Wire Transmission System for Television [1]

By D. K. GANNETT and E. I. GREEN

Synopsis: This paper deals with the transmission problems which were met and solved in connection with providing wire circuits from Washington to New York for the television demonstrations which took place on April 7, 1927, and following. For transmission of the television images a single transmission channel was set up combining the frequency ranges usually assigned to telegraph, telephone and certain carrier channels. The special line requirements were met so successfully that the television images transmitted from Washington were indistinguishable from those transmitted locally.

Introduction

A SYSTEM of television, to be worthy of the real meaning of the name, must be capable of operation over a considerable distance. Spanning this distance, there must be a connecting medium suitable for faithfully transmitting the television currents. This paper describes how the connecting medium was provided between Washington and New York for the recent television demonstrations,[2] by adapting to this purpose existing wire facilities of the Bell System.

Fortunately, wire facilities of the type which were available between Washington and New York had been utilized for some time to transmit simultaneously many telephone and telegraph messages, involving a frequency range more than ample for the television requirements, so that the transmission characteristics of the lines throughout the necessary range of frequencies were well known. The matter of providing a suitable channel to carry the television currents consisted, therefore, in throwing together the frequency ranges which had heretofore been utilized for providing a number of separate telephone and telegraph channels. In addition to providing this very wide band communication channel it was necessary to apply special distortion-correcting networks so that the overall channel would possess proper characteristics and also to take care to avoid introducing disturbances due to such things as line irregularities, noise, etc.

Due to the perfection of the transmission methods which were utilized, it was found that when the circuit was first established, in accordance with the requirements which had been deduced, the television images transmitted from Washington were indistinguishable in quality from those transmitted locally, this result being secured

[1] Presented at the Summer Convention of the A. I. E. E., Detroit, Mich., June 20–24, 1927.
[2] "Television," H. E. Ives; "The Production and Utilization of Television Signals," F. Gray, J. W. Horton and R. C. Mathes; "Synchronization in Television," H. M. Stoller and E. R. Morton.

without any deviation from the adjustments which had been worked out in the original design.

Requirements

General. The ideal requirement for a transmission line for television, or for that matter any other purpose, is, of course, that it introduce no distortion whatsoever, in which case there could be no question but that the television images obtained in the receiving apparatus after transmission over the long distance line would be identical with the image obtained with the transmission only over a distance of a few feet. Practical transmission lines, however, tend to introduce a certain amount of distortion and the less the allowable distortion which is specified the greater will be the cost of providing a proper line. Before going ahead with the matter of engineering the line required to transmit the television currents from Washington to New York it was, therefore, first necessary that the requirements be set. The requirements were made more severe than strictly necessary in cases where they were easy to meet.

Frequency Range. In any system for the electrical transmission of intelligence, the required frequency range is, in general, proportional to the speed of transmission. In the case of picture transmission or television, the speed of transmission may be expressed in terms of the number of picture elements which must be transmitted per second, where a picture element is the smallest unit area which it is intended to be able to distinguish in the received picture from its neighboring unit areas.

When the picture currents are transmitted in the most efficient manner, the frequency range necessary is approximately equal to half the number of picture elements which must be transmitted per second. A simple way of seeing this is to realize that as the picture elements are transmitted in sequence, the greatest possible rate of variation of detail is obtained when alternate picture elements are black and white. A complete cycle corresponds in this case, therefore, to the time interval required to transmit two picture elements.

According to this relationship this particular television system in which about 40,000 picture elements per second are transmitted should require a frequency range of approximately 20,000 cycles. As a matter of fact it was found by a laboratory test that due to certain characteristics of the apparatus a frequency range as great as this was ample, just detectable distortion being introduced in the reproduction of the human face when the range was narrowed to about 14,000 cycles. In providing the line circuit, however, extending the frequency range to 20,000 cycles involved so little difficulty that it was decided to provide this very liberal frequency range.

In the particular television system which has been described the very low frequencies (below about 10 cycles) are suppressed. It was, therefore, not necessary that the line transmit these very low frequencies. The frequency range which the line should transmit was accordingly set as 10 cycles to 20,000 cycles.

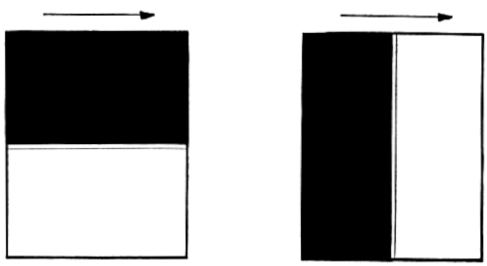
Attenuation. Referring to still picture transmission, it has been found that variations of attenuation with frequency of several transmission units do not appreciably impair the quality of the picture. Since no great difficulty was anticipated in meeting closer limits, however, it was decided to set the limits for the variation of attenuation with frequency at $\pm$ 2 T U within the frequency range of 10 to 20,000 cycles.

Phase Characteristics. A characteristic of wire lines, whose importance has been increasingly realized in recent years, is their phase characteristic. In speech transmission, transients due to unequal velocity of the different frequency components have been found to be an important consideration on some types of lines. In picture transmission and television, also, it is important that this phase distortion be controlled, as otherwise the image might be blurred due to the arrival of the various frequency components at different times. The type of transient which has been found to impair the quality of pictures is the type which is relatively rapid and the aim has been to make the phase characteristics such that those transients would be small.

The requirement with respect to phase for distortionless transmission is that β/ω be a constant where β is the phase change in radians for the entire circuit, and ω is equal to 2π times the frequency. β/ω is known as the "phase delay" or the steady-state time of transmission. $d\beta/d\omega$ is the time required for the transmission of the envelope of a wave whose components center closely about the frequency $\omega/2\pi$ and it will be referred to as the "envelope delay." Since it is more convenient to measure the envelope delay, the requirements were set up in terms of this quantity. When β/ω is constant, it is evident that $d\beta/d\omega$ is also constant. While the converse of this is not in general true, the conditions as actually encountered were such as to permit its use as a measure of the small variations involved.

The envelope delay characteristics of a number of circuits, which have been found to give varying degrees of transient on still pictures, have been measured. Also data were available from tests of picture transmission through filters and other networks whose delay characteristics were known. From these various data, the permissible deviations of the delay characteristic for still picture transmission were determined, and dividing these figures by 50, the ratio of the rate of transmission in picture elements per second in the two cases, the limits for the television circuits were obtained. In this way it was decided to attempt to keep within ± 10 microseconds, if possible, with outside limits of ± 20 microseconds. Check tests of these limits were made with the television apparatus in the laboratory by transmitting the currents through various known networks, and noting the effect on the received image.

Unlike the attenuation requirements, the delay requirements for television are not the same over the entire frequency range, but are much more lenient in the lower frequency range, as was shown by experiments in the laboratory. A physical picture of the reason for this may be obtained by reference to Fig. 1.



Arrows show direction of motion of light spot
A B
Fig. 1

Fig. 1A shows a picture placed in position before the sending machine, consisting of a piece of cardboard the same size as the image-area which can be transmitted, the upper half of the cardboard being colored black, while the lower half is white. As has been explained in the paper by Messrs. Gray, Horton and Mathes, the picture is scanned by a spot of light which moves from left to right in successive lines, tracing 50 horizontal lines across the picture in one sixteenth of a second. The first 25 of the lines lie on the black and the remaining 25 on the light part of the picture. The process is repeated 16 times per second, each repetition of 50 lines giving one complete cycle of black and white. The frequency components in this case are multiples of 16 cycles. A transient which blurs the picture outline over a given number, n, of picture elements (downwards) corresponds to a time interval equal to the time of tracing n lines, *i.e.*, $n/800$ second.

Now consider Fig. 1B. Here the picture has been rotated 90 degrees.

In this position, a complete cycle of black and white is obtained with each line instead of with each 50 lines. The frequency components in this case are multiples of 800 cycles and bear the same relations to 800 cycles as the components spoken of above bear to 16 cycles. A transient which blurs the picture outline n picture elements (horizontally, this time) corresponds to a time interval of n forty thousandths of a second. Evidently the delay requirements are 50 times more lenient in the former case than in the latter so that the delay requirement at the highest frequencies, which determine the fine detail in the direction of scanning, is 50 times as severe as at low frequencies, which determine the fine detail in a direction perpendicular to the direction of scanning.

In the still pictures referred to, the transients extended in the direction of travel of the light spot and there were no transients analogous to those discussed here in connection with Fig. 1A. For this reason the delay limits determined from still picture transmission are the ones which apply to the higher frequencies. For the lower frequencies the requirements are obtained by multiplying the high-frequency requirements by 50. For these reasons, together with the result of a Fourier analysis of the picture current, the limits were set at $\pm$ 10 or $\pm$ 20 microseconds from 400 to 20,000 cycles. Below 400 cycles, the departures from the constant delay were permitted to be $\pm$ 500 or $\pm$ 1000 microseconds.

Noise. Another important requirement is that relating to the ratio of the picture currents to the extraneous interfering currents which may arise in the line from power induction and other sources. Early experience with the television apparatus showed that considerably more noise was permissible in the case of television than in the case of still picture transmission so that in this case comparison with the still picture transmission would result in an unduly severe requirement. This is thought to be explained by the fact that in the case of television the pictures are flashed before the eye 16 times per second and the effects of the extraneous currents occur on successive flashes in different positions, so that defects of one flash are corrected on the next.

A set of experiments was performed from which it was determined that if the ratio of average picture currents to average noise currents exceeded about 10 the results were satisfactory. In order to assure considerable margin above this figure, it was decided to make the average television current to be transmitted into the line 4 milliamperes.

Echoes. If two paths exist by which the currents may travel from the sending point to the receiving point, the length of the two paths being different, a double image will be produced on the received picture, forming what may be termed visual echo. In the case of telephone lines, the echoes may exist on account of reflections between impedance irregularities in the circuit so that the currents arrive at the receiving point both by way of the direct transmission path and by way of a transmission path which includes an extra loop between two irregularities. If the echo is not greatly attenuated with respect to the main transmission, the result may be quite disturbing on the received picture. It has been found by experiment that the echo is too weak to be seen if it is more than 25 T U weaker than the main current and, accordingly, care was taken in setting up the New York-Washington circuit to avoid introducing echo paths of lower equivalent than this.

General Choice of Method

Two general methods are possible for transmitting the currents over the line circuits. One method is to transmit the currents directly without change of frequency. This method involves the transmission of the currents of the frequency range determined upon above, namely, from about 10 cycles to about 20,000 cycles per second.

The other general method is the carrier method, in which the television currents modulate a carrier current of suitable frequency and are thereby moved to another portion of the frequency spectrum prior to transmission over the line. At the receiving end of the line the carrier currents are then restored to the original frequencies of the television currents.

Several different schemes of carrier transmission are possible. The simplest is to modulate a carrier with the television currents and to transmit both side bands. This has the disadvantage of requiring the transmission of twice as wide a frequency range as that occupied by the original television currents. Another scheme is to transmit a single side band. A third possible scheme is to transmit both side bands for the lower frequencies and only one side band for the higher frequencies.

One advantage to be secured by the carrier method is that it lessens the severity of some of the line problems through avoiding the transmission of very low frequencies over the line circuit. At these frequencies the amount of noise found on lines is usually considerably greater than at the higher frequencies.

After weighing the relative merits of the carrier and direct transmission methods it was decided to make use of the latter because of its simplicity. An important factor in this decision was the successful development, for use in connecting the apparatus to the lines, of transformers providing adequate transmission of the entire frequency range from 10 cycles to 20,000 cycles.

Arrangements for Television Circuits

Line Layout between New York and Washington. The layout of the wires between New York and Washington is shown in Fig. 2. The circuit over which the waves actually carrying the pictures were transmitted (marked Picture Circuit) consisted principally of a pair of copper wires 165 mils in diameter. At a number of places on the route the circuits were carried in cable as indicated in the figure. The total length of the television circuits was about 285 miles, of which 8 miles consisted of cables and the remainder of open wire.

Transpositions. As the circuits employed were originally designed for voice-frequency operation only, except for a section at the New York end, it was necessary to add transpositions to them to prevent interaction with adjacent circuits at the high frequencies involved in the television transmission. The high-frequency currents were thus prevented from passing over into the adjacent circuits which would have resulted in irregularities in the attenuation, line impedance and phase shift characteristics of the circuit.

Incidental Cables—Loading. Any appreciable length of non-loaded cable included in an open-wire television circuit has certain very objectionable effects. The impedance irregularities introduced by the cable destroy the uniformity of the line attenuation, impedance and phase shift characteristics as a function of frequency, and tend to produce echoes as described above. Types of loading developed for use on incidental cables occurring in circuits employed for carrier telephone and carrier telegraphy operation [2] were employed to reduce these effects to a minimum. This carrier loading is designed so that when used on No. 13 A. W. G. cable circuits it provides an impedance which approximates very closely that of the open wire. With a spacing of about 930 feet between loading coils, this loading has a nominal cut-off of about 45,000 cycles, which corresponds to an effective transmission range extending up to about 36,000 cycles. In order to obtain a close match between the impedances of the open-wire and the cable pairs, thereby avoiding impedance irregularities, 13-gage pairs were selected for the television circuits in all of the cables.

The length of the submarine cable under the Hackensack River (about 1100 feet) was too great to permit the use of regular carrier

[2] "Development and Application of Loading for Telephone Circuits," T. Shaw and W. Fondiller, *Journal A. I. E. E.*, Vol. XLV, pages 253–263, March, 1926.

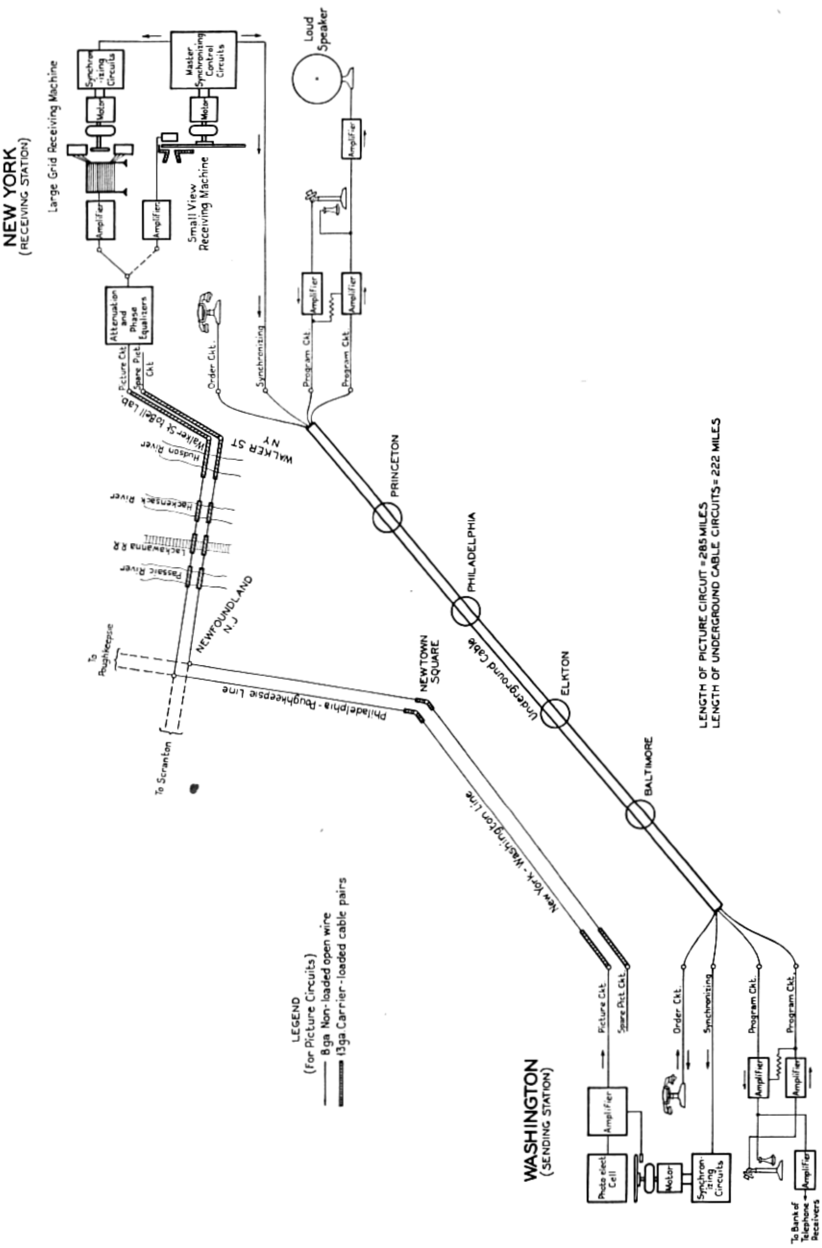


Fig. 2—Schematic diagram of circuits for television demonstration

loading, and a special loading arrangement having a slightly lower cut-off was, therefore, designed for this cable.

Equalization

Requirements. The requirements for the lines were stated earlier. In order to meet these overall requirements it was necessary to apply special forms of distortion-correcting networks.

Weather Changes. The above requirements applied, of course, to

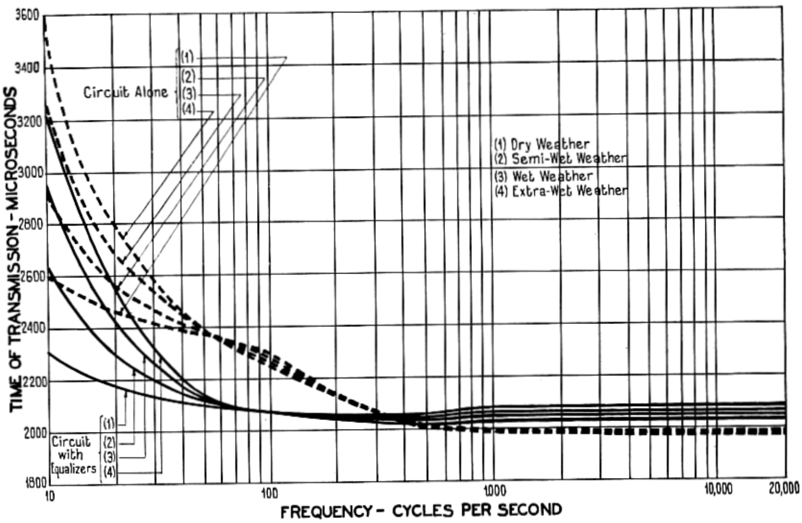


Fig. 3—Computed phase delay (β/ω) of television circuit with and without equalizers

all of the various weather conditions to which an open-wire circuit is subject. Due to the changes in the leakage conductance occurring at the insulators, the attenuation of an open-wire circuit varies with changing weather conditions. This change is particularly important at the higher frequencies. At 20,000 cycles, for example, the attenuation of a 165-mil open-wire pair may vary as much as 40 per cent for a change from dry weather to extra wet weather. For the circuit between Washington and New York this represents a possible attenuation change of about 10 T U, or a change of 10 to 1 in the magnitude of the received power. At 1000 cycles, the effect of wet weather is comparatively small, so that the net effect of the weather variations is to change the requirements for the attenuation equalizers. The phase shift introduced by an open-wire pair likewise varies to some extent with changes of weather, although the percentage variation is much smaller than in the case of the attenuation. In view of these variations in the line characteristics it was decided to provide basic networks which would equalize for dry weather conditions, and to make available, in addition, several steps of equalization which would compensate for changes in the direction of wet weather.

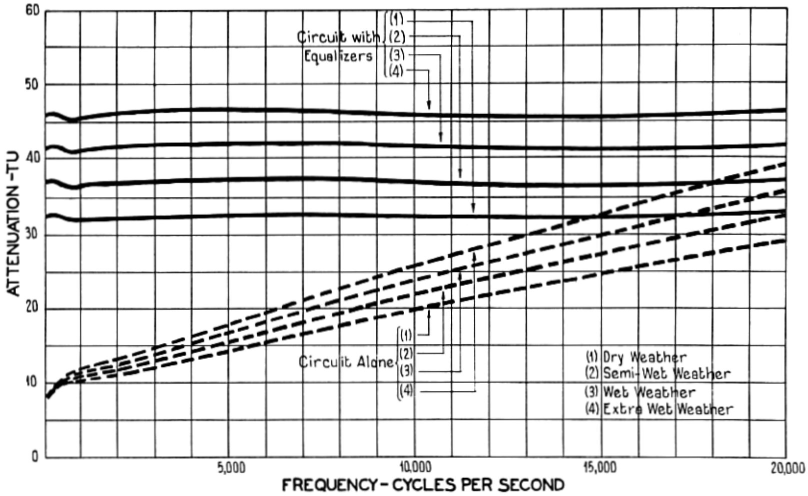


Fig. 4—Computed attenuation characteristics of television circuit with and without equalizers

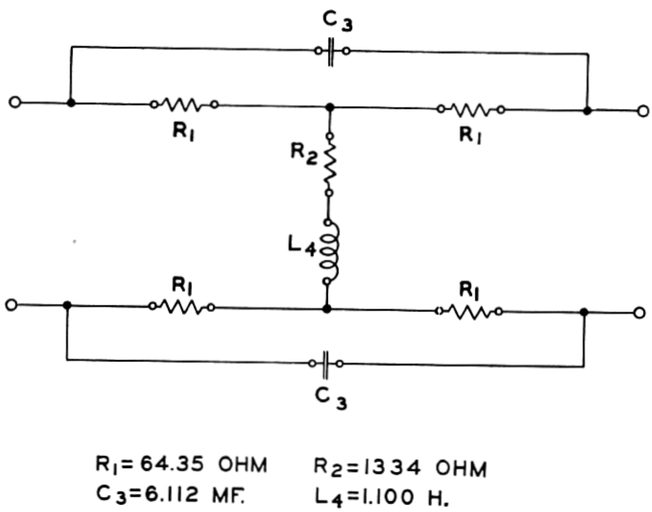


Fig. 5—Low-frequency equalizing network (dry and wet weather)

Low-Frequency Network. Computed curves of attenuation and phase delay for the overall Washington-New York circuit without correcting networks are shown in Figs. 3 and 4, respectively. The form of the dry weather attenuation curve suggested the use of two correcting networks, one for low frequencies, the other for high frequencies. The network which was designed to equalize the at-

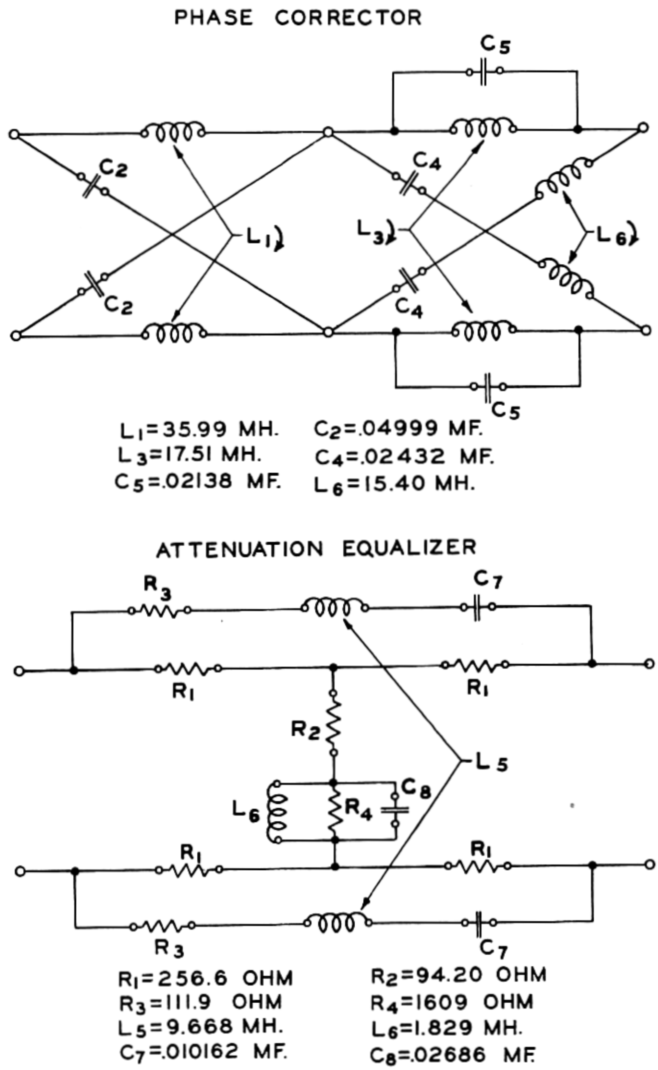


Fig. 6—High-frequency equalizing networks (dry weather)

tenuation at the lower frequencies is illustrated in Fig. 5. This network, in addition to equalizing the low-frequency attenuation, was made to provide sufficient correction for the low-frequency phase characteristic. It also proved satisfactory for all weather conditions.

High-Frequency Network for Dry Weather. The complete network for the correction at high frequencies under dry weather conditions was designed in two parts, an attenuation equalizer and a phaes corrector. These two structures are illustrated in Fig. 6. The

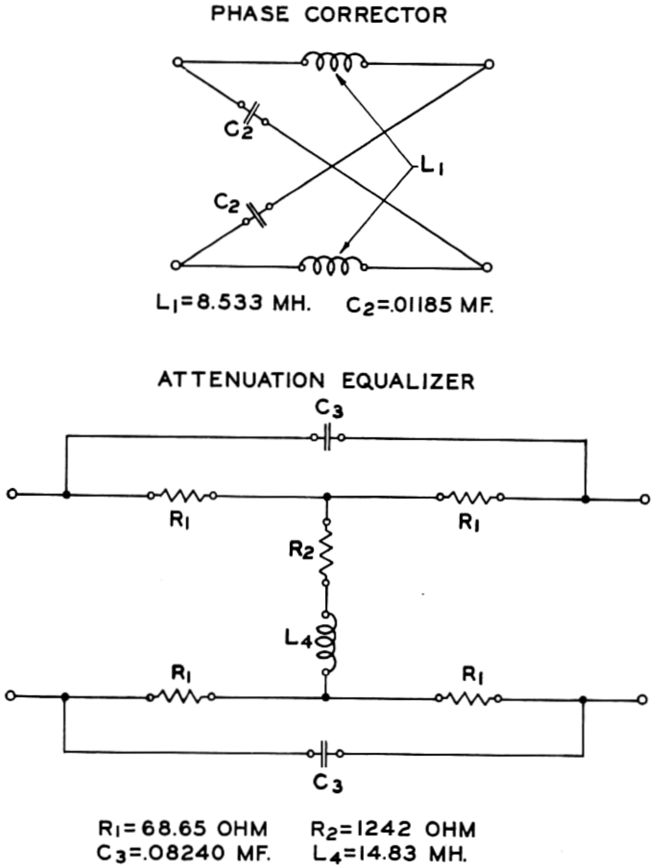


Fig. 7—Weather change equalizing networks

computed dry weather attenuation and phase delay resulting with the use of the combined low-frequency and high-frequency networks are illustrated in the curves of Figs. 3 and 4. It will be noted that the corrected attenuation curve is constant to within approximately ± 0.3 T U, while the corrected time of transmission falls well within the prescribed limits.

Weather Change Networks. Correction for the additional distortion introduced by changes from dry to wet weather was provided by three additional networks which were, for convenience, of identical design. The results obtained by using one, two or three of these networks were made to correspond, respectively, to three assumed weather conditions which may be designated semi-wet, wet, and extra-wet. These three conditions were determined upon the basis of the range of leakage conditions which exist on open-wire lines under different weather conditions.

The attenuation equalizing and phase correcting networks for one of these steps are illustrated in Fig. 7, while the computed attenuation and phase delay obtained by the use of the three different steps of weather correction are shown in Figs. 3 and 4.

The networks described above are of the "constant-resistance" type, whose characteristic impedance is a pure resistance at all frequencies.[3] These networks are designed to be connected in series. The methods used in the design of the networks involve a large amount of mathematical theory, a discussion of which is not necessary for the purposes of this paper.

Synchronizing and Voice Circuits

So far the discussion has dealt only with the problem of transmitting the television currents. In addition to this, there is required the transmission of voice currents and of synchronizing currents. It is entirely feasible to transmit these currents together with the television currents over a single circuit. However, for the purpose of simplification, separate facilities were employed in the television experiments for picture, voice and synchronizing currents.

The diagram in Fig. 2 shows the circuits which were actually provided for the demonstrations. It will be seen that in addition to the two picture or television circuits, there were provided a synchronizing circuit, a four-wire "program" circuit, and an order circuit.

The method of synchronizing the sending and the receiving machines has already been described in the paper by Mr. Stoller. It requires two currents, one having a frequency of about 18 cycles and the other about 2125 cycles. In order that an ordinary telephone circuit might be used for this purpose, the lower frequency was made to modulate by means of a telegraph relay, a carrier current having a frequency of about 750 cycles per second. An amplifier-detector at the receiving end of the synchronizing system demodulated the 750-cycle current, delivering 18 cycles to the television apparatus.

The requirements for the synchronizing circuit were that it must

[3] Partially described in U. S. Patent No. 1,603,305 to O. J. Zobel.

transmit a narrow range near 750 cycles, and the single frequency of 2125 cycles. These synchronizing frequencies are determined by the speed of the motors, which was chosen so that the frequencies would be suitable for transmission over two channels of a voice-frequency carrier telegraph system,[4] but later it was found more convenient to use a separate telephone circuit.

The circuits labeled "program" provided telephonic communication between the observer at New York and the person being viewed at Washington. A loud speaker was also connected to this circuit at New York to transmit the voice to the audience when the large grid receiving arrangement was employed. A special by-passing connection was provided between the amplifiers at the terminals of the circuit so that speech from the local microphone could be heard as well as speech from the distant city.

The order circuit was for the purpose of providing communication between the engineers operating the television apparatus.

Line Measurements

In order to determine that the circuits set up as outlined above were satisfactory, their overall characteristics were measured. Certain matters of interest in this work are noted below.

Measurements of Envelope Delay. In order to measure the envelope delay to an accuracy comparable to the requirements for the lines, it was necessary to develop special apparatus. Fig. 8 shows in schematic form the circuits of the apparatus designed for this purpose. The apparatus measures not the absolute envelope delay of a circuit, but the relative delay of one circuit at any frequency from about 600 cycles to 20,000 cycles or more with respect to the delay on the other circuit at a fixed frequency.

The functioning of the apparatus may be briefly described as follows: Simultaneously into each line there was transmitted a carrier current, each carrier being modulated by 250-cycle current from the same oscillator. The modulation was accomplished in push-pull vacuum tube circuits so that the undesired products of modulation were eliminated by balance. The carrier on the line under measurement was adjusted to the frequency at which a measurement was desired, and the carrier on the other circuit, used for reference, was kept at a fixed frequency of 5100 cycles.

At the receiving point identical circuits were provided for amplifying

[4] "Voice-Frequency Carrier Telegraph System for Cables," B. P. Hamilton, H. Nyquist, M. B. Long and W. A. Phelps, *Journal A. I. E. E.*, Vol. XLIV, pages 213–218, March, 1925.

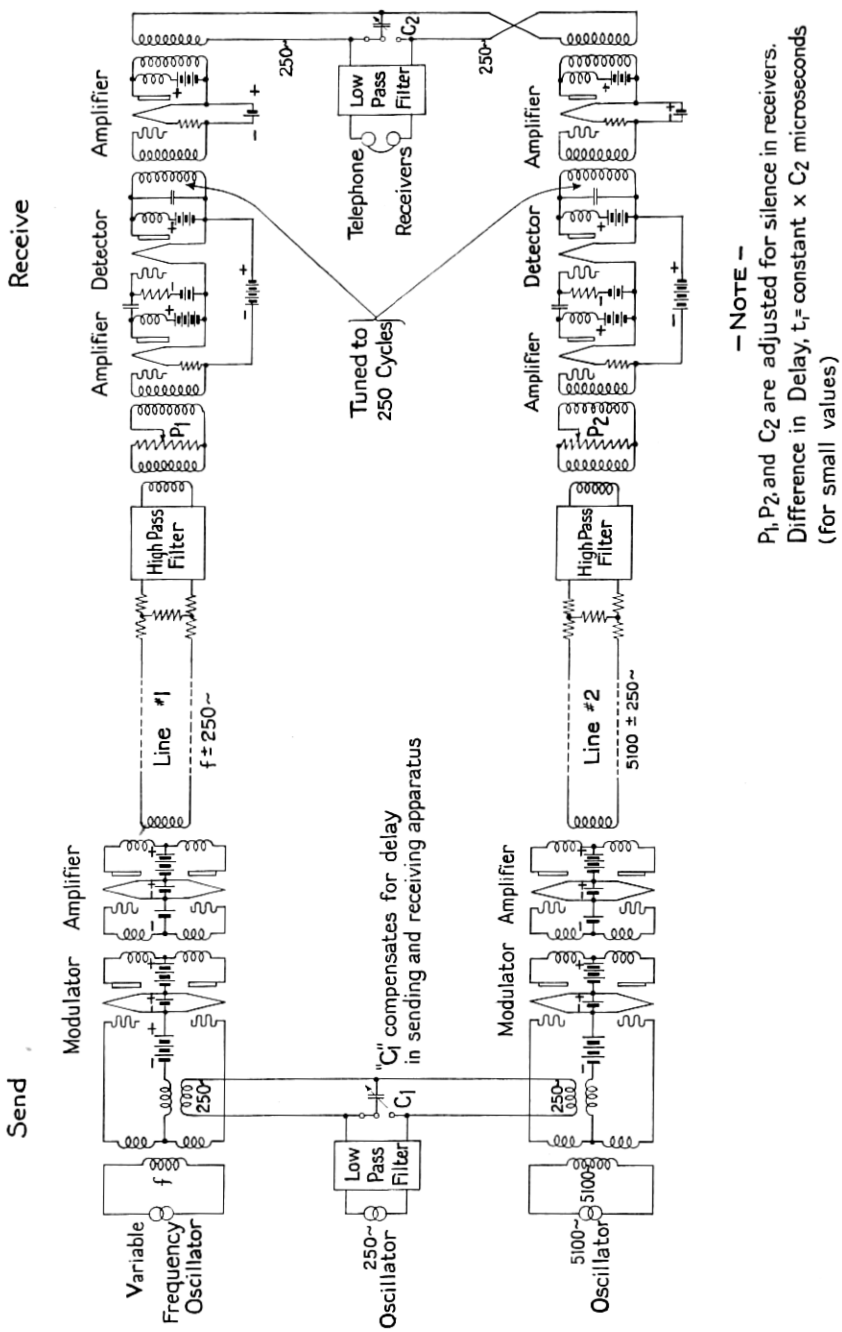


Fig. 8—Arrangements for measuring envelope delay of television circuits

and demodulating the received currents from the two circuits. The 250-cycle outputs from the two sets of receiving apparatus were connected in opposition to a pair of telephone receivers through a low-pass filter. Potentiometers P_1 and P_2 were provided for adjusting the relative intensities of the two 250-cycle output voltages and a condenser C_2 was arranged so that it could be used to change the phase of either of the 250-cycle voltages. It is evident, then, that

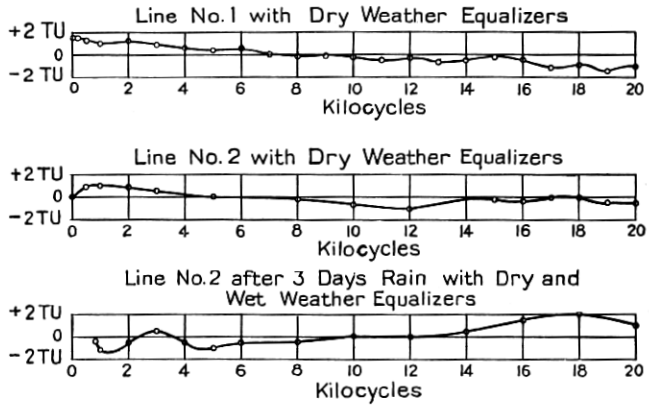


Fig. 9—Measured attenuation characteristics of line circuits plus equalizers

by making suitable adjustments the two voltages could be adjusted to exactly the same intensity and opposite phase so that no sound is heard in the telephone receivers. As long as the value of C_2 is small, the envelope delay of one line at the carrier frequency with respect to the delay of the other line at 5100 cycles is proportional to the value of C_2.

The condenser C_1 shown at the sending station is for the purpose of introducing a phase shift in the 250-cycle current of either channel relative to the other in order to compensate for the differences in delay of the apparatus itself at the two frequencies. The value of C_1 was determined by experiment before moving the sending apparatus to Washington and was adjusted to its calibrated value for each frequency when the oscillator frequency was adjusted.

The measurement of the phase shift of the 250-cycle current, which is transmitted by means of a carrier over a circuit as described above, is actually a measurement of the difference between the phases of the two received side-band currents situated 250 cycles either side of the carrier. The envelope delay is equal to $\Delta\beta/\Delta\omega$ where $\Delta\omega$ equals 2π times 500, and $\Delta\beta$ equals the measured difference in phase of the two side bands in radians.

Measurements and Performance. How well the requirements which were set up earlier were met by the lines and the distortion-correcting networks is shown in Figs. 9 and 10. The attenuation characteristics

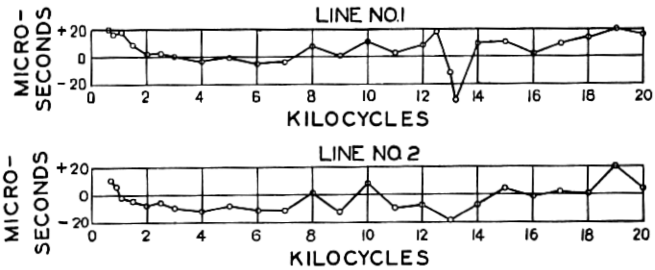


Fig. 10—Measured envelope delay of line circuits plus equalizers

are well within the established limits, and the phase characteristics show only a single slight departure for one circuit in a very narrow range of frequency. It is of interest, in view of the fact that the distortion-correcting networks were designed and built before any measurements were made on the lines they were to fit, that no changes or adjustments were found to be necessary in the networks, in order to obtain these characteristics.

Comparison of the television images obtained from transmission over the line with those obtained from transmission from one side of the room to the other, showed that no difference in quality could be observed.