Television Transmission Over Wire Lines*

By M. E. STRIEBY and J. F. WENTZ

Intercity networks appear vital to the success of television broadcasting. Experiments with wire lines for this purpose and for local transmission of present-day television signals are reported herein. The design and construction of the equipment used are described and its performance characteristics given.

The intercity lines discussed involve carrier transmission over coaxial cable with repeaters which pass a net band of about 2¾ megacycles. For local intracity connections video transmission of about a 4 mc band is obtained over existing telephone plant or by means of special low attenuation cable. Various circuit arrangements including the facilities used in bringing scenes from the Republican Convention in Philadelphia to the N.B.C. in New York are shown together with their overall television transmission characteristics.

INTRODUCTION

IF THE development of television broadcasting follows in the footsteps of its predecessor in the sound broadcasting field, networks for interconnecting television stations will be very important. In fact many students[1] of the problem believe that such networks are a virtual necessity because of the expected high cost of programs.

Considerable progress in the development of a wire line technique for this purpose has been made in connection with the Bell System's study of coaxial conductor systems for use in wide band telephony. Data previously published[2, 3, 4] have been supplemented recently by certain tests and experiments in the transmission of 441-line television images, the results of which are presented in this paper. This will cover the transmission characteristics of facilities both for intercity and local distribution, including the wire lines which were used during the television broadcast in New York of the proceedings of the Republican Convention in Philadelphia during the last week of June, 1940. This broadcast was undertaken jointly by the National Broadcasting Company and Bell System Companies as an experiment in the furtherance of the television art. A large part of the experimental facilities used were manufactured by the Western Electric Company.

LONG HAUL COAXIAL SYSTEMS

For long-distance broad-band transmission, coaxial systems have certain natural advantages which have been previously pointed out. In common

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with all long-distance systems for multiplex telephony, the carrier method of transmission is essential and has been found to be relatively straightforward. For long-distance television transmission, the carrier method is necessary with the present coaxial lines and coaxial repeaters, due to the fact that satisfactory long-distance transmission cannot be obtained at the very low frequencies involved in a video television signal. Hence for television the entire signal must be raised bodily to a higher frequency. The modulating means developed for this purpose will be described in detail later. In this section we will confine discussion to the transmission of a broad band of frequencies independently of how this band is used.

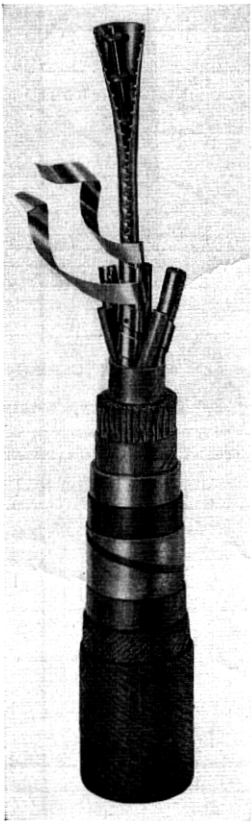

Fig. 1—Photograph of coaxial cable

Cable

The transmission characteristics of ideal coaxial cables have long been known. The properties of practical structures so far built including matters of cross-talk

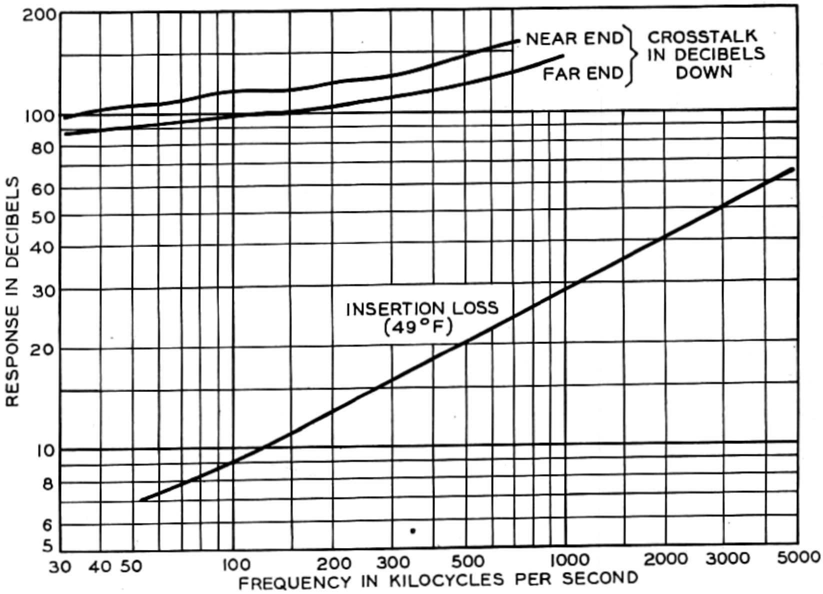

Fig. 2—Attenuation, crosstalk

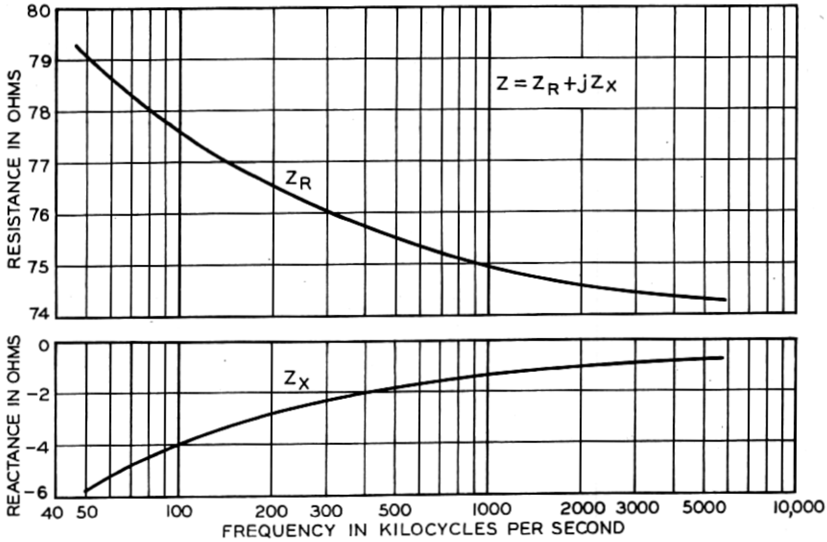

Fig. 3—Impedance of 5 miles

or shielding are also now well understood[5,6]. Certain mechanical improvements in construction have been made recently[7] and may be illustrated by a photograph,

Fig. 1, of the recently installed Baltimore-Washington coaxial cable. A similar construction was used in a cable completed last summer between Stevens Point, Wisconsin and Minneapolis, Minnesota.

These cables each contain 4 coaxial units. Two of these are used to provide a normal broad-band system having one pipe for each direction of transmission. The other two provide spare facilities for each direction. The construction of the coaxial unit itself can be seen from the photograph to use a single longitudinal copper tape for the outer conductor. This is formed into a tube which is held to a fixed diameter by the width of the tape and is prevented from collapsing by the interlocking of its saw-toothed edges. Two layers of steel tape provide the needed support against buckling and also give additional shielding. This construction results in somewhat improved transmission characteristics and lower manufacturing costs as compared with other types of construction with which we have experimented. Improvements in transmission include lower attenuation, due to a reduction in the effective resistance of the outer conductor, and a smoother impedance frequency characteristic due to greater mechanical uniformity. In spite of the thinner outer conductor satisfactory crosstalk characteristics are obtained.[8] Typical attenuation, crosstalk and impedance characteristics of this cable as a function of frequency are shown in Figs. 2 and 3 for a 5-mile length of installed cable.

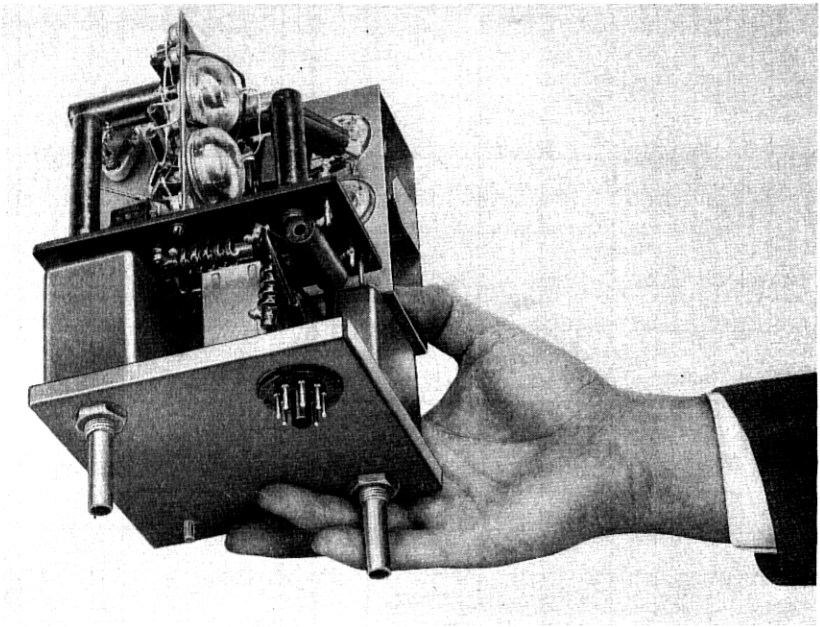

Fig. 4—3-Megacycle amplifier in hand

Repeaters

The band width of a coaxial system, at least over regions which we have studied, is limited only by the amplifiers with which it is provided. The amplifiers which have been built most recently for use in these systems are known as "3-megacycle amplifiers" and were intended to provide about a 2-megacycle band of suitable characteristics for telephone purposes or about a 2¾ megacycle band suitable for television transmission.

Figure 4 shows one of these amplifiers. It is a three-stage feedback device using two small pentodes in parallel in each stage. The mathematical design of the circuit is beyond the scope of this paper and has been treated elsewhere.[9] This type of pentode has an initial transconductance of from 2000 to 2500 micromhos and an output power of .1 to .2 watt at 130 volts as used in this system. These tubes are in parallel only to give added reliability. The gain of this amplifier is very roughly the complement of the line loss as a function of frequency. With this amplifier and the cable described above, these repeater sections are about 5¼ miles in length. As illustrated in Fig. 5, the difference between the gain and line loss is made up by a line equalizer so that to a first approximation, zero loss in transmission is obtained at all frequencies within the band over each repeater section. About 30 db of feedback is effective over the telephone frequency band (i.e. up to 2000 kc) around the entire amplifier with about 10 db additional around

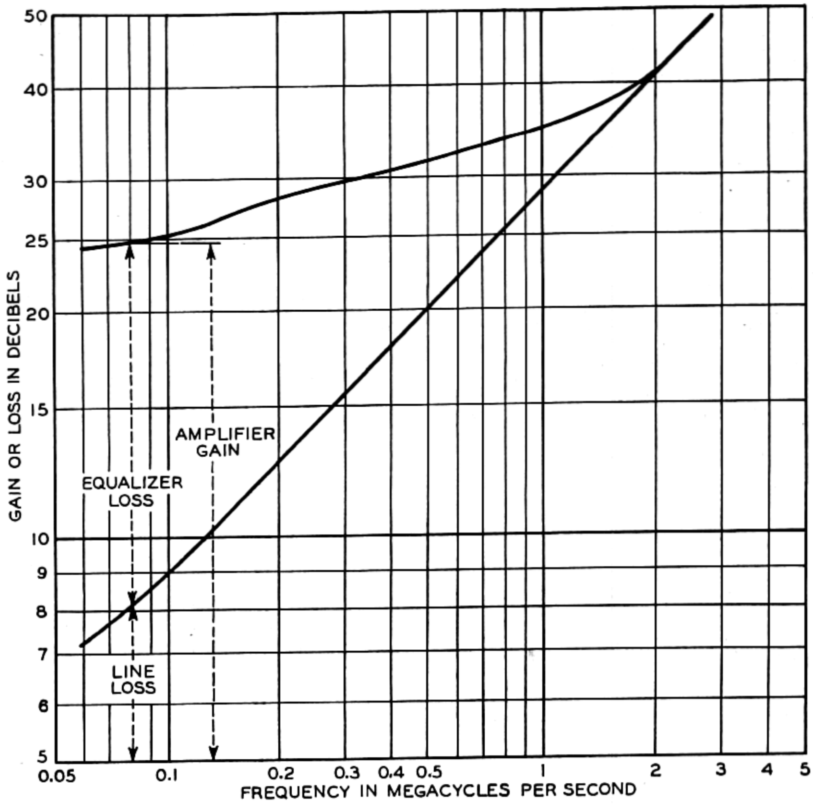

Fig. 5—Repeater gain line loss and equalization characteristics

the final stage. From 2 mc up to 3 mc the feedback gradually falls off about 10 db. This arrangement gives the high degree of transmission stability and linearity required for long telephone systems with hundreds of amplifiers in tandem, and satisfactorily meets present requirments. Limited experience with television transmission so far indicates satisfactory performance. The linearity is illustrated in Fig. 6 which shows measurements of 2nd and 3rd order modulation products of a 1000-kc signal in a typical amplifier at various signal levels. As in previous coaxial systems, power for operating the amplifiers is transmitted at 60 cycles over the coaxial cable itself from main stations located at about 50-mile intervals.

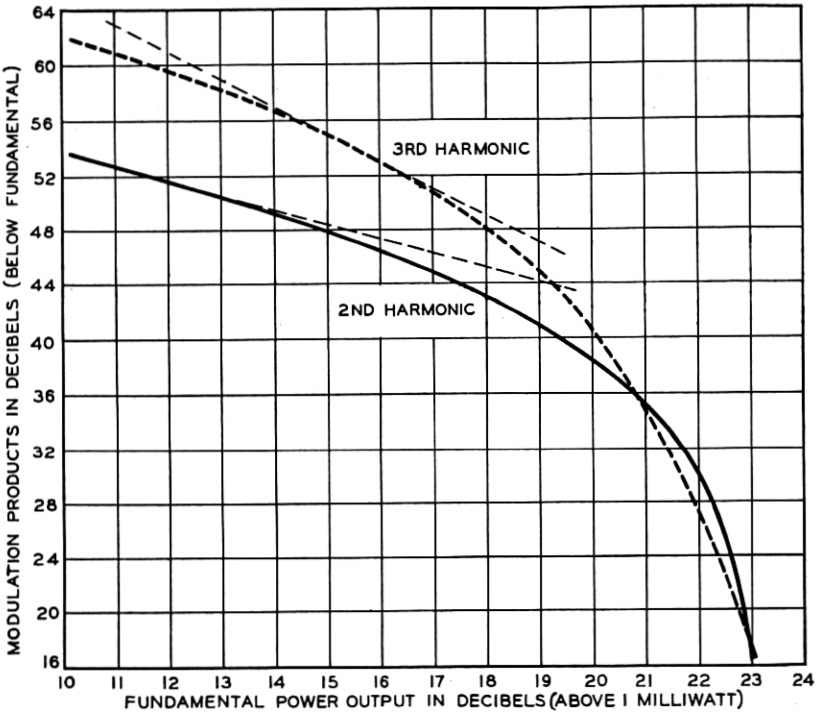

Fig. 6—Amplifier linearity

Regulation

In order to compensate for changes in attenuation due to temperature change of the copper conductors, the gain of the amplifier is regulated automatically by a device located at each amplifier point which is operated from a pilot channel. In this system a pilot frequency of 2064 kc is transmitted along the line with the signal. At the output of each amplifier, a high-impedance highly selective crystal filter is bridged on the circuit to select the pilot frequency. This is then amplified, rectified, and used to control the output of an oscillator. The oscillator output in turn is used to control the resistance of one element in the feedback circuit of the amplifier. This variable element is a very tiny thermistor[10] made up of certain oxides which have a very large negative temperature coefficient of resistance. The regulator is "back-acting" and maintains a substantially constant output voltage at the pilot frequency over a range of about 9 db in input voltage. The feedback circuit of the amplifier is so designed that the changes in the resistance of the thermistor produce changes in gain over the entire frequency band in such a way as to compensate for the changes in loss in the coaxial conductors, as illustrated in Fig. 7. Changes there shown are for ±70° F., which is about the maximum which is expected in a repeater section, even though the cable is of the aerial type.

In a long system, it has not been feasible to make the accuracy of equalization and regulation in each 5-mile section sufficient to give the desired overall uniformity of transmission. Hence, certain supplementary adjustment is required. Devices for such adjustment have been installed at 50-mile points on the Stevens Point-Minneapolis system with satisfactory results. Also, two additional pilot channels have been provided, one at 64 kc and one at 3096 kc. These serve to indicate the circuit performance and the need for manual adjustment. These pilots could be used to actuate automatic regulators if desired. For longer systems, it is expected that additional, and necessarily more complicated, supplementary devices will be required at intervals of perhaps 200 to 500 miles.

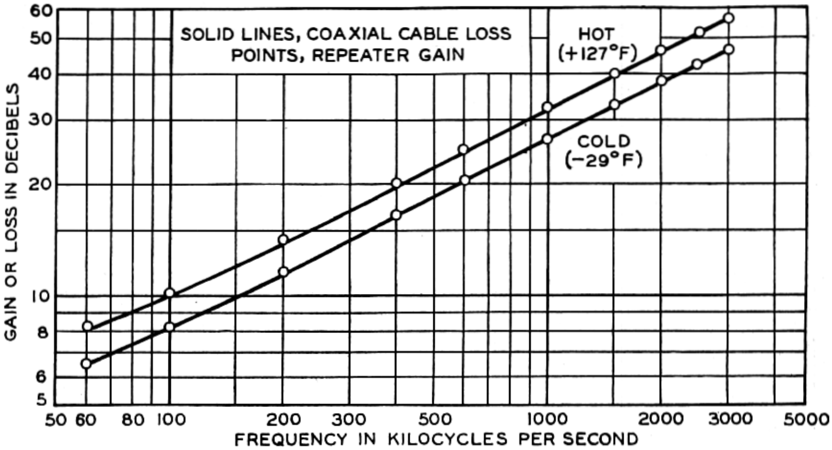

Fig. 7—Regulation hot and cold vs. frequency

Performance

A complete repeater containing amplifiers for each direction of transmission, automatic regulators, equalizers, power supply and various automatic alarm features is mounted in a box about 2 x 2 x 1 ft. as shown in a photograph (Fig. 8). Measurements on the overall performance of systems with many such repeaters in tandem indicate a high degree of transmission stability and freedom from noise. In the neighborhood of the pilot frequency the transmission variations are in the order of .1 db. At other frequencies there are slow drifts due to aging of tubes which, when they reach a few db, will require readjustment. These changes are now effected manually at the attended stations.

Interference from all sources, both external and internal, is very low in this system. The largest contributions of such interference are from tube noise and from thermal agitation in the conductors and circuit elements. The effect of interference from external sources so far encountered is lower than the above, although the presence of radio broadcasting stations can be detected. Intermodulation of signals traversing the system simultaneously has been very carefully measured because of its importance for multichannel telephony and television. In telephony, because of the large number of modulation products, principally 2nd and 3rd order, these appear as random interference.

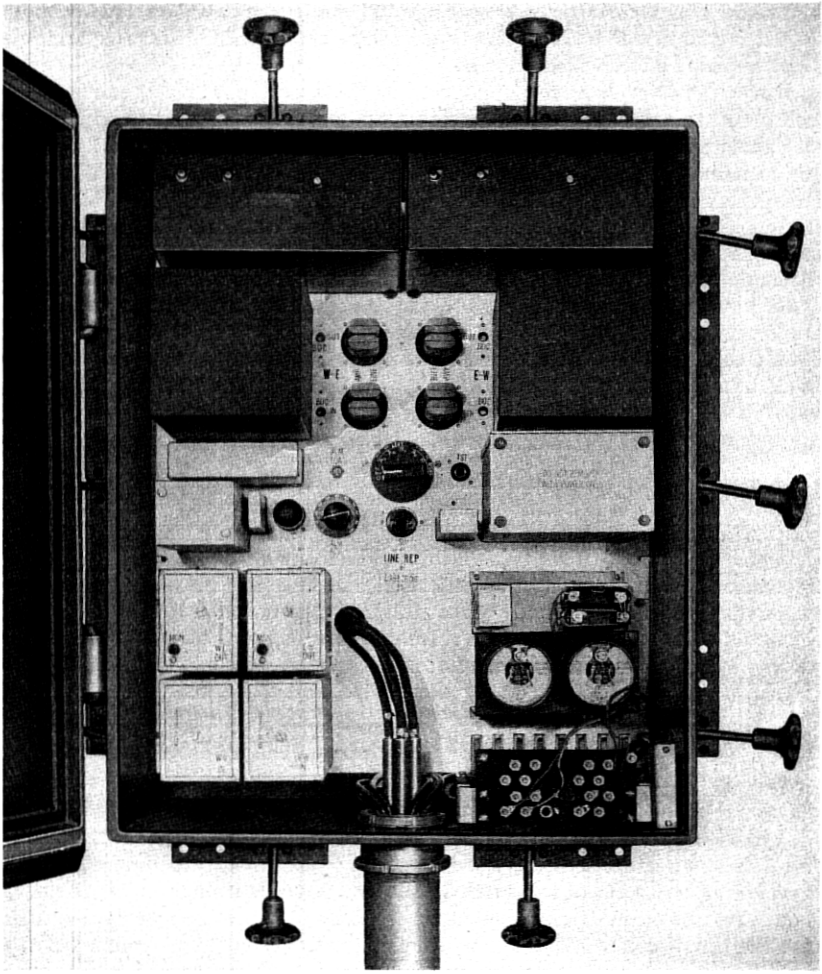

Fig. 8—Complete repeater

The method of measurement of interference from all sources was to transmit over the system a wide-band signal having a continuous spectrum such as thermal noise. At the sending end a narrow-band elimination filter was inserted. At the far end the noise was measured within that same band.

The total noise so measured depends upon the signal energy levels at the input and the output of the repeaters, the former controlling the effect of line and resistance noise and the latter controlling the effect of modulation. These levels in turn are a function of repeater spacing. The tests that have been made indicate that it is practicable to keep this type of interference within desirable limits on long telephone or television circuits.

Due to the 60-cycle power supply used on the system, power frequency modulation products require special attention. Sixty-cycle sidebands are produced on all signals transmitted due to the traces of nonlinearity in the system. As these are very small in magnitude and result mostly in a 120-cycle component they are unimportant for telephony. However, in the television transmission system used, this component is larger because of the presence of a strong carrier and one or more pilot channels. Also, 120-cycle sidebands produce a very disturbing type of horizontal bar pattern across the picture. This type of interference will increase as the circuit length is increased, and may become more visible as receiving tubes are improved. On systems so far available for test, however, it has been possible to hold this type of interference within acceptable limits, on present day television broadcast images.

Distortion in Television Images

Departures from ideal transmission in the line, equipment or in a radio path produce distortion in the form of negative or positive fringes or "ghosts." These occur when there is a lack of proportionality between phase shift and frequency through the system. This trouble in television images is perhaps more easily understood if one thinks of it as an actual difference in time of transmission of various parts of the signal. In discussing this matter in this paper, we will use the term "delay" to mean the time of transmission of the envelope of a modulated wave. This quantity is often more accurately referred to as "envelope delay".[11] If this quantity varies too widely there is an actual difference in the time of transmission of various parts of the signal, producing distortion in the form of fringes or "ghosts" which are exhibited by many television images today.

Band Width

A band width of about 3 mc is required to give equal resolution in the vertical and horizontal directions in a 441-line, 30-frame interlaced image. Recent experiments[12] with out-of-focus moving pictures have shown not only that the eye is quite insensitive in its requirement for equal detail in the two directions but also that the loss of detail due to a narrowing of the frequency band from 4 mc to $2\frac{3}{4}$ mc will pass unnoticed by many careful observers at normal viewing distance.

TELEVISION ON COAXIAL SYSTEMS

As mentioned above, no practical method has been found for transmitting television over long-haul coaxial circuits in the video frequency range. By the carrier method, however, the video frequency band may be raised to a region suitable for transmission. To conserve frequency space, single-sideband transmission, of course, is desirable. The actual method chosen involves also a modest vestigial band since it appears impracticable to select a single sideband involving video frequencies as low as 45 cycles in any other way. The present coaxial amplifiers pass a band from about 64 kc to about 3100 kc. The region useful for television, however, appeared to be somewhat less than three megacycles on account of the difficulty of equalizing the delay distortion near the lower edge of this band. About 100 kc was allotted to obtain proper shaping of the vestigial sideband. The carrier was therefore placed at about 300 kc and a net television band of about $2\frac{3}{4}$ mc was obtained. If we attempt to move a 3 mc video band up 300 kc in a single step of modulation, the result is an overlapping of the sidebands which hopelessly distorts the signal. Two steps of modulation are therefore resorted to as shown in Fig. 9.

The energy of a television system is concentrated in the lower frequencies or, in a carrier system, near the carrier. To take most advantage of the coaxial system, the carrier should be at the low end where the full feedback in the amplifiers is available. The four lines in Fig. 9 illustrate the four stages of modulation, two at the transmitting terminal and two at the receiving terminal. As can be seen the signal is first modulated with a carrier of about 8 megacycles and the lower sideband, part of the carrier, and a portion of the upper sideband, are selected by a band filter. This signal is then modulated again with a carrier of about 8.3 megacycles and the lower sideband again selected. In this position of the signal, which is the position at which it will be transmitted over the coaxial line, the frequency which corresponds to d.c. in the video signal is at 311 kc, the main sideband extends from 311 to 3111 kc and the vestigial sideband from 311 kc down to 200 kc.

The receiving terminal is in general the inverse of the transmitting terminal and will not be discussed in detail. The sideband shaping[4] is accomplished by the four filters, two at the transmitting terminal and two similar ones at the receiving terminal, acting in conjunction. The result is that at the final stage of demodulation the contribution from the vestigial sideband when added to the contribution from the shaped portion of the main sideband gives back very nearly an undistorted video signal. This last stage of demodulation is accomplished in a linear detector. The carrier amplitude at the input terminals of this detector is about six db greater than the amplitude of the video envelope of the modulated signal, the amount of carrier which was mixed with the sidebands at the output of the first modulator having been adjusted to achieve this result. The reason for using this amount of transmitted carrier is the relatively narrow vestigial sideband—111 kc vs. a main sideband of about $2\frac{3}{4}$ mc. With such a narrow vestigial sideband the quadrature component of the carrier en-

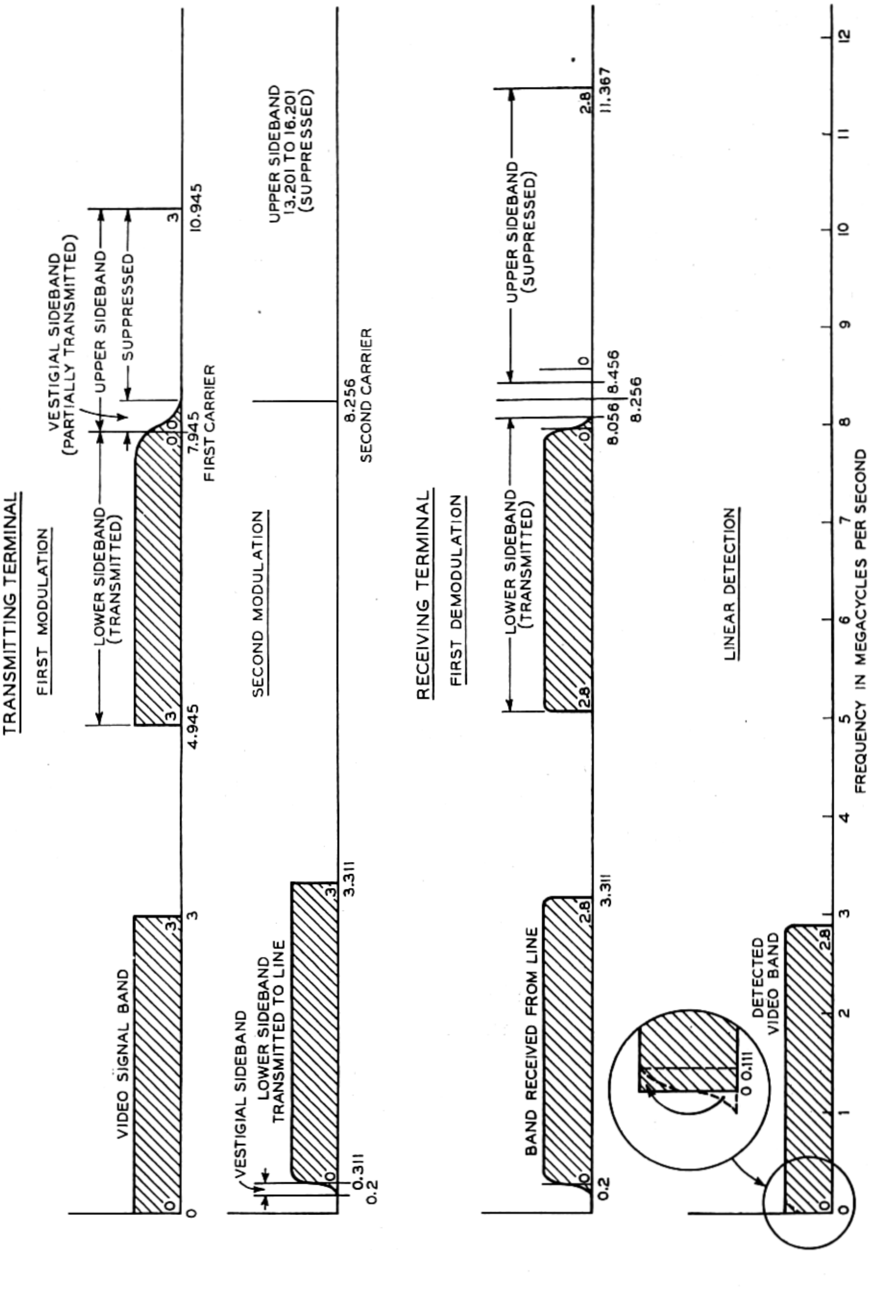

Fig. 9—Modulation steps diagram

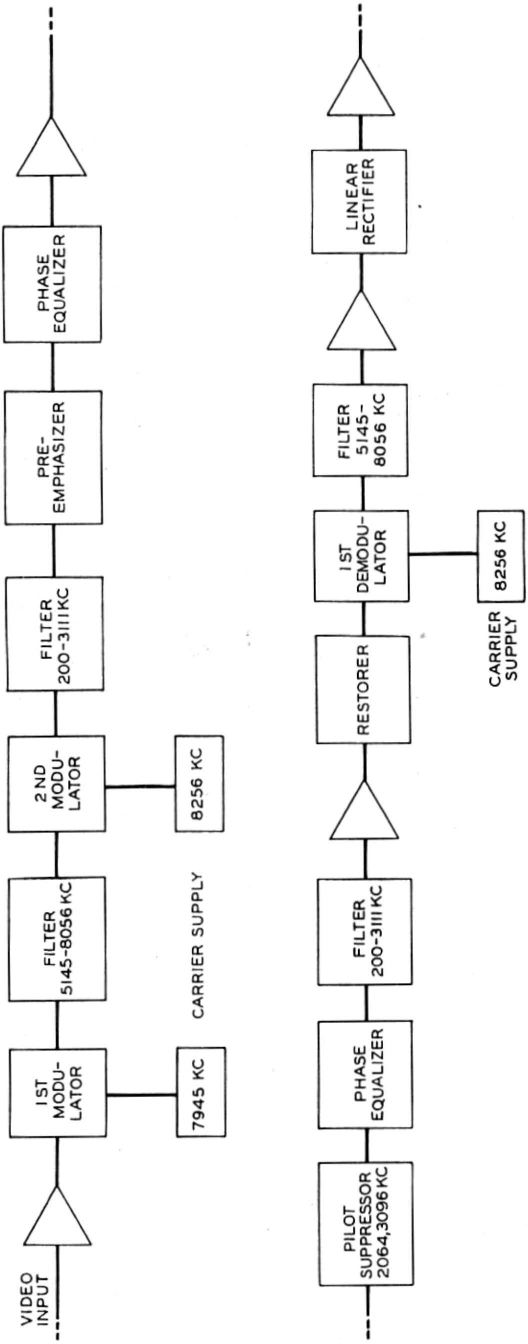

Fig. 10—Box diagram of carrier terminals

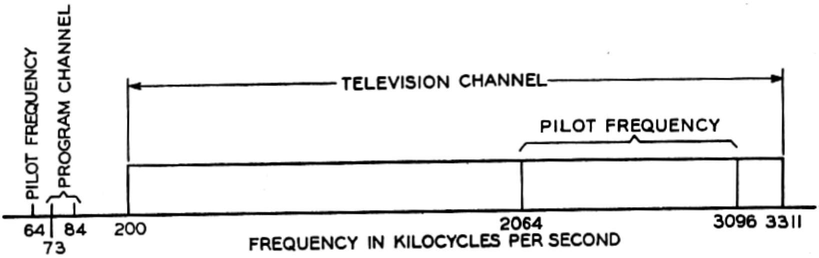

Fig. 11—Frequency allocation on line

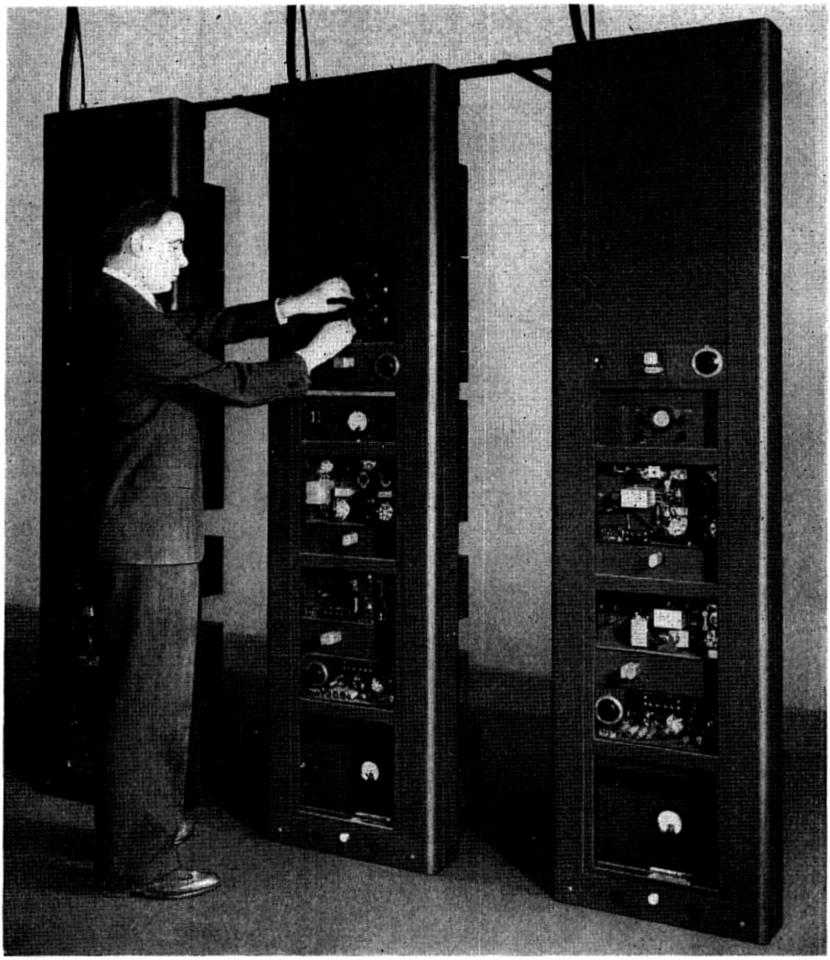

Fig. 12—Carrier terminals

velope is relatively large, resulting in objectionable distortion at sharp changes in the picture signal if the greater ratio of carrier to sideband is not employed.[13]

Figure 10 shows a box diagram of the terminal arrangements. In addition to ordinary video amplifiers and modulators and filters mentioned above, a "pre-emphasizer" and a "restorer" are shown. These networks partially equalize the energy in the various components of the signal, and thus help to override the noise and spurious modulation products introduced by the line and amplifiers. A phase equalizer is also shown which, in conjunction with a similar equalizer at the receiving end, is designed to correct for the phase distortion in both the transmitting and the receiving terminals. Before transmission over the coaxial, pilot frequencies of 64 kc, 2064 kc and 3096 kc are added, as well as a program channel from 73–84 kc. Figure 11 shows the frequency allocation of the television signal and its associated channels on the coaxial line.

At the receiving end the pilot frequencies and the program channel must be removed. The 64-kc pilot and the program channel are eliminated by the 200-3111 kc filter which precedes the first demodulator. The 2064-kc and 3096-kc pilots, however, are within the transmitted television band. The frequency allocation was so chosen as to place them approximately in the center of the "empty energy regions"[14] of the television spectrum where they can be eliminated by sharp selective networks without appreciably distorting adjacent television signal components.

Three carrier television terminals are shown in the photograph, Fig. 12. The one on the right is a transmitting terminal, the two on the left receiving terminals. Each terminal occupies one six-foot relay rack bay and is complete with power supply and means for adjustment.

SHORT HAUL LINES FOR TELEVISION

For the pickup or transmission of television within cities or metropolitan areas, it appears to be more economical, as would be expected, not to use the carrier method described above but to transmit "video" frequency signals over cable circuits. For this purpose existing telephone cables may be used or special cables may be provided. In either case amplifiers and special equalizers are required which will overcome the attenuation and delay distortion of the cable circuits. Because of high-frequency crosstalk usually only a small fraction of the circuits in any existing telephone cable can be used simultaneously.

Video Amplifiers and Equalizers

Television pickup and broadcasting equipment is quite naturally designed on an unbalanced (i.e. one side grounded) basis. Unbalanced amplifiers for the video band have been available for some time.[15] New amplifier designs have been worked out for use with balanced lines. In general, the problem is to provide approximately zero loss and constant delay between unbalanced terminals a mile or more apart. Thus, an unbalanced to balanced amplifier is required at the sending end, the converse at the receiving end. If the circuit is long, balanced amplifiers are most convenient for use at intermediate points. The equalization problem has been successfully met even if ordinary telephone cables are used. A series of variable equalizers have been experimented with which have several degrees of flexibility. A variety of circuits ranging in length up to 9 miles have been equalized with this arrangement with considerable success. A typical amplifier, equalizer, and power supply are shown in the photograph, Fig. 13.

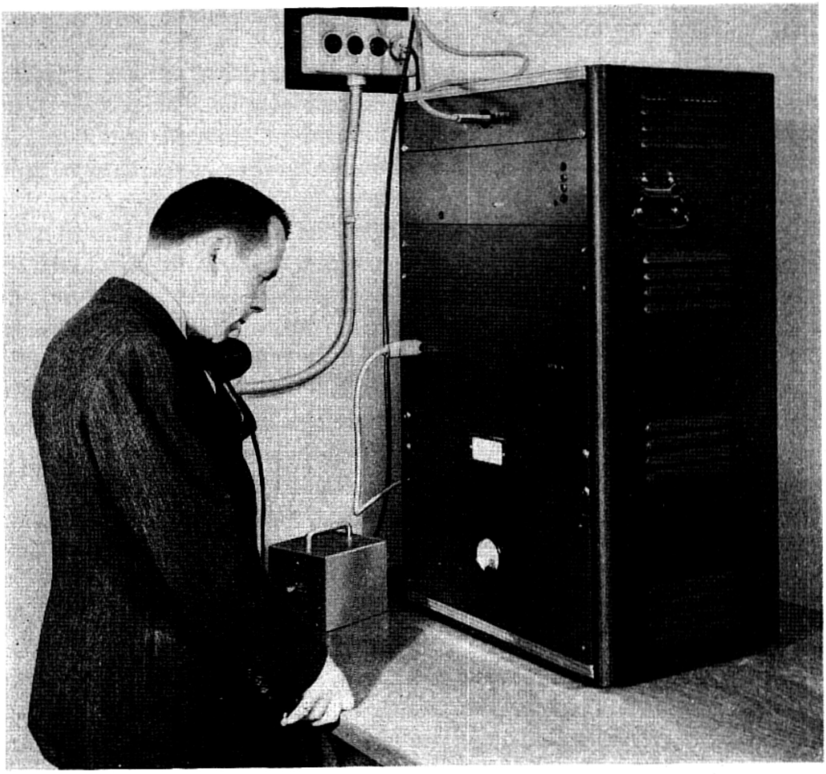

Fig. 13—Photograph of Video amplifier

Telephone Cables

Ordinary fine wire paper insulated cables have very high attenuation at the frequencies required. Typical values for loss and net loss after amplification and equalization are shown in Fig. 14. Experience has shown that the noise levels in such cables even at the higher video frequencies are rather high so that amplifiers are required at intervals of a mile or even less. Local telephone cables are usually laid out with many branches. At high frequencies these branches introduce irregularities similar to those produced by obstacles along a radio path which cause delay distortion. Plant changes are frequently required to obtain a clean circuit free from such bridged taps. When amplifiers and proper equalizers are added, however, substantially flat transmission is obtained as shown in the figure.

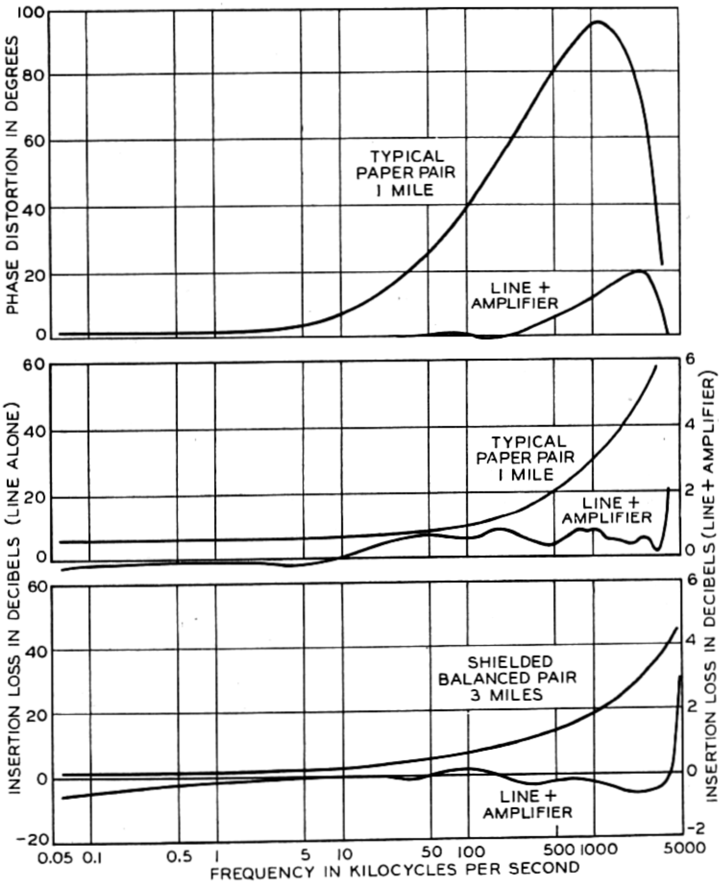

Fig. 14—Transmission characteristics of cables

Phase distortion characteristics of a typical cable circuit are also shown in Fig. 14. After the amplifiers and equalizers are added, the phase distortion is made substantially negligible.

Coaxial Cables

Coaxial cables may be used for video transmission for short distances but power or other low-frequency interference may introduce serious problems.

Coaxial units of the size discussed above have been used in a few cases a mile or so in length. Even for such distances, however, it has been found desirable to reduce the power interference by balancing it out. One method which we have used is shown in Fig. 15. This has given an improvement at power frequencies of the order of 50 db in certain cases.

Balanced Shielded Cables

The ideal type of transmission line for video signals combines the balance feature with low attenuation and a high-frequency shield. The distance over which such cables could be used appears to depend upon the perfection of balanced video amplifiers and the equalization, although power interference may also present difficulties. Such cables have been built using a pair of wires and a disc type of insulation analogous to the coaxial structure described above. Attenuation measurements on a 3-mile test length installed in New York City are shown in Fig. 14. This figure also shows the net result after amplifiers and equalizers were added. The attenuation of this special type of cable is such that amplifiers would be required at only about 5-mile intervals. The useful range of such a cable for video transmission has not been determined but in any case it should be considerably greater than that of the paper-insulated telephone cable circuit.

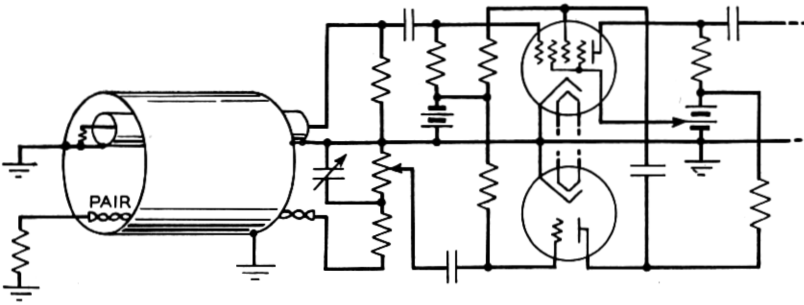

Fig. 15—60-Cycle balance on coaxial line

Experiment in Network Broadcasting

During the last week of June 1940, the proceedings of the Republican Convention in Philadelphia were broadcast in New York by television. The facilities used included the 3-megacycle coaxial system plus certain video connections at each end as shown in Fig. 16.

Because of the interest in this circuit and its good performance in transmitting 441-line television, the overall attenuation and delay characteristics are given on Fig. 17. It will be noticed that a net band of about $2\frac{3}{4}$ megacycles was transmitted and that over most of that band the delay distortion did not exceed ±0.2 microsecond. The random noise, modulation and other distortions introduced by the wire line network appeared to be unimportant when viewed on a commercial television receiver.

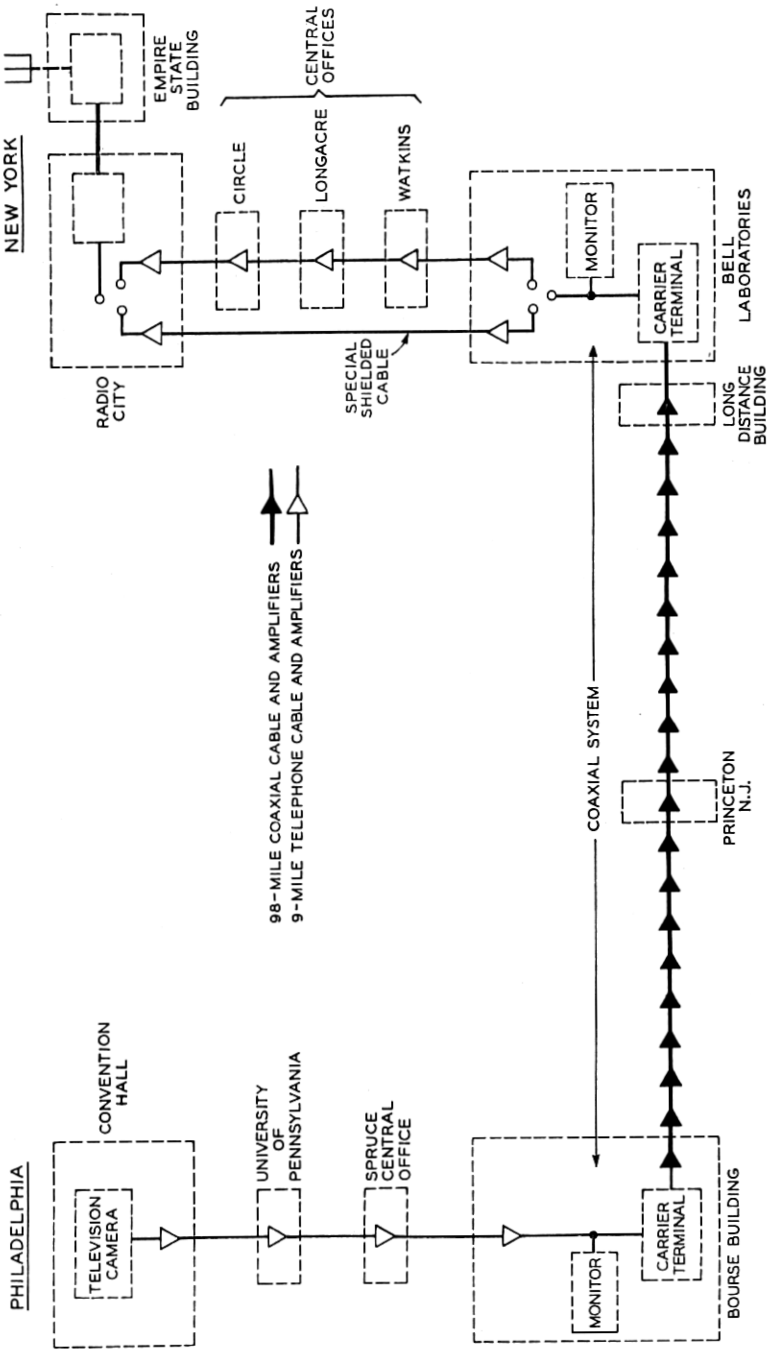

Fig. 16—Map of New York-Philadelphia network

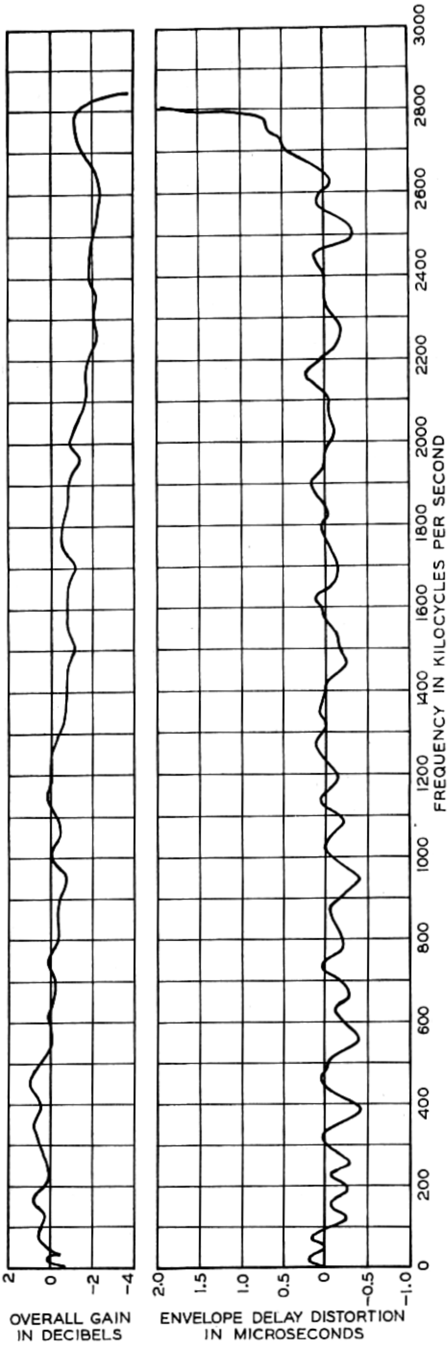

Fig. 17—Attenuation and delay—New York-Philadelphia network

CONCLUSION

The experiments so far made in the transmission of present-day television indicate that wire lines can be provided at least for moderate size intercity networks; also, that such lines if properly equalized for delay and attenuation do not materially alter or distort the transmission of present-day 441-line images, even though the frequency band is somewhat narrower than the nominal 4-mc band.

The use of ordinary telephone cables for local television connections also has been found to be feasible for all of the conditions so far tested. The $2\frac{3}{4}$ mc television transmission experiments over wire lines reported herein have proved very successful. Experiments with wider band coaxial systems are being undertaken.

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