The L3 Coaxial System

Equalization and Regulation

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The equalization and regulation problems of the L3 system are described and a theory of equalization of complex systems is outlined. The location and function of the various equalizers are explained including the roles and design of the various fixed, dynamic and manual equalizer networks. The analog computer used in the regulation system is described together with the cosine-equalizer adjusting technique used with manual equalizers. Finally the circuits and operation of the regulation system and its components are presented.

Introduction

Equalization is the process of correcting system gain and delay deviations sufficiently to permit the satisfactory transmission of signals. Regulation refers to that part of equalization which, by automatic means, corrects for relatively rapid changes in transmission. In the L3 coaxial system the transmission of television signals through more than 1,000 amplifiers introduces relatively severe equalization and regulation problems. Compared to the L1 system, the L3 system has nearly three times the bandwidth and over three times more stringent transmission objectives. Thus it has been necessary to devote considerable effort towards finding equalization methods that yield practical and economical solutions.

In previous systems it has often been the practice to design the bulk of the equalization system after the completion of an initial installation and the determination of the deviation characteristics of the system. In order to expedite the introduction of the L3 system into the field, equalization study and planning were initiated at the very beginning of the development of the system. One of the design methods was to make highly detailed studies using relatively inadequate data in order to find the major problems. As the data improved the studies were likewise improved. While on the surface it might appear more practical to defer this work until the data are more adequate it has been found that these speculative studies are the only sure guide to ever getting the right data. Faced with such a complicated problem it is difficult to select from the vast amounts of things that might be important those relatively few items on which success or failure depends. In the L3 system there have been a number of critical problems which required intensive effort to find acceptable solutions, for example, the design of stable regulators to permit operation of 700 regulators in tandem, the choice of shapes for manual and dynamic equalizers and the selection of equalizer adjustment methods.

The design of equalization for the L3 system is not yet complete since the dynamic equalizer shapes are still subject to considerable uncertainty and the details of some of the final television mop-up equalization are yet to be settled. However no major difficulties are anticipated in equalizing the telephone system to be installed from Philadelphia to Chicago during 1953. Although amplifiers having the final gain characteristic were operated in the trial line between New York and Philadelphia for the first time in November, 1952, it was immediately possible to transmit quite satisfactory television pictures over the 200-mile loop using existing equalizers. It therefore appears that equalization will not limit the rate of field installation of the L3 system.

THE PROBLEM

The 4,000-mile coaxial cable has a gain distortion of nearly 40,000 db between 0.3 and 8.5 mc. Although the amplifiers reduce the distortion to perhaps 200 db, (and 100 microseconds), they leave a residue characteristic that is considerably more difficult to equalize. Further it is necessary to deliver service to intermediate offices spaced on the average about 120 miles apart. This requires equalization of high precision at numerous intermediate points. A further problem is the variability of the transmission characteristic due to manufacturing deviations plus time and temperature changes. Also, gain distortion cannot be permitted to exceed about 5 db at any point in the line or the signal misalignment will result in degraded signal-to-noise ratios.[1]

The overall transmission objectives[1] are of the order of 0.25 db and 0.1 microsecond which, if allocated among the over 1,000 amplifiers, lead to rather unrealistic amplifier requirements. In fact, individual amplifiers do not always meet the 4,000-mile overall requirements. Thus it is the problem of the equalization designer to provide a mop-up system that will permit attainment of the transmission objectives at all service points and at all times.

EQUALIZATION THEORY

One of the steps in the solution of the general problem has been to develop a "theory" of equalization. This theory merely applies information concepts to the equalization problem to determine what information is required, when it is needed and how it may best be used. This theory has stimulated the development of novel equalizer adjustment techniques and has been of assistance as a guide to the attack on the general problem.

In order to equalize a system the man or machine who is to perform the action must know what corrective steps are required, and for this he must have some kind of information as to the present state of the system and as to the desired state. Second, he must have the necessary tools to convert the system from its present state to the desired state. Consider the first problem, the determination of the corrective steps required. The problem is to determine what we need to know, when we need to know it and especially in what form we are able to utilize the information most efficiently.

We can assume we know the desired state of the system; which is usually a constant loss with constant delay over the frequency range of interest. As to the present state of the system we note that sufficient information can never be obtained to equalize a system perfectly because of the finite bandwidth of the system and because the system changes with time. This is not a new fact, nor apparently a very important fact, because the system need not be perfectly equalized for satisfactory transmission of signals. It leads, however, to the converse idea, which is important — namely, that out of this infinite amount of information regarding the state of the system one should collect only the minimum amount that is needed. This implies making no more measurements of the state of the system than are absolutely necessary to perform the correction to a degree permitting satisfactory transmittal of the signals. The main purpose of this is, of course, to economize on time and effort required to obtain information, but it should be noted that excess information may be a source of confusion to the equalization operator.

To put this in the form of a rule, we have:

Rule I

Collect only that minimum of information as to the state of the system as will permit equalization to the required degree for satisfactory transmission of the signals.

Having established that a minimum of information should be collected, we return to the time variation of the system, which in theory can make the information obsolete before it can be used. However, without yet bringing in the practical fact that its most rapid rate is relatively slow, we should introduce the fact that the ways in which the system can vary at its most rapid rate are quite restricted as compared with the manner in which it can vary at slower rates, and we note that even these are relatively limited. (This probably applies to most transmission systems, not just to the L3 coaxial.)

Thus while the information regarding the more rapid, but simple changes must be collected more frequently it consists of a small amount of information per sample; whereas the information regarding the slow (but more complex) changes need not be collected very often, but it represents a relatively large amount of information per sample. Since the total rate of information collection is proportional to the information per sample times the rate of sampling, the minimum information collection principle would say that the rate of sampling should also be held to a minimum.

This demonstrates the value of association of particular types of system change with the rate and amount of their variation, because one may thus eliminate from the more rapid sampling the collection of information about changes that occur at slow rates. Furthermore, one may establish the sampling rates for the various system effects at the lowest possible value. (There is also a very practical value in knowing the rates and amounts of the various deviations, because system misalignment requirements force the equalization to be suitably distributed along the line.)

In the form of a rule, this is:

Rule II

To the greatest practicable extent the overall system behavior should be separated into individual effects each having its own time rate of occurrence and corrections should be made for each effect at the minimum tolerable rate for each.

It is of interest to note that, if we couple the logic of Rule II with the fact that the fastest changes (due to changes in the temperature of the repeater huts) take hours to become appreciable, we see that the continuous collection of information from continuous pilots (and the continuous correction by pilot-controlled regulators) is in principle unnecessary and inefficient — except, of course, for its other function of giving alarms under trouble conditions.

The technical problem of determining the equalization states of the system is normally solved by sending some kind of signals over the system and observing the effect of the system on those signals. The raw data are usually in the form of loss and delay as a function of frequency. On the basis of these data, the equalization operator desires to correct the system by means of some equalizers which have adjustable transmissions and delays as a function of frequency. Thus the operator has a group of controls to be operated plus some data which has encoded in it the information as to the proper adjustment of each control. From these data, and a knowledge of the effect of each control, the operator must suitably compute the proper adjustments. As this may be too complicated a process to attempt on a trial and error basis, (or by numerical methods), it is quite an obvious advantage to the operator to receive the data as to the state of the system, not in its original form, but in the form of the necessary adjustments to his equalizer controls. This new form of the data simply represents a decoding process based on the available controls. An operator with the same data, but different and perhaps more complicated equalizers, would need the data in a form suited to his different equalizers.

Consequently:

Rule IIIa

The information as to the state of the system may best be presented to the equalization operator in the form of the necessary adjustments of the available equalization controls.

This rule has a closely related corollary which is based on the fact that the available equalization controls determine the amount of information that is needed. For example, if the independent gain equalization controls are "n" in number, measurement of the gain of the system at "n" suitably chosen frequencies is sufficient to determine the settings. (If the controls are not independent, fewer than "n" frequencies need be measured.) This is, of course, a restatement of the fact that "n" unknowns may be determined by solution of "n" independent simultaneous equations. The unknowns are the equalizer settings and the simultaneous equations are the relationships of the shapes controlled by each equalizer to the total system error.

Thus:

Rule IIIb

In general, the necessary and sufficient condition for the determination of "n" independent equalization control settings is the knowledge of the system's *equalization error at "n" independent frequencies plus the knowledge of the effect of each of the "n" controls at each of the "n" frequencies.*

It should be noted that this statement of the rule assumes analysis by frequency rather than by transient behavior. This approach is used because, at present, equalizers are usually designed on a frequency characteristic basis. The validity of the rule is however more general.

From these two rules we can derive another regarding the minimum information principle that is similar to Rule I but is actually quite independent of it.

Rule IV

No more information should be gathered from the system than is necessary to provide sufficiently accurate control setting information for the equalization operator.

In this case the superfluous information may actually cause confusion or harm. It will, at the very least, confuse a manual operator to know of an error he is powerless to correct, whereas a mechanized system, on the other hand, would probably go berserk if it obtained too much information.

It is evident that the minimum amount of information that would be obtained in accordance with Rule IV would be the same as that obtained in accordance with Rule I only if the design of the equalization were optimum, because then the equalizer shapes (and the number of shapes) would just suffice to permit satisfactory transmission of the signals.

Up to this point we have determined in general what information is needed, when it is needed and the optimum form of its presentation. Now let us proceed to examine what to do with the data; which involves the nature of the equalization operator as well as his equalization tools.

If we followed Rule II rigorously, we should have several different type of controls; one for each of the effects having different time rates of occurrence. For purposes of illustration, however, we need assume only two rates — one quite rapid and the other very slow. It will be postulated here that very rapid equalization operations are most economically performed by machine, such as for example, the automatic regulation for cable temperature variations. Likewise relatively infrequent adjustment will be assumed to be best performed by a suitably informed human operator.

The first principle to note is that the only real distinction here is the rate at which data should be refreshed and acted upon. In either case the data should be in the same form; a set of numbers (or their equivalent) representing equalizer changes.

Probably the most useful result of this theory of equalization has been the conclusion that mechanization of the equalization process, particularly in regards to computational techniques, permits substitution of simple logical methods for inefficient trial-and-error adjustment processes. This led to the use of an analog computer in the regulation system and, for manual equalizers, the development of measuring circuits that read directly in terms of equalizer adjustment error.

Equalization

LOCATION AND FUNCTION OF EQUALIZERS

The location of equalizers in the L3 system when only telephone is transmitted is shown in Fig. 1(a). Combined telephone-television equalization is shown on Fig. 1(b). When telephone and combined systems use the same spare line, that line is equipped for television. The general features of the main-repeater layout have been described in a companion paper.[1] The detailed layout of equalization is designed to meet the requirements of both telephone and television service and the need for flexibility in television network arrangements. In addition, switching of telephone or television service to a spare line must not appreciably degrade service.

Switching sections longer than 120 miles must be provided with an intermediate step of equalization to prevent excessive signal misalign-

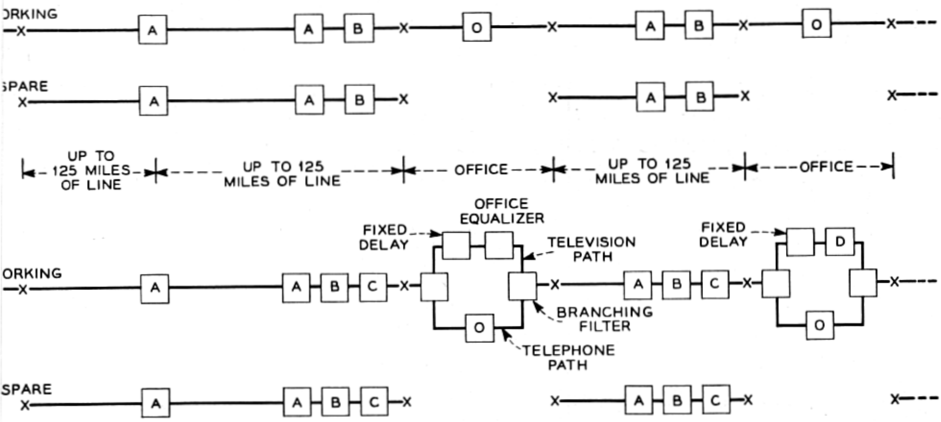

Fig. 1 — Typical equalizer locations in (a) telephone and (b) combined systems.

ment. This intermediate point is referred to as an equalizing auxiliary repeater. It is provided with the so-called A equalizer consisting in turn of fixed, manual and automatic gain equalizers. It reduces the gain error to less than 0.5 db using the fixed and manual sections and prevents appreciable degradation of this residue during an ensuing three month period by the action of three "office" regulators using pilots at 308, 2,064, and 7,266 kc controlling three regulating networks. One of these networks is the $\sqrt{f}$ shape of the receiving amplifier.[2] The other two are first order corrections for vacuum tube aging and repeater temperature changes.

At offices, (switching main repeaters), on telephone systems further equalization is required to permit line switching of telephone channels and special service signals such as telegraph. Also it is not practical to provide telephone equalization on a cumulative basis over longer links than a switching link because of frogging and dropping.[1] No telephone channel rides for more than 800 miles in the same frequency location and dropping breaks up the pattern still further. Thus, for telephone, the switching links, which may number between 30 and 40 in a long system, are independently equalized.

The B equalizer contains manual and automatic sections, the latter being three regulating networks omitted in the A equalizer. Thus an A plus a B forms the final telephone equalization. The residue of five, independently-adjusted AB links must meet telephone requirements without frogging and 30 to 40 links must meet these requirements with 800-mile frogging. This performance must continue to be met in the presence of a normal amount of spare line switching. Also it is very important that the character of the residues be such as not to throw an undue burden on the television equalization.

In combined systems the more stringent requirements require the addition of further manual equalization to the switching section. The residue at the output of a C equalized switching section must be sufficiently small that a 4,000-mile circuit will continue to meet television transmission requirements in spite of a normal amount of spare line switching. Also the C equalizer in conjunction with the AB must permit several switching links to be connected in tandem without further line equalization. The C equalization also contains an adjustable delay section which in conjunction with a fixed delay equalizer in the office path provides delay equalization for the television part of the band, 3.6 to 8.5 mc. This adjustable section builds out the line to match the fixed unit.

The A-B-C pattern is for equalization of individual switching lines and these equalizers are adjusted on a single switching link basis. On the office side of the switches are system components that also require equalization. In the telephone system these include such things as office cabling and hybrid coils. Also there is an office flat loss of nearly 30 db. Thus the lines are, in effect, operated to give a 30 db gain while the offices give a 30 db loss. Aside from the flat losses there are distortion shapes but fortunately these are all well approximated by a $\sqrt{f}$ shape and a single manually adjustable $\sqrt{f}$ equalizer plus suitable choice of flat loss provides adequate telephone office equalization. This is referred to as the O equalizer. It is adjusted to make the particular office have a flat characteristic.

In the office circuits of combined systems are branching filters to separate the telephone and television bands. The O equalizer is reused in the telephone path. The television path includes the fixed delay equalizer and a manual gain equalizer to correct for office cables, hybrids etc. After the tandem combination of several independently equalized lines and offices further equalization will be required. This will be accomplished by a multi-control manual D equalizer, having both gain and delay sections, inserted in the television only path at approximately 400-mile intervals. These D equalizers will be used to form 800-mile pilot links which are independently equalized to a degree permitting putting any five such links in tandem to form a 4,000-mile circuit without further equalization.

FIXED EQUALIZERS

The line amplifier can properly be considered as the first step of fixed equalization.[2] Also acting at this same level are artificial cable networks used to build out the repeater spacing to 4 ± 0.2 miles, as well as the basic equalizer of the amplifier to take up differences between cable types. These devices are described in a companion paper.[1] The final step of fixed equalization is the so-called "design deviation equalizer" associated with all A equalizers. This equalizer comes in two versions, one for use with sections containing 23 to 32 repeaters and one for use in sections of 10 to 22 repeaters. In those few cases of less than 10 repeaters the fixed equalizer is omitted.

The function of the design deviation equalizer is, first, to correct for the design error of the average repeater and second, to recenter the manual (cosine) equalizers. Although the average repeater matches its four miles of cable to within ±0.12 db this design error accumulates to over 3 db in 30 repeaters and further the shape is a difficult one to equalize. In order to keep the number of designs to a minimum only two sizes are used, 19 and 28 repeaters, and the residue is corrected by the manual equalizers. This residue may be positive or negative depending on whether the fixed equalizer over or under compensates. Thus there is only a small tendency for these residues to accumulate in long systems. However the inaccuracies of match between the fixed equalizer and the gain of the average repeater section tend to accumulate systematically and must therefore be kept small. This brings out the importance of statistical quality control of amplifier manufacture[2] since any systematic shift in the amplifier gain characteristic will accumulate and may consume excessive manual equalizer range or may lead to excessive equalization errors. For example, a shift of only 0.05 db in the gain of the average amplifier would represent 1.5 db in 30 repeaters, 50.0 db in 1000 amplifiers and thereby becomes an extremely serious matter. Thus quality control of the amplifier is a vital part of the solving of the equalization problem.

The various effects that consume the range of the manual equalizers produce for some shapes an unsymmetrical consumption of range. If uncorrected this would produce larger range requirements in the manual equalizers as well as introduce new shapes to be equalized. The manual equalizer shapes are symmetrical and their errors cancel if equal amounts of positive and negative range occur in the system. Any systematic offset of a particular shape tends to introduce new shapes due to the manual equalizer networks themselves. By appropriate modification of the shape of the fixed equalizer it is possible to recenter the manual equalizers so that on the average the manual shapes are in the center of their range.

DYNAMIC EQUALIZERS

Any long transmission system suffers from relatively rapid gain changes and in the L3 coaxial system, as in many previous systems, the necessary corrections are performed automatically by pilot controlled regulators. Pilot tones are transmitted over the line at a reference level and, at appropriate points, regulators pick the pilots off the line, observe the deviation in pilot levels from the reference values and restore the pilots to or very nearly to the reference values by the use of regulating networks.

There are fundamentally two causes of fast gain changes, time and temperature. Time produces vacuum tube aging and in spite of their feedback the line amplifiers change gain. In one week a 4,000-mile system is expected to change by as much as 5 db due to the aging of the 6000 tubes or so in the transmission path. Because of different thermal characteristics, temperature affects cable and repeaters semi-independently. In a 4,000-mile system one week is expected to engender as much as 8 db gain change by change in repeater temperature. Cable changes can exceed 100 db per week. Thus these effects must be corrected to a very high order of precision to maintain good television or telephone service.

These gain changes are not the entire story; when the gain changes in the band it also changes outside the band and usually by an even larger amount. Thus equalization of the in-band gain leaves outband (above 8.5 mc) gain changes which produce in-band delay changes of several microseconds. Because of the difficulty and complication of providing automatic delay equalization it is necessary to equalize these delay changes on a gain basis, by at least partial correction for outband gain changes. Further, since satisfactory pilot transmission is possible only within the band, these out-band changes must be predicted from the in-band gain changes. This effect, in itself, indicates the use of equalizers whose individual shapes are those produced by specific system causes producing a correlated change in many elements. Thus building the regulating networks to match the effects of the individual system causes and matching to 10 or 12 mc rather than just to 8.5 mc permits simultaneous gain and delay equalization. Such a set of shapes is also more accurate because it is matched to the special ways in which the specific system can change rapidly.

In theory the regulating networks could be built to match linear combinations of the cause shapes but there are two difficulties. First, not all of the cause shapes are known accurately or often even roughly at the introduction of a new system into the field. The mixtures of shapes cannot be determined without the missing ingredients. Second, a system is not a static design. Experience suggests improvements and thus occasions will arise where one will want to change the correction for a particular cause. If the networks represent mixtures of the causes this necessitates changing all the networks. If specific networks match specific causes only the appropriate network needs replacement.

The Computer

The use of cause shapes leads to a problem to which the computer provides the solution. These cause shapes are broad effects covering the entire band and more. Thus no one pilot is a measure of a specific cause. However by a process equivalent to the solution of simultaneous equations the pilots determine the amounts of an equal number of cause shapes that will restore the pilots to normal. Thus the computer translates pilot errors into shape errors and drives the appropriate regulating networks to obtain the corrections.

Let the equalizer shapes be given by functions of the form

$$S_n(f) = k_n F_n(f), \tag{1}$$

where "n" is the subscript number identifying the particular equalizer. (The capital "N" is reserved for the total number of equalizers.)

"$F_n(f)$" is the equalizer shape (on a "unit basis") as a function of the frequency "f".

"k_n" is the amount of shape introduced by adjustment, "k_n" may be positive or negative.

"$S_n(f)$" is the resultant shape put in the system by adjusting $F_n(f)$ by an amount k_n.

The total shape introduced by all "N" equalizers is obviously;

$$S_{\text{total}}(f) = \sum_{n=1}^{n=N} S_n(f) = \sum_{n=1}^{n=N} k_n F_n(f). \tag{2}$$

To obtain a match of S_{total} to the given equalization error, S_{given}, at "M" frequencies from $m = 1$ to $m = M$, requires that;

$$S_{\text{total}}(f_m) = S_{\text{given}}(f_m). \tag{3}$$

at each frequency from f_1 to f_M. Or, in terms of equation (2)

$$S_{\text{given}}(f_m) = \sum_{n=1}^{n=N} k_n F_n(f_m) \tag{4}$$

again, at each frequency from f_1 to f_M.

All of the important conclusions regarding the action of an equalization computer are implicit in the "M" equations indicated by equation (4).

Consider a case where there are three shapes. Let the information as to the difference between the system state and its desired state be determined by the deviation of three pilot levels which are observed to be δ_1, δ_2 and δ_3 at the pilot frequencies f_1, f_2 and f_3. The problem is to find the values of k_1, k_2 and k_3 that will give a match at these frequencies. This means that the following equations must be satisfied:

$$S_1(f_1) + S_2(f_1) + S_3(f_1) = \delta_1 \tag{5}$$

$$S_1(f_2) + S_2(f_2) + S_3(f_2) = \delta_2 \tag{6}$$

$$S_1(f_3) + S_2(f_3) + S_3(f_3) = \delta_3 \tag{7}$$

Thus

$$k_1F_1(f_1) + k_2F_2(f_1) + k_3F_3(f_1) = \delta_1 \tag{8}$$

$$k_1F_1(f_2) + k_2F_2(f_2) + k_3F_3(f_2) = \delta_2 \tag{9}$$

$$k_1F_1(f_3) + k_2F_2(f_3) + k_3F_3(f_3) = \delta_3 \tag{10}$$

The solutions for k_1, k_2 and k_3 take the form

$$k_n = a\delta_1 + b\delta_2 + c\delta_3, \tag{11}$$

where a, b and c depend solely on the shapes $F_m(f)$.

Thus the values of the δ's may be decoded into the values of the equivalent k's by the simple process of multiplying each "δ" by some fraction that is a function of the equalizer shapes; or, more precisely, by a fraction that is a function of the values of the various shapes at the frequencies f_1, f_2, etc.

The circuit of the computer is quite simple; consisting of about N^2 resistors for the control of "N" networks by the deviations that are measured at $M = N$ pilot frequencies. This simplicity is valuable for its own sake, but, as previously noted, there is considerable value in the fact that substitution of new equalizer shapes requires only that changes be made in the values of some of the resistors.

Fig. 2 illustrates the principle by showing the computer circuit required for the previous example of three shapes for which information is given at three frequencies, f_1, f_2 and f_3. The three dc voltages representing the deviations δ_1, δ_2 and δ_3 are decoded by simply cross-connecting them to the three pairs of output terminals through fixed resistors chosen to satisfy the relationships of equations (8), (9) and (10). The output voltages will be proportional to the desired equalizer correction quantities k_1, k_2 and k_3.

In general the calculation of some of these resistors will give negative values. Thus it will generally be necessary to require that the dc voltages representing the errors δ_1, δ_2, etc., be available in both polarities. Alternately, the errors can be provided in only one polarity and the circuits to which the computer outputs connect can provide the push-pull circuit. This latter course has been used in the L3 regulators as indicated on Fig. 2.

The effect of using the computer is as follows. If one pilot changes, all regulating networks correct but in such proportions and polarities as to produce no gain change at any pilot frequency except at the one originally disturbed. If all pilots deviate in proportions corresponding to one of the shapes, no network corrects except the one corresponding to the original pattern of pilot deviation.

If conventional regulator circuits were used with particular pilots assigned to particular shapes the interactions would be intolerable. Thus the computer removes the restrictions on the choice of shapes imposed by regulator interactions. In turn this permits freedom in changing shapes as system data improves. It is important to provide the initial equalizers before adequate data on the system are available. As the system grows in length the equalization must be improved but the data improves also. Thus there is an economic benefit in providing a flexible equalization plan which allows the earliest possible commercial use of the system.

Dynamic Equalizer Requirements

Because temperature and aging variations can result in both gain and loss variation with respect to the average transmission, the equalizers must be capable of inserting both loss and gain compensation. Also, it is extremely desirable that equal gain and loss settings for the equalizer result in symmetrical transmission characteristics with respect to the average. In a long transmission system, some of the sections will insert excess gain and others, excess loss. If the equalizer gain and loss characteristics are symmetrical, the residue will be related to the system

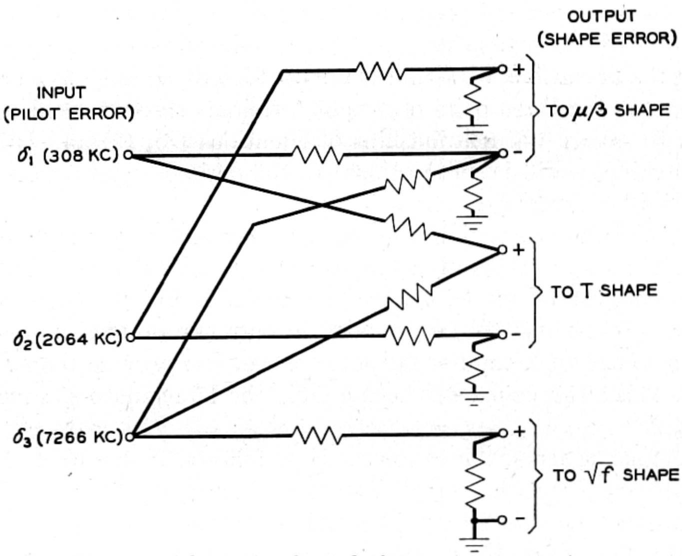

Fig. 2 — Schematic of regulation system computer.

deviation and some constant part of the equalizer characteristics. If this is not the case the residues can produce new variable deviations shapes and thereby lead to increased complexity in following stages of equalization.

As previously described, equalization of both gain and loss is required and this implies active equalizers. Although a number of methods were studied, noise and modulation requirements led the L3 system to the so-called "block of gain-block of loss" design. The equalizers are passive networks and in order to realize both gain and loss adjustability, the normal setting loss must at least equal the total amount of gain adjustment. The various equalizers are combined into two to four groups whose loss is compensated by corresponding numbers of flat gain amplifiers.[2]

The required number of such blocks of loss and gain depends upon the amount of system gain variation to be equalized. The determination of the shapes and magnitudes of system variations is an important system problem. Large amounts of study are necessary in order to evaluate the system sensitivity to various changes; the determination of the magnitude of these causes, such as temperature variation, aging rates, etc.; and the determination of maintenance intervals that provide an economic balance between maintenance expense and system cost. These must be studied in detail to provide the equalizer designer with shape and range data for his dynamic equalizer designs. The equalization characteristics and maximum ranges for the two most important dynamic equalizers aside from cable temperature, namely, repeater temperature (T) and vacuum tube aging $\mu\beta$ are shown on Fig. 3. In order to maintain satisfactory transmission during a maintenance interval, the dynamic equalizers must be able to match any characteristic within the maximum ranges and throughout the transmission band to within 1 to 2 per cent. As noted previously the necessity for simultaneous delay equalization requires the dynamic networks to also make at least an approximate correction in the out-band region. This is shown on Fig. 4.

The control element in the equalizers is a thermistor whose available resistance range is 30 to 1050 ohms. ($\sqrt{f}$ of line amplifier[1, 2] 125 to 2000 ohms). Thus the regulation ranges shown in Fig. 3 are realized using this one variable resistance element in each equalizer.

The following is a summary of the dynamic equalizer requirements.

1. Provide symmetry in regulation characteristic.
2. Minimize flat loss.
3. Match prescribed gain variation to a high degree of accuracy within transmission band.

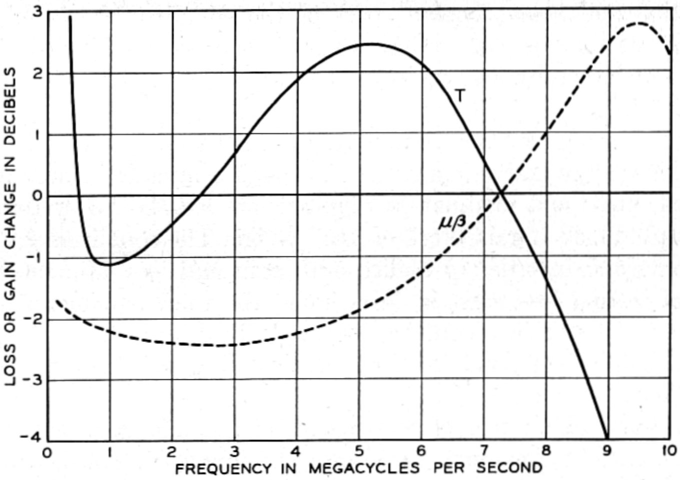

Fig. 3 — Regulation shapes and ranges for tube aging ($\mu\beta$) and repeater temperature (T). The curves given can occur as either gain or loss and apply to 30 repeaters.

4. Provide satisfactory equalization of in-band delay distortion due to out-band gain change.
5. Each equalizer controlled by a single variable resistance element.
6. The desired performance to be realized in 75-ohm circuits.

Dynamic Equalizer Design

The design used is the structure commonly known as the Bode Regulator,[3, 4] and shown in block schematic form in Fig. 5. An ideal regulating

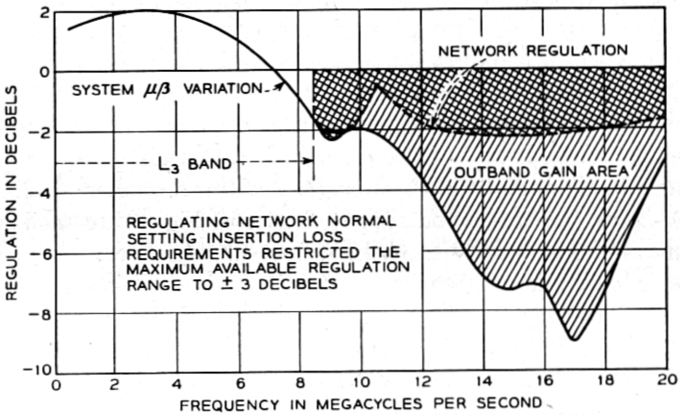

Fig. 4 — Match to out-band gain change to reduce in-band delay distortion.

network would insert a deviation characteristic

$$\theta = f(R_T) \cdot f(\omega) \text{ db.} \tag{12}$$

Such a network would yield a given shape independant of setting and thus would have linearity as well as symmetry. Actually the Bode network has symmetry but only approximates linearity. As shown, it may be designed to insert a variable impedance either in series or in shunt with the line. When using only one control element it is not a constant resistance structure and must be operated between terminations of the design value. The choice of series or shunt configuration was governed for L3 by the fact that very low thermistor resistance would require excessive dc currents from the regulators. For a 75-ohm circuit and this thermistor limitation the series regulator provides lower normal-setting loss.

The insertion gain for the series regulator may be written as:

$$\theta = \theta_N + 2 \text{ arc tanh} \left[\frac{R_1 - R}{R_1 + R} \cdot \rho e^{-2\Gamma} \right], \tag{13}$$

where θ_N = The normal setting flat loss as given by

$$\alpha_N = 20 \log \frac{R_1}{R} \text{ decibels.} \tag{14}$$

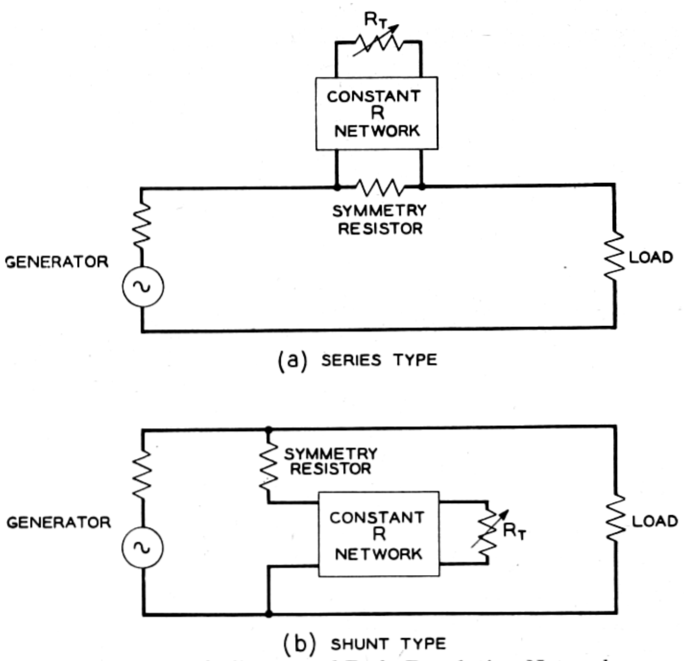

Fig. 5 — Block diagram of Bode Regulating Network.

R_1 is the symmetry determining resistor and is in parallel with the input terminals of the shaping network in order to limit the maximum value of the series impedance. The equation of symmetry may be expressed as

$$R_1^2 = \left(1 + \frac{R_1}{2R_0}\right)R^2. \tag{15}$$

R is the image impedance of the shaping network. The thermistor has this value at its normal setting.

R_0 is the impedance of the circuit in which the regulator is inserted, in this case, 75 ohms.

ρ is the reflection factor between the network impedance, R, and the thermistor impedance, R_T and is given by

$$\rho = \frac{R_T - R}{R_T + R}. \tag{16}$$

Γ is the image transfer constant of the shaping network and may be expressed as

$$\Gamma = \sigma + i\psi. \tag{17}$$

Returning to expression (13) for the insertion gain, if the series expansion of the arc tangent is used and the higher order terms discarded, the insertion transfer constant becomes

$$\theta = \alpha_N + Ke^{-2\sigma} \cos 2\psi + iKe^{-2\sigma} \sin 2\psi, \tag{18}$$

or the insertion loss may be expressed

$$\alpha = \alpha_N + Ke^{-2\sigma} \cos 2\psi \text{ nepers}, \tag{19}$$

$$K = 2 \cdot \frac{R_1 - R}{R_1 + R} \cdot \rho. \tag{20}$$

This approximation is valid for design purposes if the regulation range is not too large or the accuracy required too great. For example, omission of the cubed term in the repeater temperature design produced a maximum error of 0.014 db and in the tube aging design, 0.007 db.

From the above expression it is seen that both real and imaginary parts of the image transfer constant for the shaping network enter into the insertion loss expression, and thus the relationship between the desired insertion loss and the shaping network makes the design process difficult. At this stage in the design considerable art and ingenuity is required in order to continue the design efficiently. The approach taken depends upon the regulation characteristic desired and the experience of the designer. Since both loss and phase are involved, familiarity with loss-phase relations is important. After a design has been blocked out, repeated modifications of the network parameters usually indicate the adequacy of the configuration chosen. Usually several sections in tandem are required in the shaping network in order to obtain precision of match, and some of these most likely will be all pass sections in order to control the phase ψ independently of the real part σ. It may be noted that at cross over points in the regulation characteristic, i.e., zero regulation, either the phase ψ has to be 45 degrees, or odd multiples thereof, or the loss σ has to be infinite. Usually the

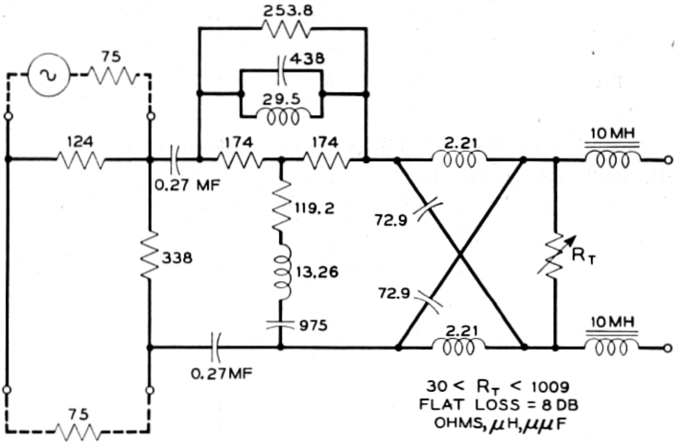

Fig. 6 — Circuit of the regulating network for repeater temperature.

phase is made the controlling term in both zero and peak regulation points.

The designs presently used on the L3 system for the repeater temperature and tube aging equalizer are shown in schematic form on Figs. 6 and 7. The 0.27 microfarad capacitors and 10-millihenry inductors are employed in order to supply the dc heating current to the thermistor. The shunt resistors placed across the 75-ohm line, in one case 124 ohms and in the other case 133.4 ohms are used in order to make the left side driving point impedance equal 75 ohms at normal setting of the thermistor. These networks are used in cascade with the manually adjusted, constant resistance networks and it seemed desirable that the impedance characteristic of the dynamic equalizers be relatively good at one pair of terminals.

MANUAL GAIN EQUALIZERS

One of the more difficult equalization design choices is the selection of shapes for the manual equalizers. In the L1 system some of the shapes used were so-called "bump" shapes. This type of shape reduces the amount of shape overlap and thereby tends to reduce the adjustment problem when conventional adjustment methods are used. For the L3 system many types of shapes and circuits were carefully studied. The computational concepts of equalizer adjustment resulted in the consideration of shapes that would otherwise be impractical.

The shapes finally chosen for L3 are "cosine" shapes. Any continuous function may be matched over a 180-degree interval by a Fourier series of cosines only. By making the 180-degree interval the frequency range from 0 to 8.5 mc the cosines are cosines of frequency and can match any gain characteristic if enough terms are used. These cosine equalizers have the following advantages.

1. The range required for any term is less than the total shape to be matched, usually less than half.

2. The residues are always higher harmonics and therefore easily matched if necessary.

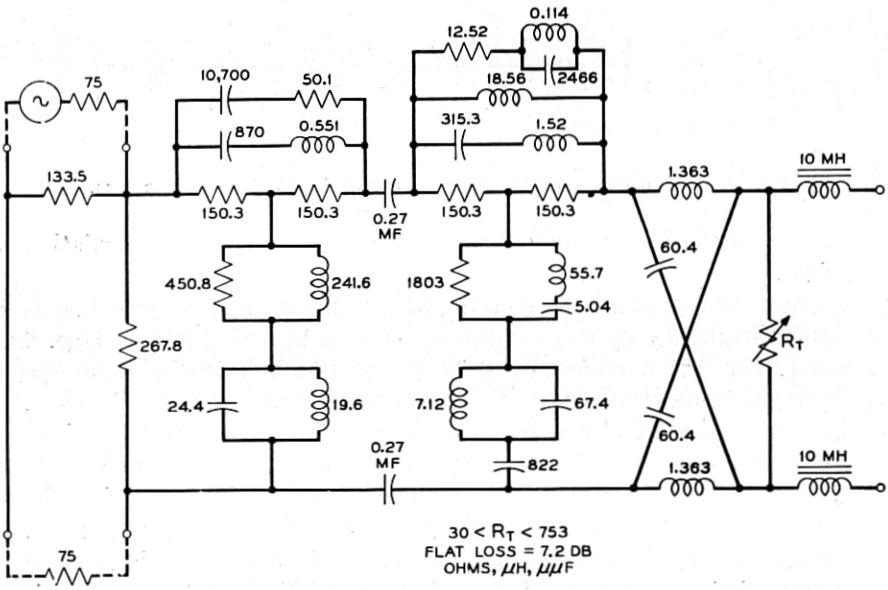

Fig. 7 — Circuit of the regulating network for tube aging.

3. The controls are easily adjusted using methods to be described.

4. If better equalization is required at any point the existing equalizer is retained, additional harmonic terms are added.

5. The major portions of the equalizers require only one value of inductance and two values of capacitance to form the delay lines used in the networks. This also assists in the application of distribution requirements.

6. The manual equalization can be designed with a minimum of information about the system characteristics.

7. The equalization is on a least square error basis rather than minimum peak error.

The networks used to realize these cosine shapes are constant resistance Bode regulating networks[3] employing second degree all-pass sections.[5] If the phase of the all-pass sections were made proportional to frequency, the transmission performance within the frequency band of interest would be that provided by a Fourier series composed of cosine terms in the variable ω. By appropriate choice of the all-pass sections the frequency-phase relationship can be warped to give greater weighting to a specified portion of the frequency range. The phase of the all-pass section is given by

$$\psi = 2 \cot^{-1} \left[\frac{b}{2} \left(\frac{fc}{f} - \frac{f}{fc} \right) \right]. \tag{21}$$

Small b and high f_c weights the low frequencies, the linear phase case $b = 1.2$, $f_c = 10.2$ mc gives uniform weighting and large b weights the high frequencies. A $b = 2$, $f_c = 13.75$ mc, was selected for the L3 equalizers because it weights somewhat the higher frequencies where the television signal is transmitted and second, each unbalanced bridge T network section can be constructed with only four elements, two like inductors and two capacitors. For b's smaller than 2, coupling between the two like coils is required, and for b's larger than 2, an additional element is required.

The all-pass networks are designed on a 75-ohm impedance level and thus the flat, normal setting of each regulating network is 4.18 db maximum. The 75-ohm level makes the series and shunt networks identical and also facilitates manufacturing testing. A special dual variable resistor is used as the control element. It has a resistance range of 15 to 375 ohms and provides a regulation range of ± 2.78 db maximum.

A schematic of this network is shown on Fig. 8. In the case of the O harmonic, flat gain, the phase sections are omitted. For the nth harmonic term, n sections are used in both the series and shunt arms. The constant resistance structure permits the complete equalizer to be formed by a cascade of such networks without interaction effects. This provides a loss characteristic given by

$$\text{Loss} = k_0 + k_1 \cos 2\psi + k_2 \cos 4\psi + k_3 \cos 6\psi + \cdots \qquad (22)$$

where ψ is the phase of the individual all-pass section which goes from 0 to 90 degress between 0 and 8.5 mc. The k's are adjusted by means of the dual adjustable resistors. Note that each term of the series is represented by a corresponding equalizer.

Application of this mop-up polynominal to a large number of L3 deviation characteristics indicates that considerably less range than the maximum ±2.78 db will be required for most of the cosine terms. Fig. 9 illustrates this convergence of the series for the eight largest amplifier manufacturing variations. This and other studies show that after the first three harmonics the range may be reduced. It can be shown,[6] for example, that if the system gain deviations are finite within the range of interest (interval of convergence) the coefficients of the approximating polynominal will decrease in magnitude linearly proportional to the number of the terms, that is, the nth coefficient will be smaller than some constant divided by n. If the deviation characteristics are continuous and hence have finite first derivatives, then the coefficients of the apprximating polynominal will decrease as the square of

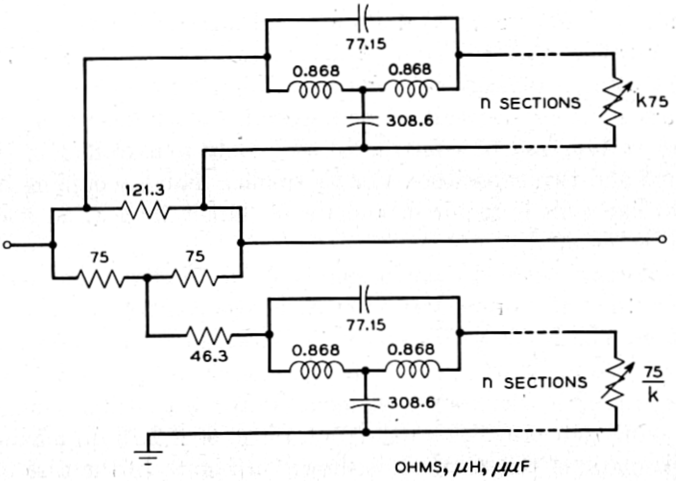

Fig. 8 — Circuit of a cosine equalizer without dissipation correction.

the number of the term. If all derivatives are finite the coefficients will decrease exponentially. This last case is believed to describe the convergence for at least most of the L3 system shapes. Thus for the high order terms that require little range it is possible to reduce the flat loss of the networks.

In order to reduce the flat loss without changes in the 75-ohm impedance level of the phase sections or in the dual adjustable resistors, pads are inserted between the resistance T and the all-pass sections. In this manner the loss could be reduced to 2.2 db for ± 0.5 db range if it were not for the dissipation in the all-pass sections. This dissipation is due to the coils and increases with frequency. It tends to produce a reduced cosine amplitude in the high frequency part of the band. To correct this effect, the pad mentioned above is actually made an equalizer section whose loss change with frequency corrects for the dissipation in the coils thereby yielding cosine amplitudes independent of frequency. The price of this is an increase of the flat loss to 3.4 db for ± 0.5 db range. The circuit of the term 10 network is shown on Fig. 10. The range

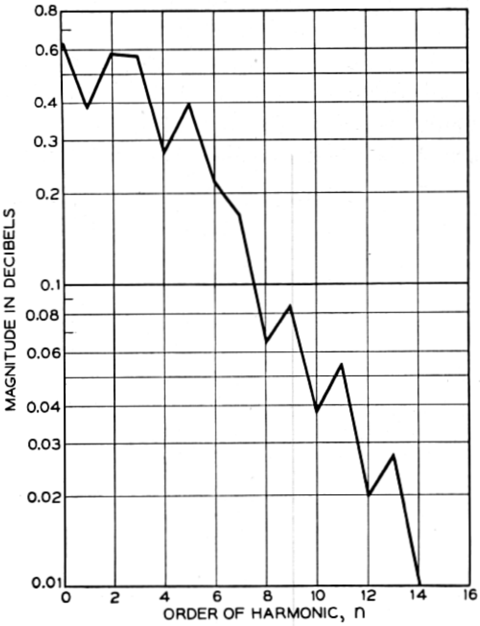

Fig. 9 — Range required for various cosine terms due to expected manufacturing variations of eight critical elements. The magnitudes are based on RSS addition in 25 repeaters.

of this term is ±0.5 db as is that of all higher terms (to 24). Terms 1, 2, 3 have full range, 4, 5, 6 have 1.5 db and 7, 8, 9 have 1 db. The O term, flat gain, is also 1 db because additional flat shape is obtainable from the flat amplifiers used to make up for the equalizer loss.

The shapes provided by the first three terms are shown on Fig. 11. Note that the shapes are cosines of a warped frequency variable and that on this warped scale the shapes are orthogonal. In all, 24 such harmonics plus flat gain are used in the high frequency line for combined systems. For all telephone use only 14 harmonics plus flat gain are required. Fig. 12 shows the construction of one of the cosine networks. These are mounted in groups of five as indicated in Fig. 13. The fixed equalizer and regulating networks are mounted to the rear of the cosine assembly.

Harmonic Adjusting Set

To make a mental harmonic analysis of a complicated gain characteristic is difficult if not impossible. Therefore a special cosine-equalizer adjusting set has been developed which eliminates trial and error from the adjustment process and which leads to a unique optimum adjustment. Broadly the method consists of using sweep frequency methods to convert the gain-frequency characteristic into a repetitive voltage-time function. Gain cosines on the warped frequency scale are converted to voltage cosines of time and the audio harmonic-spectrum components

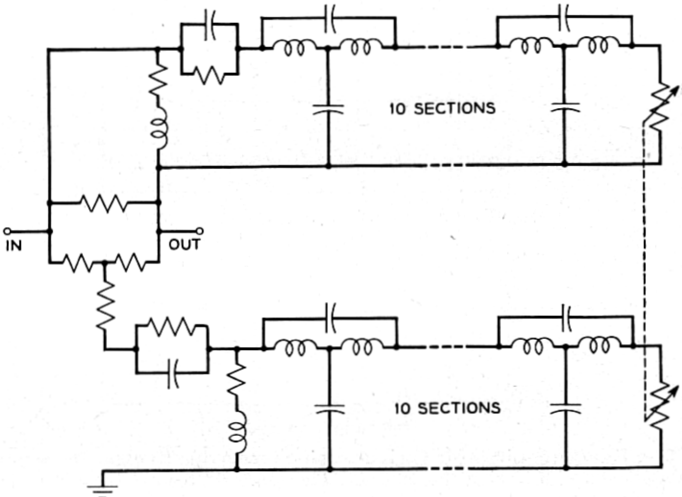

Fig. 10 — Cosine equalizer circuit (tenth harmonic) showing dissipation and range corrections.

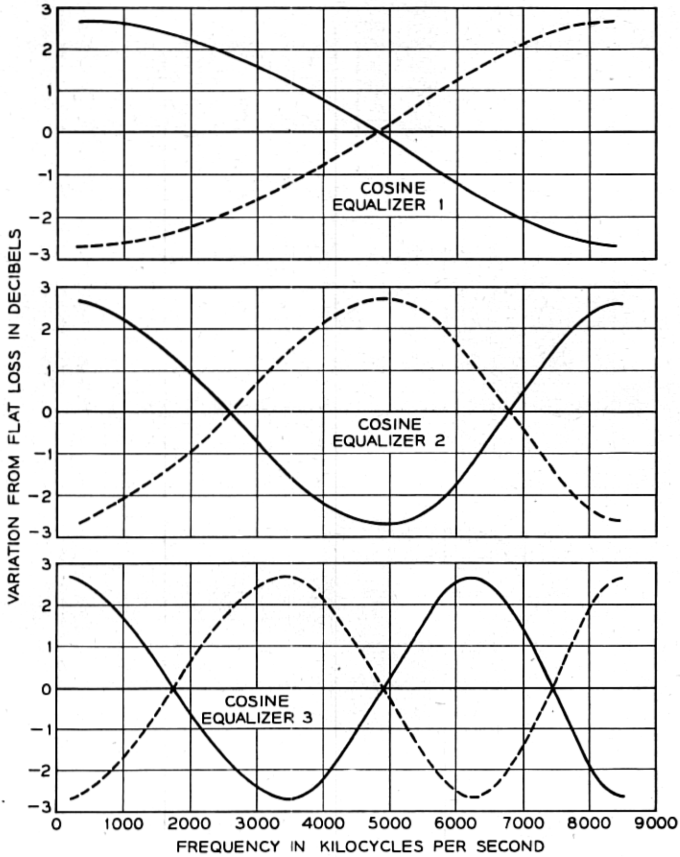

Fig. 11 — Shapes introduced by the first three cosine harmonics.

are individual measures of equalizer control-setting errors. By the adjustment process these audio harmonics are removed thus yielding a gain characteristic describable in terms of only the higher cosine components not available to the equalization operator.

The operation can be explained using the block diagram shown on Fig. 14. The sweep oscillator sends a constant level, variable frequency, over the line and through the cosine equalizer to the detector. The output of the detector on terminals x-x at any instant is a measure of the transmission of the line and equalizer at the frequency being sent by the sweep oscillator at that instant. The sweep frequency starts at zero and sweeps to 8.5 mc in a period t_1. As shown on Fig. 15 the frequency-time relationship is warped to correct for the warping of the equalizer

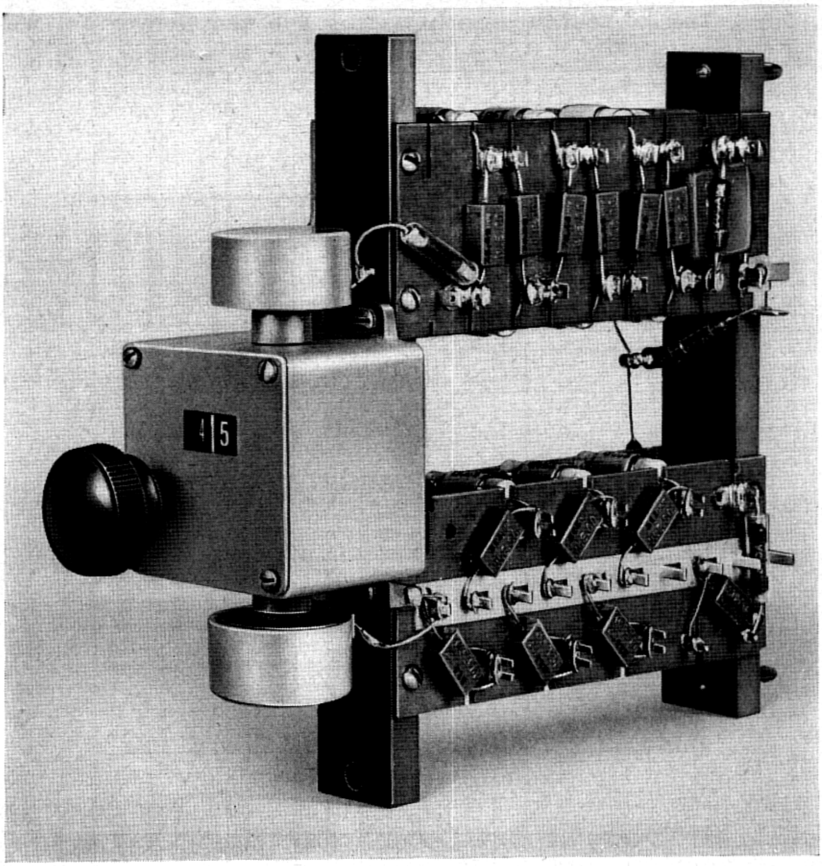

Fig. 12 — View of single cosine term network.

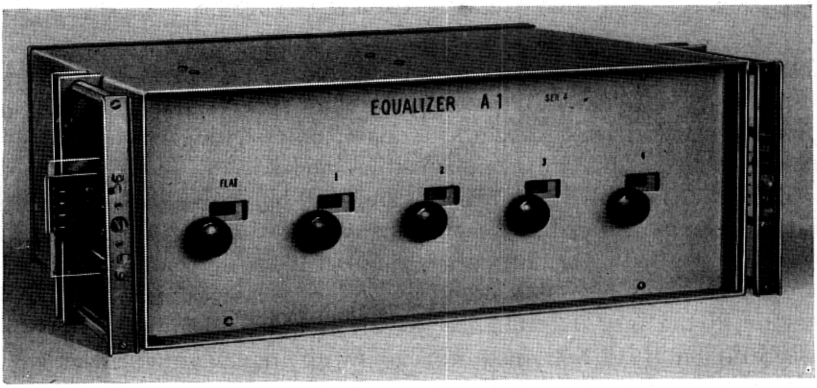

Fig. 13 — Assembly of five cosine terms. A "C" equalizer requires five of these assemblies, a "B" equalizer, three, and an "A", two.

phase-frequency relationship. The sweep oscillator therefore scans at a linear rate in cosine degrees vs time. Upon reaching 8.5 mc the sweep reverses and returns to zero. If the cosine shapes were linear cosines of frequency the sweep would be a triangular wave.

Assume that the line is perfectly equalized except that the first harmonic term is misadjusted. As the sweep goes from 0 to 8.5 mc the voltage at x-x follows the first harmonic curve of Fig. 16 from 0 to t_1. When the oscillator scans back to 0 the voltage at x-x follows the first harmonic curve from t_1 to $2t_1$. Then the cycle repeats. The voltage at x-x thus becomes a pure cosine of time oscillation of frequency, $\frac{1}{2}t_1$. Although the equalizer shapes are actually cosine on a decibel rather than an amplitude basis this has little practical effect because for small deviations the two are nearly identical.

If instead of a first harmonic error the second or third cosine harmonic

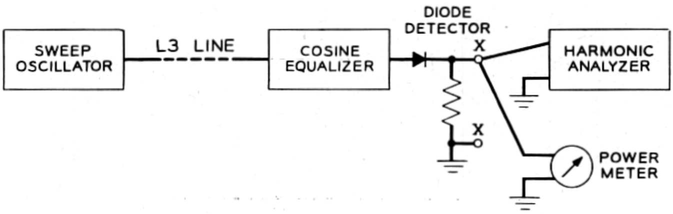

Fig. 14 — Block diagram showing the method used to adjust cosine or other orthogonal equalizers.

is misadjusted, the voltage at x-x will follow the appropriate curve of Fig. 16. The dc component measures the zero harmonic but in practice only the ac components are measured and the flat gain is set as a final step to make the pilot levels correct at the line output. If it takes 0.01 seconds for the oscillator to scan up and back, the first harmonic produces 100 cps output from the detector. The second harmonic equalizer produces 200 cps, the third 300 cps, etc. Therefore at the output of the detector there exist a set of audio frequency harmonics whose amplitudes are a measure of the equalization error of the setting of the cosine controls of corresponding periodicity.

These harmonics can be separated by convention filtering techniques, for example, by an audio tuned detector or harmonic analyzer as noted on Fig. 14. The analyzer can be tuned to 100 cps and the first harmonic control rotated to remove the 100 cps component. Then tuning to 200 cps the second control is operated, etc. This null method is similar to bridge balancing and may be instrumented to similar high precision. After all of the harmonics corresponding to equalizer controls have been removed the process is complete and the equalization residue must be composed solely of those terms not provided by the equalizer.

The harmonic analyzer method requires tuning or switching and thus to simplify the method still further the actual field equipment uses a power indicator in place of the analyzer as noted on Fig. 14. Given a spectrum of signals of differing frequencies, removing any one reduces the total power. Therefore the entire spectrum may be applied to a power indicator and the reading reduced by adjusting the various equalizer controls. In practice this process is assisted by filtering out the high harmonics which cannot be equalized. This reduces the total power and increases the ease of reading the meter. While the method has been demonstrated using an ordinary 60 cps wattmeter, an electronic wattmeter is used in the field equipment.

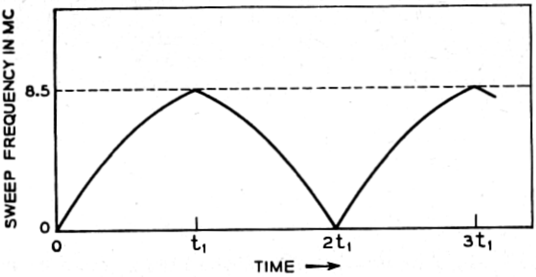

Fig. 15 — Method of scanning the system gain characteristic to convert cosines of frequency into cosines of time.

While the receiver unit can be quite simple, the sweep oscillator is complicated by such things as circuits to control the warping and to hold the sweep limits accurately. In practice the sweep is between 0.3 and 8.5 mc and is at a 37 cps rate. Further there are six pilots on the system and although the dynamic regulators at the adjusting point are paralyzed during the cosine adjustment the pilots to intermediate regulators must not be disturbed. Thus the sweep frequency is shifted very rapidly through the pilots. When the sweep frequency gets within about 25 kc of a pilot it is shifted suddenly to the other side of the pilot frequency. This materially reduces the interference to the pilot without producing transients in the receiver.

While other methods of cosine equalizer adjustment were tested and found to work satisfactorily, the above method was found to be superior. In addition, removal of the filtering permits the power meter to read the rms equalization error and thus the equalization operator can determine the quality of the job and observe whether the state of the line is satisfactory. Also the power method is usable with sawtooth as well as triangular scanning and, further, works on any set of orthogonal gain or delay shapes. Thus the basic equipment is readily adaptable to the adjustment of D equalizers if their gain and delay shapes are orthogonal.

FIELD PERFORMANCE

In the L3 system the function of the dynamic equalizers is solely to prevent excessive deterioration of the transmission characteristic from one manual line-up to the next. During the manual adjustment the dynamic networks are held at that point in their range which minimizes the probability of running out of range in either direction before the next manual line-up. This is done to hold the dynamic ranges to a minimum. Thus the transmission errors remaining at the completion of a manual line-up are chiefly due to the fixed and manual equalizers. It should be noted however that, when the dynamic regulators are restored to operation after the manual adjustment, any residues will be seized by the dynamics and regulated.

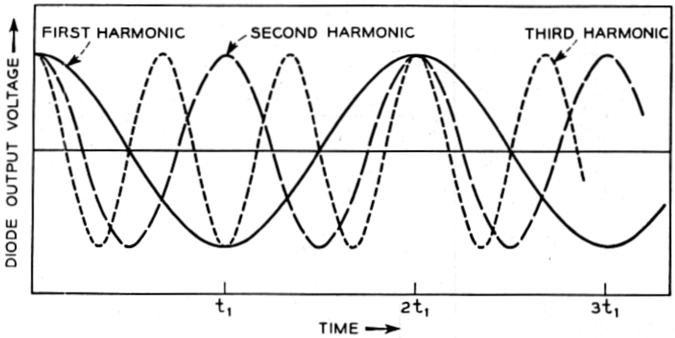

Fig. 16 — Detector output produced by scanning the first three cosine shapes.

As yet the field experience with the regulation system and the dynamic shape performance is quite limited. However, the stability of the regulation system and the action of the computer have been well established. It would appear that the major remaining regulation system problem will be the determination of the cause shapes to the accuracy required for long television systems.

Somewhat more experience has been gained with the cosine equalizers. Using a fixed equalizer design based on ten line amplifiers from initial production, a 100-mile circuit equalized using 15-cosine terms yields the residues plotted on Fig. 17. The ripple at the extreme high end of the band is largely due to the failure of the fixed equalizer to match the very sharp cut-off of the line between 8.35 and 8.50 mc. Since telephone channels are not transmitted in this region and since television requirements are less severe at such high video frequencies (4.2 mc) this effect does not limit the transmission quality. Also note that long television circuits, over 400 miles, will have a further level of equalization, D. There is no visible impairment of ordinary television pictures due to insertion of the 200-mile L3 line in their path. With critical types of test patterns there is a slight effect. While there are problems yet to be solved before 4,000-mile transmission can be obtained, the 200-mile performance is most encouraging.

In the past the adjustment of manual equalizers has often been a difficult and time consuming task. The cosine adjusting set described

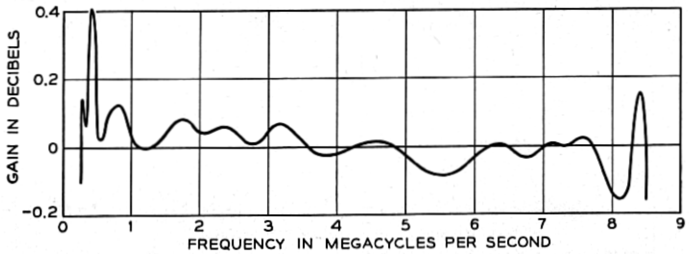

Fig. 17 — Final gain characteristic of a 100 mile L3 line after equalication with 15 cosine shapes.

previously appears to have made sizable inroads on this problem. The adjustment of the 25 controls used for television is a three minute job. The fact that the equalization operator is working toward a unique solution and therefore knows when he is done appears to be of material value.

Regulation

The L3 regulation system is in many respects, similar to the L1 system. However, the design of a stable regulation system for over five hundred regulators in tandem introduces unusual problems. Also the accuracy and stability requirements have led to the use of novel regulator circuits including, for example, an analog computer as an element of the system.

Six pilots are used, 308, 556, 2,064, 3,096, 7,266 and 8,320 kc. These frequencies were selected to best measure the anticipated system changes as restricted by where signal allocations would permit their insertion.

For example, the wide gap from 3,096 to 7,266 is largely due to the difficulty of inserting and removing pilots in the lower video frequencies of television signals. The problem of finding a satisfactory set of pilot levels and frequencies which will at the same time, be compatible with the desired signals is an important part of the system design problem.[1]

The change of four-mile cable loss with temperature is so large (±1.2 db) that regulation is required at each repeater. It takes three months or more for the cable loss to change 2 db but the normal line maintenance interval is of this order. A gain error of this magnitude could not be allowed to accumulate over very many repeaters before the signal to noise performance of the system would collapse. Other effects such as vacuum tube aging and repeater temperature changes can be allowed to accumulate over as many as 30 repeaters before regulation. These facts dictate the location of regulators in the system. At each repeater there is a "line" regulator controlling a square-root-of-frequency-shape regulating network. Then at equalizing points and dropping points "office" regulators correct for the remaining effects.

CHAIN ACTION

Pilot controlled dynamic regulators derive much of their advantage from the fact that they prevent gain changes from accumulating from repeater to repeater. This advantage is one manifestation of what might be called the "chain action" of a series of regulators. There is however a corresponding disadvantage, disturbances of the pilot cause the accumulation of unwanted gain fluctuations. In previous systems this disadvantage has been aggravated by positive envelope feedback ($1-\mu\beta$ less than one), at some frequencies, an effect known as "gain enhancement". In the L3 system the "gain enhancement" is nearly negligible but the television requirements still require careful control of certain types of gain fluctuations.

The advantage noted above can easily be demonstrated by a simple example. Consider a chain of regulators each having 20 db envelope feedback so that pilot level changes are reduced by 10 to 1. Now consider what happens if each cable section changes loss by one db. Table I illustrates the action.

The first regulator inserts a gain change of 0.9 db in response to the 1.0 db input change. The 0.1 db error increases the input change to the second regulator to 1.1 db and it therefore inserts a 0.99 db correction.

The total resultant error of 0.11 db adds to the change at the third regulator input, etc. Simply stated: The error of the first regulator rides through the system forcing the other regulators to make an accurate

TABLE I

Regulator Number	Input Pilot Change	Inserted Correction	Output Pilot Change
	db	*db*	*db*
1	1	0.9	0.1
2	1.1	0.99	0.11
3	1.11	0.999	0.111
4	1.111	0.9999	0.1111

correction. Actually, of course, the above statement is oversimplified but it should be clear that the effective feedback of the regulation system is the (voltage) sum of the feedbacks of the individual regulators. Thus 100 regulators each having 20 db of feedback tend to act like a single regulator having 60 db of feedback. The rigorous treatment of these effects will be developed later.

Fig. 18 shows a block diagram of a regulator in a form intended to indicate the feedback structure. The feedback loop includes a pilot pickoff filter, amplifier and rectifier. This converts the output pilot level into a dc voltage. The "battery", which is the actual input signal for the circuit, represents the equivalent of the desired pilot output level. The signal applied to the dc amplifier is a dc signal representing the error in pilot level. This dc signal is, in effect, converted back to a pilot level by the action of the regulating network and its modulation of the input pilot level. Thus changes in input pilot level are equivalent to gain changes in the μ circuit of the feedback structure and are resisted by feedback action just as in any other feedback "amplifier". It is also valuable to note the respective μ and β roles played by the various components since the stability requirements, etc. then become clear. For

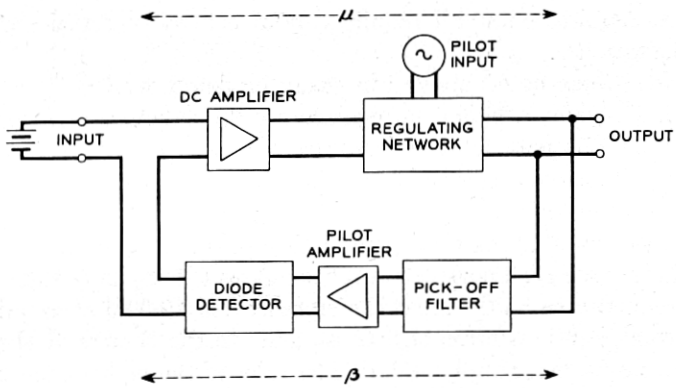

Fig. 18 — Block diagram of regulator showing the feedback structure.

example, the pilot amplifier is in the beta circuit and therefore must be a highly stable device. On the other hand, the dc amplifier is in the μ circuit and its drifts are reduced by the loop feedback.

Having developed the feedback nature of the structure and the roles of the components, the conventional feedback art can be used for the analysis of the individual regulator. One can show that:

$$\frac{\text{Change in output pilot level}}{\text{Change in input pilot level}} = \frac{1}{1 - \mu\beta} \tag{23}$$

$$\frac{\text{System gain change to pilot frequency}}{\text{Change in input pilot level}} = \frac{\mu\beta}{1 - \mu\beta} \tag{24}$$

This result is not very surprising but it can be used to determine the performance of the following regulators in a chain. Many different cases must be considered. Sometimes the pilot levels change because of an effect distributed all along the system. In other cases the change occurs only at the input to the line. Sometimes the pilot level changes are the important effect. In other cases the importance resides in the gain change to the signals. In all cases the results may be complicated by the fact that $\mu\beta$ is, in general, a complex number and thus phase as well as amplitude is important.

Adopting the notation:

ΔP_{in} = fractional change in input pilot at nth regulator,
ΔP_{on} = fractional change in output pilot at nth regulator,
ΔG_n = gain change to signals (near pilot frequency) of nth regulator, and
ΔG_t = total system gain change $= \sum G_n$,

one can readily show the following:

Case I — Disturbance of pilot only at input to system:

$$\frac{\Delta P_0 n}{\Delta P_{il}} = \left(\frac{1}{1 - \mu\beta}\right)^n \tag{25}$$

$$\frac{\Delta G_n}{\Delta P_{il}} = \mu\beta\left(\frac{1}{1 - \mu\beta}\right)^n \tag{26}$$

$$\frac{\Delta G_T}{\Delta P_{il}} = \left(\frac{1}{1 - \mu\beta}\right)^n - 1 \tag{27}$$

Case 2 — Equal gain change in each regulating section.

$$\Delta P_c = \text{fractional gain change of section}$$

$$\frac{\Delta P_{0n}}{\Delta P_c} = \frac{1}{\mu\beta}\left[\left(\frac{1}{1 - \mu\beta}\right)^n - 1\right] \tag{28}$$

$$\frac{\Delta G_n}{\Delta P_c} = \left[\left(\frac{1}{1 - \mu\beta}\right)^n - 1\right] \tag{29}$$

$$\frac{\Delta G_T}{\Delta P_c} = \left[\frac{1}{\mu\beta}\left(\left(\frac{1}{1 - \mu\beta}\right)^n - 1\right) - n\right] \tag{30}$$

As an example of the application of these formalas consider the effect of television induced compression. The presence of the television signal reduces the gain of the line amplifier. The effect is small but cumulative. In the absence of regulator action it merely compresses the television signal slightly and makes a negligible change in the contrast rendering of the picture. However the regulators observe a gain change to the pilots and attempt a correction. The very rapid changes are ignored but 60 cps, for example, is partially corrected. This introduces a 60 cps gain change which will lag the picture and therefore must meet 60 cps bar pattern requirements. This problem is solved by keeping the regulator response low at 60 cps.

For $\mu\beta$ of -70 db, 90 degrees, at 60 cps a chain of 700 regulators will insert a total gain change approximately one tenth that of the total compression. If the $\mu\beta$ were allowed to approach -50db the total gain change would equal the compression and certain types of pictures would be degraded.

The above example brings out one of the important facts: When designing regulators for long systems the $\mu\beta$ characteristic must be carefully controlled to losses much higher than is customary in amplifier design. In a conventional feed-back-amplifier loop-cutoff the magnitude and phase of $\mu\beta$ is no longer of much interest after it drops below -10 db. In L3 regulators the loop is of vital interest to losses of the order of 70 db. This is, of course, largely due to the fact that the chain action increases the effective system feedback by nearly 60 db. Thus the over-all system is similar to conventional amplifier practice. Loop gain ($\mu\beta$) and feedback (1-$\mu\beta$) characteristics for the line and office regulators are shown on Figs. 19, 20, 21 and 22. Note that 1,000 line regulators in tandem give an over-all gain enhancement of only 1.2 db. This would be even less if it were not for a 100 cps roll-off in the dc amplifier to reduce noise. One hundred office regulators give 0.8 db gain enhancement even with their 20 cps roll-off.

THE DYNAMIC LINE REGULATOR

As indicated in Fig. 23 a crystal filter is used to pick the pilot off the line in the presence of the other signals. The filter impedance goes

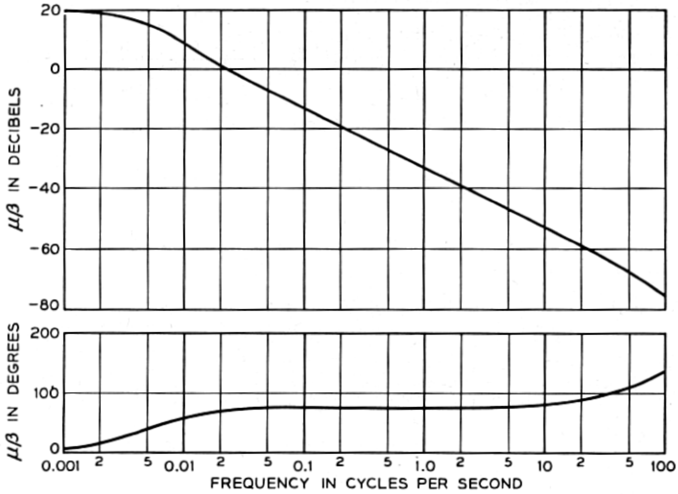

Fig. 19 — Loop gain characteristic for the line regulator.

through resonances due to the crystals and introduces a gain characteristic on the line that cannot, in practice, be equalized. Thus it is necessary to hide the filter from the line with loss. To hold the transmission distortion of signals to 0.15 db with 500 regulators (0.0003 db per regulator) requires a voltage loss of 23 db with the filter impedance changing by large factors from its nominal 25,000-ohm level. The power loss bridging on the 37.5-ohm (75 into 75) circuit is, of course, much greater.

The 7,266-kc pilot level at the line amplifier output is -16 dbm into 75 ohms. The filter and pad loss totals 24 db (voltage ratio) leaving an

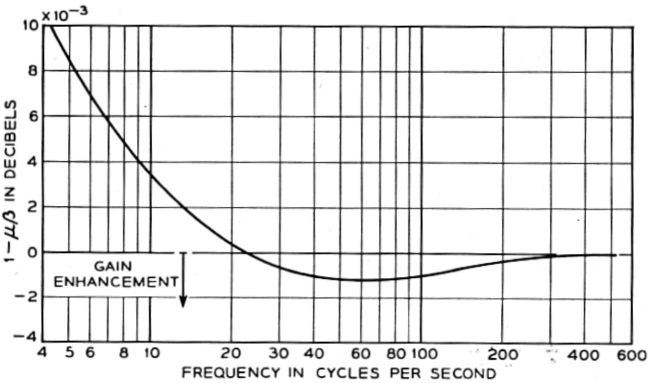

Fig. 20 — Feedback characteristic for the line regulator showing the gain enhancement effect.

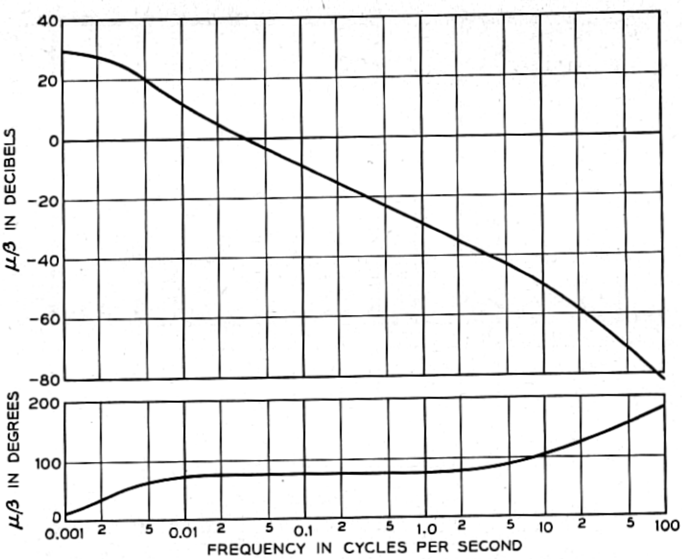

Fig. 21 — Loop gain characteristic for office regulators.

available pilot signal of about 0.002 volts in 25,000 ohms. In order to solve drift and stability problems in the dc circuits the pilot is converted to a dc voltage of 60 volts. This requires an amplifier-rectifier of 90 db voltage gain, stable with time and temperature.

As indicated on Fig. 23, the amplifier consists of three stages using

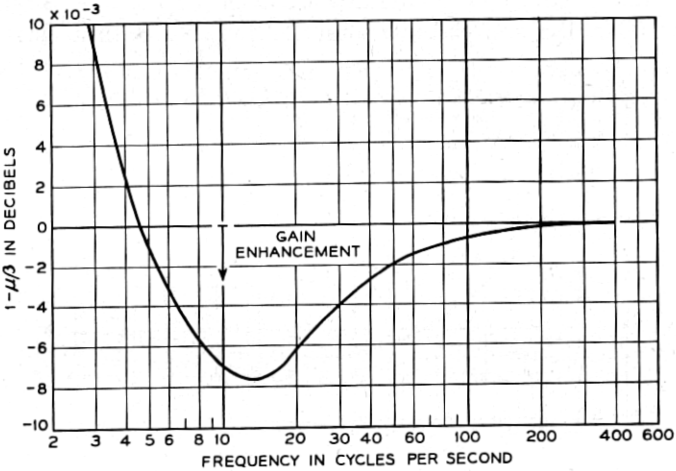

Fig. 22 — Feedback characteristic for office regulators showing the gain enhancement effect.

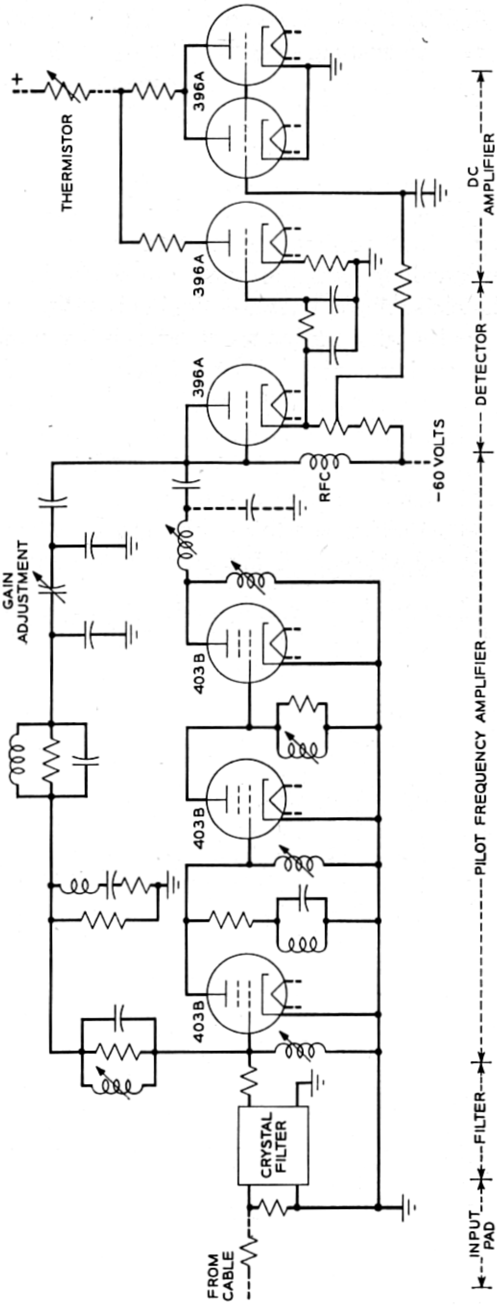

Fig. 23 — Simplified schematic of the line dynamic regulator showing the signal circuits.

403B (long life 6AK5) tubes. Feedback is taken shunt-shunt, output plate to input grid, to stabilize the input and output tuned circuits against Q changes with temperature. The regulators are designed to operate from −20° F to +160° F and the amplifier gain does not change by more than 0.3 db over this range.

The beta circuit contains an adjustable condenser divider for field gain adjustment. The tuned sections are heavily damped to get temperature stability but nevertheless compensate for the cutoffs of the μ circuit. The resultant loop gain and phase are shown in Fig. 24. It will be noted that the phase margin against singing is rather large, about 60 degrees. This permits tube replacement without retuning as well as protection against tuning changes due to time and temperature.

Grid-plate capacity places a limit on the permissible interstage impedance for stability. Thus the output circuit between the third stage and the rectifier is operated as a reactive transformer giving a voltage step-up of 2. This increases the output voltage obtainable without raising the impedance facing the third tube above 12,500 ohms.

About 16 db of local dc feedback is used on each stage to stabilize the

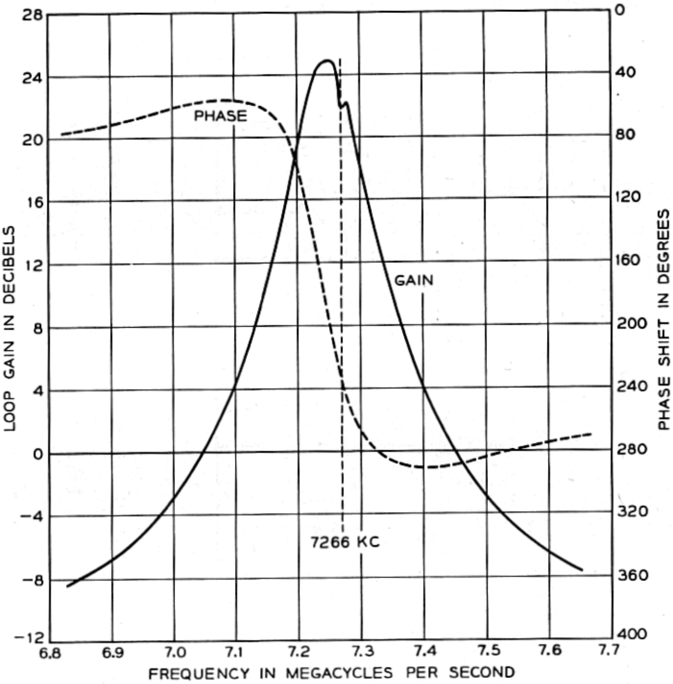

Fig. 24 — Loop gain and phase of the 7266 kc pilot amplifier.

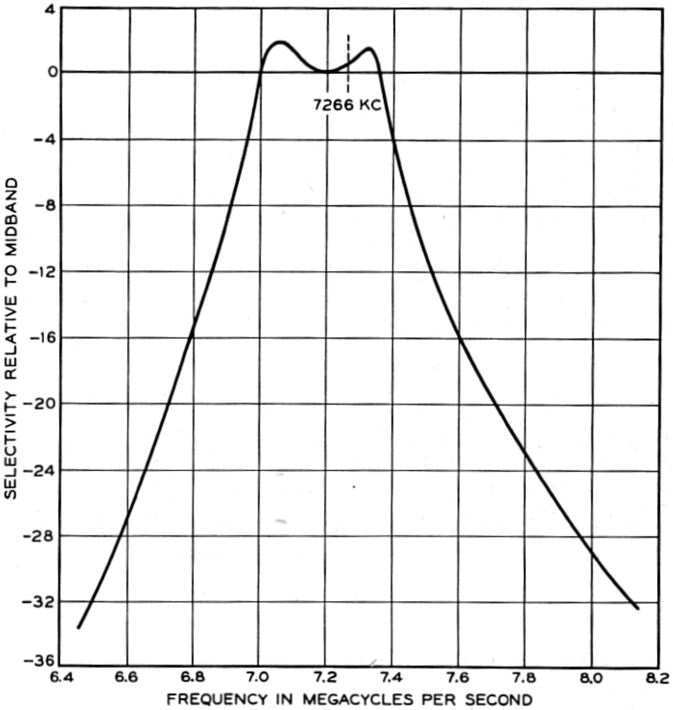

Fig. 25 — Regulator selectivity without the crystal filter.

cathode current. In so far as trans-conductance depends upon cathode current, trans-conductance changes are reduced. This is of material value in further reducing the effects of vacuum tube aging.

Fig. 25 shows the external gain of the 7,266-kc amplifier without the crystal filter. The filter response is shown in Fig. 26. The relatively wide 3 db bandwidth of ± 1.5 kc is to reduce the contribution of the filter to the gain enhancement problem. The large rejections to frequencies further removed from the pilot prevents operation of the regulator by signals other than the pilot. Also note that for very strong signals such as the television carrier at 4,139 kc the filter is aided by the amplifier selectivity.

The diode detector is also designed to reduce the effects of interference. The time constant of the detector is made short so that the output will follow envelope fluctuations up to about 40 kc. Thus the output of the detector in the presence of an interfering signal within 40 kc of the pilot becomes the power sum rather than the voltage sum of the two signals. This is readily understood from Fig. 27. Here E_p is

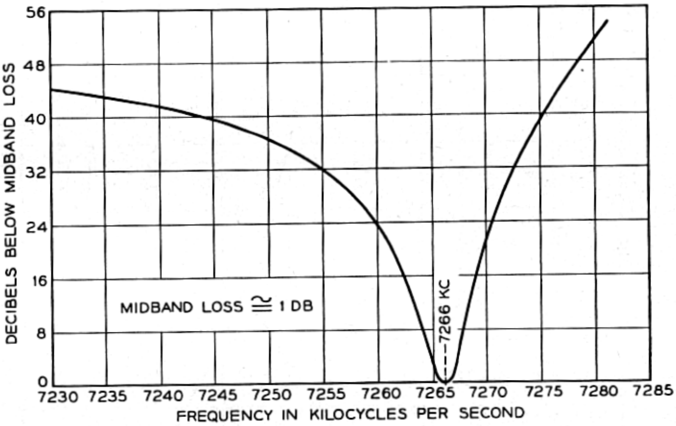

Fig. 26 — Loss characteristic of the 7266 kc crystal filter.

the normal rectified pilot. In the presence of the interfering signal E_i a diode detector with a long time constants will deliver a dc output of of $E_p + E_i$ and thus give voltage addition between the pilot and the interference. With a fast time constant the detector output can follow the nearly sinusodial envelope variations and the dc level is changed only slightly. The ac component may be suppressed by the cutoff of the dc amplifier, but, even if this is not the case, the thermistor being a thermal device responds to the total power rather than the peak amplitude. Thus the diode time constant is made long enough to hold over a few cycles of the pilot frequency but short enough to follow the important interference difference-frequencies.

The dc amplifier consists of three triode sections essentially in parallel

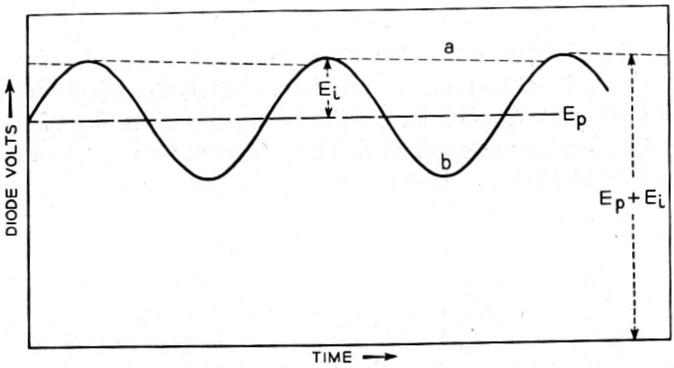

Fig. 27 — Diode detector output in presence of interference E_I. E_P is normal pilot signal. Curve a obtains with long time constant, b with short time constant.

but with the biases and feedbacks differing in order to provide an EI characteristic that corrects for sensitivity changes of the thermistor with operating current. This maintains the overall loop feedback relatively constant over the 1 to 20-ma current range. The thermistor is directly heated by the plate current of the dc amplifier in order to obtain single time-constant performance of the thermistor. The thermistor transmission, plate current changes as an input and pilot level as an output, is the main frequency characteristic of the regulator loop.

LINE THERMOMETER REGULATORS

It is possible to dilute the regulation system with less costly, less accurate regulators without undue loss of overall performance. This is

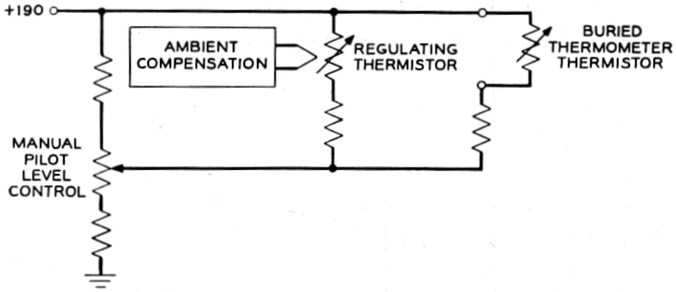

Fig. 28 — Thermometer regulator schematic.

accomplished by the use of thermometer regulators at alternate regulating points. These consist of a thermometer thermistor buried in the ground, electrically in parallel with the regulating thermistor. The circuit is quite simple as indicated by Fig. 28. Ground temperature changes vary the resistance of the thermometer thermistor thereby changing the current and resistance of the regulating thermistor. The manual control is used to effect initial alignment of the system. The regulating sensitivity is designed to slightly overcompensate for cable loss changes in order to somewhat ease the burden on the following dynamic regulator.

AMBIENT TEMPERATURE COMPENSATION

Both types of line regulators require the assistance of ambient temperature compensation of the regulating thermistor. Conventional compensation circuits would hold the thermistor resistance within about 20 per cent but this would produce an error of one db at a thermometer regulator and about 0.2 db at a dynamic unit. Thus an improved compensation scheme was required which would connect only to an indirect heater, the bead itself being already controlled by dc heating from the regulators.

The compensation circuit adopted is shown on Fig. 29. A second thermistor called the compensating thermistor is mounted in the same glass envelope with the regulating thermistor. The fixed resistor R_1 and the compensating thermistor together with transformer T form a bridge which is made a feedback path for tuned amplifier A. The feedback is positive when the compensating unit is cold so oscillation begins at the tuning frequency (4 kc). These oscillations heat the thermistor and tend to bring the bridge into balance. The bridge stabilizes at a

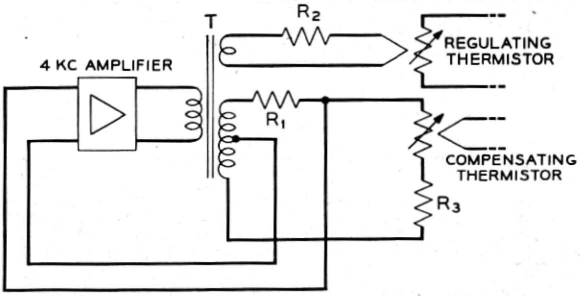

Fig. 29 — Ambient temperature compensation oscillator.

small unbalance just sufficient to yield a loop gain of unity. The level of oscillation is forced to that value which will maintain this small unbalance. Any changes in balance thereafter produce deviations of loop gain from unity and the oscillation level increases or descreases until the equilibrium is reestablished. Thus the level of oscillation changes with temperature but the resistance of the compensating thermistor is held constant.

Because the circuit supplies nearly perfect temperature compensation to the unit in the bridge a suitable fraction of the oscillator power may be fed to the heater of the regulating thermistor to achieve very close compensation of it. Resistors R_2 and R_3 are adjusted in manufacture to correct for slight differences between the two thermistors. Note that the compensating thermistor is provided with an unused heater to match the thermal properties of the two units.

The amplifier consists of a single 403B tube with 20 db dc feedback for current (and transconductance) stabilization. This feedback is vital because it also introduces a slight compressive action in the amplification of the tube and thereby prevents rapid wild changes in oscillation level. Bypassed dc feedback on an amplifier causes dc second order distortion to increase the bias and thereby reduce the transconductance. This effect overcomes the tendency of the third order distortion to create expansion in this particular tube. If the thermistor response were fast compared to the reciprocal of the bandwidth of the amplifier the compression action would be unnecessary. However with an audio frequency amplifier and a 100 second thermistor the compression is essential in preventing motorboating.

The field limits on the compensation of the regulating thermistor over the range -20 to $+160$ degrees F are ± 3 per cent in resistance due to all causes including manufacture and aging. Specific units can be adjusted to yield compensation to a fraction of a per cent.

OFFICE REGULATORS

The L3 office regulators are similar in design to the line regulator. However the office regulators operate their regulating networks via an analog computer and, of course, a variety of pilot frequencies are employed. Because signals are dropped at offices, higher loop feedbacks are used to insure accurate equalization. However, temperature variations are smaller and conventional thermistor ambient temperature compensation is adequate. Also the smaller number of office regulators permits less isolating loss for nick effect (except for the 7,266-kc office regulator).

The lower levels of the pilots (except 7,266) are compensated by reduced isolation loss, (12 instead of 23 db), and reduced detector level (40 instead of 60 volts). Thus the gain required is not sustantially increased. The pilot amplifier design is therefore different primarily in the tuning frequency and in the simplifications in the lower frequency units permitted by the higher permissible interstage impedances.

The diode detector feeds a cathode follower to obtain the dc voltage representing the deviation of the pilot from its assigned value as a low impedance source to feed the computer. The appropriate signals from the computer are fed to the dc amplifier. This amplifier differs from that used in the line regulators in that (1) a push pull input is provided, (2) higher gain is required to produce greater feedback, 30 db, and overcome computer losses, 5 db and (3) the output stage supplies somewhat higher currents, 1 to 30 ma, (except 7,266) because the regulating networks use a lower impedance thermistor.

OTHER REGULATOR FUNCTIONS

The regulators are also used for alarm and pilot indicator functions. At line dynamic regulators the current flowing through the diode detector load resistance is also passed through a relay to obtain an alarm indication whenever the pilot level deviates from normal by more than 3 db. At offices similar arrangements operating on a 2 db error are provided both for alarm and switch initiation purposes. If any pilot deviates by 2 db the service switches to the spare line. In addition fast switch initiation is obtained from the 7,266-kc regulator by direct connection to the detector output. This arrangement avoids the time delay of the relay operation. For pilot level indication the diode load current is read on appropriate meters. This avoids the necessity of providing separate pilot level indicators and is possible because of the reliability and stability of the regulator amplifiers.

MECHANICAL FEATURES

Figs. 30 and 31 are views of a regulator seen from the wiring side and from the top respectively. The chasis consists of two steel end plates riveted to steel angles, with a punched copper plate screwed to this

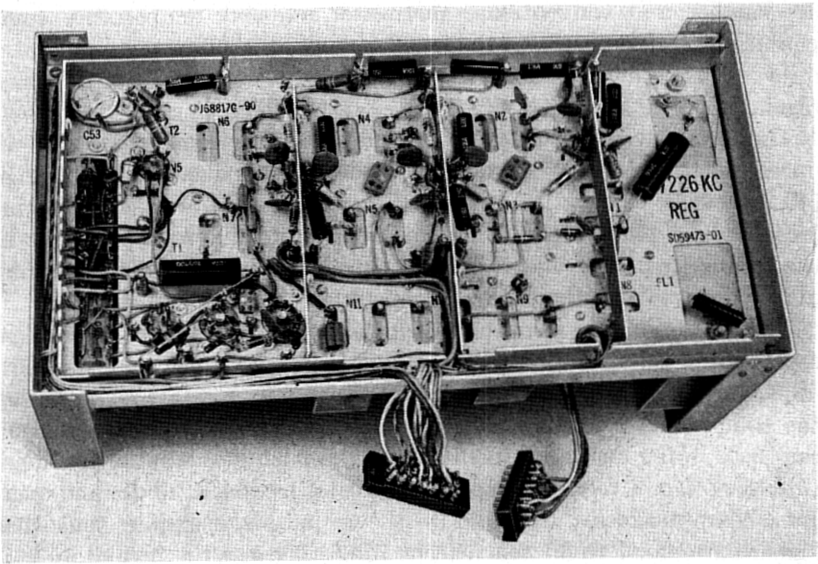

Fig. 30 — Line dynamic regulator as seen from wiring side.

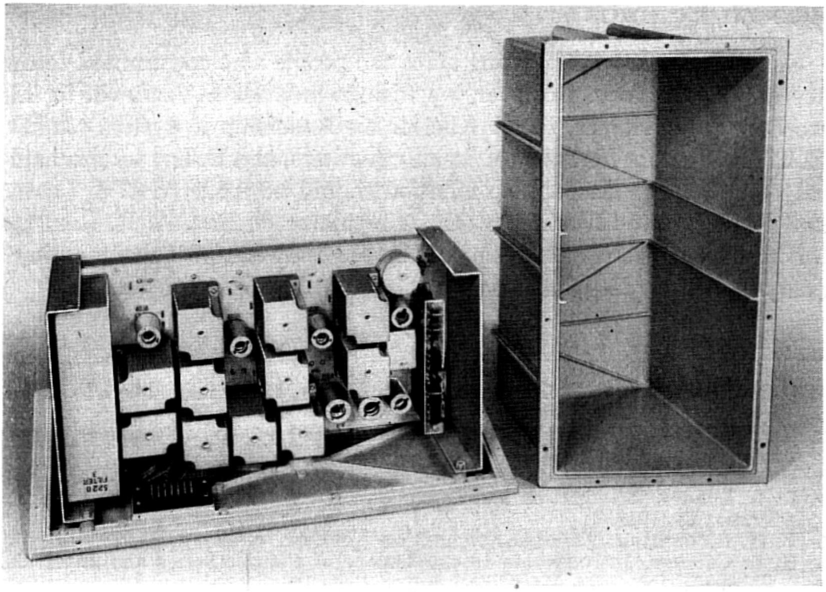

Fig. 31 — Top view of line dynamic regulator showing case.

structure. The salient feature of this type of construction is that one universal punched plate can be used for all the regulators (including the thermometer regulator), any individual regulator being fabricated by mounting the necessary component cans and vacuum tube sockets on it. Power wiring and all leads that are not critical as to length or placement can be run in the wiring trough around the edge of the chasis shown on Fig. 30. This eliminates the necessity of lacing the wires into a cable, a significant saving in production effort.

The component cases are shown on Fig. 31. They are zinc die-castings and contain network elements assembled on stypol forms which fit inside the cans. One universal case accomodates sixty-four different combinations of elements required by the various regulators. The necessary wiring of the individual cases may be completed before assembly on the regulator chassis. This feature also saves production effort.

The whole chassis is mounted inside a die-cast zinc housing, and all power and test leads are brought into the regulator through airtight connections. The two parts of the housing when assembled together are made airtight by a rubber gasket which fits into the slot around their inner edges. The general construction features and size of the regulator assembly can best be understood by inspection of the illustrations.

Acknowledgements

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References

1. C. H. Elmendorf, A. J. Grossman, R. D. Ehrbar, R. H. Klie, The L3 Coaxial System — System Design, see pp. 781 to 832 of this issue.
2. L. H. Morris, G. H. Lovell, F. R. Dickinson, The L3 Coaxial System — Amplifiers, see pp. 879 to 914 of this issue.
3. H. W. Bode, Variable Equalizer, Bell Sys. Tech J., April, 1938.
4. R. L. Lundry, Attenuation and Delay Equalizer for Coaxial Lines, A.I.E.E., Trans., **68,** 1949.
5. P. H. Richardson, Variable Attenuation Network, patent 2,096,028.
6. H. S. Carslaw, Introduction to the Theory of Fourier Series and Integrals, Third Edition, 1930, MacMillan & Co., Page 148.