these effects resulted largely from the loading associated with the circuit pairs and that the effect could be considerably reduced by using a much lighter loading for the circuits.[2] Lighter loading systems were applied to telephone circuits so that as a result these transient effects were minimized to such an extent as to make circuits commercial for telephone use.

Recent developments in telephone transmission and in special services requiring the use of telephone circuits have emphasized these high-frequency effects due to phase distortion and have indicated a similar effect at low frequencies which results from the equipment associated with the circuit. The use of loaded cable circuits in place of open-wire circuits, with a corresponding increase in the number of repeaters, has increased the phase distortion considerably on telephone circuits. This is particularly true when very long telephone circuits in cable result so that these effects are quite disturbing. Certain special uses to which circuits have been put within the last five or six years require either a much wider band of frequencies for transmission, or can allow only a very small amount of distortion within the required band. Circuits which would ordinarily be satisfactory for telephone use are not good enough for these purposes.

* Presented at New York Section, A. I. E. E., May 1930.

[1] "Telephone Transmission of Long Cable Circuits," A. B. Clark, *Jour. A. I. E. E.*, Vol. XLII, p. 1, 1923, and *B. S. T. J.*, Vol. II, p. 67, 1923.

[2] J. R. Carson, A. B. Clark, J. Mills, U. S. Patent 1,564,201.

For example, telephotography,[3] which requires a relatively narrow band of frequencies, can allow so little phase distortion within this band for satisfactory transmission of a picture, that the use of H-174* side circuits for distances greater than about 100 miles requires the use of some means for correcting the phase distortion introduced by the loading on the cable pairs. The transmission of programs for the interconnection of radio broadcasting stations requires a wide frequency band for satisfactory quality; and unless corrected, effects due to phase distortion outside the usual telephone range of frequencies, which would not be very disturbing for telephone conversation, make the program transmitted unsatisfactory to the listener. Television, of course, with its very wide frequency band and its very rigid requirements regarding phase distortion, does not allow even the use of open wire circuits for its transmission for any great distance without the aid of phase correction.[4]

It is the purpose of this paper to describe and discuss various methods which have been devised for the measurement of phase distortion. Phase distortion and its effects, as well as methods of correcting for it [5, 6, 7, 8], are considered here only sufficiently for the understanding of these measuring means. It is, of course, necessary that before the correction can be designed, the amount of distortion be known, and that, after the corrective apparatus has been built and applied to the circuit, the overall system be checked to find out how complete the correction has been. The devices described below are for this particular purpose, and before describing them, the fundamental theory upon which they are based will be considered. Some of the principles underlying particular methods of measurement will be considered in the description of the devices themselves.

After the discussion of the various measuring devices, certain data will be given which give the results of various measurements made on actual telephone circuits with some of these measuring devices.

[3] "The Transmission of Pictures over Telephone Lines," H. E. Ives, J. W. Horton, R. D. Parker, A. B. Clark, *B. S. T. J.*, Vol. IV., p. 187, 1925.

* In designating loading systems, the initial letter denotes spacing, *H* denoting 6000 feet and *B* denoting 3000 feet; the first number denotes the inductance of the loading unit in the side circuit in millihenries; a second number denotes the inductance of the loading unit in the phantom circuit in millihenries; the letter *N* following the number denotes non-phantomed pairs.

[4] "Wire Transmission System for Television," D. K. Gannett and E. I. Green, *A. I. E. E. Transactions*, Vol. XLVI, p. 946, 1927 and *B. S. T. J.*, Vol. VI, p. 616, 1927.

[5] "Phase Distortion and Phase Distortion Correction," Sallie Pero Mead, *B. S. T. J.*, Vol. VII, p. 195, 1928.

[6] "Distortion Correction in Electrical Circuits with Constant Resistance Recurrent Networks," O. J. Zobel, *B. S. T. J.*, Vol. VII, p. 438, 1928.

[7] "Phase Distortion in Telephone Apparatus," a companion paper by C. E. Lane.

[8] "Effects of Phase Distortion on Telephone Quality," a companion paper by J. C. Steinberg.

Theory Underlying Phase Distortion Measurement

It should be understood that what is meant here by phase shift is really the insertion phase shift; that is, the phase shift of a system is the change in phase at the receiving terminal due to the insertion of the system under consideration between the generator and the receiving terminal. In the same way, when delays are mentioned, insertion delays are understood unless otherwise specified.

A certain amount of time is required for the transmission of any signal from one place to another; and it has been found that, for a natural reproduction of tone or speech, or the satisfactory transmission of any signal, not only must the attenuation of the various component frequencies be approximately equalized, but also the time of propagation of these same component parts must be nearly the same for different frequencies. This time of propagation is, of course, closely related to the change in phase of the component frequencies during transmission.

In order to have no phase distortion it is necessary that the phase shift be linear with frequency within the frequency range required for transmission.[5, 7] Graphically, this means that if the phase shift is plotted as a function of frequency, the resulting graph will be a straight line within the frequency range under consideration. It is evident then that for such a condition the first derivative of the phase shift with respect to frequency, or the slope of the phase shift-frequency curve, is constant.

The slope or first derivative is closely related to the delay of the envelope. The following statement results from a mathematical consideration of the building up of sinusoidal currents in systems similar to those which we are considering here.[9] *The envelope of the oscillations in response to an e.m.f. $E \cos \omega t$ applied at time $t = 0$ reaches 50 per cent of its ultimate steady value at time $t = d\beta/d\omega$ and its rate of building up is inversely proportional to $\sqrt{d^2\beta/d\omega^2}$.* Various assumptions are made in arriving at this conclusion, but it does not seem necessary to discuss these here except to mention the condition that the attenuation of the system under consideration should be approximately equalized over the frequency range in the neighborhood of the applied frequency.

It is apparent then that this quantity $d\beta/d\omega$ plays a fundamental rôle in determining the delay of a system. Moreover, the use of $d\beta/d\omega$ has an advantage over β in that it is constant for a distortionless system, while β varies with frequency. The quantity $d\beta/d\omega$ will simply be defined here as the "envelope delay" of a system in frequency

[9] "Building Up of Sinusoidal Currents in Long Periodically Loaded Lines," J. R. Carson, *B. S. T. J.*, Vol. III, p. 558, 1924.

ranges where the attenuation is not a function of frequency; that is, the envelope delay in seconds is

$$T = \frac{d\beta}{d\omega} = \frac{dB}{df},$$

where

$\beta =$ the phase shift measured in radians,

$B =$ the phase shift measured in cycles,

$f =$ the frequency measured in cycles per second,

and

$\omega = 2\pi f.$

Hereafter in this paper this notation will be used.

For a distortionless system this quantity is the actual delay of the signal transmitted through the system. However, for a system which introduces phase distortion, the received envelope is usually quite different from the impressed envelope; and the delay of this envelope through the system is then quite indefinite depending upon what particular feature of the envelope is taken for observation. Nevertheless, the quantity defined as envelope delay is perfectly definite for such a system.

The significance of phase shift and envelope delay and the relation between the two is considered at some length in other papers.[6*, 7] The use of phase shift and delay data as a measure of phase distortion is also considered there. Phase shift itself is a rather fundamental quantity and various means of measuring it can be devised when both ends of the system under consideration are available. In this paper, one method of doing this is referred to which has proved very useful in laboratory measurements in the design of apparatus. However, for field measurements on telephone circuits, envelope delay seems to be a more useful quantity with which to work. The derived nature of this quantity makes its measurement somewhat complicated and consequently considerable space is given to methods for this purpose.

The envelope delay is determined from the difference in the steady-state phase shift for a definite interval of frequency. In practical cases finite intervals are used instead of infinitesimally small intervals which would be required for the determination of the derivative, or of the slope of the phase shift-frequency curve. This means then that the measured value is actually the slope of the secant of the curve and is simply an approximate value for the envelope delay, the amount of approximation depending on the size of the interval chosen. The value of envelope delay arrived at in this way will be called T_Δ so that

[6*] l.c. Appendix I.

$$T_\Delta = \frac{\Delta\beta}{\Delta\omega} = \frac{\Delta B}{\Delta f},$$

where $\Delta\beta$ represents a finite difference in β, etc.

The use of steady-state conditions for the measurements of envelope delay * has quite evident advantages practically over a method which would tend to measure the delay of the envelope itself in a transient state.

Methods of Measurement

In making measurements of phase shift or envelope delay for the purpose of determining the phase distortion of a telephone system, it should be borne in mind that the absolute value is usually of small importance and that the chief purpose is to determine the relative values from one frequency to another; that is, the characteristic of the phase shift or delay with frequency is the desired information as regards phase distortion.

1. *Measurement of Phase Shift*

The first method of measurement described here will be one which may be used to measure the phase shift itself.[10] Fig. 1 shows schemati-

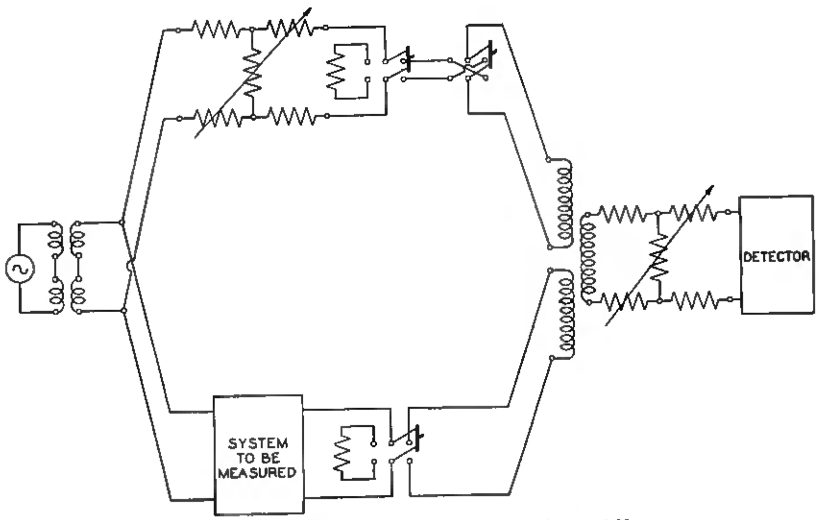

Fig. 1—Arrangement for measuring phase shift.

cally an arrangement of apparatus for measuring phase shift. Current of the frequency of measurement is sent through two paths, one con-

* The envelope delay is generally different from the phase delay which is the ratio of the phase shift to the frequency being considered, and should not be confused with it.

[10] W. P. Mason, U. S. Patent 1,684,403.

taining a resistance line (introducing only constant attenuation) and the other the system under consideration, to a detector which measures the magnitudes of the currents received from the two paths. Initially, by adjustment of the attenuation in the distortionless path the magnitudes of the two received currents are made the same. Then by operation of the switches the vector sum and difference of the two received currents can be measured. From the amount of attenuation introduced in the common path to the input of the detector to make the sum and difference equal, the difference in phase of the two received currents can be computed. This is the insertion phase shift of the system under consideration. This method of measurement has been only briefly described here, as all of its details are described in the patent referred to. This method does not involve an elaborate set-up of apparatus and gives accurate results, and is particularly useful where very small amounts of phase shift are involved.

2. *Measurement of Delay*

A number of measuring methods will now be described which vary somewhat in the amount of apparatus required and in the convenience with which the measurements can be made. The method of measuring envelope delay from impedance measurements is given first because of the very small amount of apparatus required, and for certain interesting steady-state phenomena which will appear in discussing the method of its operation. Following this, several modifications of a method will be referred to for determining the envelope delay from phase shift measurements. The application of this method and the determination of the results are usually quite laborious, but are given here since the apparatus required is fairly small in amount and usually readily available in a laboratory. When a number of delay measurements are to be made so that the saving of time during measurement is of importance, direct measurements of envelope delay can be made using somewhat complicated measuring circuits which require considerable time for building and calibrating, but which will allow measurements to be made simply with the loss of relatively little time. Several such circuits will also be considered.

a. Determination of Envelope Delay from Impedance Measurements

A method is given here for determining the envelope delay from steady-state impedance measurements. The method is limited to the measurement of systems which are capable of transmitting in both directions, and in certain cases it is further restricted in that both terminals of the system under test must be readily available at the point where the test is conducted. The method is unsatisfactory for measuring extremely small amounts of envelope delay. It is particularly suitable for measurements on correcting networks in the field where special delay measuring apparatus is not available.

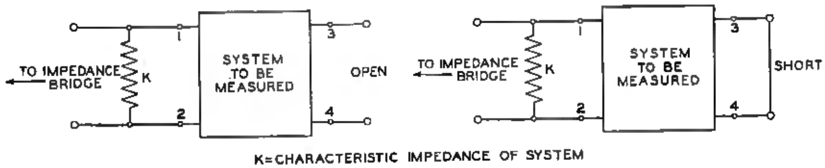

Fig. 2—Arrangement for special impedance measurements.

The system to be measured is connected to the impedance bridge as indicated in Fig. 2. The termination (short or open) used at the far end of the system constitutes a 100 per cent irregularity in its structure and the alternating current transmitted by the system from the impedance bridge to the far end is totally reflected at this irregularity and retransmitted by the system to its input terminals. When a steady-state has been established, this reflected current bears a definite phase relation to the incident current at the input terminals, this relation depending on the steady-state phase shift of the system at the frequency used for the measurement. This phase relation varies with frequency and, consequently, the measured impedance of the system will also vary with frequency. These variations in impedance are evident from the impedance-frequency curves plotted from the measurements taken, and it can be seen that the impedance varies cyclically over the frequency range.

To begin with we shall assume that the impedance bridged across the measuring trunk equals the characteristic impedance, K, of the system, as shown in the figure, and that the characteristic impedance is the same in both directions. Then if the variation of impedance completes one half cycle when the frequency is increased from f_1 to f_2 cycles, it is evident that the steady-state phase shift of twice the system is one half cycle greater at f_2 than at f_1. Now the envelope delay of a system in seconds at any frequency f is approximately

$$T_\Delta = \frac{\Delta B}{\Delta f},$$

where $\Delta B =$ the change in phase shift in cycles for a small change in frequency of Δf cycles per second. Here the change in the steady-state phase shift of the system is one quarter cycle for a finite change in frequency of $f_2 - f_1$. Dividing this change of phase shift by the change of frequency gives for the envelope delay of the system

$$T_\Delta = \frac{1}{4(f_2 - f_1)}\,.$$

T_Δ here is not the envelope delay of frequency f_1 or of frequency f_2, but it is the envelope delay of some intermediate frequency. For our purpose, it is sufficiently accurate to assume that T_Δ is the envelope delay of the system at the frequency $(f_2 + f_1)/2$. The envelope delay of the system at any frequency can thus be determined from the impedance curves by making measurements over a sufficient frequency range to find the length in cycles per second of one half an impedance cycle with its mid-point at the frequency of which the delay is to be determined.

If a system has constant envelope delay and attenuation over the frequency range involved, then the impedance curves are periodic. The resistance and reactance curves are in quadrature with each other. The resistance and reactance curves for an open termination are 180° out of phase, respectively, with those for a short-circuit termination. In the usual case, however, there is attenuation in the system and this varies with frequency. The change caused by this attenuation in the impedance curves is in the amplitude of the impedance variations. The amplitude varies inversely with the attenuation of twice the system, expressed in terms of current ratio. Due to the variation of the envelope delay of the system with frequency, the length of an impedance cycle in cycles per second of frequency varies with frequency. The effect of this variable delay on the impedance curves is that the impedance cycles are concentrated more and more along the axis of the curve as the delay increases, the length of the impedance cycle varying inversely with the envelope delay of the network.

By way of illustration, Fig. 3 shows the computed impedance curves for short and open terminations on a 100-mile unit of phase corrector for 19-gauge, H-174 side circuit. Fig. 3 also gives the corresponding envelope delay-frequency curve. The characteristic impedance of this particular network is 600 ohms resistance. It will be noted that for this case the resistance curves for open and short terminations at the far end intersect on the line +300 ohms, while the corresponding reactance curves intersect on the zero line. The curve passing through the points of intersection of the curves for open and short terminations should be used as the axis for determining the length of impedance cycles. The delay obtained in this way is, of course, the delay of the system between its characteristic impedances.

When the characteristic impedance of the system under consideration is not the same for both directions, the delay obtained in this way is one half that of two such systems connected in tandem "back to back." Furthermore, when the impedance bridged across the measuring trunk

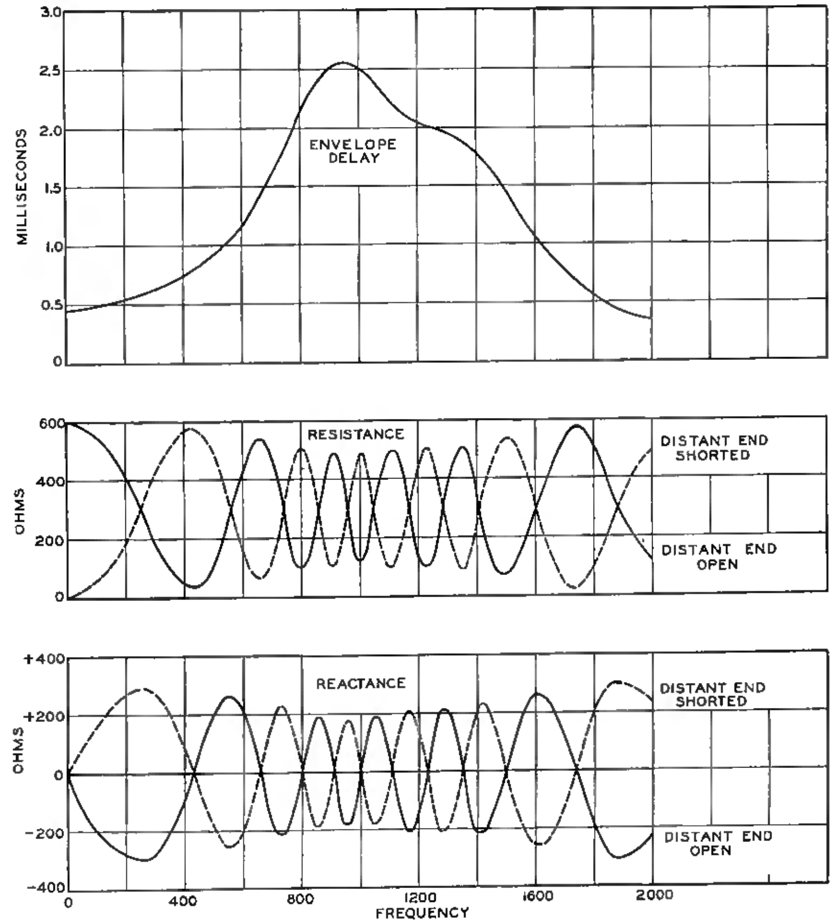

Fig. 3—Computed curves illustrating method of Fig. 2.

is not the characteristic impedance of the system being measured, then the delay measured is the insertion delay between two such impedances as the bridging impedance. Fundamentally, it is the periodicity of the difference of the impedance curves for open and short terminations which determines the insertion delay, and it follows that the periodicity obtained from the intersections of these curves gives the same delay.

The following method of measurement is given for those cases where the method already described is not sufficiently accurate because of the smallness of the impedance cycles for systems having large attenuations or delays.[11] It is assumed here that the characteristic impedance of the system is the same for both directions.

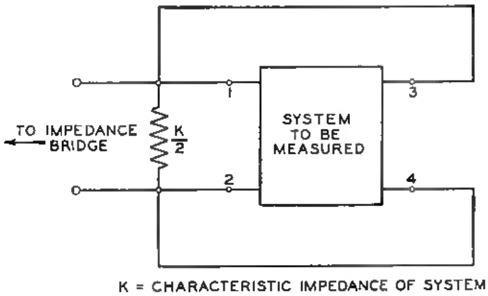

Fig. 4—Modified arrangement for special impedance measurements. (Open termination.)

Impedance measurements are made as before with the following changes as shown in Fig. 4: (1) $K/2$ is bridged across the measuring trunk in place of K; (2) instead of having the output of the network short-circuited or open, the output is bridged on the input. This case corresponds somewhat to the one above in which the open termination was used on the output of the system, with the exception that the return current now traverses the system only once in its complete trip from the bridge back to the bridge and, consequently, is attenuated and delayed only one half as much as before. These impedance curves are quite similar to those obtained above and may be interpreted in a similar manner. In this case, the envelope delay of the system in seconds at the frequency $(f_2 + f_1)/2$ cycles is, approximately,

$$T_\Delta = \frac{1}{2(f_2 - f_1)},$$

where $(f_2 - f_1)$ is the length in cycles per second of one half an impedance cycle of an impedance curve. Fig. 5 shows the computed impedance curves resulting from measurements made in this way on the same 100-mile unit of phase corrector and also gives the corresponding envelope delay-frequency characteristic of this network.

The case just described corresponds to the former case with the open end termination; that is, the results obtained are the same as those which would be obtained from the former case by using only one half

[11] D. K. Gannett, U. S. Patent 1,725,756.

of the system terminated at the far end in an open circuit. Impedance curves 180° out of phase with those obtained by the last method described can be obtained by using what is equivalent to one half of the system terminated at the far end in a short circuit. The circuit ar-

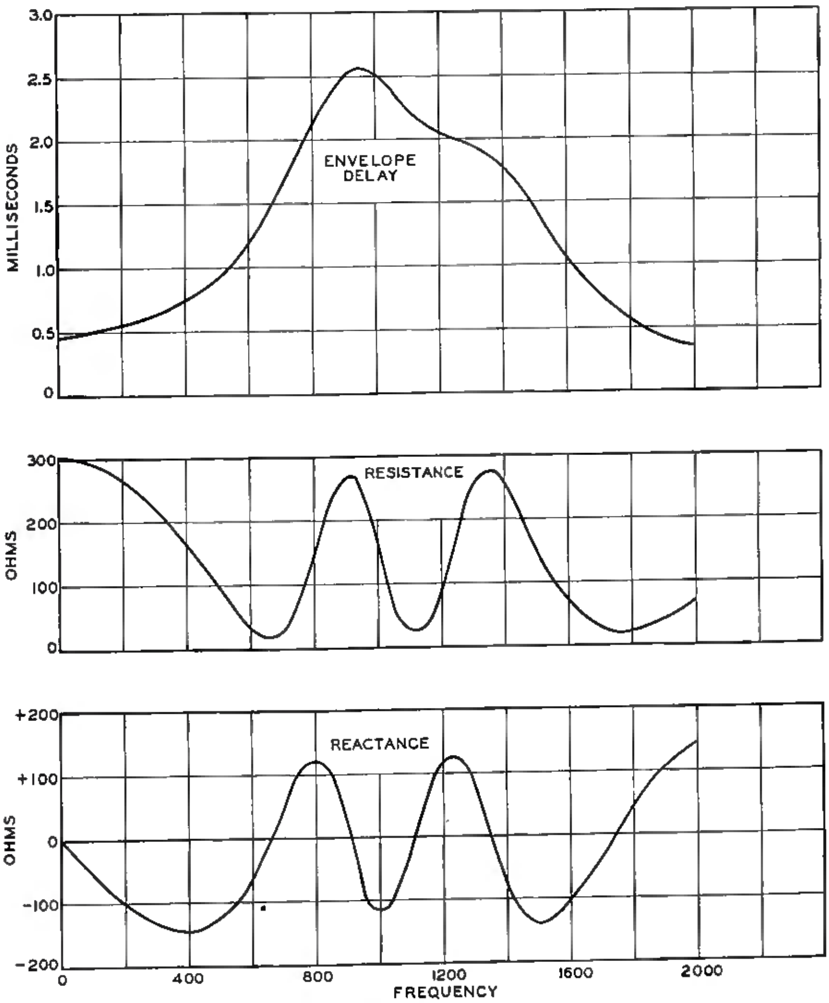

Fig. 5—Computed curves illustrating method of Fig. 4.

rangement for such measurements is given in Fig. 6. When the system being considered is balanced, the connections can be made as shown on the left. However, when the system is completely unbalanced, for example, a network built with no apparatus in one side so that all points in this side of the network are at the same potential, the measurements may be made with the arrangements shown on the right of the figure. In the latter case, the measured impedance is four times that obtained for an equivalent system by the method shown on the left of the figure; and in plotting these values for comparison with those obtained by the method of Fig. 4, one fourth of the measured values should be used. The results obtained in this way are evident from what has already been described and will not be illustrated here.

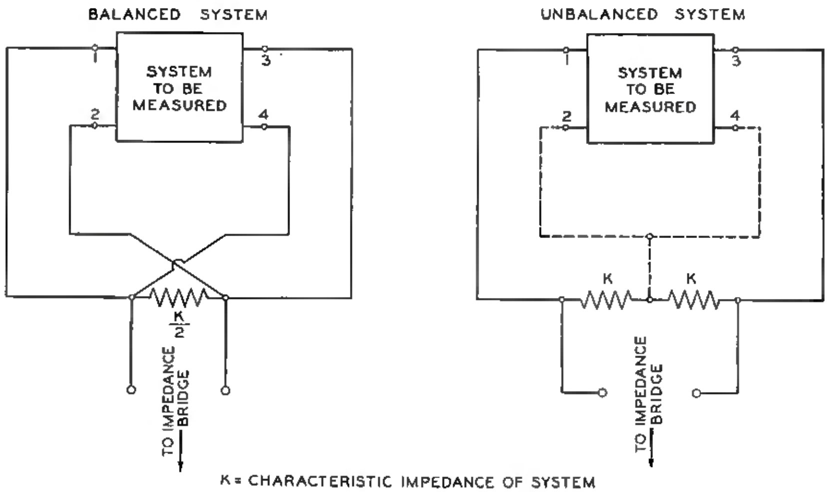

Fig. 6—Modified arrangement for special impedance measurements. (Short termination.)

As before, the curve passing through the points of intersection of the impedance curves corresponding to the open and short terminations should be used as the axis in determining the length of impedance cycles. For the network illustrated in Fig. 5, the resistance curves would intersect on the line +150 ohms, while the corresponding reactance curves would intersect on the zero line. The delay obtained in this way is the delay of the system between characteristic impedances. When other impedances are bridged across the measuring trunk than those shown in the figures, the delay measured is the insertion delay between impedances having the same relation to the actual bridging impedance as K has to the value of bridging impedance shown in the figures.

In most practical cases, the characteristic impedance of the network to be measured is a pure resistance and the network is designed to work between this impedance at each end. The value of resistance which should be bridged across the measuring trunk to measure the delay of the network under these conditions is obvious from the above discussion. Sufficient accuracy can often be obtained by considering only the impedance curve obtained for either the open or the short termination and using the axis of this curve for determining the length of the impedance cycle; e.g., in Fig. 5 (which gives curves corresponding to the open termination) using the lines +150 ohms and zero as the axes of the resistance and reactance curves, respectively.

b. Determination of Envelope Delay from Phase Shift Measurements

Methods will now be briefly described for determining the envelope delay of a system from special measurements of the steady-state phase shift; that is, the difference in phase shift for a definite frequency difference or the difference in frequency for a certain difference in phase shift will be measured and the delay computed therefrom. Three measuring methods will be considered in which the fundamental principles involved are much the same. Practical circuits for measuring delay by these methods may be rather complicated from an apparatus standpoint in order to facilitate the measurements as much as possible. The details of these circuits are not given here, but they are disclosed in various patents.[12, 13, 14]

The following gives the essential principles on which these methods of measurement are based: The current of the measuring frequency from an oscillator traverses two separate paths and is then combined at the receiving end of the measuring circuit. In the first path no phase distortion is introduced, while in the second the frequency is transmitted through the system of which the delay is to be measured. Both paths contain resistance attenuators, so that the magnitudes of the currents received from the two paths may be adjusted as desired. If now a frequency is chosen such that the phase shifts through the two paths cause the two received frequencies to be exactly out of phase, an adjustment can be made so that an observer listening with a receiver to the combined received currents will hear no tone when the two received currents are equal in magnitude. If the frequency is now changed continuously, the observer will hear the tone increase and then decrease again to zero when the two received currents are again exactly out of phase, care being taken that the two received currents are kept equal in magnitude. This means then, that for this difference in frequency, the phase shift in the system under measurement has changed a complete cycle. From what has gone before it is simple to calculate

[12] U. S. Patent 1,596,941.
[13] H. Nyquist and H. A. Etheridge, Jr., U. S. Patent 1,596,942.
[14] S. B. Wright and K. W. Pfleger, U. S. Patent 1,596,916.

the approximate value of the envelope delay for the system under consideration.

In the three patents referred to, circuits for different purposes are given. In all of these methods both ends of the system to be measured must be available to the tester. The first describes a circuit in which the method of measuring is quite similar to that just described except that by means of a reversing switch the frequency interval is found corresponding to a change in phase shift of one half cycle. This method is suitable for measuring relatively large delays. The second circuit referred to is much the same as the first except that a definite phase shift can be introduced in the path which contains the system under consideration by means of a reactance inserted between two artificial resistance lines of considerable length. The method of operation is exactly the same as before except that here frequency intervals can be measured for changes in phase shift which are not integral multiples of one half cycle. This method is suitable for measuring much smaller values of delay than the first circuit referred to, but is not particularly suited to measuring very small delays. The third method is adaptable to measuring very small values of delay, such as those introduced by separate units of equipment. Here a phase shifter is introduced in the path containing the system under consideration and the change in phase shift through the system for a particular frequency interval is measured. The phase shifter for this purpose should be continuous in its operation; and in the circuit referred to, the relative phases of the received currents from the two paths are compared by means of a vacuum tube device which indicates a zero condition on a meter when the two received currents are in quadrature.

c. Direct Measurement of Envelope Delay

Here the phase shift of the envelope of a modulated wave is measured under steady-state conditions and this gives a direct measurement of the envelope delay when the measuring set is properly calibrated, inasmuch as the delay of the envelope of the modulated wave is closely related to the differences in phase shift for the component frequencies of the modulated wave transmitted. Before describing the details of the measuring circuits, some of the principles underlying the transmission of simple modulated waves will be considered; and for this purpose envelopes produced by sine wave modulations will be used. It is assumed in this discussion that the modulations in the transmitted current are repeated periodically and that the attenuation of the system used for transmission is completely equalized for all the frequency components.

Consider a 1000-cycle sine wave which is modulated by a 25-cycle sine wave in such a manner that the envelope just reaches zero once per cycle of the modulating wave. This wave is found on analysis to consist of three components, namely, 1000 cycles of two units amplitude, 975 cycles of one unit amplitude, and 1025 cycles of one unit amplitude. At the start, it is somewhat simpler to consider this case with the 1000-cycle component removed. In other words, the current transmitted through the system now consists of 975 and 1025 cycles in equal amounts. This value at the sending end may be conveniently written

$$\sin 975\, \overline{2\pi t} + \sin 1025\, \overline{2\pi t}.$$

The equivalent graphical expression is

$$2 \cos 25\, \overline{2\pi t} \sin 1000\, \overline{2\pi t}.$$

Now suppose that the 975-cycle current suffers a phase change of β_{975} during transmission and that the 1025-cycle current suffers a phase change of β_{1025}, then the analytical expression for the current at the receiving end is

$$\sin (975\, \overline{2\pi t} - \beta_{975}) + \sin (1025\, \overline{2\pi t} - \beta_{1025}).$$

The corresponding graphical expression is

$$2 \cos \left(25\, \overline{2\pi t} - \frac{\beta_{1025} - \beta_{975}}{2} \right) \sin \left(1000\, \overline{2\pi t} - \frac{\beta_{1025} + \beta_{975}}{2} \right).$$

In comparing the graphical expressions for the current at the sending end and the current at the receiving end, it is apparent that the only changes that have taken place are phase shifts of the 1000-cycle carrier wave and of the 25-cycle modulating wave. The phase shift of the 25-cycle modulating wave represents the actual delay of the deformation of the carrier wave. If the circuit is sufficiently long so that this phase shift amounts to one complete cycle, then the corresponding delay equals one period. For any other delay, the phase shift and delay are, of course, proportional. It will be apparent, therefore, that the delay may be represented by the following equation:

$$T_\Delta = \frac{\beta_{1025} - \beta_{975}}{2 \times 25\ (2\pi)} = \frac{\Delta\beta}{\Delta\omega},$$

where T_Δ is expressed in seconds, the numerator in radians and the denominator in radians per second. T_Δ, the value of the delay of this envelope, is according to our previous definition substantially the envelope delay.

This is the simplest form of transmitted current to which the term envelope delay can be applied. This type of wave, being made up of two sinusoidal components of equal magnitude, has the important property that its envelope suffers no distortion regardless of the length and complexity of the circuit as long as it has no non-linear element and as long as the two component frequencies are transmitted with equal attenuation.

Going back now to the original case of the 1000-cycle sine wave modulated by the 25-cycle sine wave where both sidebands and carrier are transmitted, the corresponding graphical expression for this current is

$$2(1 + \cos 25\, \overline{2\pi t}) \sin 1000\, \overline{2\pi t}$$

and the corresponding analytical expression is

$$2 \sin 1000\, \overline{2\pi t} + \sin 975\, \overline{2\pi t} + \sin 1025\, \overline{2\pi t}.$$

Now if the three components suffer phase changes equal to β_{975}, β_{1000}, and β_{1025}, the analytical expression for the wave at the receiving end is

$$2 \sin (1000\, \overline{2\pi t} - \beta_{1000}) + \sin (975\, \overline{2\pi t} - \beta_{975}) + \sin (1025\, \overline{2\pi t} - \beta_{1025});$$

and there is no simple corresponding graphical expression. It will be convenient to consider this wave as being made up of two components, one being the steady component

$$2 \sin (1000\, \overline{2\pi t} - \beta_{1000})$$

and the other being a variable component

$$2 \cos \left(25\, \overline{2\pi t} - \frac{\beta_{1025} - \beta_{975}}{2} \right) \sin \left(1000\, \overline{2\pi t} - \frac{\beta_{1025} + \beta_{975}}{2} \right),$$

which is the same as the total current discussed above. The outstanding complexity in this wave is the presence of a distortion which arises from the fact that the 1000-cycle carrier wave in these two components is not transmitted with the same phase change. The phase change of the 1000-cycle current, making up the steady component, is equal to β_{1000}, whereas the phase change in the variable wave is represented by

$$\frac{\beta_{975} + \beta_{1025}}{2}.$$

In other words, it is the average of the phase changes at 975 and 1025 cycles. Now, if it happens that these two expressions are equal, then there is no distortion. If, however, as is the general case, these expressions are not equal, then there is a distortion which may be very easily exhibited by considering the case where the difference between $(\beta_{1025} + \beta_{975})/2$ and β_{1000} equals 90°. The current which then results is modulated by 50 cycles whereas the original wave was modulated by 25 cycles. Where the difference in question is intermediate in value between 0 and 90°, the detected modulating wave is complex, but has a component equal to 25 cycles. This component gradually gets smaller and disappears completely when 90° is reached. Now, if the circuit is made still longer, the 25-cycle component in the detected modulating wave again makes its appearance but has suffered a discontinuous shift of 180° in passing through the extinguishing point. By the time the phase difference in question has reached 180°, the received wave is distortionless except for the phase shift of 180° in the envelope which is not apparent, or at least is not distinguishable from a delay of one half cycle.

With this distortion in mind, it will now be apparent that the delay suffered by the modulated wave we are considering is no longer a definite quantity. However, it can be made definite for practical purposes by confining attention to the 25-cycle component of the envelope only. The distortion in question consists merely in adding other components to this one but does not shift its phase (except for the discontinuous change spoken of above). Consequently, for practical measuring purposes, if a device is used which eliminates the various harmonics of the 25-cycle current, this wave is perfectly definite for delay measuring purposes excluding the exceptional case where the fundamental component passes through zero.

These two forms of envelopes have been discussed in more or less detail because of the fact that they are the simplest ones for transmission without phase distortion. For this reason they have been used as the basis of the measuring devices which will now be described. The phase shift suffered by the envelope during transmission can be measured by comparison with a standard of the same frequency as the modulating frequency. This will be, of course, a direct measure of the envelope delay.

From the preceding discussion of some of the principles involved in the transmission of modulated waves, it is evident that the phase shift during transmission of the simple envelope considered is equal to one half the difference of the phase shifts of each of the sideband frequencies. This phase shift of the envelope is then the difference in phase shift for a definite frequency interval and is quite convenient for the measurement of the envelope delay. The envelope delay so measured is that for some frequency intermediate between the two sideband frequencies and, although it is not accurately the envelope delay for the carrier frequency, it may be taken as such for all practical cases when the modulating frequency is taken small enough so that the slope of the phase shift-frequency curve for the carrier and the two sidebands may be considered constant.

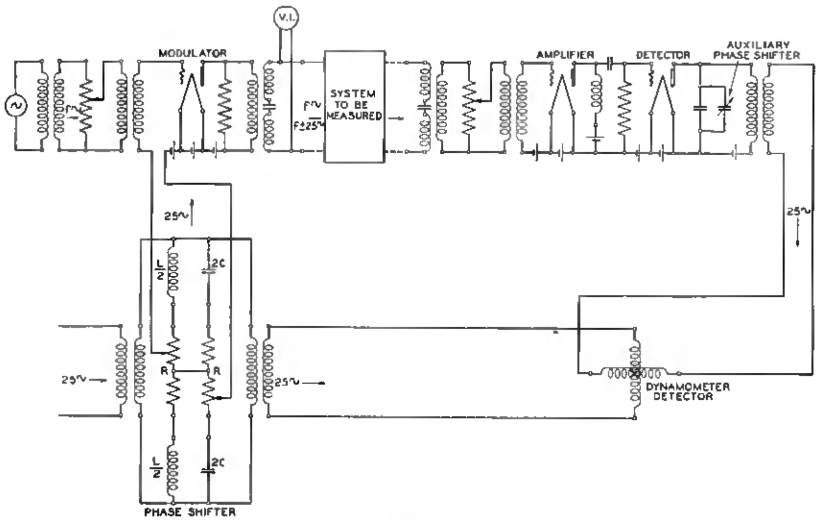

Fig. 7—Arrangement for direct measurement of envelope delay. In the phase shifter shown $R = 50\pi L = 1/50\pi C$.

Fig. 7 shows schematically a circuit for measuring the envelope delay by measuring the phase shift of the envelope.[15] The carrier frequency is modulated with another frequency, 25 cycles for example, and then transmitted through the system to be measured. At the receiving end an ordinary amplifier-detector is used to demodulate the received wave and obtain the modulating frequency. This source can then be compared in phase with a reference frequency which is obtained from the original source. In order to avoid including the effects of the measuring apparatus itself, the change in phase shift so measured through the system under consideration should be compared with a similar measurement made with an artificial resistance line substituted for the system under test. The difference of these two will, of course, be the phase shift suffered in the system by the envelope of the modulated current; and the envelope delay of the system in seconds at the carrier frequency, f, is then given approximately by

$$T_\Delta = \frac{1}{360}\frac{M}{p},$$

[15] U. S. Patent 1,645,618.

where p = the modulating frequency in cycles per second
and M = the phase shift of the envelope of the modulated wave in degrees.

In order to measure the value of M, some method of comparing the phases of various currents must be used. Also it is convenient to have in the measuring circuit a phase shifter or some means of controlling the phase of the modulating frequency.

The value used for the modulating frequency will vary somewhat with the frequency used for measurement and with the conditions under which the measurement is made. Of course, other things being equal, the greater the value of this modulating frequency the greater will be the frequency difference for which the phase shift is measured and the accuracy of the measurement will be correspondingly increased. This is true, however, only when the envelope delay is changing very slowly within this frequency interval. In most cases where the envelope delay is changing quite rapidly with frequency, it is necessary, therefore, to use as small a value for the modulating frequency as will give the required accuracy. In practice, both conditions of measurement will be encountered so that some sort of compromise value should be chosen for a particular measuring set which will do fairly well for its requirements. Various modifications of this circuit for loop and straightaway measurements are given in the patent referred to. Various methods of modulation and detection may be used.

(1) The set-up [16] shown in Fig. 7 has been used extensively for loop measurements on systems, including various telephone circuits and phase correcting networks. The details of the circuit of this set are not given here, but certain phases of its makeup and operation will be discussed. A frequency of 25 cycles from a tuning fork is used for modulation. In measuring the phase shift of the transmitted envelope, a dynamometer detector and phase shifter are used as described in the patent referred to.[15]

When the modulated wave as transmitted over the system is detected, the modulating frequency is obtained. This will, in general, differ in phase from the original modulating frequency. If the detected frequency and the original frequency are now put into the dynamometer detector, the phase of one of these frequencies can be shifted by means of the phase shifter until these two frequencies are 90° out of phase, which is indicated by zero reading of the dynamometer. The amount of phase shift which has been introduced in order to bring about this condition is a measure of the delay of the system being

[16] Compare "Phase Compensation III—Nyquist Method of Measuring Time Delay da/dw," E. K. Sandeman and I. L. Turnbull, *Electric Communication*, Vol. VII, p. 327, 1929.

measured. If the detector were balanced with a zero delay system and, then, rebalanced with the system under question inserted, the difference in these readings as given by the phase shifter would indicate the delay of the system. An integral multiple of π might not be taken care of in this measurement, but this is of little consequence.

For the modulating frequency of 25 cycles, a phase shift of nine degrees in the envelope of the 25-cycle modulation corresponds to a delay of .001 second. For convenience, therefore, the phase shifter used in this set is arranged in steps so that each step corresponds to a phase shift of nine degrees, or a delay of .001 second. In order to read intermediate values of delay, an auxiliary phase shifter, which

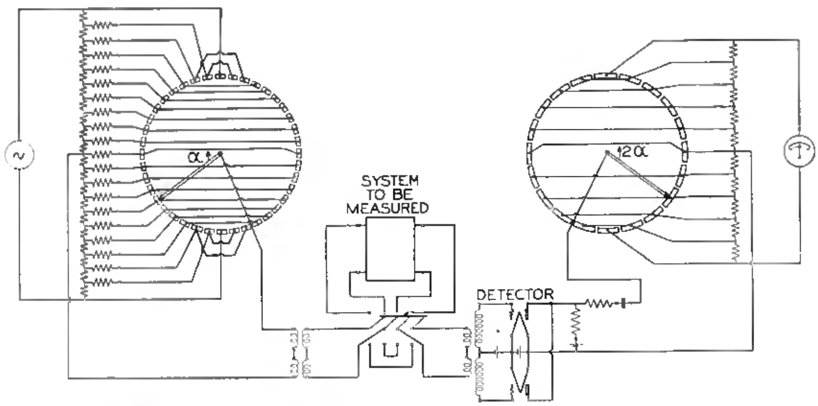

Fig. 8—Arrangement for direct measurement of envelope delay at low frequencies.

consists of a variable condenser bridged across the output circuit of the detector tube, is used and calibrated directly in steps of .0001 second.

This particular delay measuring set has been found quite useful in the frequency range of 300 to about 10,000 cycles per second. The absolute value of delay, of course, is not that which is measured, but this can usually be determined from the measured value by adding this measured value to the integral multiple of .04 second, which is suitable for the case in hand.

(2) For measurements below 300 cycles, the circuit arrangement shown in Fig. 8 can be advantageously used. This is based on principles exactly the same as those just described but differs considerably in the application of these principles.

Here a relatively low frequency must be used for modulation. One and a quarter cycles per second has been chosen because it is satisfactory for measuring at frequencies as low as 10 cycles and is easily obtainable from a distributor driven by the 25-cycle tuning fork used in the measuring set described above. The frequency used here for modulation is exactly 1/20 that used in the other set.

Modulation is accomplished mechanically by means of a commutator and resistance potentiometer arranged as shown at the left end of the figure. The commutator brushes are rotated at a speed of 1¼ revolutions per second. The carrier frequency is connected to the potentiometer as shown so that the brushes as they pass over the commutator segments will pick off various voltages from the potentiometer, and on the completion of one revolution the resultant current at the output is equivalent to a cycle of complete modulation of the carrier such that both sidebands are transmitted with the suppression of the carrier frequency. The potentiometer has been designed with steps in such a way that, for all practical purposes, a modulation of pure 1¼ cycles is obtained, the higher harmonics in the modulated wave being so far removed from the fundamental and relatively so small that they are negligible.

As only the two sidebands of the modulated wave are transmitted here, the current which results from detection of this transmitted wave at the receiving end will have a frequency of 2½ cycles or twice the modulating frequency. Another set of commutator brushes is revolved over a set of segments, somewhat similar to that already mentioned, with a speed exactly twice that of the first, namely 2½ revolutions per second. The output of the detector is connected to these brushes and transmitted through the potentiometer shown connected to the segments of the commutator to a very sensitive galvanometer. The result of this arrangement is effectively a 2½-cycle modulation of the 2½-cycle current received from the detector and as a result of this modulation the current received by the meter will consist of a d.-c. component and a 5-cycle component, the relative amounts of each depending on the relation of the commutation to the phase of the received current. The brushes of the first commutator may be rotated at any instant relative to those of the second by a manual adjustment and their position relative to some arbitrary point noted. The galvanometer is arranged so that it does not respond readily to any except direct current. There is a particular position of the commutator brushes (and another 180 degrees removed from it) which will give no deflection in the galvanometer.

The particular details of measurement are considerably different from those of the preceding circuit, but in principle the arrangement is much the same. With a resistance line between the sending and receiving terminals the adjustable brushes are shifted until no deflection is obtained in the galvanometer. Then with the system to be measured inserted between the terminals of the measuring set, the brushes are again adjusted until the galvanometer shows no deflection. The setting in both cases can be noted by means of a suitable scale and the difference between the two settings for calibration and measurement is, of course, the phase shift of the envelope of the modulated wave in the system used for measurement. This scale can be calibrated in terms of seconds so that it measures the envelope delay directly. It is evident from the above description that a one-degree shift of the commutator brushes corresponds to an envelope delay of .00222 second.

This set has been found useful in measuring the phase distortion in circuits below 300 cycles per second, especially recently when considerable importance has been attached to the low-frequency distortion on circuits which have been developed for program transmission.

(3) When small amounts of distortion are to be measured and the frequency range will permit, a higher frequency may be used advantageously for modulation. Such a circuit, adapted for straightaway measurements, was used for checking up the phase correction of certain circuits used for television demonstrations.[4] The circuit arrangement has been described in the reference given.

In this particular case, it was not expected that the distortion of the overall system including the phase correction would be very great, so that the chief point of interest in these measurements was the detection of small changes in delay over the relatively large frequency range concerned. The modulating frequency used was 250 cycles per second, this larger value being used to obtain the desired accuracy. The frequency required for reference at the receiving end was provided by sending the modulating frequency over another circuit in the same manner as that used on the circuit being measured, except that a constant frequency for the carrier was used in the reference circuit. The purpose of this was to introduce approximately the same delay in the reference circuit as in the measured circuit because of the fact that the phase shifter used at the receiving end was capable of measuring only small differences in phase.

d. Direct Measurement of Delay of Envelope

Instead of measuring the envelope delay, which is $d\beta/d\omega$ by definition, it may sometimes be desirable to measure the delay of the envelope, say, the interval between the instant of application of a sinusoidal wave and the instant of the received wave reaching a predetermined value. One suitable arrangement which may be utilized to this end has been described by Herman.[17] His description, particularly his Fig. 2, should make it unnecessary to describe it here.

Some Results Obtained by Various Methods of Measurement

In the accompanying figures results will be given in graphical form of various results which have been obtained from using the measuring

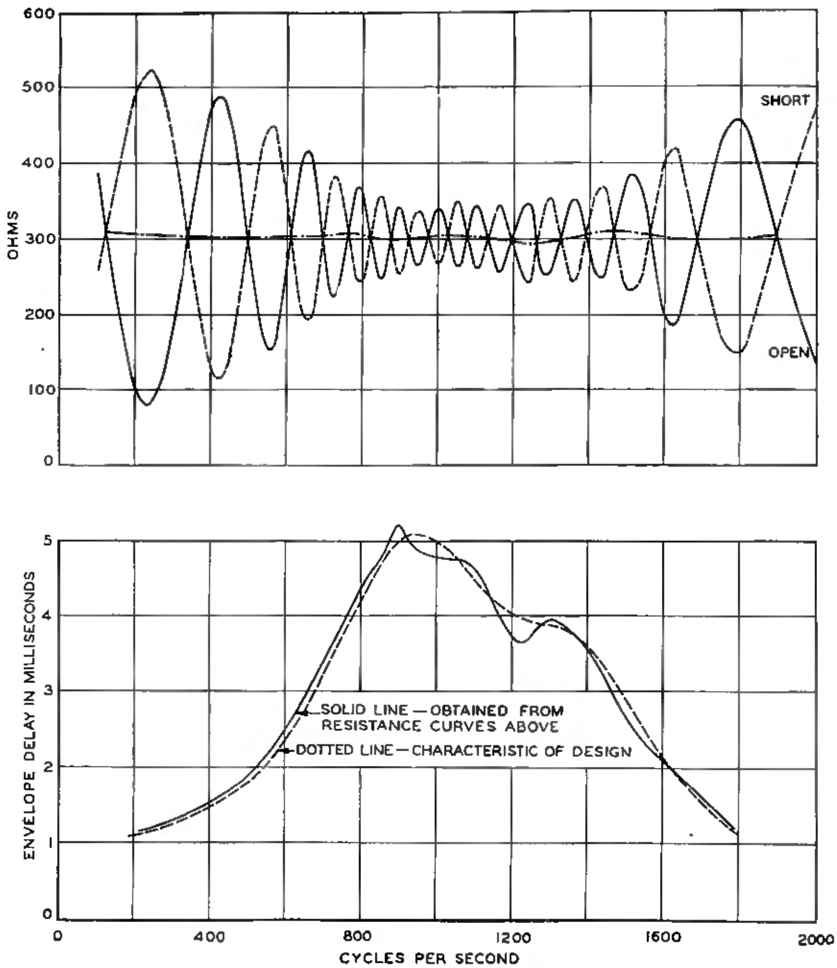

Fig. 9—Results of impedance measurements on phase corrector for 200 miles of 19-ga. H-174 side circuit.

devices described above on actual telephone circuits or networks designed to be associated with them. The values added to the meas-

[17] "Bridge for Measuring Small Time Intervals," J. Herman, *B. S. T. J.*, Vol. VII, p. 343, 1928; particularly application No. 2, p. 349.

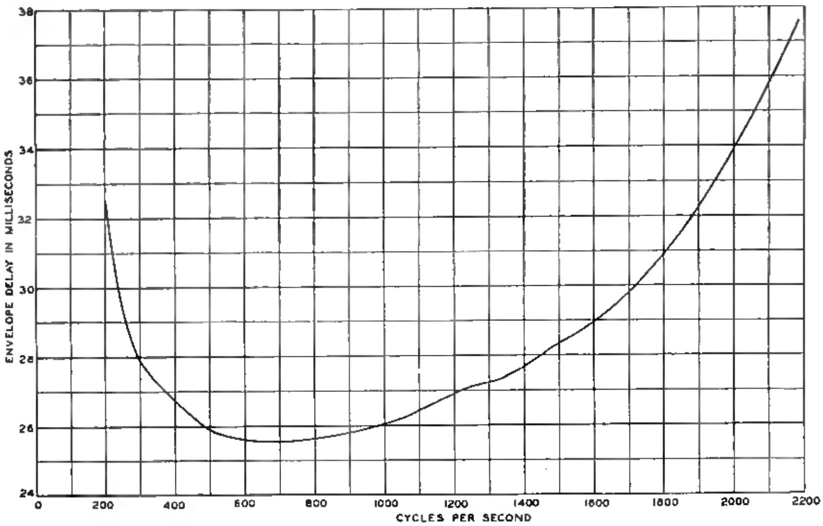

Fig. 10—Envelope delay characteristic for 231 miles of 19-ga. H-174 side circuit.

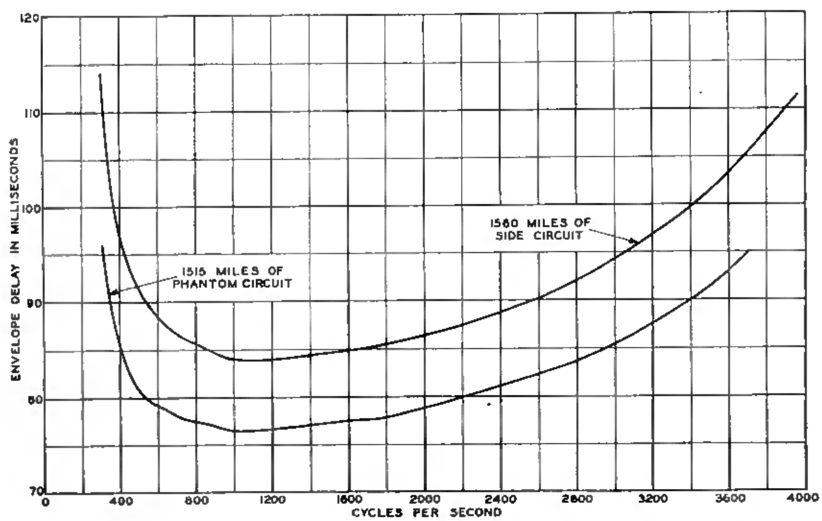

Fig. 11—Envelope delay characteristics for 19-ga. H-44-25 circuits.

ured values to give the absolute values of envelope delay shown on the curves are obtained from an approximate estimate of the delay of the system under consideration.

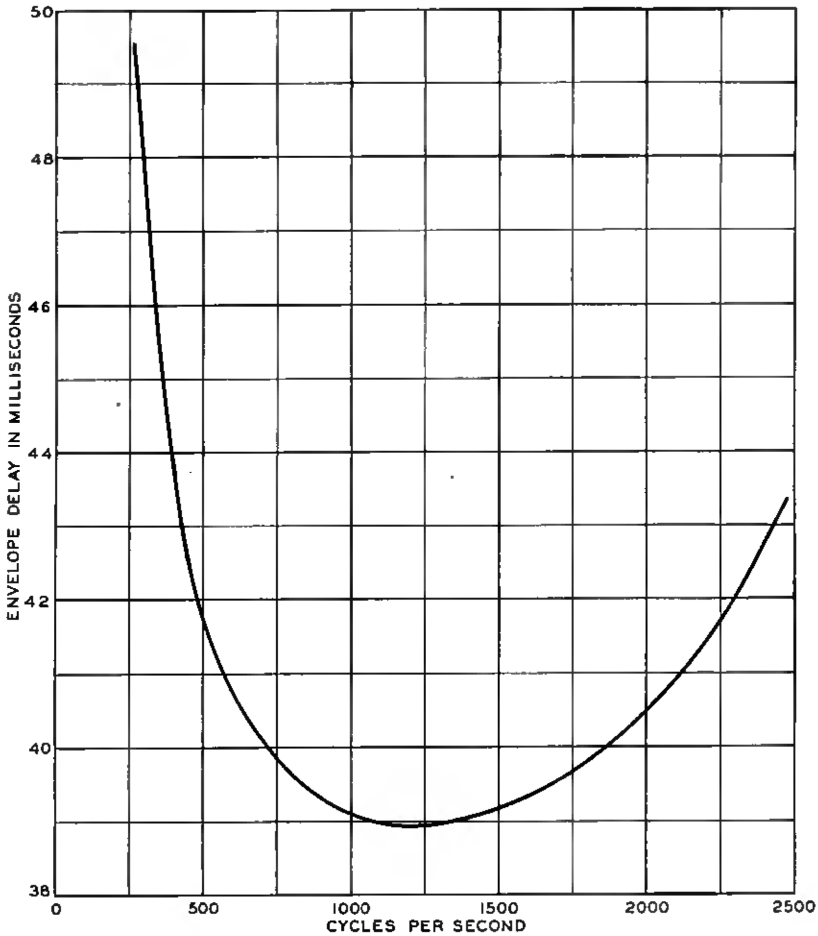

Fig. 12—Envelope delay characteristic for 708 miles of 16-ga. B-22-N two-wire circuit.

No data are given here to show the results of measurements by the method of Fig. 1. This circuit is particularly useful in the measurement of networks and many examples of data obtained in this way are included in another paper.[7]

Fig. 9 shows the results of impedance measurements made as shown in Fig. 2 on a phase correcting network which was designed to equalize the delay for 200 miles of 19-gauge H-174 side circuit for picture transmission. In the upper part of the figure the resistance-frequency curves are shown and the envelope delay-frequency curve derived therefrom is shown in the lower part of the figure. The delay characteristic for which this particular network was designed is also shown for comparison and gives a rough idea of the accuracy of this method of measurement.

No figures are shown here which give the results of measurements made by the methods referred to for determining envelope delay from special phase shift measurements. Although the actual methods of

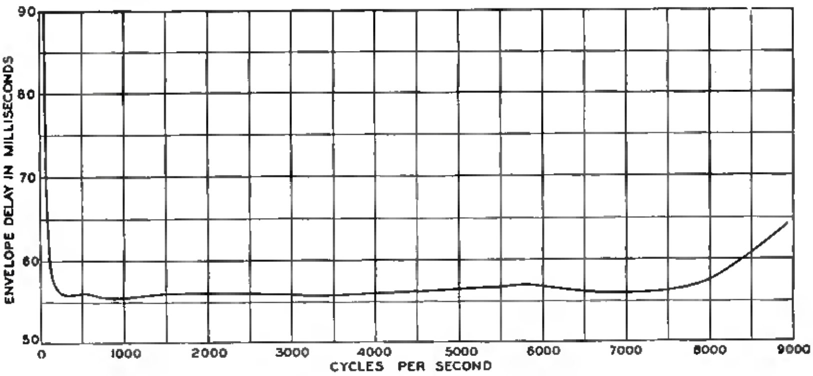

Fig. 13—Envelope delay characteristic of 737 miles of 16-ga. B-22-N program circuit.

measurement in these cases are quite different from the impedance measurement method, the delay results are obtained in a similar manner, and these have just been illustrated by the figure above.

Figs. 10, 11 and 12 show the results of direct measurements of the envelope delay, using the method described above which has a modulating frequency of 25 cycles per second. Fig. 10 gives the measured envelope delay-frequency characteristic for 231 miles of 19-gauge H-174 side circuit. Fig. 11 gives the envelope delay-frequency characteristics as measured for approximately 1560 miles of 19-gauge H-44-25 side circuit and for approximately 1515 miles of 19-gauge H-44-25 phantom circuit. Fig. 12 gives the corresponding characteristic for 708 miles of 16-gauge B-22-N two-wire circuit.

Fig. 13 gives the envelope delay-frequency characteristic for 737 miles of 16-gauge B-22-N cable circuit equipped with phase correctors for program transmission.[13] The measurements for frequencies above 300 cycles per second were made with the measuring device using a modulating frequency of 25 cycles while the measurements below 300

[13] "Long Distance Cable Circuit for Program Transmission," A. B. Clark and C. W. Green. To be presented at Summer Convention of A. I. E. E. at Toronto, June 1930.

were made with the set which used 1¼ cycles as the modulating frequency.

Fig. 14 shows the measured envelope delay-frequency characteristic for a special open-wire circuit[4] used for a television demonstration between Washington, D. C. and New York, N. Y. Curves are shown for measurements on the circuit alone and for the circuit equipped with its dry weather equalizer. The curves do not appear to be as smooth as the curves shown in the above figures, but this is largely due to the difference of the scales used for plotting the measurements. However,

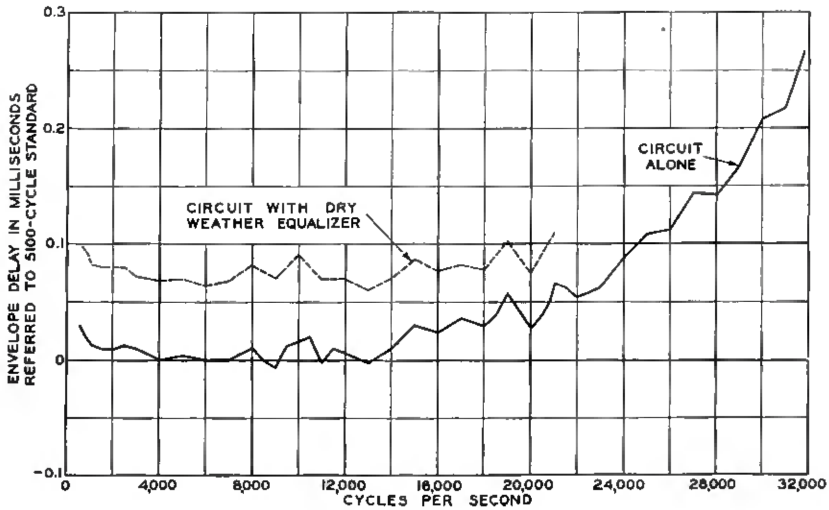

Fig. 14—Envelope delay characteristic for special open-wire circuit; Washington, D. C.—New York, N. Y.

some of the irregularity is due to the method of measurement and the fact that noise on the open-wire circuits obscured somewhat the exact point of balance.

Conclusion

It has not been the intent of this paper to include all the known methods of measuring phase distortion. Various methods for measuring phase shift are, of course, known and these can often be used to indicate phase distortion. In a practical way on telephone circuits, the term defined as envelope delay has certain advantages, and the paper is chiefly concerned with methods of measuring this quantity. In order to avoid including information which is contained elsewhere, the methods have not been given in detail; but references have been given, when possible, to sources where more detailed information can be found. In setting up any of these circuits for actual use, certain precautions must be taken which will soon be evident. One particular point that might be mentioned here is the fact that the phase distortion introduced by the apparatus necessary for amplifiers and particularly detectors varies somewhat with the amount of power being transmitted through it, and this consideration must be given weight.

Keys, switches, and such apparatus may be introduced for the convenience of the tester. The amount of amplification and the sensitivity of the detectors used depend somewhat on the accuracy required of the measurement.

Effects of Phase Distortionon Telephone Quality *

By JOHN C. STEINBERG

This paper discusses the effects of the type of phase distortion found in low pass filters and the loaded line on telephone quality. The effects are ascribed to three factors; the first involves the slopes of the phase characteristic at various frequencies in the range of interest, the second involves the intercept values on the phase shift axis of the tangents to the phase curve, the third involves the interference caused by portions of one sound overlapping portions of a succeeding sound. The first factor appears to be the one of most importance.

IN the engineering of telephone systems it is convenient to define their transmission properties in terms of the changes that occur in transmission in the amplitude and the phase of steady state sinusoidal waves of different frequency. The terms attenuation characteristic and phase characteristic refer, respectively, to the amplitude change, usually expressed in decibels, and to the phase shift, expressed in radians or degrees, as functions of frequency. That distortion which is attributable to the attenuation characteristic is spoken of as attenuation distortion, and that attributable to the phase characteristic, as phase distortion.

To be of greatest use in evaluating a system the steady state properties must be experimentally correlated with the satisfactoriness, or quality in its broad sense, of the system from the viewpoint of the individual receiving the signals. If the signals are speech, quality involves the recognizability of the speech sounds and their naturalness. If the signals are music, the second factor is the one of chief concern. A reasonably quantitative measure of the recognizability of the received speech sounds may be obtained by means of the articulation test which is described in a later paragraph. Naturalness is considerably less definite, and the procedure in this case has been to compare the distorted signals, speech or music, with the original or undistorted signals and obtain the amounts of distortion that cause just noticeable differences.

The purpose of this paper is to discuss the effects of phase distortion on the quality of speech.[1] Brief reference will be made also to a small amount of data that have been obtained for music.

* Presented at New York Section, A. I. E. E., May 1930.

[1] A companion paper by C. E. Lane on "Phase Distortion in Telephone Apparatus" shows the types of phase characteristics found in various networks and discusses their relation to the transmission properties. For a discussion of methods of measuring phase characteristics the reader is referred to a companion paper on "Measurement of Phase Distortion" by H. Nyquist and S. Brand.

Nature of Speech and Hearing

Since the manifestation of phase distortion depends upon the type of signal and the method of observation, it is of interest to first consider the nature of the waves of speech sounds and certain facts of audition.

Speech waves may be regarded as non-periodic in that they start at some time, take on some finite values, and then approximate zero again as may be seen from the wave form [2] of the word "seems" in Fig. 1. In this particular word the wave form of each sound and the transition periods are readily distinguishable. Although in other cases of connected speech this may not be done so easily it is usually possible to

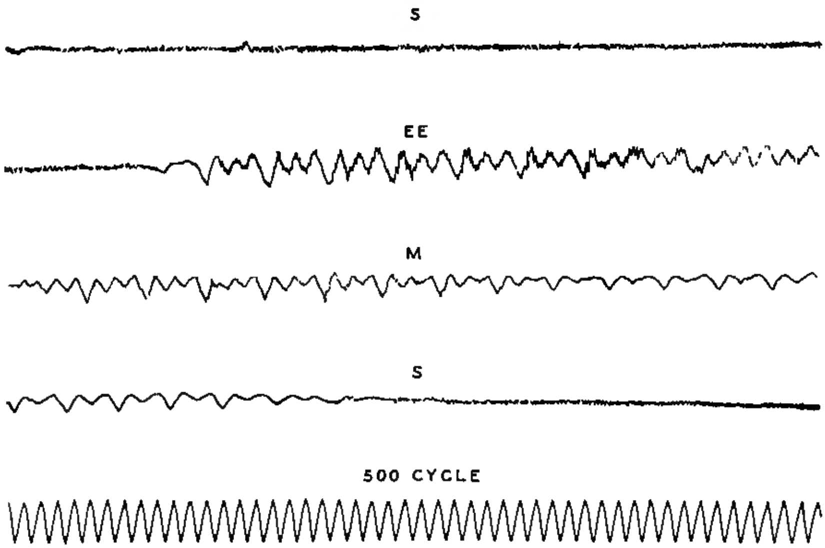

Fig. 1—Wave form of the word "seems."

approximately distinguish between sounds and to ascribe to each an initial period of growth, an intermediate period which in some cases approximates a steady state and then a final period of decay. The duration intervals of different sounds vary from about .03 to as much as .3 or .35 seconds.

Hearing appears to be concerned more with the spectra of sound waves, i.e., something corresponding to the amplitudes of the Fourier components, than with the actual wave form of the disturbance. For the type of steady state complex waves that the speech sound waves approximate for a considerable portion of their duration intervals, it has been observed that phase changes in the component waves cause

[2] Speech and Hearing, H. Fletcher, D. Van Nostrand Co., 1929.

little if any change in the character of the sound. A possible exception may arise for complex waves of large amplitude because of non-linearity in the hearing mechanism. It would be expected then that the observable effects of phase shift would arise from the intervals preceding and following the steady state intervals of the sound waves. For this reason the wave of a speech sound is regarded as non-periodic and when an amplitude frequency distribution is spoken of a Fourier Integral is implied.

Types of Phase Characteristics

The determination of the effects of phase distortion on quality involved the characteristics of the experimental system as a whole although, for convenience, the distortion usually originated in a specific network in the system. The procedure that was followed was to make the system, except for the network, as distortionless as possible. In most cases the characteristic of the system from the viewpoint of distortion, was the insertion characteristic of the network.

Before taking up experimental results on phase distortion it will be helpful to briefly review certain conclusions bearing on the relation between phase shift and wave distortion that have been obtained by analytical methods.[3] A phase characteristic of interest is one of form $B = B_0 + B_1\omega$, where B = phase shift in radians and $\omega = 2\pi f$. If the original wave be represented by a Fourier Integral, the expression for the received wave may be obtained by shifting the phases of all of the sinusoidal components in the original in accordance with the above expression, assuming negligible attenuation distortion. For convenience the two terms in the above expression may be considered separately. If this is done, it can be shown by inspection that a constant shift of B_0 in the phases of all of the sinusoidal components gives a wave which is the sum of two waves, one the original wave multiplied by an amplitude factor $\cos B_0$, the other a wave obtained from the original by shifting all of its components by $\pi/2$ radians and multiplying by an amplitude factor $\sin B_0$.

If the phases of the sinusoidal components in the original are shifted by the amounts $B_1\omega$, where $\omega = 2\pi$ times the frequency of the component, it can be shown that the resulting wave differs from the original only in that the origin of time is displaced by an amount B_1 or the slope $dB/d\omega$ of the above expression.

[3] Transient Oscillations in Electrical Wave Filters, Carson and Zobel, *Bell Sys. Tech. Jour.*, July 1923. Building Up of Currents in Long Periodically Loaded Lines, Carson, *Bell Sys. Tech. Jour.*, Oct. 1924. Phase Distortion and Phase Distortion Correction, Mead, *Bell Sys. Tech. Jour.*, Apr. 1928. Phase Compensation, Sandeman, *Electrical Communication*, 1929. Transient Solutions of Electrical Networks, Mason, *Bell Sys. Tech. Jour.*, Jan. 1929. Phase Distortion in Telephone Apparatus, Loc. cit.

As will be seen later, it is convenient to regard these two operations as occurring in sequence. The second term of the expression introduces a definite time delay of B_1, sometimes called the envelope delay, and no distortion in the form of the original wave. Following this operation, the phases of all of the sinusoidal components of the delayed original are shifted by the constant amount B_0 the resulting wave being the received wave.

If B_0 equals zero or even multiples of π, the amplitude factor sin B_0 equals zero, so that, the received and original waves are identical in form. If B_0 is an odd multiple of π the received wave is reversed in sign only. In both cases the received wave is delayed by an amount $dB/d\omega$, and the wave cannot appear until this time has elapsed.

For all other values of B_0 the form of the received wave differs from that of the original to a greater or less degree depending upon the original wave form and the value of B_0. In this case the delay in the received wave as a whole cannot be spoken of precisely for no point on the received wave can be said to correspond to a point on the original wave. Theoretically the received wave may begin to appear at some earlier time than $dB/d\omega$, as has been shown by Mr. T. C. Fry in some unpublished work for the case of a wave having the form of a telegraph dot.

When the phase characteristics are curved over appreciable portions of the frequency range, as is usually the case in actual systems, exact statements of the above nature are difficult to make. It seems best, therefore, to confine the discussion to particular characteristics and to the case of speech waves.

A qualitative picture of what happens for the type of characteristic shown in Fig. 2 may be seen by regarding it as the limiting case of a characteristic made up of a number of straight lines of different slopes, each line approximating the curved characteristic for a frequency range Δf. As discussed above, the wave of a speech sound may be regarded as made up of steady state component waves of different frequency. The resultants of the component waves in various frequency ranges Δf are subject to the phase distortion discussed in the preceding paragraphs, that is, the original forms of the resultants are delayed by times $dB/d\omega$, and then undergo a distortion that depends upon the terms B_0 or the intercepts of the straight lines with the vertical axis.

As mentioned above it is convenient to regard these operations as taking place in sequence, the first introducing definite delays and no distortion in portions of the original signal corresponding to frequency ranges Δf, the second introducing a constant amount of phase shift in the component waves of each delayed portion. Thus the first operation spreads the wave out on a time scale, the part of the original wave corresponding to the frequency range having the minimum slope arriving first and followed successively by portions corresponding to the remaining frequency ranges. The relative delay for a range Δf is given by the difference between the slope of the phase characteristic

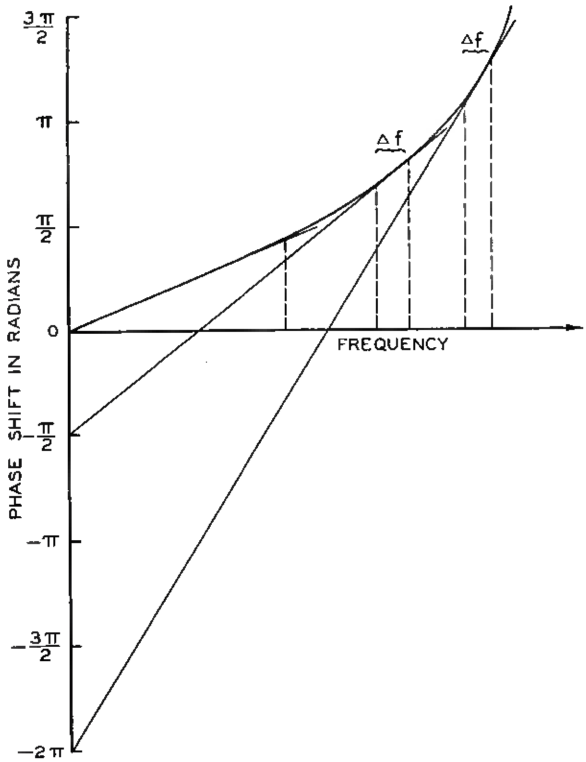

Fig. 2—A curved phase characteristic.

in the range Δf and the minimum slope. This difference or the expression $[(dB/d\omega)_f - (dB/d\omega)_{min}]$ is spoken of as the delay distortion. The delay distortion characteristic is simply a graph of the above expression plotted against frequency. The second operation distorts the wave forms of the delayed portions corresponding to the frequency ranges Δf, thus making it impossible to speak of the delay of the final or received portions or of the received wave as a whole.

This may be described in other terms by saying that a network having a characteristic of the type shown in Fig. 2 may be thought of as if it were made up of two sets of networks, the two sets being connected in series. The first set consists of a number of networks in parallel, each network passing a frequency range Δf and having a phase characteristic of the form $B_1\omega$, where B_1 is the slope of the straight line approximating the curved phase characteristic in the range Δf. The second set consists of a number of corresponding networks having phase characteristics of the form B_0, where B_0 for a network passing the range Δf, is the constant term in the equation of the straight line approximating the curved phase characteristic in this range. The phase distortion thus consists of two operations in sequence, the first introducing definite delays in various portions of the original wave, the second introducing constant phase shifts in the component waves of each delayed portion.

A definite contribution to the recognizability of a speech sound may be associated with each frequency range Δf in the undistorted state. At the output terminals of the first set of networks the various portions corresponding to the ranges Δf do not combine to form an exact copy of the original wave, because of the different delays that have been introduced. It is supposed that their normal contributions to recognizability are decreased by a factor depending upon the delay distortion and the duration time of the speech sound. This factor is referred to here as the "time factor" and it would be expected to operate even though the second set of networks were non-existent.

Since the constant phase shifts of the second set of networks are not all multiples of 2π, additional distortion will be introduced by this set of networks. To take account of this another factor called the "intercept factor" is introduced. As will be seen later this factor seems to be negligible for the case of speech waves due in part, no doubt, to the sustained character of the waves and to the mechanism of hearing as previously described.

In addition to the above, when we deal with a succession of speech sounds, as in connected speech, a third factor might be expected to operate because the delayed frequency ranges of one sound may overlap the least delayed ranges of a succeeding sound and interfere with its perception in the manner of an extraneous noise. As will also be seen later on this factor appears to be negligible for the type of characteristic shown in Fig. 2 because the so-called noise and the signal with which it interferes do not have components in a common frequency range. When this is true, noise in general interferes much less than when the signal and the noise have components in a common range.

Phase Distortion and Quality

Quite aside from the recognizability viewpoint, when speech from a system having phase distortion is compared with that from a system having negligible distortion, it is noticed that the distorted speech is accompanied by certain audible effects which appear to be extraneous to the speech and transient in character. As discussed above phase changes in the component frequencies of steady state waves cause little if any change in the character of the sound. This would indicate that the so-called audible effects of phase distortion arise in the transition periods, i.e., in the period between the approximate steady state of one speech sound and that of the succeeding sound, and are due to the spreading out effect of phase distortion. Data on the amount of distortion that will cause just noticeable effects will be discussed in a later paragraph.

Before discussing the various factors affecting the recognizability, it is of interest to consider the importance as obtained from articulation tests,[4] of different portions of the duration intervals of speech sounds, and also the importance of different portions of the speech frequency range.

Fig. 3 shows the effects upon sound articulation of limiting the transmitted frequency range by means of high or low pass filters in a system having neglible distortion in other respects. Although the curves do not intersect at 50 per cent nor do the articulation values of complementary filters add up to 100 per cent, they may be used with qualifications, to measure the contribution or importance to articulation of a portion of the speech frequency range. Thus the slope vs. cut-off frequency for the low pass filter curve gives a measure of the contribution to articulation of a frequency range Δf when contiguously added to the range 275 to f.

Articulation tests that have been made with voice operated relays give an indication of the importance to articulation of portions of the duration intervals of speech sounds. In the tests, syllables of the consonant-vowel-consonant type were spoken at intervals of about 3 seconds. A circuit having a relay adjusted so as to break contact almost simultaneously with the beginning of a syllable, was used. The contacts of a second relay formed a short circuit across the receiver. The operation of the first relay caused the second relay to break contact

[4] Articulation Testing Methods, H. Fletcher and J. C. Steinberg, *Bell Sys. Tech. Jour.*, Oct. 1929. In an articulation test lists of syllables are spoken into the transmitter of a system having phase distortion and observers at the receiving end write down the sounds which they hear. The observed lists are compared with the spoken lists and the errors determined. The percentage of the total number of spoken syllables that are correctly observed is called the syllable articulation. A syllable is considered to be incorrectly observed if one or more of the fundamental speech sounds which it contains are mistaken. The percentage of the total number of spoken speech sounds which are correctly observed is called the sound articulation. When attention is directed toward a specific sound such as "e," the term individual sound articulation is used. It is the percentage of the number of times that "e" was spoken that it was observed correctly.

after an interval of time depending on the time constants of the relay circuit alone. The time taken for the second relay to operate represents the time clipped from the initial consonants of the syllables. Fig. 4 shows the initial consonant articulation plotted against the operating time of the second relay. If equal elements of time in the

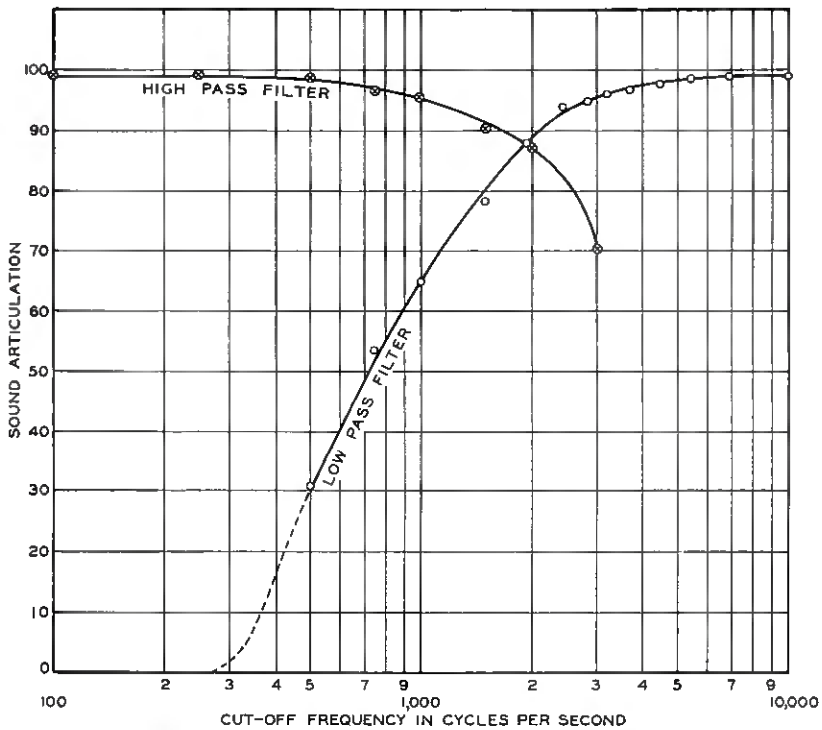

Fig. 3—Importance of frequency range to articulation.

duration intervals of the consonants are of equal importance, then the clipping by an amount ΔT should decrease the articulation by a factor,

$$K = (1 - \Delta T/T), \tag{1}$$

where T is the average duration time of a consonant. In the above tests, the syllables were spoken separately. Oscillograms taken for syllables spoken in a similar manner show an average duration time of .16 seconds for the consonant sounds.[5] The straight line in Fig. 4 was calculated by multipling the articulation obtained for zero operating time by a factor K as determined from the above equation with

[5] Speech and Hearing, H. Fletcher, D. Van Nostrand Co., Inc., 1929.

$T = .16$ seconds. The data indicate that equal elements of time in the duration intervals of the sounds are of approximately equal importance to the average articulation of a group of sounds. It should be pointed out that this might not be the case for individual speech sounds and also for certain types of speech distortion. In the above tests a carbon transmitter was used of a type which introduced attenuation distortion. Tests have also been made with speech having negligible attenuation distortion. Although they indicated a relation of the

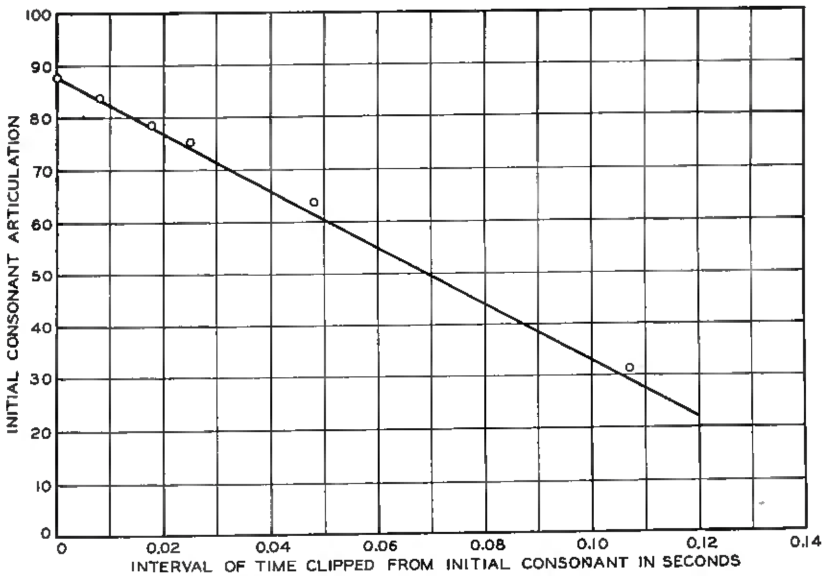

Fig. 4—Importance of an element of time to articulation.

above type the data are somewhat questionable because of uncertainties in the operating time of the relay.

In the next series of articulation tests a nominal undistorted speech frequency range of 0 – 4500 cycles was divided into two parts by means of filters and each part transmitted through a different channel. After transmission the two parts were recombined. The phase characteristic of each channel approximated a straight line over the greater part of the frequency range. The slope of the characteristic of one channel could be increased by various amounts over that of the other channel. One channel thus introduced a definite time delay, in the sense used here, with respect to the other channel, i.e., a delay given by the difference in the slopes of their phase characteristics. The observed sound articulations plotted against time of delay are shown in Fig. 5. The articulation values decrease with increasing delay and approach the articulation of the more intelligible band which was also the least delayed band. For convenience it is spoken of as the non-delayed band.

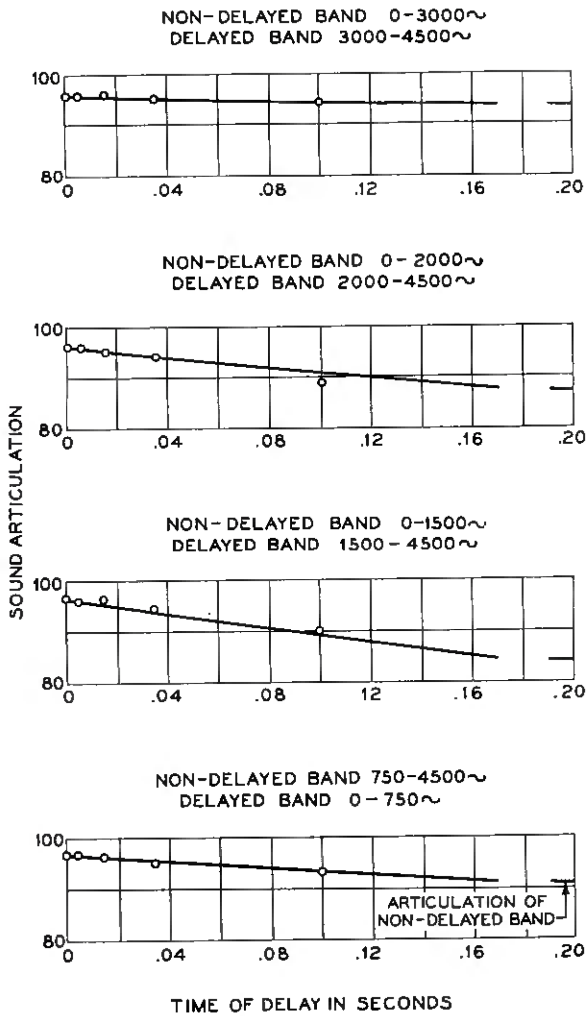

Fig. 5—Articulation vs. time of delay.

If the decrease is due primarily to the inability of the delayed range to contribute to articulation for a time equal to the delay interval, then if,

A_1 = sound articulation for zero delay
A_2 = sound articulation of the non-delayed band

the sound articulation for a delay ΔT should be

$$A = A_2 + K(A_1 - A_2), \tag{2}$$

where K is a factor obtained from Eq. (1) for $T = .17$ seconds.

This value of T is used because in these tests the articulation syllables were spoken as parts of introductory sentences, such as, "The first syllable is *nif*," etc. Oscillograph records for this manner of speaking indicate an average duration time for vowel and consonant sounds of an order of .16 to .18 seconds. This is somewhat less than the duration time for sounds spoken in detached syllables, and somewhat greater than the duration time for sounds spoken in connected speech containing words of one or more syllables. For the latter case, the average duration time is probably more of an order of .08 to .12 seconds.

The solid lines shown in Fig. 5 were calculated from Eq. 2 which involved only the time factor. The agreement between observed and calculated results indicates that the two other factors were comparatively small in these cases. As regards the noise factor it should be noted that the frequency range of the so-called noise and that of the sound wave with which it interferes have no part in common. When this is true, as previously pointed out, the interference from noise is small.

The following tests were made with networks having curved phase characteristics of the type shown in Fig. 2. One of these networks was an all pass structure made up of two types of sections, a "B" section having a critical frequency of 2000 cycles and an "A" section having a critical frequency of 2500 cycles. By using different numbers of sections different amounts of delay distortion could be obtained. Fig. 6 shows the delay distortion for the conditions that were tested. The attenuation characteristic was equalized up to 2500 cycles, and a 2400 cycle low pass filter having negligible phase distortion was associated with the network. Fig. 7 shows the sound articulation values versus the number of sections. A time factor K_f for an element Δf in the frequency range 0 to 2400 cycles, may be obtained from Eq. 1 by setting $T = 0.17$ seconds and ΔT equal to the delay distortion given in Fig. 6, for the element Δf. Delays in some frequency ranges will impair the articulation much more than similar delays in other ranges because some frequency ranges are of greater importance to articulation. The importance of various frequency ranges is closely related to the slopes of the curves in Fig. 3. To obtain an effective factor $\overline{K}$, the values of K_f must be weighted in accordance with the importance of the frequency ranges considered. This may be done approximately for the 2400 cycle range by averaging the values of K_f

corresponding to successive elements Δf, the elements being chosen so as to represent equal increments of increase, say 5 per cent, on the sound articulation versus cut-off frequency curve for low pass filters (Fig. 3).

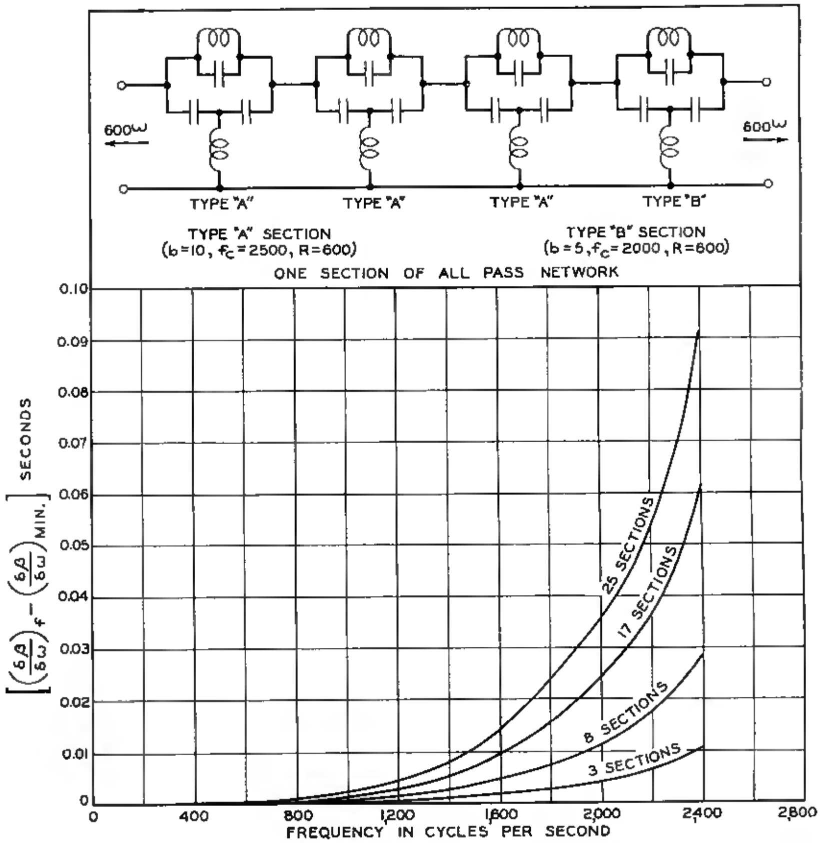

Fig. 6—Delay distortion for an all pass network.

The solid curve shown in Fig. 7 was calculated by multiplying the articulation obtained for zero phase distortion by the effective values of $\bar{K}$ obtained as described above.

Articulation tests were also made upon a system containing first one, and then twenty-five 5000 cycle low pass filters in series. In both cases the attenuation was equalized to 5000 cycles. Fig. 8 shows the delay distortion and the articulation results that were obtained. The calculated results were obtained in the manner described above.

The foregoing calculations have not been made for the purpose of setting up methods of determining the loss in articulation due to phase distortion, but rather to show the relative importance of the various factors for particular cases. In these cases the time factor appeared to be the one of most importance.

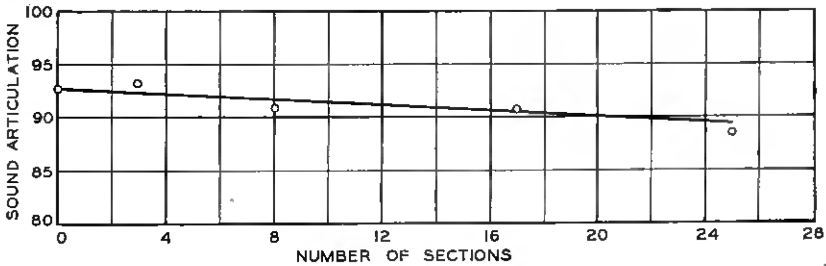

Fig. 7—Articulation vs. delay distortion.

It is evident that the primary effect of phase distortion was to effectively narrow the transmitted frequency range. The phase distortion

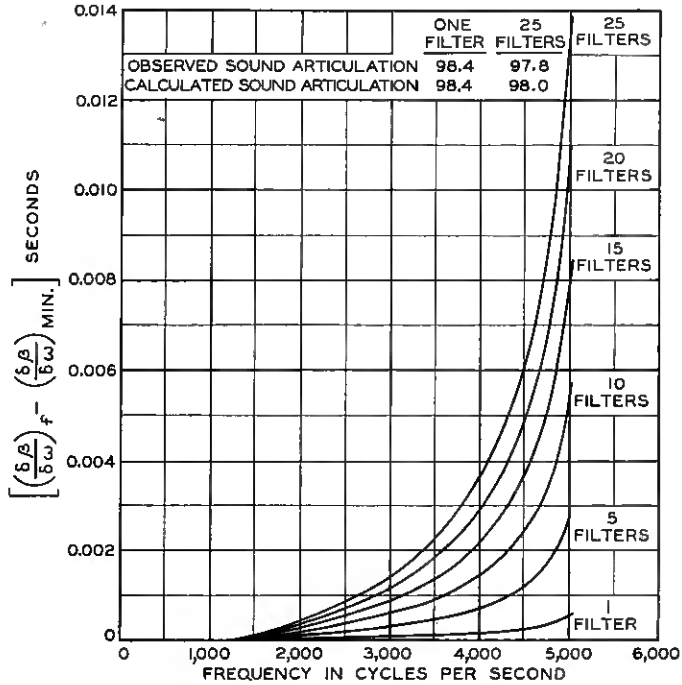

Fig. 8—Articulation and delay distortion for a 5000 cycle low pass filter.

caused by the twenty-five sections of the all pass network associated with a 2400 cycle low pass filter reduced the articulation from 92.7 per cent to approximately 89 per cent. Reference to Fig. 3 shows that lowering the cut-off of a low pass filter having negligible phase distortion from 2400 to 2000 cycles causes an equal change in articulation. Similar considerations show that the effective cut-off for twenty-five 5000 cycle low pass filters in tandem is of an order of 4700 cycles, although the attenuation distortion of the twenty-five filters was essentially the same as that of one filter. The effective transmitting range of a network is a function therefore of both the phase and the attenuation characteristics.

In addition to decreasing the understandability of speech, phase distortion introduces certain audible effects, as previously discussed, which may be a source of considerable annoyance to the listener. Their noticeableness depends upon the amount of delay distortion and the frequency range in which it occurs. For speech, it was found that one section of the all pass network when associated with a 2400 cycle low pass filter, had sufficiently small delay distortion so as to be just noticeable. This determination was made by alternately listening to speech from the system under two conditions, one, the filter alone, two, the filter with the all pass network. Judgments of which condition contained the network were correct about 50 per cent of the time and wrong about 50 per cent of the time for one section of the network. The total delay distortion at the cut-off frequency in this case, i.e. that due to the filter plus that due to one section of the network was about .006 seconds. When three sections were used the distortion was easily noticed.

Similar tests with the 5000 cycle low pass filters indicated that some number between five and ten filters in tandem would cause just noticeable distortion and that the distortion was clearly noticeable for 20 filters in tandem. The amount of delay distortion at the cut-off frequency for five filters is about .003 seconds, and for ten filters about .006 seconds.

The above figures depend somewhat upon the attenuation characteristic as the cut-off frequency is approached, small amounts of attenuation reducing the noticeability of the effects. The figures also vary somewhat with individuals depending upon their experience and hearing characteristics.

Tests on piano reproduction when single notes were struck or when a passage of music was played indicated that the distortion caused by twenty-five of the 5000 low-pass filters in tandem was not noticeable. As in the case of speech, it would be expected that the noticeableness of the distortion would depend upon the frequency range in which it occurs. In general, the effects of delay distortion on music are very much less noticeable than on speech which is probably due in part to the more sustained character of music.

Phase and Attenuation Distortion

To illustrate how phase and attenuation distortion operate to reduce the effective transmitted frequency range, the filter characteristics shown in Figs. 9 and 10 will be considered.[6] One of the uses of filters in telephone systems is to provide a number of channels for one transmission line by using filters in parallel, each filter transmitting a different frequency range. In a long line as many as twenty or twenty-five filters may be used in series for each channel. In this use it is

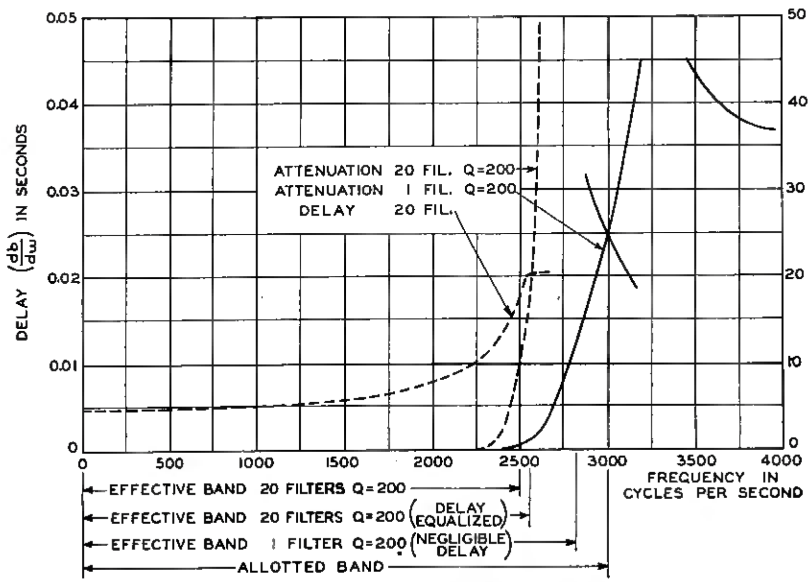

Fig. 9—Transmission for a filter having a slow rate of attenuation increase.

desirable that the attenuation at the edge of the transmitted band should increase at a very rapid rate, and that the delay distortion at the edge should be small.

The solid curve in Fig. 9 shows the attenuation distortion, i.e., the difference between the minimum attenuation and the attenuation for any frequency f, for a filter having a *slow* rate of attenuation increase. The delay for one filter is not shown, but it is about 1/20 of the delay shown by the dotted curve. The allotted frequency band is determined by the frequency value at which the attenuation curve of the filter crosses that of the filter transmitting the adjacent band. The attenuation at the crossover for the purposes of this discussion may be taken as

[6] For a discussion of the relation between these characteristics and the type of filter section, the reader is referred to the previously cited paper by C. E. Lane.

25 db. The effective band is the frequency range that will give the same articulation as that given by the filter. The delay distortion is so small for one filter of this type that its effects can be neglected and the effective band may be determined from the attenuation curve alone. The effective band is given approximately when the area bounded by the attenuation curve and a line parallel to the frequency axis through the 25 db point equals the area under the 25 db line between the frequency limits zero and f, where f is the upper limit of the effective band.

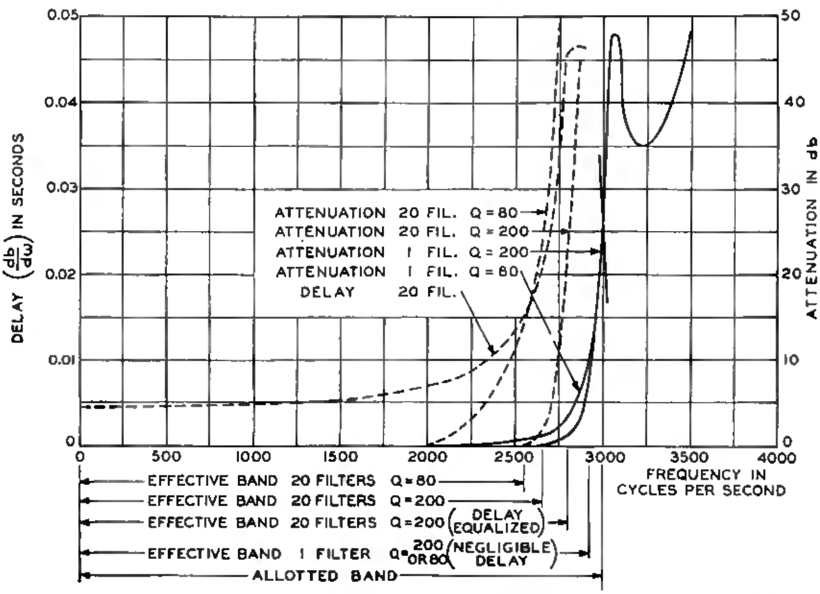

Fig. 10—Transmission for a filter having a rapid rate of attenuation increase.

This is true because the effect of attenuation near the cutoff frequency is to reduce the contributions of the various frequency ranges by a factor that is proportional to their attenuation, for the attenuation limits considered. In the above case this factor varies from zero at 3000 cycles to unity at 2400 cycles. The effective band width is 2825 cycles.

The dotted curves on Fig. 9 show the delay and attenuation values for 20 filters in tandem. The effective band width that is shown for "delay equalized" is that due to the attenuation distortion alone. It was obtained as described in the preceding paragraph except that the attenuation for zero articulation was taken as 40 rather than 25 db since there is no interference from the signals in the adjacent band. In this case the effective band due to attenuation distortion alone is 2550 cycles. The effect of delay distortion when taken into account in the manner previously described further reduces the effective range to 2500 cycles. Thus the additional reduction due to delay distortion is small.

Fig. 10 shows similar data for two filters having *rapid* rates of attenuation increase, one having coils with a Q of 80, the other [7] having coils with a Q of 200. For 20 filters ($Q = 200$) in tandem the effective band due to attenuation distortion alone (delay equalized) is 2800 cycles. The effect of delay distortion further reduces the effective range to 2650 cycles. Comparing these ranges with the corresponding ranges for the filters of Fig. 9 shows that the filters of Fig. 10 use the allotted band, which is the same for both figures, more efficiently from an articulation standpoint, i.e., the effective band is a larger fraction of the allotted band. The delay distortion, however, in the filters ($Q = 200$) of Fig. 10 is more noticeable. This will be seen by noting that the amount of delay near the cutoff for the filters of Fig. 9 is very much smaller than that of Fig. 10.

The noticeableness of the delay distortion may be decreased by equalizing for the delay distortion, or by using filters with coils of smaller Q. Any gain made by the former method is made at the expense of the minimum delay, i.e., the constant delay in the major part of the transmitted range. Any gain made by the latter method is made at the expense of the effective frequency range as shown by the effective band for 20 filters ($Q = 80$) of Fig. 10. Twenty filters of the type shown in Fig. 9 have about the same overall performance as 20 filters of the type shown in Fig. 10 having coils with a Q of 80.

It is evident that in the design of filters, compromises must be made between the rate of attenuation increase at the edge of the transmitted band, the minimum delay and the delay distortion. The compromises that are made in an actual system depend upon many factors and their discussion is beyond the scopeof this paper.

Although the time factor appeared to be the one of most importance for the phase characteristics that have been discussed here, it should be pointed out that this may not be true for all types of phase characteristics. Much work remains to be done for other types of phase characteristics, for example, characteristics which show irregular changes with frequency rather than the smooth changes of the type discussed here. It seems, however, that the main thing in securing transmission free from phase distortion is to provide a phase characteristic that is linear with frequency over the frequency range of interest.

[7] Q refers to the ratio of the reactance of a coil to its effective resistance.

Long Distance Cable Circuit for Program Transmission *

By A. B. CLARK AND C. W. GREEN

The rapid growth of the telephone cable network in this country has made it desirable to develop a system whereby this network may be utilized to transmit programs for broadcasting stations over distances upwards of 2,000 miles. Such a system has recently been developed and given a trial on a looped-back circuit 2,200 miles long with very satisfactory results. It transmits ranges of frequency and volume somewhat in excess of those now handled by the open-wire circuits which are used for program work, and also in excess of those handled by present-day radio broadcasting systems when no long distance lines are involved.

The paper deals first with the transmission requirements of broadcasting systems and then gives a description of this new cable system.

As discussed in two recent papers,[1] one of which was presented before this Institute, telephone circuits are now extensively used for chain broadcasting. Radio broadcasting stations covering various local areas in the United States are connected together by wire circuits so that programs are delivered simultaneously to all of them. Thus, it is possible to deliver a program to the whole nation at once. About 35,000 miles of telephone circuits are now being regularly utilized for this service and about 150 radio broadcasting stations receive programs from one or more of the chains of wire circuits.

Today practically all of this service is being furnished by means of open wires using voice-frequency channels. Long distance cable routes are growing rapidly and are supplementing the open-wire routes, particularly those carrying very heavy traffic. Fig. 1 shows the long distance cable routes now in use in the United States, together with the additional routes proposed for installation within the next few years. The advantages in placing some circuits in these cables which will adequately handle program transmission service were evident and led to the development described in this paper.

Because of the special characteristics which program transmission circuits must possess it was necessary to develop an entirely new type of cable circuit, in which the method of placing the wires in the cables, the type of loading and all of the apparatus, including amplifiers and distortion correcting apparatus for both amplitude and delay, differ radically from other cable circuits. The development was recently completed and a trial installation made in which wires were looped

[1] F. A. Cowan, "Telephone Circuits for Program Transmission," presented at Regional Meeting of S.W. District of A. I. E. E., Dallas, Texas, May 7–9 1929, *Proceedings of A. I. E. E.*, July, 1929, A. B. Clark, "Wire Line Sys tems for National Broadcasting," presented before the World Engineering Con gress at Tokio, Japan, October, 1929, *Proceedings of I. R. E.*, November, 1929 *Bell System Technical Journal*, January, 1930.

* Presented at Convention of A. I. E. E., Toronto, June, 1930.

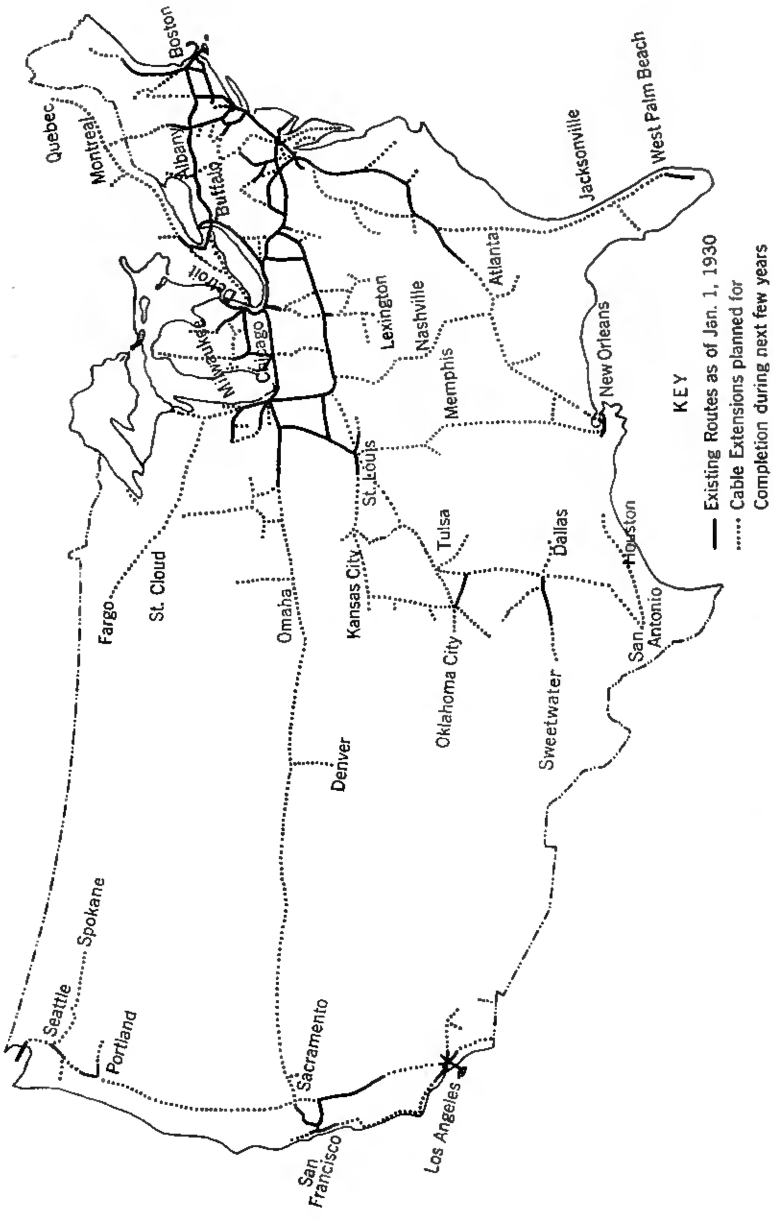

Fig. 1—Main toll cable routes of United States and Canada.

back and forth in the cables between New York and Pittsburgh so as to produce a circuit 2,200 miles in length. Tests were made on this circuit over a period of several months and very satisfactory results were obtained. It is, therefore, planned to make extensive application of this system and eventually program circuits may be provided in cable over practically all of the long toll cable routes.

So as to appreciate what is involved in the design of this system there will first be presented a discussion of the transmission requirements. Following this, the new system will be described and its more important transmission characteristics set forth.

Transmission Requirements

For program transmission the ideal, of course, is to provide a transmission line such that no distortion whatsoever will be caused to program material transmitted over the line whatever be its length. Ideally also, program pickup apparatus, radio transmitters, radio receivers and loudspeakers should be such that the program delivered from the loudspeaker should sound exactly like the original program delivered to a direct listener in the best location. To meet this ideal, however, would require that the whole audible range of frequencies, extending from about 20 to 20,000 cycles, and a tremendously wide range of volumes representing power differences of more than a million-fold be handled without any distortion whatsoever.

Actually the radio art is far from attaining this ideal. It does not seem reasonable, therefore, to provide lines very much superior in transmission performance to the rest of the system since this would unnecessarily increase the cost for providing the service. However, telephone lines represent a fixed investment which must remain in service for many years in order to keep costs within reason and, furthermore, it is, in general, not practical to change the transmission characteristics of the lines once they have been installed. It is, therefore, necessary to take into account the fact that the broadcasting art has considerably improved in the past and is likely to improve in the future and provide telephone lines of sufficiently good characteristics to anticipate the improvements which are likely to come within a reasonable period of time.

These general considerations have led to the adoption of the following as practical standards of performance for the new cable system:

Frequency range to be transmitted without material distortion—about 50 to 8,000 cycles.

Volume range to be transmitted without material interference from extraneous line noise—about 40 db, which corresponds to an energy range of 10,000 to 1.

Some of the more detailed considerations which have led to the setting of these standards will now be given.

Frequency Band

Figure 2 gives some data in regard to the frequency range required for different musical instruments as well as speech. These data were obtained in the Bell Telephone Laboratories using an arrangement capable of picking up and reproducing practically the whole audible frequency range. Certain very low-frequency instruments, such as organ pipes and bass drums, were not included in the tests owing to laboratory limitations. A number of observers listened to the reproduced material, first, when practically the whole frequency range was transmitted and, second, with either the high frequencies or low

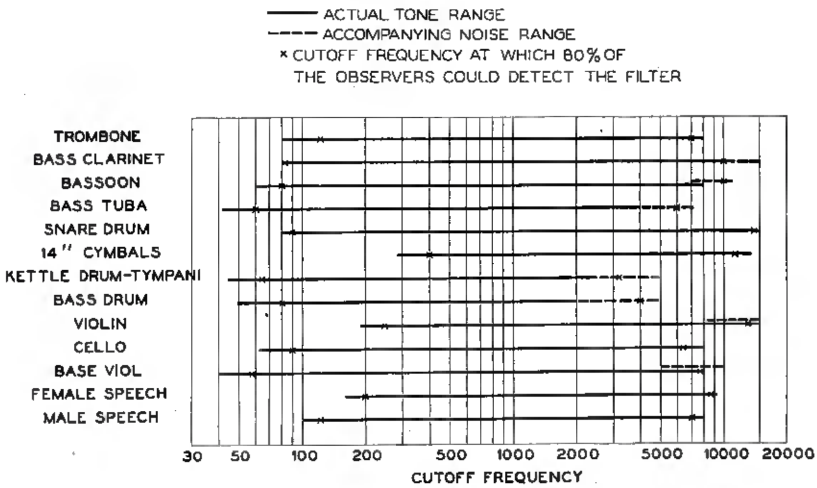

Fig. 2—Summary of important ranges required for different instruments.

frequencies cut off by means of filters. The observers endeavored to note whether there was any perceptible effect when the filters were introduced but did not attempt to determine whether introducing the filters made the reproduced material sound more or less pleasing.

Referring to the figure, it will be noticed that at the lower frequencies little appears to be lost by cutting off frequencies below about 50 cycles. At the upper frequencies, however, with certain of the musical instruments something is lost by cutting off frequencies above 8,000 cycles. Hissing sounds, sounds of a percussion nature and sounds of jingling keys, rustling paper, etc., appear to be most affected by cutting off the high frequencies.

Tests have shown, however, that when the frequency range 50 to

8,000 cycles is transmitted with very little distortion within the band the results obtained are very pleasing. The ordinary observer without making direct comparison tests is unlikely to detect the absence of the higher frequencies.

From the standpoint of radio transmission there will probably be some difficulties in handling the 8,000-cycle range which has been tentatively set as a standard for the cable line. Each radio station, theoretically at least, is now being allowed only a 10,000-cycle band of frequencies and, since both sidebands are transmitted, each band is fully occupied when transmitting 5,000 cycles. Since adjacent frequency ranges are not assigned to stations in the same locality, a certain amount of spreading out is, no doubt, tolerable, so that those listeners who are close to broadcasting stations should, in general, be able to pick up the 8,000-cycle range without undue interference from other stations. The more distant listeners will have trouble if their sets take in the complete 16,000-cycle band required to handle, on a double-sideband basis, the 8,000-cycle program range. Letting in this wide frequency range will bring in increased interference from other stations and will also increase the atmospheric interference.

In spite of this increased trouble which the distant listeners will have, it can no doubt be argued that it will do little harm for the radio stations to put out the full 8,000-cycle band. The nearby listeners, if they have very good sets, will in general be able to appreciate this, while the distant listeners, if their sets are arranged to receive only a 5,000-cycle band, should receive only slightly more interference from wide-band stations occupying adjacent frequency bands.

Evidently, if the frequency range were doubled so as to furnish the listener with practically the whole audible range of frequencies, these radio difficulties would be exaggerated. It seems certain that, if radio stations were to handle the whole audible band of frequencies, a reassignment of frequency bands to these broad-band broadcasting stations would be called for and also quite probably these radio stations would be forced to resort to single sideband transmission.

It is not sufficient merely to fix the limits of the frequency band. Limits to the allowable distortion within it must be established. Tests have indicated that it is desirable that different frequencies within the transmitted band should not suffer attenuations differing by more than about 5 db corresponding to power differences of about three-fold.

The transmission delay* suffered by different portions of the fre-

* "Delay" as used in this paper has the same significance as "envelope delay" used in literature on phase distortion. It is defined as $d\beta/d\omega$ where β is the phase shift and ω is 2π times the frequency.

quency band must also be considered. This is necessary because, when transmission over long distance lines is involved, this delay tends to be different for different parts of the frequency band and the distortion produced is a function of the frequency-delay characteristics. Tests have indicated that the high frequencies, say those in the range 5,000 to 8,000 cycles, should not suffer delay in transmission over the line more than 5 to 10 milli-seconds greater than the delay suffered by frequencies in the neighborhood of 1,000 cycles. However, at the low end of the scale more delay may be tolerated: for example, 50 cycle waves may be delayed as much as 75 milli-seconds more than those in the neighborhood of 1,000 cycles without noticeable deterioration in quality.

Requirements must also be imposed as to "linearity" of the transmission, that is, constancy of efficiency with different current strengths. If the transmission departs too much from "linearity" several disagreeable effects may be produced: (1) Spurious frequencies which are by-products of the true frequencies will become large enough to be annoying, (2) strong sounds will not be reproduced as well as weak sounds, and (3) when weak sounds are transmitted along with strong sounds the strong sounds will tend to obliterate the weak sounds.

In the design of this program transmission circuit the criterion was adopted that transmission put over the circuit at the maximum prescribed volume level must not sound appreciably different than transmission put over the circuit at a considerably lower level, at which lower level the non-linear distortion is negligible.

Volume Range

A favorably-seated listener to a high-grade orchestra is treated to a wide range of volumes. Opinions differ as to just how wide a volume range can be appreciated by such a listener, but it seems certain that it is at least 60 db, corresponding to a power range of one million to one. The human ear can hear volume ranges in excess of 100 db, corresponding to a power range of ten billion to one. For loudspeaker reproduction it has been found that a room must be particularly quiet in order to be able to appreciate a volume range of 60 db. Rooms in three-quarters of the usual residences are probably too noisy for a volume range as great as this to be appreciated. A 40 db volume range, corresponding to a power range of 10,000 to 1, can be appreciated in most rooms where radio listening is done and is quite satisfactory for most musical selections.

From the standpoint of design, the maximum volume of a wire program transmission system is limited by the requirement that the program must not be allowed to spill over unduly as crosstalk into neighboring circuits which may be carrying telephone messages or other programs. The volume may also be limited by the requirement that serious non-linear distortion be not introduced by effects produced in the vacuum tubes of the amplifiers or in any magnetic-core coils either in the apparatus or in the line. On the other hand, the minimum volume which a wire program circuit can handle is limited by the tendency of the noise present on the circuit to annoy the listener when the program volume is very weak. Crosstalk from other circuits into the program circuit also enters as an important consideration, since radio listeners must not be able to pick up intelligible conversations during those times when the program volume is very weak or when actual pauses occur in the programs.

From this, it is seen that the matter of widening the volume range of a wire program transmission system involves not only added cost to keep non-linear distortion and noise within limits but also, and perhaps even more important, added cost to isolate the circuit from other circuits on the same route.

From the standpoint of the radio part of broadcasting systems handling very wide volume ranges also presents difficulties. Radio transmitter and other radio equipment noises become more serious as the volume range is widened. More important, however, widening the volume range without corresponding increase in the radio transmitter capacity reduces the effective range of a radio broadcasting station, since this increases the tendency for the faint parts of the programs to sink below the level of atmospheric and receiver-set noises.

At present it is understood that most radio broadcast programs where no long distance wire circuits are involved are being delivered with a volume range of about 30 db.[3] In order to anticipate improvements which may come in the broadcasting art, however, it has seemed desirable to provide wire circuits in cable which will handle a wider volume range than this and, accordingly, 40 db has been taken as a working standard. This volume range appears to satisfy almost everybody with the possible exception of some who listen to broadcasts of symphony orchestras and the like. With the present limitations of volume ranges to about 30 db, there has been some complaint that much of the artistic quality and effectiveness of broadcasts of such high-grade music has been lost because of the fact that the operator manipulating the volume range control seemed to reduce the range an undue amount.

[3] O. B. Hanson, "Volume Control in Broadcasting," *Radio Broadcast*, March, 1930.

Studies are now under way looking toward systems which will compress the volume range transmitted over the line and expand it at the far terminal, but possible applications to radio systems may be difficult since receiver characteristics need to be considered.

If some volume range compression and expansion system is not employed, ability to handle a materially wider volume range can only be obtained with considerable difficulty. In the radio part of systems it will require reductions in radio transmitter noises and involve loss in the effective range of radio stations, unless higher powered transmitters are employed. In the wire part of systems it may involve the use of amplifiers and loading coils capable of handling more power, means for materially reducing the crosstalk coupling between circuits and also means for making the program transmission circuits more quiet.

Description of New Cable System

In this program transmission system the nominal telephone repeater spacing of 50 miles, common with message telephone circuits, is retained. The pilot-wire regulator system which compensates for changes in transmission caused by temperature changes in message circuits is also used for the program circuits.[3] The diagram in the top part of Fig. 3 shows several hundred miles of program transmission circuit, illustrating how it is divided up into repeater sections and pilot-wire regulator sections and also indicating the principal pieces of equipment located at the repeater stations.

As indicated on the diagram of Fig. 3, there are two classes of repeater stations, known as regulator stations and non-regulator stations. At the non-regulator stations the repeater gains are maintained at fixed values while at the regulator stations they are varied under control of the master pilot-wire regulating mechanism in such a way as to compensate for the transmission variations of the cable conductors caused by temperature changes.

At each non-regulating repeater station are placed:

1. An attenuation equalizer which corrects for the attenuation differences at different frequencies (at average temperature) introduced by the preceding repeater section.
2. A delay equalizer which corrects for the difference in delay at different frequencies introduced by the preceding cable section.
3. A one-way amplifier introducing sufficient gain to overcome the line loss, together with the added losses introduced by the attenuation and delay equalizers.

[3] A. B. Clark, "Telephone Transmission Over Long Cable Circuits," *A. I. E. E. Transactions*, Vol. 42, Feruary, 1923.

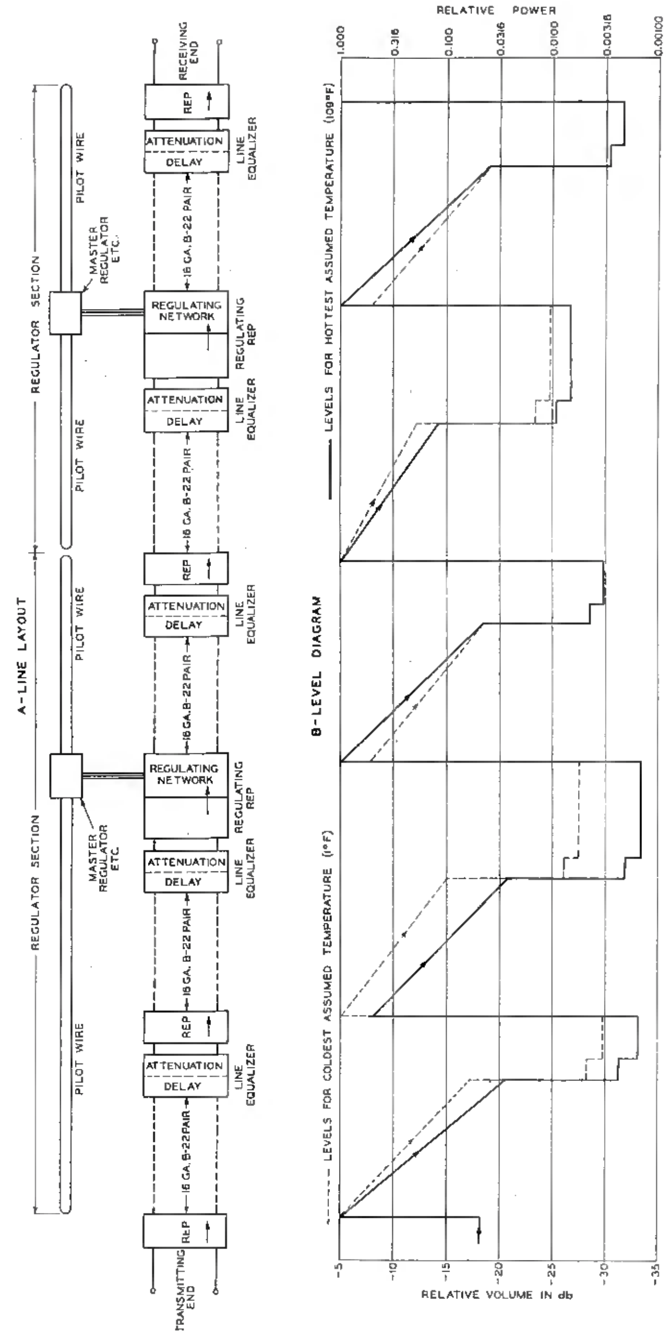

Fig. 3—Typical line layout and level diagram for B-22 program transmission system.

At the regulating repeater stations the arrangement is the same as at the non-regulating stations, except that another stage is added to the amplifiers. This stage includes a potentiometer associated with relays controlled by the master pilot-wire mechanism, the whole being arranged so as to compensate for the changes in transmission loss of the cable pairs caused by temperature changes.

In the lower part of Fig. 3 is shown a transmission level diagram, from which can be noted the losses and gains introduced by the different parts of the system, for a frequency of 1,000 cycles.

Cable

The transmission paths are provided by means of 16 B. & S. gauge non-phantomed pairs having a capacitance of 0.062 microfarads per

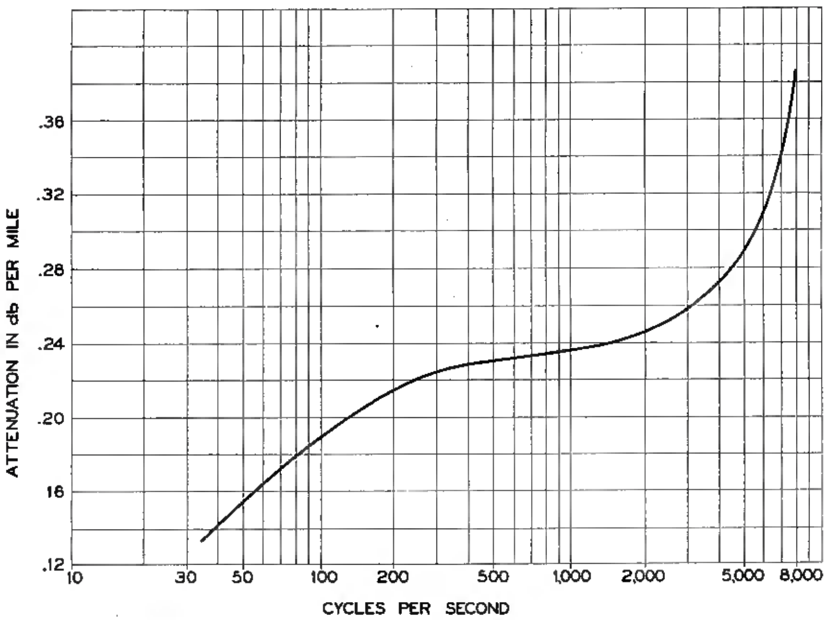

Fig. 4—Attenuation-frequency characteristic for 16-ga. B-22 cable pairs at 55° F. terminated in characteristic impedance.

mile. These pairs are loaded with 22-milhenry inductance coils spaced 3,000 feet apart. Present long distance message telephone circuits in cable have loading coils spaced 6,000 feet apart. The nominal cutoff frequency of the new circuit is about 11,000 cycles, permitting effective transmission of a frequency band extending up to about 8,000 cycles.

The nominal impedance is about 800 ohms and the attenuation per mile, at 1,000 cycles and average temperature, about .24 db. Fig. 4

shows the attenuation at average temperature plotted as a function of frequency, while Fig. 5 shows the line impedance.

Figure 6 shows how the cable circuit attenuation varies with temperature at different frequencies. As will be seen from the curves, temperature change produces effects not only in the series losses but also in the shunt losses. The series losses are changed largely because

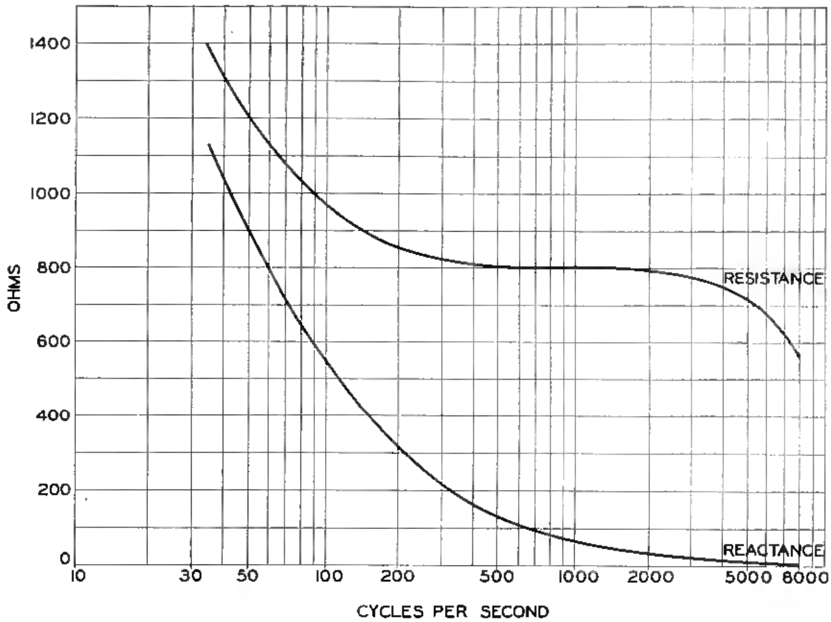

Fig. 5—Mid-coil characteristic impedance for 16-ga. B-22 cable pairs at 55° F.

the resistance of the copper cable conductors changes with temperature, and to a smaller degree because of changes in effective resistance of the loading coils. The shunt losses change with temperature due largely to changes in the conductance losses and, to a lesser extent, changes in the cable capacity with temperature. The conductance loss is approximately directly proportional to frequency so that it has maximum effect at the highest frequency. The effect of temperature on the conductance loss is opposite to the effect of temperature on the series loss so that increase of temperature reduces the shunt loss.

The matter of securing the necessary electrical separation between the 16-gauge program transmission circuits and the other circuits contained within the same lead sheath involved particular study. The use of shielded pairs was considered. Such use of shields, however, would very greatly increase the space occupied by each program circuit and, therefore, considerably increase the cost. By careful design of the cable and control of methods of splicing, it was found possible to avoid the use of shields. It was not found practicable, however, to make use of the phantom possibilities on the program pairs.

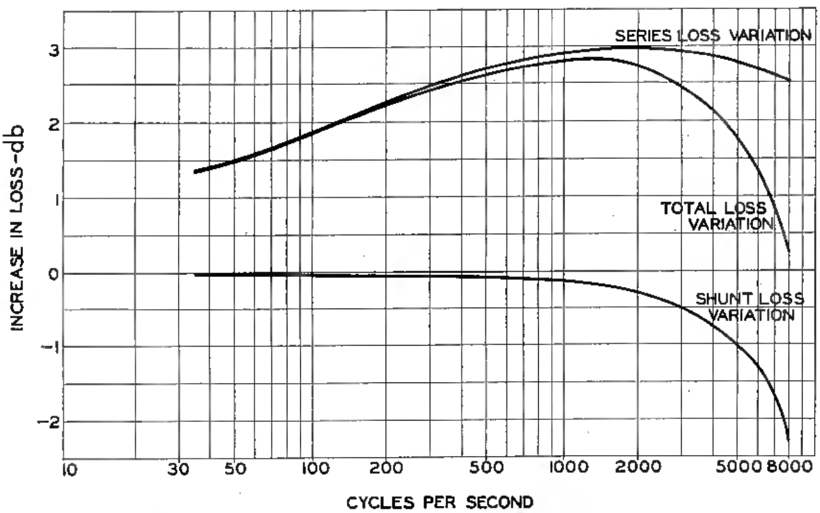

Fig. 6—Attenuation variation of 100 miles of 16-ga. B-22 loaded cable circuit for a temperature change from 55° F. to 109° F.

The method adopted was as follows: Restrict transmission over a particular 16-gauge program transmission pair, as a general proposition, to one direction only. Place the program pairs assigned to transmission in one direction among the 19-gauge quads used for four-wire transmission paths going in the same direction, and the program pairs transmitting in the other direction in the oppositely-bound four-wire group. Fig. 7 shows a cross-section of a typical cable containing six program transmission pairs, three for transmission in each direction.

Loading Coils

The 22-milhenry loading coils used on the program transmission circuit have cores of compressed powered permalloy, which is the magnetic material now generally used in the Bell System loading coils.[4] Their overall dimensions are the same as those of the loading coils for the ordinary telephone circuits in toll cables.

[4] W. J. Shackelton and I. G. Barber, "Compressed Powdered Permalloy—Manufacture and Magnetic Properties," *Transactions, A. I. E. E.*, Vol. 47, No. 2, April, 1928.

Typical effective resistance-frequency curves for the loading coils are given in Fig. 8; these curves include current magnitudes greater than those involved in program transmission service. The core eddy current losses, varying with the square of the frequency, are principally responsible for the resistance increase at the higher frequencies. The increase of attenuation with frequency caused by these core losses is readily corrected, however, by the attenuation equalizers which, as described later, also correct for the attenuation-frequency distortion caused by other factors in the cable circuit.

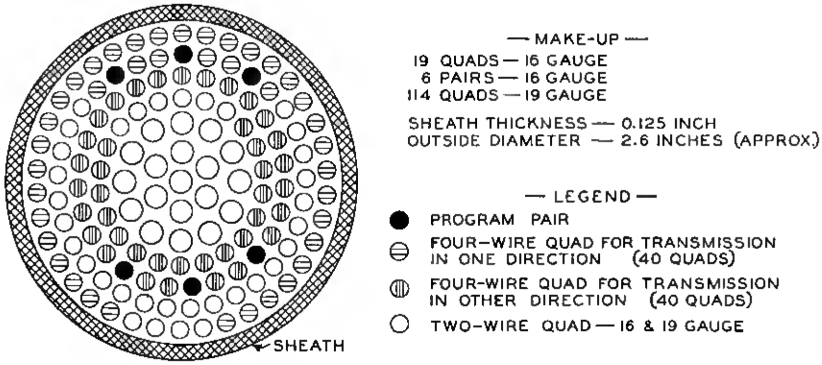

Fig. 7—Cross section of typical full sized cable.

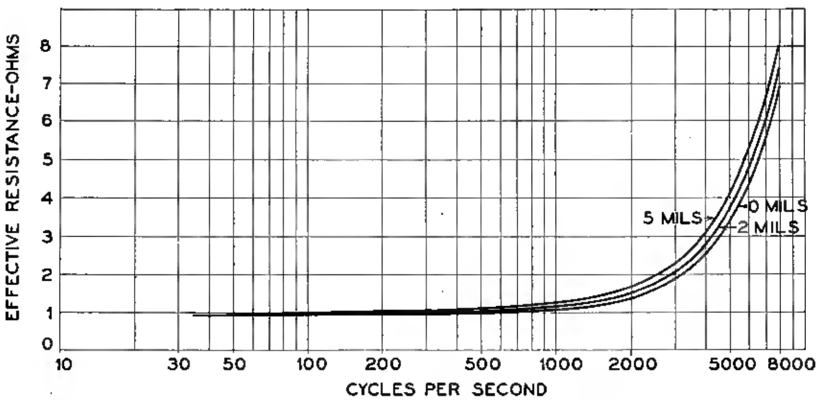

Fig. 8—Effective resistance of 22 milli-henry loading coils used on program transmission circuits in toll cables.

Owing to the low hysteresis loss of the compressed powdered permalloy material, the non-linear distortion introduced by the loading is inappreciable within the range of volumes handled by this program system. For example, in a 1,000-mile circuit for the condition where the power output from each repeater is 1 milliwatt (corresponding roughly to the average power when the program volume is maximum), the non-linear distortion that occurs in the loading causes an increase in the overall transmission loss of the circuit of only 1 db at 8,000 cycles, as compared to the loss for negligibly small power. At 1,000 cycles, the loss increment for the same comparison is .13 db. The

Fig. 9—6-Coil loading case for cable program circuit. $\frac{1}{9}$th actual size.

harmonic production in the coils is another measure of their excellence with respect to non-linear distortion. For a 400-cycle line current of 1 milliampere, the ratio of the third harmonic e.m.f. generated in an individual loading coil to the fundamental e.m.f. is equivalent to a loss of 80 db. The current magnitude above assumed corresponds approximately to the maximum repeater output (single-frequency basis) of 1 milliwatt; the average current that flows in the loading coils is very much smaller due to the smaller average repeater output and to line attenuation. In this connection, it is to be noted that the third harmonic voltage varies with the square of the magnitude of the fundamental current, and directly with frequency. The higher harmonics are, of course, much lower in magnitude than the third harmonic.

For the purpose of minimizing crosstalk, the loading coils are shielded individually by placing each in a metal container. In addition, the leads to the coils in the stub cable and within the coil case are cabled in individually shielded quads, the "IN" and "OUT" leads of a loading coil being in the same shielded quad. As a result of these precautions, the crosstalk between the loading coils is practically negligible. Even at the highest frequencies involved in program transmission, the crosstalk is only of the order of 2 crosstalk units, corresponding to an attenuation of about 114 db.

The shielded program circuit coils required on a given cable are potted separately from the loading coils used on the telephone message circuits. These cases are of welded steel construction. A photograph of a 6-coil case for underground use is shown in Fig. 9. The underground type of case has a special protective coating supplemented by a wrapping of heavy paper.

Amplifiers

Figure 10 is a schematic of the amplifier circuit as used at non-regulating repeater stations. (At regulating stations an automatic transmission adjustment stage is added, which will be described later.) Front and rear views of the amplifier, which is designed for relay-rack mounting in accordance with present-day telephone practice, are shown in Figs. 11 and 12. The lower panel is the amplifier, the upper the transmission adjustment stage, which will be treated later.

In the regular amplifier a standard Western Electric 102-F tube is used in the first stage and a 101-F tube in the second. The amplifier uses resistance coupling and the various coils which affect the transmission performance have very high inductance so as to give the device very uniform transmission performance at different frequencies. The use of permalloy for the cores of these coils makes it possible to obtain the necessary high inductance without going to unreasonable coil dimensions. The gain is controlled by 5 db and 10 db artificial lines in the input circuit with a slide-wire potentiometer for the fine adjustments. Resistances in the grid circuit of the second tube allow an adjustment of the gain at high frequencies. Increasing the resistance causes a decrease in gain at these frequencies. The grid potential of the tubes is obtained from voltage drop in the filament circuit. The condenser in the grid circuit with its associated resistance serves to keep noise which may be present in the filament circuit from entering the grid circuit.

The ideal amplifier should give a constant gain for all frequencies over the band to be transmitted regardless of variations in magnitude

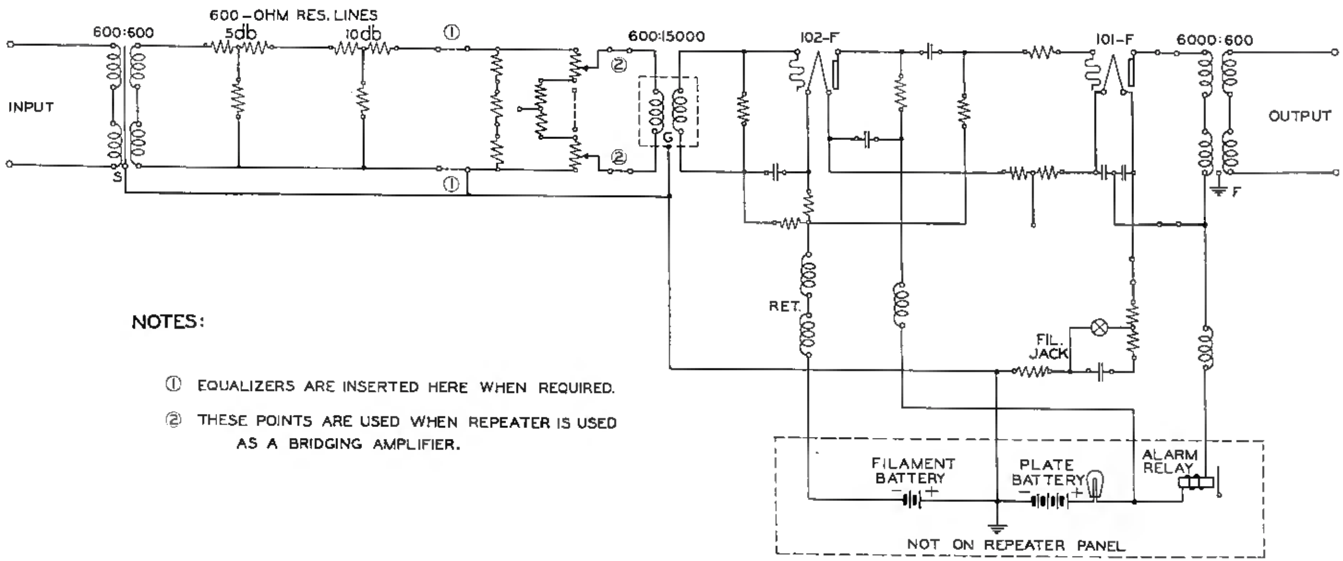

Fig. 10—Schematic of non-regulating repeater for cable program system.

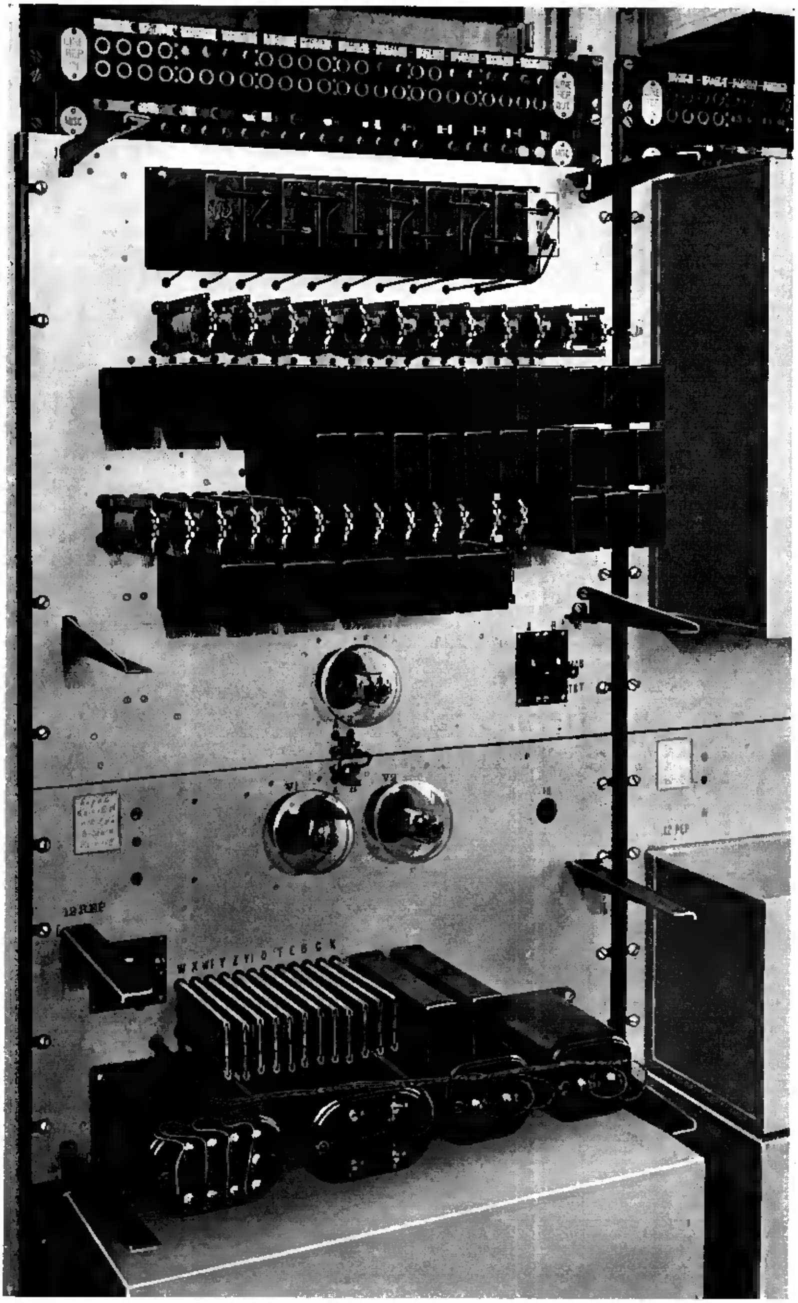

Fig. 11—Front view of program repeater and associated regulating stage.

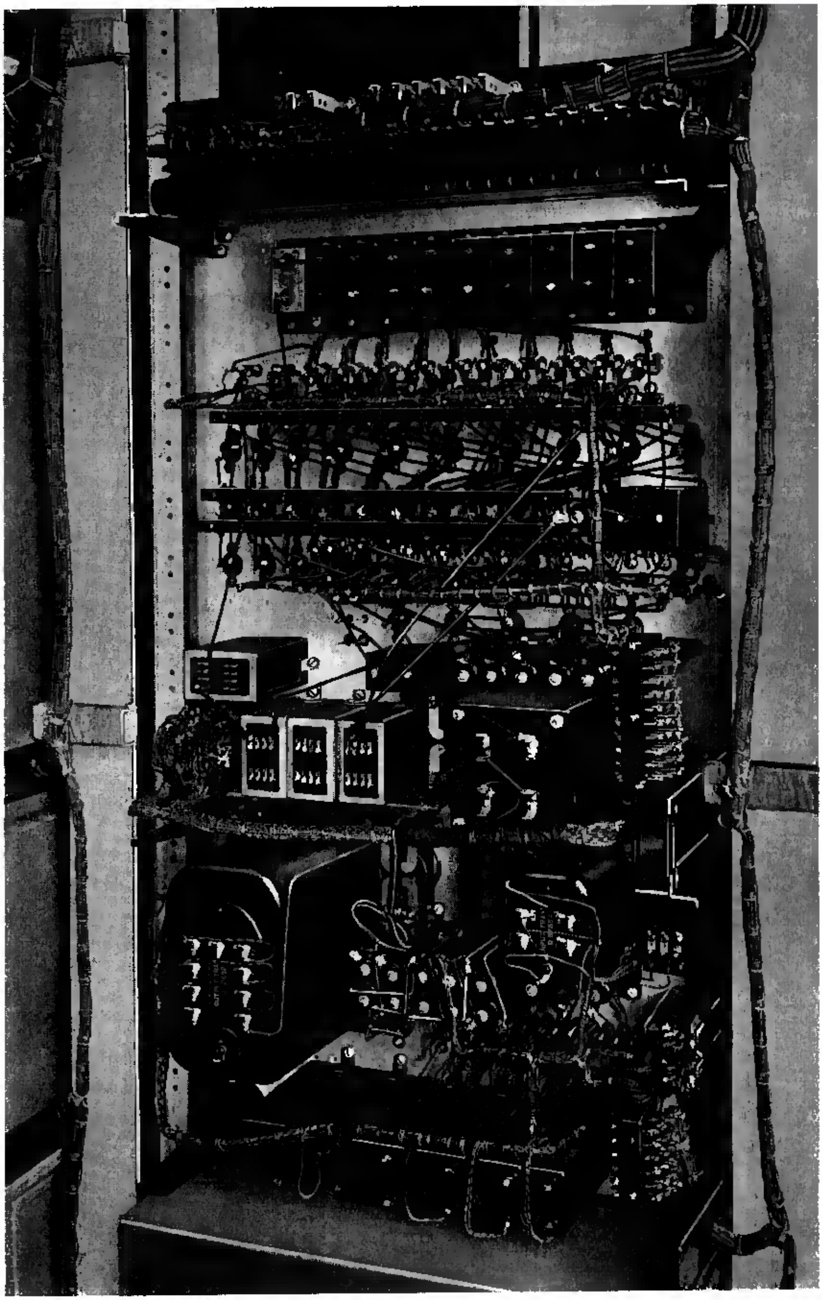

Fig. 12—Rear view of program repeater and associated regulating stage.

of current. No extraneous frequencies should appear in the output and all the frequencies in the band should be transmitted from input to output with equal velocity. With an average spacing of 50 miles for the repeaters, 40 of these are required on a circuit 2,000 miles long so that obtaining proper performance allows only very small departures of the individual repeaters from the ideal characteristics.

With respect to equality of gain at different frequencies, if the top and bottom frequencies of the band transmitted over a 2,000-mile circuit are not to drop more than, say, 2 db, below frequencies in the middle of the band, each amplifier is permitted to be only .05 db down at the edges of the band. (This corresponds to a power difference of 1 per cent.) By the use of resistance coupling and high mutual inductance transformers throughout, the amplifiers developed for this system have been given the characteristics shown in Fig. 13. It will be observed that between 100 and 10,000 cycles the gain differences are less than .05 db while at 35 cycles the gain is only .2 db below the gain at 1,000 cycles.

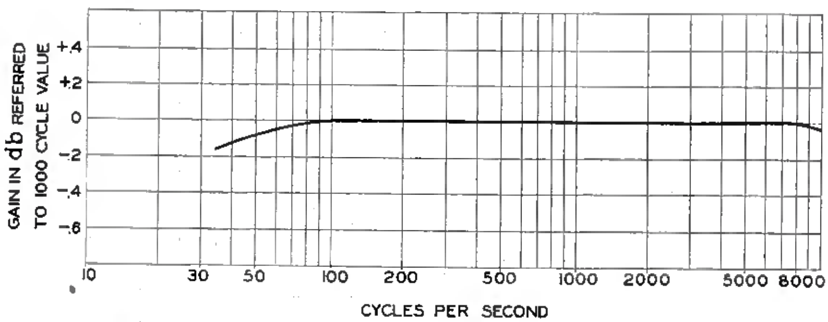

Fig. 13—Gain-frequency characteristic of non-regulating repeater without line equalizer.

With respect to departure of the amplifier from linearity, the effects produced are largely caused by the vacuum tubes. Very little of such distortion is introduced by the amplifier coils. Measurements on one of these amplifiers have shown that with a single frequency output of 1 milliwatt, which is about the average power corresponding to the maximum program volume, the second harmonics are about 50 db weaker than the fundamental, i.e., differ in power from the fundamental in the ratio 1 to 100,000. Other harmonics are lower in magnitude.

Non-linearity in the amplifier also manifests itself by change in gain with current strength. In this amplifier a variation in load from 1 milliwatt to a much weaker load causes a change in gain of only about .01 db, while a variation in load from 60 milliwatts to 6 milliwatts causes a change in gain of about .4 db.

The input and output coils in the amplifier and, in the case of the regulating repeater, the retardation coil also, tend to delay the transmission of low-frequency currents more than those of high frequency; an action which is due to the inductance of these coils shunting the circuit. As this reactance becomes less at the lower frequencies, the delay becomes greater. It can be reduced by increasing the values of shunting inductances. It is largely to reduce this effect that permalloy core coils of extremely high inductance are used, as noted

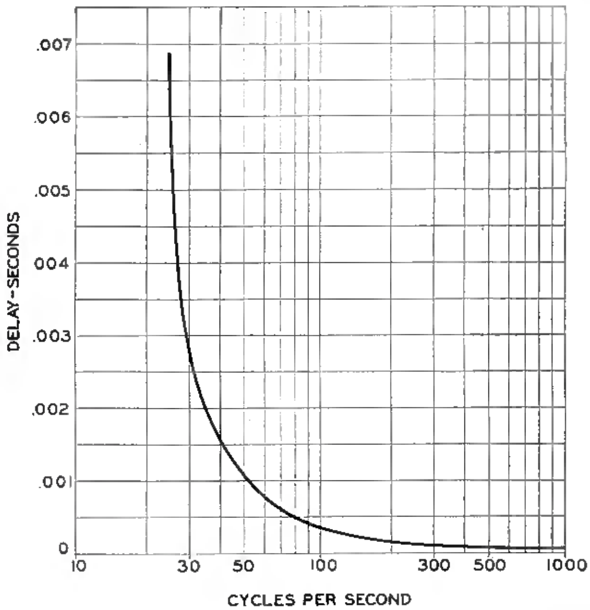

Fig. 14—Delay-frequency characteristic of non-regulating repeater.

above. The condensers appearing in series also cause delay at low frequencies and must be given capacity sufficiently great to keep the delay within proper limits. Inductance in series or capacity in shunt will also result in delay at the high-frequency end. However, in the frequency range covered by these amplifiers there is no difficulty in keeping this delay small enough to be negligible.

The delay characteristic of one of these amplifiers is shown in Fig. 14. With 40 amplifiers in tandem, the overall delay at 35 cycles is 75 milli-seconds greater than at 1,000 cycles, while there is no appreciable difference between the delay at 1,000 cycles and the delay at higher frequencies.

Attenuation Equalizers

As will be observed from Fig. 4, the transmission loss of the cable circuit varies considerably with frequency. Since the amplifier has a flat gain characteristic, an attenuation equalizer is called for to correct the distortion introduced by the cable. A diagram of one of these equalizers is shown in Fig. 15. In Fig. 16 is shown the loss

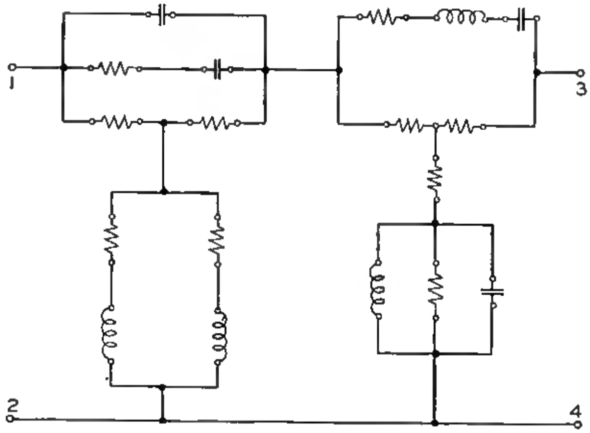

Fig. 15—Schematic circuit of attenuation equalizer.

introduced by a 50-mile section of cable at average temperature, the loss introduced by one of these attenuation equalizers and the total loss of line and equalizer with the offsetting gain introduced by the amplifier.

Automatic Device to Overcome Effects of Varying Temperature Transmission Adjusting

As the temperature of the cable changes its attenuation changes, the amount of the change being different at different frequencies. Referring back to Fig. 6, it is seen that on a cable circuit 1,000 miles long a temperature change from 55° F. to 109° F. causes changes in the transmission as follows:

At 100 cycles	18 db change,	power change of	63
At 1,000 cycles	28 db change,	power change of	625
At 8,000 cycles	3 db change,	power change of	2

When it is appreciated that in an aerial cable a temperature change of 54° F. may take place in only a day or two, the importance of compensating for this effect may be appreciated.

In order to compensate for this effect of varying temperature, a regulating stage is added to the amplifiers at the various regulator stations. Fig. 17 shows how the regulating network stage is added to one of the amplifiers and also shows the general nature of the regulating network circuit. Because of the peculiar and complicated way the transmission loss of the cable circuit varies with temperature,

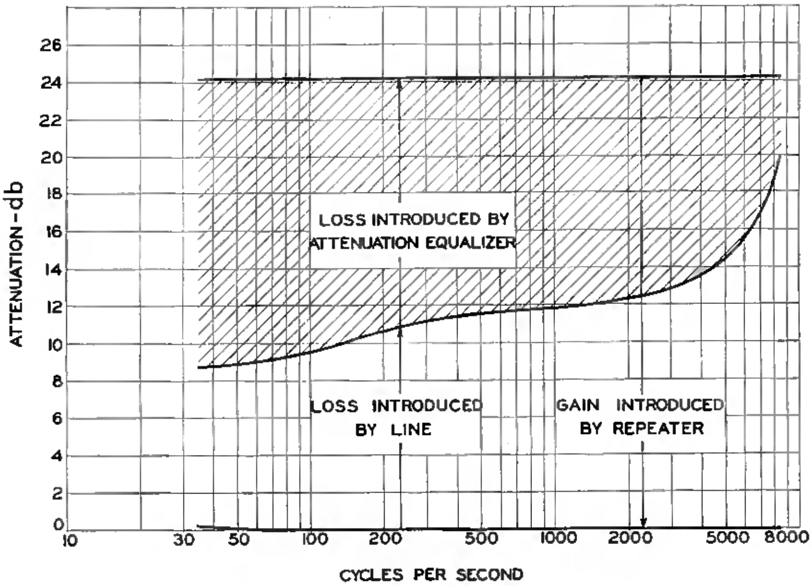

Fig. 16—Attenuation-frequency characteristic of line equalizer and 50 miles of 16-ga. B-22 cable circuits.

a somewhat complicated regulating network is called for. Front and rear views of one of these regulating networks are shown in Figs. 11 and 12, the upper panel being the regulating network and the lower the normal amplifier. Fig. 18 shows how the gain characteristic of the amplifier is altered by different steps of the regulating network. This is very closely complementary to the change in cable loss caused by the temperature variations and thus it will be evident that the effects of the temperature changes are largely eliminated.

Delay Equalizers

The velocity of transmission through a loaded cable decreases as the frequency is increased toward the cutoff point of the loading. To neutralize this effect, delay-equalizing networks are inserted in the circuit which retard the lower frequencies, thus equalizing the velocity

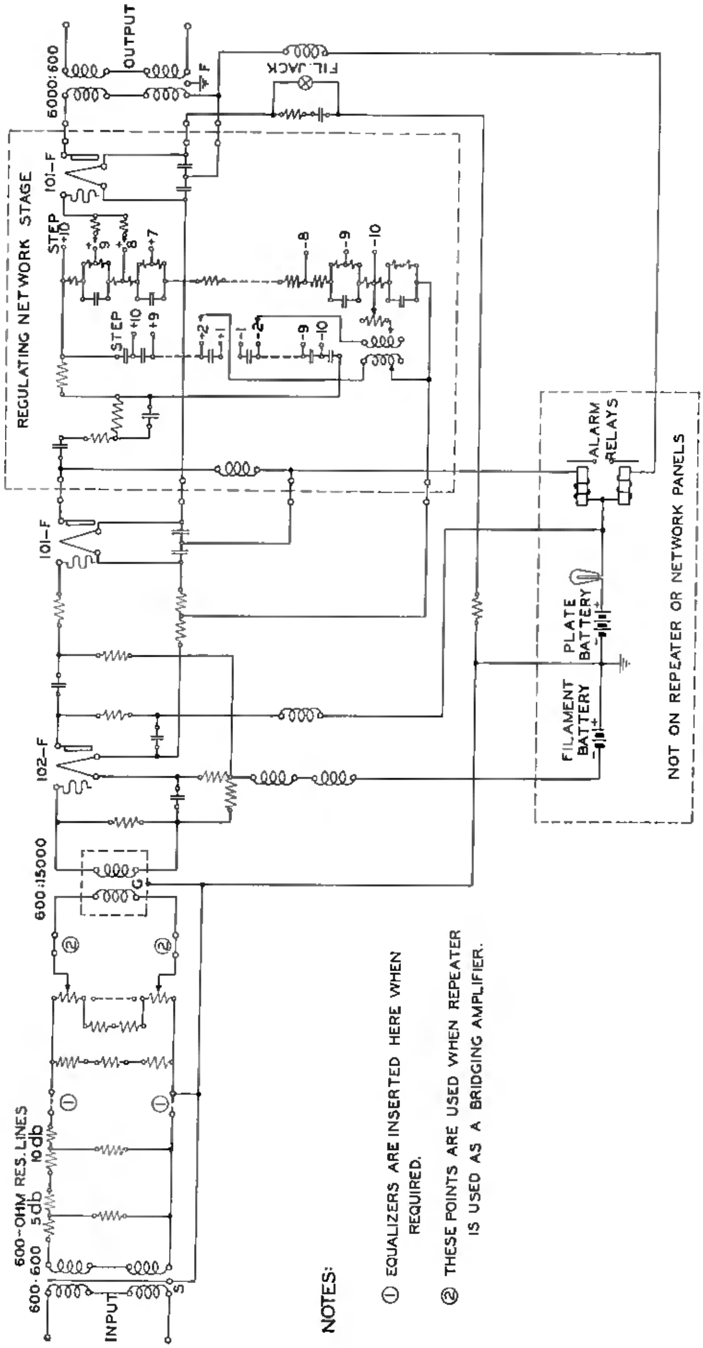

Fig. 17—Schematic of regulating repeater for cable program system.

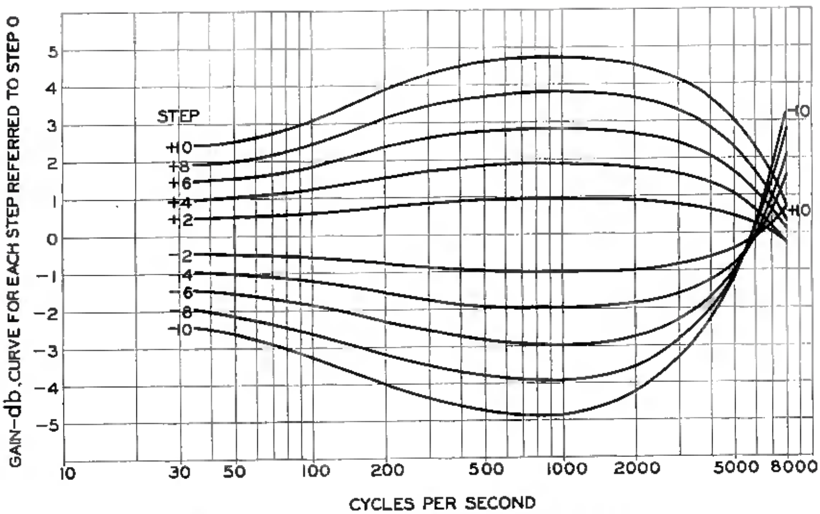

Fig. 18—Gain-frequency characteristic of regulating repeater without line equalizer.

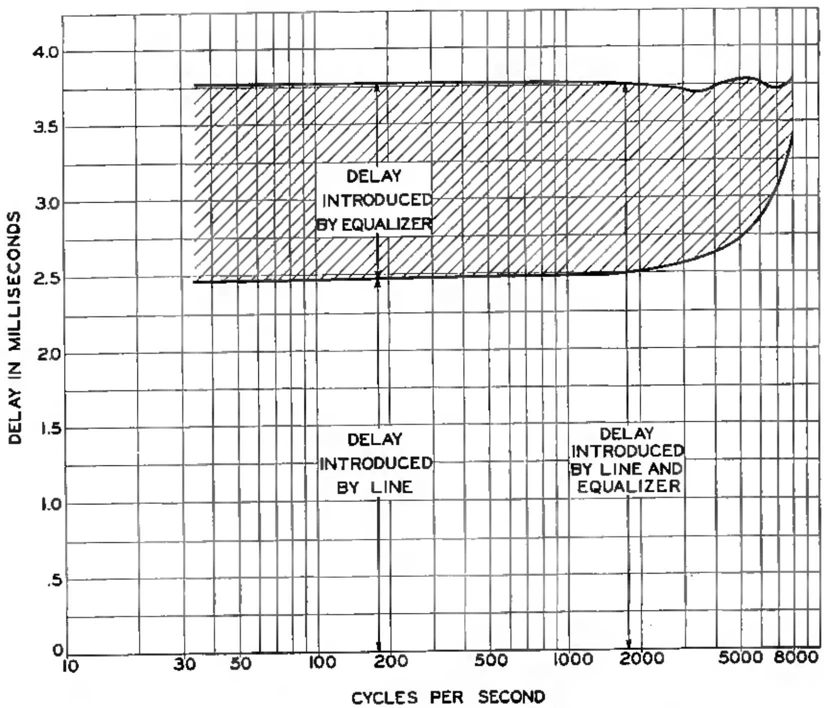

Fig. 19—Delay-frequency characteristic of 50 miles 16-ga. B-22 cable with and without delay equalizer.

of transmission through the combination of cable and networks for all frequencies in the band to be transmitted. Fig. 19 shows the delay characteristic of a section of cable 50 miles in length, with and without the delay-equalizing networks. The delay is seen to be maintained within ± 0.05 milli-second of a constant value. A schematic circuit of these networks is shown in Fig. 20. With the greatest

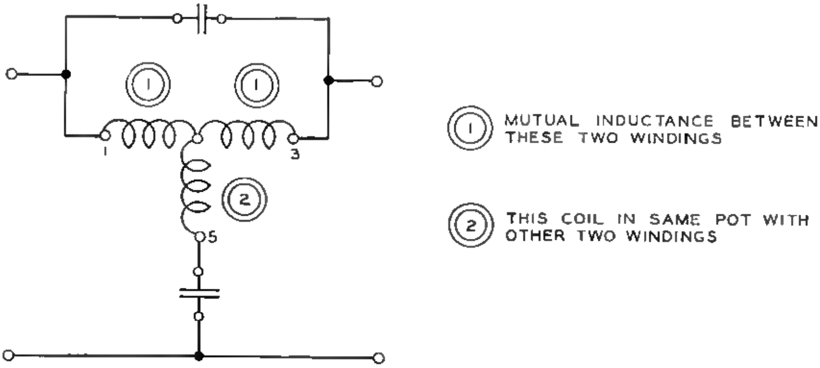

Fig. 20—Schematic circuit of section of delay equalizer. For a 50-mile equalizer, three kinds of sections are used which vary in the resonant frequency and in the sharpness of resonance. The first three sections are of one kind, the fourth is of another and the last seven are of the third kind.

length of cable circuits which will be used in this country for program transmission, this amount of deviation per section is not sufficient to cause objectionable distortion. For a 50-mile section uncorrected, the delay at 8,000 cycles would be 0.9 milli-second greater than at 1,000. A description of these delay-equalizing networks with the theory of their performance is being presented in another paper so that a more detailed description is omitted in this paper.

Office Wiring

Owing to the wide frequency range transmitted over the circuit, special care must be taken with the office wiring. This is to avoid excessive variations in the losses introduced by this wiring due to changing humidity conditions. A new type of insulated cable is used in which the textile material of the insulating wires has been very thoroughly washed to remove all traces of foreign substances, so that the absorption of moisture with its accompanying increase in loss is greatly reduced.[5] The office cabling is also shortened as much as possible, the outside cable connecting directly to the repeaters without

[5] H. H. Glenn and E. B. Wood, "Purified Textile Insulation for Telephone Central Office Wiring," *A. I. E. E. Transactions*, Vol. 48, April, 1929.

passing through the usual test board. At points in the circuit sensitive to noise interference or crosstalk where the energy level of the transmitted signals is very low, the circuit units are connected by means of shielded pairs. This shield is connected to filament ground, as are also the cases of the various transformers which are insulated from the supporting metallic frame. The unavoidable noise potential existing between the frame and the filament circuit cannot then produce any appreciable disturbance in the circuit.

Overall Performance of System

A measurement of the transmission loss of the 2,200-mile test length of B-22-N cable circuit gave results as indicated in Fig. 21.

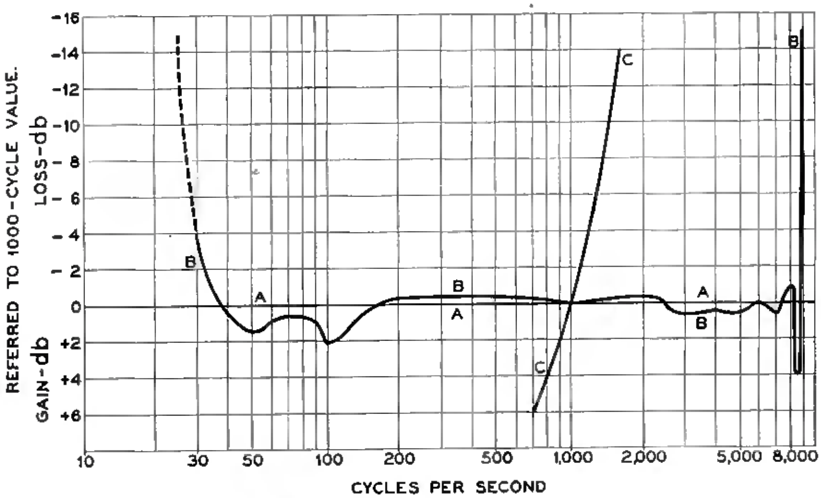

Fig. 21—Transmission-frequency characteristics of 2,200 miles of 16-ga. B-22 cable program transmission circuit. Curve A—Ideal characteristic. Curve B—Measured characteristic. Curve C—Line without equalizers.

It will be observed that over the range from 35 cycles to 8,000 cycles the transmission loss was practically the same at all frequencies, departing only about $\pm$ 2 db. For comparison, another curve (*C*) is given on the same drawing showing the transmission characteristic which would have been obtained if distortionless amplification had simply been added to the line with no attenuation equalizers.

The delay-frequency characteristics of the 2,200-mile test length of B-22 circuit are shown in Fig. 22. Two curves are given, one for the circuit without delay equalizers, the other with delay equalizers.

With respect to non-linear distortion, it was found by test that when the maximum volume was held at about $-$ 5 db, as read on a volume indicator, or about 1 milliwatt of average power, the nonlinear distortion became inappreciable. As a matter of fact, occasional bursts up to at least 0 db were not badly distorted. It may be observed that the − 5 db volume is about 10 db less than repeaters

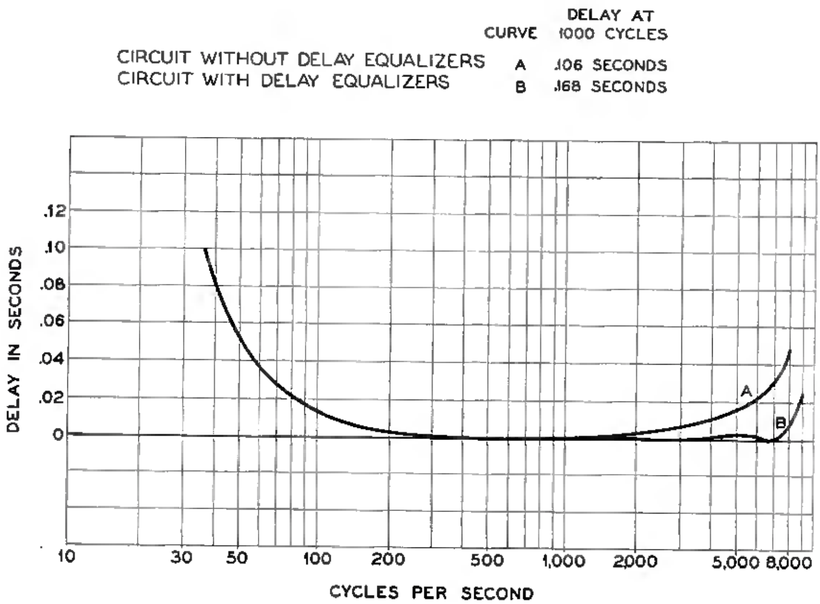

Fig. 22—Delay characteristics of 2,200 miles of 16-ga. B-22 cable program transmission circuit.

of the same nominal capacity and loading coils of similar characteristics handle without appreciable distortion under regular message telephone circuit conditions.

The minimum volume which could be transmitted over the cable circuit, which was set by noise and crosstalk picked up by the program circuit, was found to be about − 50 db at the repeater outputs. This means that the volume range carrying capacity of the circuit was about 45 db, just a little more than the figure 40 db which was previously mentioned as a reasonable standard for present-day conditions of broadcasting. If short bursts of music are allowed to go up to the zero volume at the repeater outputs, the system can evidently handle about 50 db volume range.

Using special pickup apparatus and loudspeakers capable of handling practically the whole audible frequency range, tests have been made over the 2,200-mile looped-back circuit in which comparison was made of the transmission with and without the cable included. When an

8,000-cycle low-pass filter was included under both conditions it was found that listeners had considerable difficulty in consistently picking a difference. In fact, the ordinary observer could not be relied upon to pick differences consistently even when the 8,000-cycle filter was not included.

Conclusion

This development was undertaken to provide a system for obtaining satisfactory channels for the transmission of broadcast programs in the rapidly growing cable network of the Bell Telephone System. The time required to complete such a development and the need for advance planning in the cable plant made it essential that the channels be adequate to render service for a number of years. Improvements in broadcast reproduction may be expected to continue and may very well result in changes in the present frequency allocations to give space for wider bands. The cable system described in this paper was, therefore, developed to possess transmission characteristics superior to present-day radio systems, the margin anticipating improvements which may take place in the future.

Acknowledgment

The authors gratefully acknowledge the assistance of many of their associates in the preparation of this paper and particularly of Mr. H. S. Hamilton.

Abstracts of Technical Articles from Bell System Sources

Barkhausen Effect II. Determination of the Average Size of the Discontinuities in Magnetization.[1] R. M. Bozorth and J. F. Dillinger. When the magnetic field-strength acting on a ferro-magnetic material is changed, the magnetization changes discontinuously (Barkhausen effect). These discontinuous changes have been examined in 1 mm. wires; an expression is derived and experimental arrangements are described for determining their average size for a given material in a given state of magnetization.

Experimental determinations of the average size have been made for iron (including a single crystal and a hard-drawn wire), nickel, and several iron-nickel alloys (permalloys). The average size is greatest on or near the steepest part of the hysteresis loop. The greatest average size, expressed as the volume of material the magnetization of which must be changed from saturation in one sense to saturation in the opposite sense to produce the same change in magnetization, is much the same for all of the materials examined, the extremes being 1.2×10^{-9} cm.^{3} for annealed iron and 45×10^{-9} cm.^{3} for 50 per cent nickel permalloy. This shows that the sizes of the discontinuities do not depend to any considerable extent on the size or kind of crystals.

Criticism is made of previous work on the size of the coherence region, the region within which the change in magnetization is confined. Although the effect of a single discontinuity in magnetization may be detected as far as 10 cm. from its source because of the eddy-currents induced, the experimental evidence is consistent with the view that the permanent change in magnetization is confined to the volume in terms of which the size of the discontinuity is measured as stated above, always less than 10^{-5} cm.^{3}.

Particle Size as a Factor in the Corrosion of Lead by Soils.[2] R. M. Burns and D. J. Salley. In order to determine that part which particle size plays in the corrosion of lead by soils, lead specimens were buried in sands (generally inert in character) of various particle sizes and were maintained for periods of time ranging from 8 days to 5 months at 40° C. in a closed system in which the humidity and the composition of the atmosphere were controlled.

[1] *Phys. Rev.*, Apr. 1, 1930.
[2] *Ind. and Engg. Chem.*, Mar., 1930.

It has been shown that lead is corroded by contact with moist inert sands in the presence of air, and that the rate of attack is increased by increasing within certain limits the particle size of the sand, the moisture content of the sand, and the oxygen content of the atmosphere.

Corrosion is caused by oxygen concentration cells which are set up as a result of the partial or complete exclusion of oxygen at the points of contact of metal and soil.

Soil particle size influences the rate of corrosion by determining the extent of the electrode areas, and therefore the degree of cathodic polarization, of these oxygen concentration cells.

Reverberation Time in "Dead" Rooms.[3] CARL F. EYRING. With the advent of radio broadcasting and sound pictures very "dead" rooms have been built, and the significant problem of just how much reverberation should be used in broadcasting and recording presents itself. The direct measurement of reverberation time or its calculation by the aid of a reliable formula, then, is an important aspect of applied acoustics. A reverberation time formula enables one to calculate the reverberation time once the volume, surface area and average absorption coefficient of the surface of the room are known; or if the reverberation time is measured it enables one to calculate the average coefficient of absorption of the surface treatment. A correct reverberation time formula is, therefore, much to be desired.

Theories of reverberation leading to Sabine's reverberation time equation have been given by W. C. Sabine (1900), Franklin (1903), Jaeger (1911), Buckingham (1925). Recently Schuster and Waetzmann (1929) have pointed out that Sabine's formula is essentially a "live" room formula and they have shown as we also show that the reverberation time equation varies somewhat with the shape of the room. The present paper presents an analysis based on the assumption that image sources may replace the walls of a room in calculating the rate of decay of sound intensity after the sound source is cut off, which gives a form of reverberation time equation more general than Sabine's; it points out the difference between the basic assumptions leading to the two types of formulæ; it adds experimental data which support the more general type; and it ends with the conclusion that no one formula without modification is essentially all inclusive.

The Provision of Radio Facilities for Aircraft Communication.[4] E. L. NELSON and F. M. RYAN. This subject is discussed by the authors from the viewpoint of the radio engineer. The periods of fundamental

[3] *Jour. Acou. Soc. Amer.*, Jan., 1930.
[4] *Soc. Auto. Engs.*, Mar., 1930.

study and development of apparatus are stated to be drawing to a close, and we are said to be well advanced toward the third and last period—that of general application to commercial flying.

The discussion of radio-communication outfits is based on aircraft equipment recently developed by the Bell Telephone Laboratories for receiving weather reports and beacon signals and for two-way telephonic communication between the airplane and ground stations.

Units of different types of apparatus for use in small mail-planes and in large transports are illustrated and described, together with tabular data of sizes and weights of individual units of both general types of outfit.

Information regarding the requirements of shielding, bonding and installation is given, and the airplane factory is stated to be the place where provisions for radio installation can best be made. If suitable provisions have been made therefor, the installation of two-way radio equipment is said to be simple and inexpensive.

A number of the larger air-transport organizations have made noteworthy progress toward providing suitable radio systems and the Department of Commerce is giving much assistance in the way of radio aids to air navigation, but a great deal of work remains to be done by the industry as a whole and numerous problems will require solution. New requirements will be encountered as the number and size of airplanes increase, but continuing radio studies promise that the development of aircraft radio communication will keep abreast of the development of airplanes.

Transmission Characteristics of a Short-Wave Telephone Circuit.[5] R. K. POTTER. A method of observing and recording the audio-frequency transmission characteristics of a short-wave radiotelephone channel is described. These characteristics undergo rapid changes. They appear to be the result of wave interference between signals arriving at the receiver over paths of different group or electrical length possibly combined with the distortion produced by a progressive change in the angle of rotation of the polarization plane with frequency over the signal band. The persistence of certain pattern shapes during the observation periods and the changes in these shapes from hour-to-hour suggest that they are the result of progressive rather than erratic disturbances in the transmission medium. Times when the audio-frequency characteristics were flat were very rare. However, a consider-

[5] *Proc. Inst. Radio Engineers*, Apr., 1930.

able departure from flatness may occur without serious effect on the intelligibility of the speech transmission.

Synthetic patterns used in the analysis of the characteristics are explained and illustrated. Types of audio-frequency distortion resulting from selective fading are discussed. The effect of frequency or phase modulation in producing distortion on such a circuit is considered.

Records are shown of the effect of an automatic gain control, following carrier amplitude variations, upon the audio-frequency transmission characteristic. "Rapid" fading records revealing unlike fading on radio frequencies separated by 170 cycles are included. The seasonal variation in susceptibility of the circuit to this "rapid" fading is illustrated.

The records mentioned above are for ordinary modulated carrier transmission and involve the results of interaction between the two side bands in the detection process. There are also shown records made on single side-band carrier-suppressed transmission. In this case detection does not modify the frequency-amplitude relations and the record delineates directly the frequency-amplitude characteristics of the received radio-frequency band.

Age Hardening Lead-Calcium Alloys.[6] EARLE E. SCHUMACHER and GEORGE M. BOUTON. The lead end of the system lead-calcium has been investigated and a constitutional diagram given. A peritectic reaction has been discovered and the solid solubility of calcium in lead has been determined for five temperatures. The solubility changes from 0.1 per cent calcium at 328.3° C. to approximately 0.01 per cent calcium at 25° C. Data for locating the solid solubility curve were obtained from thermal analysis, electrical conductivity measurements, microscopic examinations and age hardening studies.

It has been shown on the basis of laboratory tests that greater tensile strengths and resistances to fatigue failure can be developed in some of the lead-calcium alloys than in the lead—1 per cent antimony alloy. Certain lead-calcium alloys have been suggested as sheathing materials for electrical cables.

Preparation of Air of Known Humidity and Its Application to the Calibration of an Absolute-Humidity Recorder.[7] A. C. WALKER and E. J. ERNEST, JR. An apparatus is described whereby constant flowing mixtures of air and water vapor may be prepared, in which the moisture content varies not more than 0.001 per cent by volume, over

[6] *Metals & Alloys*, Mar., 1930.
[7] *Ind. and Engg. Chem.*, Apr. 15, 1930.

long periods. This apparatus has been utilized to calibrate a sensitive humidity recorder capable of continuously recording atmospheric humidities up to 2.9 per cent by volume of water vapor in air (equivalent to about 95 per cent relative humidity at 25° C.) with a sensitivity of 0.0016 per cent by volume (0.05 per cent relative humidity at 25° C.). The use of the recorder in connection with the constant humidity apparatus is described and certain typical data illustrating the performance are given.

Contributors to this Issue

Millard W. Baldwin, Jr., E.E., Cornell, 1925; M.A., Columbia, 1928; Bell Telephone Laboratories, 1925–. Mr. Baldwin has been engaged in studies of vacuum tube modulation; more recently his work has had to do with some of the problems of picture transmission and television.

David George Blattner, B.S.E.E., Kansas State Agricultural College, 1911; Assistant Instructor in Physics, Kansas State Agricultural College, 1911–13. Engineering Department, Western Electric Company, 1914–25. Bell Telephone Laboratories 1925–. Mr. Blattner's work has been in loud speaker, public address systems, and phonograph recorder and reproducer developments.

L. G. Bostwick, B.S. in E.E., University of Vermont, 1922; American Telephone and Telegraph Company, Development and Research Department, 1922–26; Bell Telephone Laboratories, Inc., Research Department, 1926–. While with the Development and Research Department, Mr. Bostwick's work involved general problems on systems for the high quality transmission of speech and music; since then his work has been largely on loud speakers and loud speaker measuring methods.

S. Brand, B.S., Trinity College, 1915; Yale University Graduate School, 1915–17; U. S. Air Service, 1917–19; Plant Department, Southern New England Telephone Company, 1920–23; Department of Development and Research, American Telephone and Telegraph Company, 1923–. Mr. Brand has been engaged mainly in transmission development work on repeatered circuits.

A. B. Clark, B.E.E., University of Michigan, 1911; American Telephone and Telegraph Company, 1911–. Toll Transmission Development Engineer, 1928–. Mr. Clark's work has been largely concerned with toll telephone and telegraph systems.

Lloyd Espenschied. Mr. Espenschied is in charge of radio development, assisting the Transmission Development Engineer, Department of Development and Research, American Telephone and Telegraph Company. He joined the Bell System in 1910, having graduated from Pratt Institute the previous year. He has taken an important part in practically all of the Bell System radio developments, beginning with the first long-distance radio-telephone tests of 1915, at which time he received the voice in Hawaii from Arlington, Va. He has participated in a number of international conferences on electric communications.

Frank Gray, B.S., Purdue, 1911; instructor and graduate student in physics at the University of Wisconsin, Ph.D., 1916; member of the Naval Experimental Station during the war. Mr. Gray entered the Bell Telephone Laboratories—then the Engineering Department of the Western Electric Company—in 1919 and has been closely associated with Dr. Ives in his studies on light.

C. W. Green, B.S. in Electrical Engineering, University of Wisconsin, 1907; Instructor and Assistant Professor, Massachusetts Institute of Technology, 1907–17; Captain 1917, Major 1918, U. S. Army; Bell Telephone Laboratories, 1919. Mr. Green's work has had to do with the development of Carrier Telephone Systems and Voice Frequency Repeaters.

Herbert E. Ives, B.S., University of Pennsylvania, 1905; Ph.D., Johns Hopkins, 1908; assistant and assistant physicist, Bureau of Standards, 1908–09; physicist, Nela Research Laboratory, Cleveland 1909–12; physicist, United Gas Improvement Company, Philadelphia, 1912–18; U. S. Army Air Service, 1918–19; research engineer, Western Electric Company and Bell Telephone Laboratories, 1919 to date. Dr. Ives' work has had to do principally with the production, measurement and utilization of light.

C. E. Lane, A.B., University of Iowa, 1920; M.S., University of Iowa, 1921; Engineering Department of the Western Electric Company, 1921–25; Bell Telephone Laboratories, 1925–. During the last four years Mr. Lane has been engaged in the development of such transmission networks as filters, attenuation equalizers and phase correctors in the Apparatus Development Department. The five years prior to this were spent by him in the Research Department, engaged in general studies in acoustics, such as speech, hearing and loud speaker development.

W. H. Martin, A.B., Johns Hopkins University, 1909; B.Sc., Massachusetts Institute of Technology, 1911; American Telephone and Telegraph Company, Engineering Department, 1911–19; Department of Development and Research, 1919–. Mr. Martin's work has related particularly to transmission of telephone sets and local exchange circuits, transmission quality and loading.

H. Nyquist, B.S. in Electrical Engineering, North Dakota, 1914; M.S., North Dakota, 1915; Ph.D., Yale, 1917; Engineering Department, American Telephone and Telegraph Company, 1917–19; Department of Development and Research, 1919–. Mr. Nyquist has been engaged in transmission work particularly relating to toll cables.

H. S. Osborne, B.S., Massachusetts Institute of Technology, 1908; Austin Research Fellow in Engineering, 1908–10; Eng.D., 1910; American Telephone and Telegraph Company, Engineering Department, 1910–19; Department of Development and Research, 1919–20; Department of Operation and Engineering, 1920–. Mr. Osborne is Transmission Engineer and as such is responsible for assisting the Associated Companies in connection with telephone and telegraph transmission and protection matters.

J. C. Steinberg, B.Sc., M.Sc., Coe College, 1916, 1917; U. S. Air Service, 1917–19; Ph.D., Iowa, 1922; Engineering Department, Western Electric Company, 1922–25; Bell Telephone Laboratories, 1925–. Dr. Steinberg's work since coming with the Bell System has related largely to speech and hearing.

H. M. Stoller, E.E., Union College, 1913; M.S. in Electrical Engineering, 1915; Engineering Department of Western Electric Company, 1914 and 1916–25; Bell Telephone Laboratories, 1925–. Mr. Stoller's work has dealt with special problems connected with electrical power machinery, particularly voltage and speed regulators; multi-frequency generators employed in voice frequency carrier telegraph systems; and synchronization and speed control equipment for sound-picture systems.

William Wilson, Victoria University of Manchester, 1904–10; B.Sc., 1907; M.Sc., 1908; Cavendish Laboratory, Cambridge University, 1910–12, B.A., 1912; Lecturer in Physics, Toronto University, 1912–14; D.Sc. Manchester, 1913. Engineering Department Western Electric Company, 1914–24; 1925– Bell Telephone Laboratories; Assistant Director of Research 1928–. Dr. Wilson has published numerous papers on radioactivity and thermionics and since 1917 has been in direct charge of vacuum tube development and design and since 1925 has also been in charge of radio development.