The L3 Coaxial System

System Design

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The L3 coaxial system is a new broadband facility for use with existing and new coaxial cables. It makes possible the transmission of 1,860 telephone channels or 600 telephone channels and a television channel in each direction on a pair of coaxial tubes. The principal system design problems and the methods used in their solution are described. The over-all system is described in terms of its components and their location in the system.

1.0 Introduction

The L3 coaxial carrier system is a new broadband transmission system capable of transmitting either 1,860 telephone message channels or 600 message channels and a 4.2-megacycle broadcast television channel, in each direction, on a pair of coaxials. The system is designed so that signals transmitted over any of these channels will meet high quality Bell System objectives after 4,000 miles of transmission.

The system is composed of auxiliary or line repeaters spaced at approximately four-mile intervals along the cable route and connecting terminal or dropping repeaters where telephone or television signals are translated to or from the L3 frequency band. Equalization equipment, power generating and power transmission equipment, and maintenance equipment are required at 100 to 200-mile intervals.

Planning and exploratory development for the system was started late in 1945 with the objective of designing a trunk route system which would provide the maximum channel capacity on the existing coaxial cable consistent with the state of the repeater art. At that time and for the next four years a large amount of new cable employing the 600 channel-three megacycle L1 coaxial carrier system was being installed or projected.[1]

Since a major field of use of the L3 system was to replace the L1

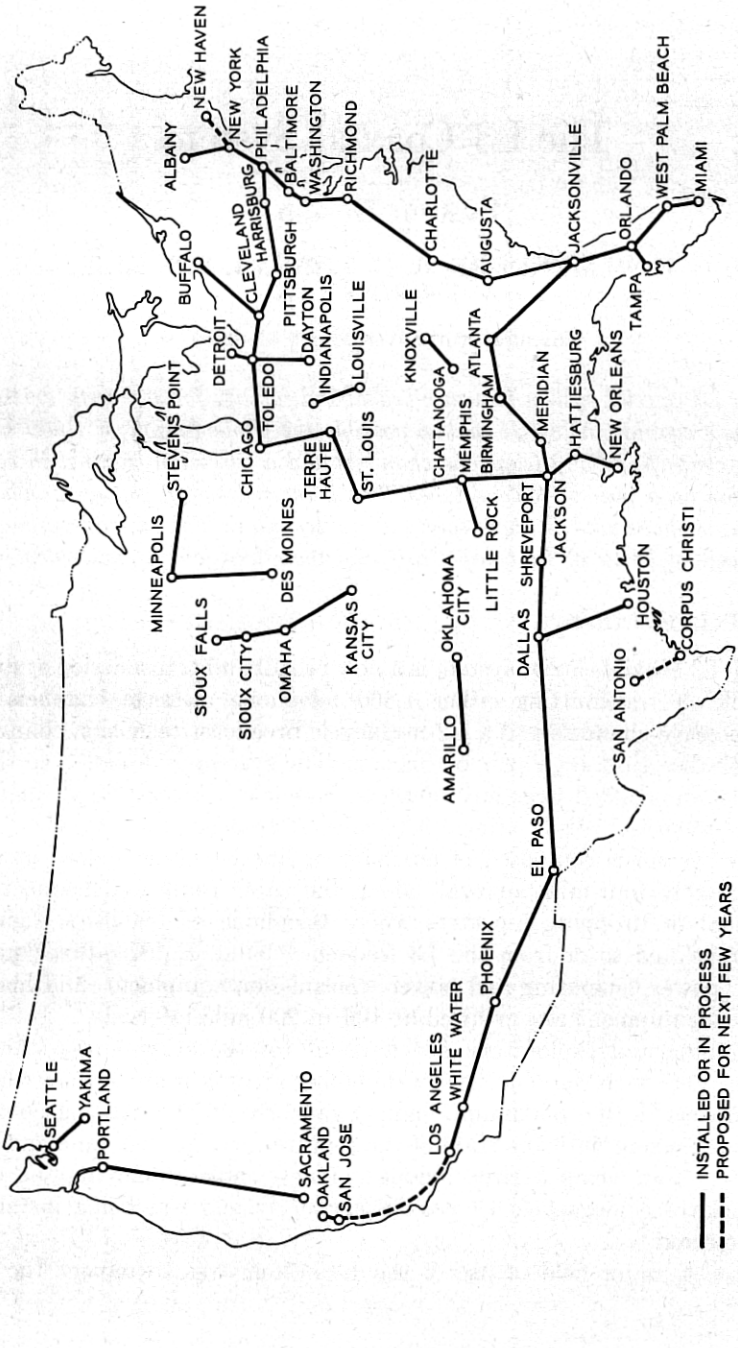


Fig. 1 — Coaxial cable routes.

system on existing routes, the design of the L1 system, the cable, and the cable route layouts presented the L3 system with a definite plant framework. The present day network of L1 coaxial systems is shown in Fig. 1. There are about 8,000 route miles of cable installed of which about 70 per cent consists of eight coaxials, the remainder consisting of six and four coaxials. About 70 per cent of this cable uses coaxials with a ⅜″ diameter outer conductor, the present day standard. The remainder uses the older 0.27″ diameter coaxials. All but a few miles of this cable is plowed into the ground or placed in underground conduit. A piece of a typical eight coaxial cable is shown in Fig. 2. Normally, the coaxials are included in a lead sheath with interstitial pairs which are used for

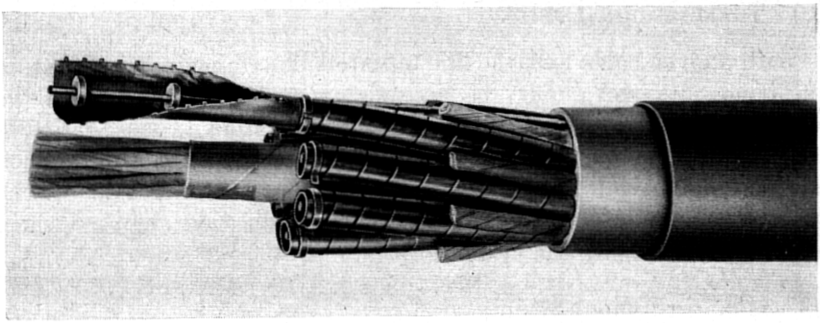


Fig. 2 — An 8-coaxial cable.

control purposes. In many cases additional quads are included in the cable for other types of transmission systems.

The broad objectives of the L3 system planning were:

1. The existing cable was to be reused. Thus, the cable loss and its variation with temperature, the cable irregularities due to manufacturing and splicing, and the power transmission capabilities of the cable became basic restrictions on the design of the L3 system.

2. The L1 telephone terminal equipment was to be reused. This equipment involves channel banks, group and super-group equipment and carrier supplies.[2] This limited the system planning to the use of frequency division multiplex on a single sideband carrier suppressed basis.

3. It would be desirable to reuse existing L1 repeater locations and buildings. The L1 auxiliary repeaters are spaced at eight mile intervals and housed in 6′ x 9′ concrete block huts. The L1 main repeaters are spaced at 40 to 160-mile intervals largely dictated by geographical and power transmission considerations.

4. Sufficient bandwidth should be provided so that a black and white television signal of at least four-megacycle quality could be transmitted simultaneously with 600-message signals, the message capacity of the L1 system. Alternatively, as many message channels as possible should be transmitted when there was no need for television service.

5. The channels should meet Bell System high quality signal-to-noise and equalization objectives after 4,000 miles of transmission.

Section 2 of the paper is devoted to a discussion of the principal system design problems and descriptions of methods used in solving these problems. Section 3 contains descriptions of the components of the system, their locations and their functions.

2.0 Transmission Design

With a given cable loss, the line repeaters determine in large measure the bandwidth and quality of transmission and the economics of the system. The basic system plan therefore evolves from a consideration of the signal-to-noise and equalization performance — i.e., the transmission stability — that can be designed into the repeaters. This leads to the development of broad signal-to-noise and equalization analyses which guide and coordinate the system design.

2.1 SIGNAL-TO-NOISE DESIGN

Simply stated, the signal-to-noise problem is to adjust the repeater spacing and bandwidth of the system so that channel objectives can be met with the repeater noise, linearity, and gain performance that the electron tube and circuit art permit. In detail this means the following: (1) to translate the broad transmission objectives on message and television channels into detailed requirements on noise, specific modulation products and compression; (2) analyzing the amount of these interferences that result from various repeater design choices; (3) determining the effect of signal wave form and frequency allocations on both the channel requirements and the repeater performance; and (4) integrating these studies into a specific system design plan that meets the objectives.

2.11 *Telephone Channel Interference Objectives*

The amount of noise, tone interferences or crosstalk that is considered tolerable in telephone channels is generally determined by judgements involving the subjective reactions of representative observers to specific interferences on typical transmitted signals and by the cost of providing a given grade of service. The broad objectives for message channels stem from early unpublished work on transmission standards. The interference and load capacity requirements for transmission systems involving large numbers of message channels were developed by Dixon, Holbrook and Bennett.[3, 4] In effect, they provide techniques for translating channel objectives into linearity and power handling requirements on repeaters, taking into account the statistical properties of individual and multi-channel speech. Based on the data and techniques in these papers, the requirements on individual channels shown in Table I can be derived. These requirements in themselves form an important basis for the signal-to-noise design of the system. However, in a highly refined system design it is necessary to extend our notions of requirements somewhat further.

In the L3 signal-to-noise design the message channel requirements of Table I were used as the initial basis for study. However, when specific interferences of a complex nature were found to be limiting, the wave forms and the probability of their occurrence were examined in detail. As a result of these studies, two distinctive types of interferences were found to be important when the system is used to carry message and television signals simultaneously. The first of these, due to both second and third order modulation involving multifrequency key pulse signals and components of the television signal, has the characteristics of intermittent musical tones. The second, due to the second order difference products generated by the television signal components, produces tones in the message channels which vary in amplitude and frequency as the television signal changes with picture content. Both types of interference were generated in the laboratory and recorded on tapes. From these tapes, records were cut and then used in a series of subjective tests

TABLE I — SUMMARY OF MESSAGE CIRCUIT OBJECTIVES
(*Allowable Zero Level Interference in 3 kc band*)

Source of Interference	Type of Interference	dba (message Weighting)	dbm* Unweighted
Terminals.......	Largely spillover between channels, cross-modulation, and crosstalk	+32	−50†
Line............	Noise and multichannel modulation	+36	−46†
Line............	Unintelligible crosstalk and babble	+24	−58†
Line............	Tones	+24	−61‡
Total........	All sources	+38	−44†

* The translations from dba to dbm are effected by noting that a 3000 cycle band of flat noise with one milliwatt of power equals +82 dba and that one milliwatt of 1000 cycle single frequency is equal to +85 dba.
† Interference assumed evenly distributed over 3000 cycle band.
‡ Tones assumed to be at 1000 cycles.

which were made to determine the maximum permissible magnitudes consistent with other important message circuit objectives.

2.12 *Television Channel Interference Objectives*

The amount of noise and single-frequency interference that can be tolerated in a commercial grade television channel again depends on judgements involving the subjective reactions of observers and the cost of providing a given grade of service. The broad objectives are based on subjective measurements which have been reported on by Messrs. Mertz and Baldwin.[5, 6, 7] From this work it has been determined that 95 per cent of the observers consider a signal-to-noise ratio of 40 db (composite signal to rms noise) tolerable, providing the noise has a frequency characteristic that rises about 11 db across the video band. Likewise the tolerable single frequency interference can be set at −70 db (peak sine wave below composite signal) if the interference falls below about one megacycle. The requirement becomes more lenient for interferences falling in the upper part of the band.

Again, for a refined system design, more detailed account must again be taken of the requirements on short duration interferences, the probability of interference occurring, and the exact frequency in the television spectrum that an interference occurs.

In the L3 signal-to-noise design the broad television channel objectives outlined above were used except when a specific complex interference was found to be limiting. For complex interferences, three additional types of requirement data were used; (1) tests were made to determine visual thresholds relative to steady tones of short bursts of energy such as occur in the television channel due to switchhook "bang-up" and multifrequency key pulsing signals in the message channels. Fig. 3 shows the relation between the steady state and transient requirement: (2) advantage was taken from the fact that interferences falling between the 15.75-kc line scan multiples of the television signal would be less interfering than unwanted energy falling directly at the line scan multiples; and (3) a judgement was used that the tolerability of an interference depends on its probability of occurrence. The judgement was not made on a quantitative basis but when an interference was found to exceed its requirement by a few db two or three times a day it was ignored in the signal-to-noise design.

2.13 *Frequency Allocations*

The final frequency allocations shown in Fig. 4 are a result of the signal-to-noise design. The principal features were determined on rather

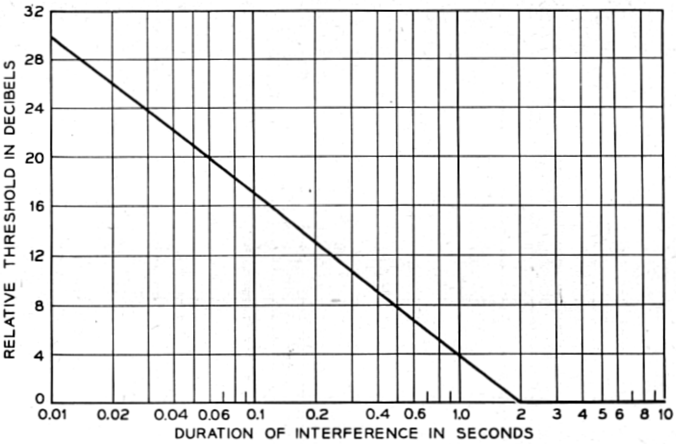


Fig. 3 — Television bar pattern threshold versus duration.

general grounds. When the system is arranged for combined television-message transmission, the television channel is placed above the message channels so that the second harmonic of the television carrier and its immediately adjacent side bands will fall at the top edge of the band where the requirement is more lenient. Likewise, the line repeater noise tends to rise with frequency as does the amount of noise that the television channel can tolerate. Details of the frequency allocations shown on Fig. 4 will be discussed in later sections.

Pilot frequencies, indicated on Fig. 4, are transmitted to control the transmission characteristic of the system as described in a companion paper.[10] The frequencies, and the power at which the tones are transmitted, were selected on two bases; (1) where possible, frequencies used for similar purposes in the L1 system were selected for possible economies in pilot supply design and manufacture; these are the 556, 2,064 and 3,096-kc pilots; and (2) the transmission of these pilots should not materially degrade the signal-to-noise or load capacity performance of the system. The latter requirement led to a careful study of cross-modulation products involving the pilot frequencies to assure that message and television objectives would be met.

2.14 *Repeater Performance*

The details of the amplifier design and the factors which determine its performance are covered in a companion paper.[8] For purposes of the signal-to-noise design it is sufficient to know the noise power vs frequency characteristic, the second and third order modulation coefficients

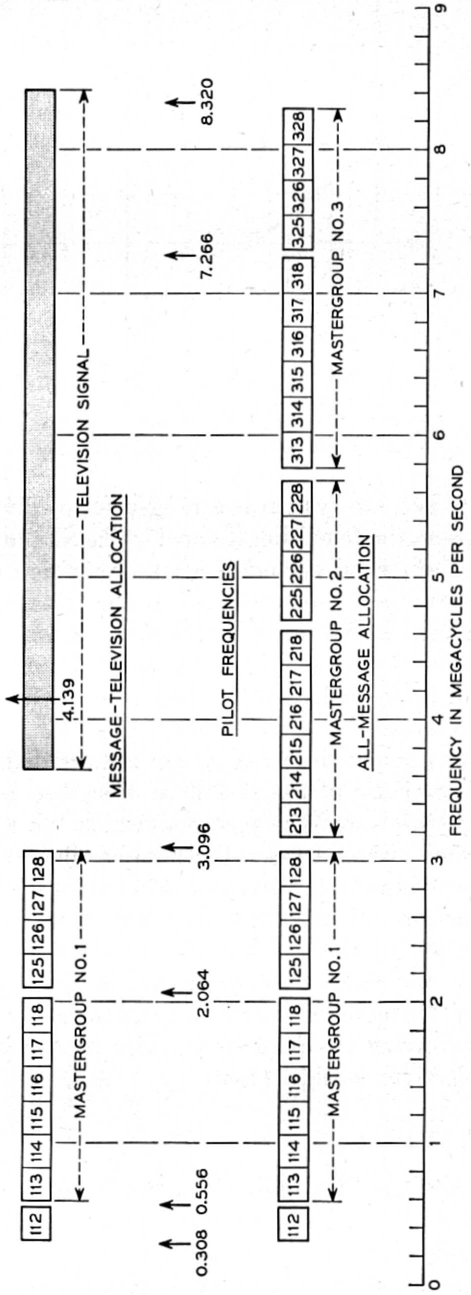


Fig. 4 — L3 frequency allocations.

of the repeater as functions of frequency and the overload performance of the repeaters. These factors depend on the repeater spacing and cable loss characteristic, electron tube parameters, achievable feedback, and the bandwidth to be transmitted. Thus, in the design procedures the dependence of these properties on repeater gain and bandwidth are determined and used in adjusting the system parameters for a final compatible design. Figs. 5 and 6 show the noise and linearity properties of the final L3 repeater. The four mile repeater spacing requires a repeater gain shown on Fig. 7.

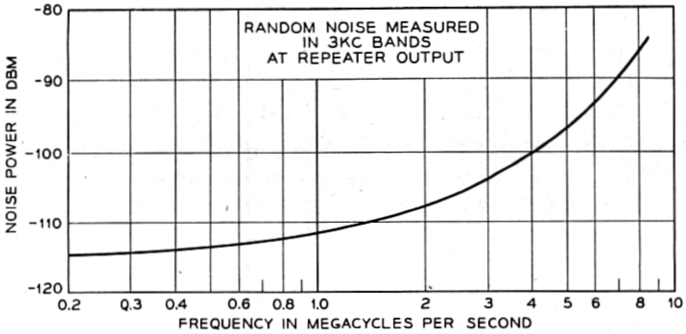


Fig. 5 — L3 Auxiliary repeater noise characteristic.

2.15 SIGNAL MECHANISMS

A signal-to-noise plan which contemplates transmitting the complex wave form of the combined telephone and television channels through 1,000 auxiliary amplifiers and about 200 flat amplifiers with performance factors that are variable with frequency will depend very strongly on the detailed analysis of the interactions between the signals and the repeater system characteristics. In developing this aspect of the signal-to-noise design four related phenomena had to be examined in detail.

2.151 *Intermodulation Between Signals in Different Parts of the Band*

In the classical multichannel modulation theory for a large number of message channels, the modulation noise generated by interaction of the speech signals due to the non linear characteristics of the amplifier is shown to be equivalent in interfering effect to random noise. In addition to this type of interference in message channels, cross modulation between components of the message and television signals result in a host of specific individual modulation products which have been examined by determining their amplitude, duration and probability of

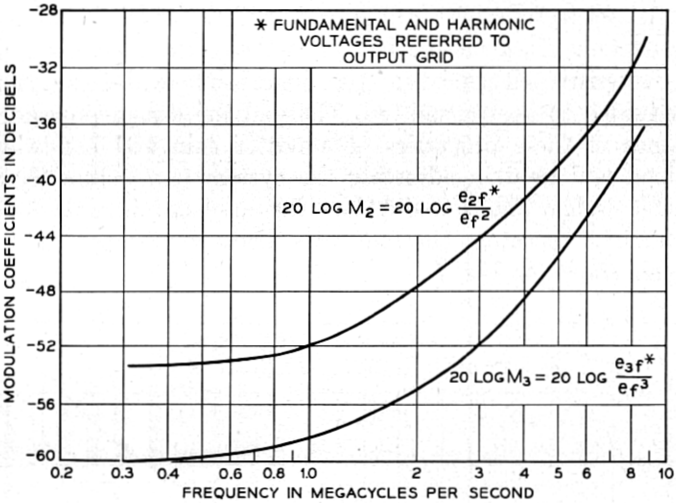


Fig. 6 —L3 amplifier modulation coefficients.

occurrence and then relating them to the requirements previously discussed. Approximately 400 different products or groups of products were studied in the design of the L3 system. All but about thirty of these were found to be of negligible importance for the signal levels and frequency allocations being given serious consideration. On final analysis six of these thirty products were found to be controlling in establishing system levels. Fig. 8 shows the generating signals and the products they form for the six most critical products. The exact way in which the critical pro-

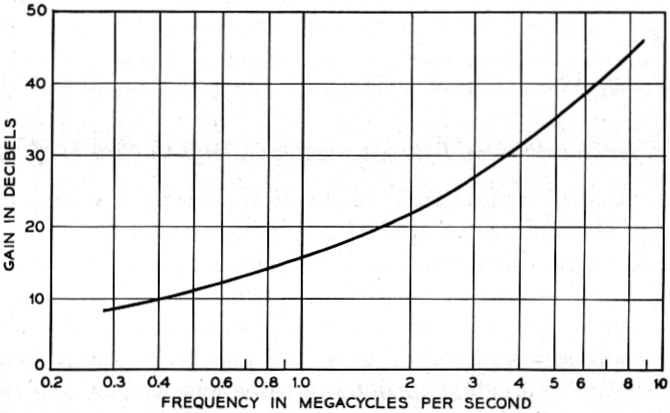


Fig. 7 — L3 repeater gain characteristic.

ducts entered into the determination of signal levels and frequency allocation will be discussed later.

2.152 *Location of the Television Carrier Relative to the Telephone Channel Carriers*

Among the important modulation product types is one formed by difference frequencies involving components of the telephone and television signals, see Fig. 8(d). These interferences fall back into the telephone band and are of different magnitudes depending, among other things, on which components of the television signal produce them; those

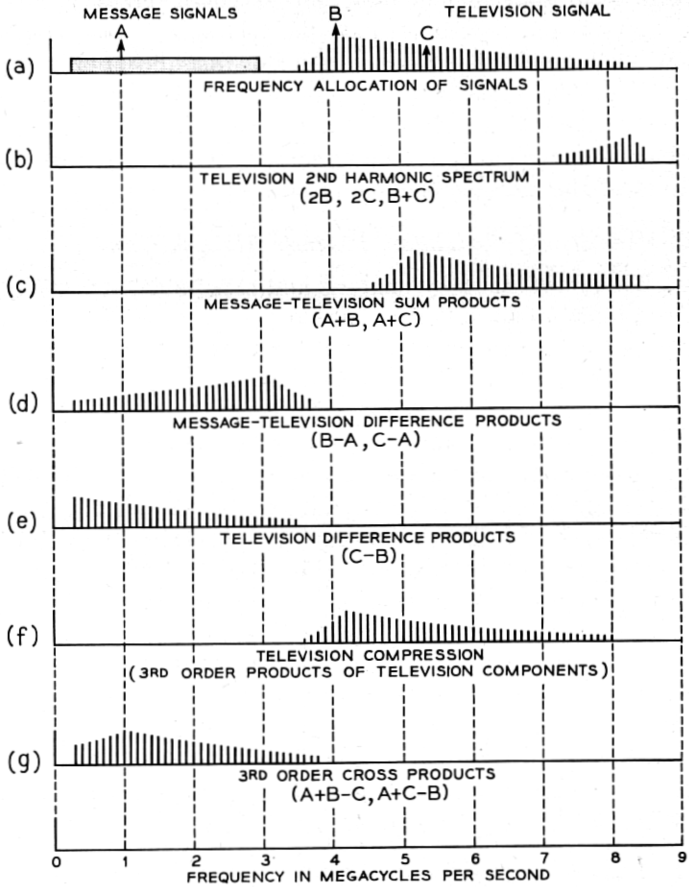


Fig. 8. — L3 coaxial system. Critical modulation products in combined message-television application.

produced by the television carrier and adjacent line scan multiples are by far the strongest.

The energy in a disturbing telephone channel tends to be concentrated near the 1,000-cycle point in the voice frequency band. By careful choice of the television carrier frequency, the difference products produced by cross modulation between telephone signals and the high magnitude television signal components can be made to fall at frequencies such that the high energy portions of these products are greatly attenuated by the cut-off characteristics of channel filters.

The message channels are spaced at 4-kc intervals controlled by carrier frequencies which are multiples of 4 kc. To obtain the maximum advantage from the channel filter cut-off characteristic as described above, it was found desirable to set the television carrier frequency 1 kc below a 4-kc multiple. A direct result of this allocation is a gain of 12 db in television signal-to-noise performance over what could be realized if the carrier had been set at a 4-kc multiple. Such an allocation would have required a 12 db lower magnitude of television signal in order to meet the message channel objectives.

2.153 *Addition of Modulation Products Along the Line*

It has been established by analysis and experiment, that in a multi-repeater system second order modulation products tend to accumulate on a power basis while certain third order products tend to add on a direct or voltage basis. This direct addition of third order products depends on the slope of the phase curve being the same over small frequency intervals from repeater to repeater. In multi-channel telephone systems, the locations of channels in the frequency band are shifted at intervals along the line to avoid this direct addition of third order products. In the combined telephone-television application of the L3 system the A+B−C product illustrated in Fig. 8(g) is formed. Since the B and C components are television line scan multiples which cannot be shifted in location, certain components of this type product would add directly in a 4,000-mile system. If this were allowed to take place the requirements would be exceeded by many db. However, by placing the delay distortion equalization only in the television band at approximately 200-mile intervals the phase of these products can be shifted so that rms addition of products accumulated over several 200-mile links of the system may be assumed.

2.154 *Wave Form of the Transmitted Television Signal*

Early studies of L3 led to the conclusion that the most economical method of transmitting the television signal would be by amplitude modulation of a carrier with one sideband partially suppressed, i.e., vestigial sideband transmission. There remained, however, three major problems for detailed study; (1) the transmission of dc components of the video signal; (2) the per cent modulation of the carrier which for convenience is defined in terms of "excess carrier ratio", the ratio of the peak (white) signal to the peak-to-peak composite signal as measured in the carrier frequency envelope; and (3) the sign or sense of modulation, that is, whether increasing or decreasing brightness should correspond to increasing signal voltage on the high frequency line. Typical wave forms illustrating the alternatives are shown in Fig. 9.

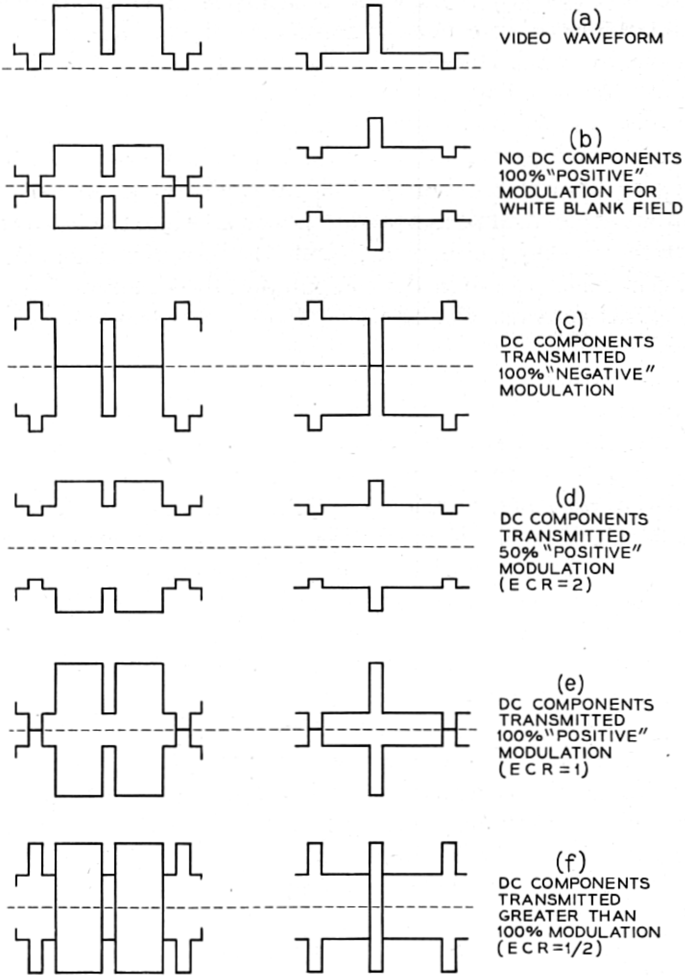


Fig. 9 — Typical television signals. Alternative carrier frequency waveforms.

The solution to each of these problems required an understanding of how the various alternatives would be affected by the system noise and linearity performance and an understanding of representative television viewing tube performance with respect to susceptibility to different types of interference. In analyzing the effect of system performance on these problems, it was found that non-linearity (cross modulation) would produce interferences in the television band which, while very complex electrically because of the effect of cross modulation involving line scan components of the signal, would produce the same effect on viewing tubes as single frequency interferences, i.e., bar patterns. Further simplifications were made in the analysis when it was found that such interferences were most visible in relatively large areas of television pictures having essentially constant brightness. During the time intervals corresponding to such areas, the video frequency voltage of the television signal is essentially constant and therefore, in the cases of interest, it could be assumed that the magnitude of the television carrier would also be constant during such intervals. Thus, to compute the magnitude of any modulation product which falls into the television band and which has as one of its components the television signal itself, it is found convenient to use in the computation the magnitude of the television carrier corresponding to either black or white portions of a picture signal. (The reason for intermediate shades of gray being less susceptible than either black or white is discussed below).

To evaluate the effect of television viewing tubes on wave-form problems, a number of tests were made to determine blank field threshold values of single frequency interference as a function of frequency for typical viewing tubes. Furthermore, judgements were made as to what might be expected of future viewing tubes with respect to achievable high light brightness, contrast ratio, and operating characteristics. As a result of these tests and judgements, a series of requirements were derived on the basis of long range objectives to be met for these projected characteristics. The results of these tests and judgements are summarized in Table II.

Using the parameters and methods of analysis outlined in the preceding paragraphs, the relative system performance achievable with each of the carrier frequency wave forms of Fig. 9 was computed or determined by observation. For example, these wave forms are all drawn to the same peak-to-peak amplitude. If we assume that the coaxial system is limited only by the peak amplitude transmitted we may use Fig. 9 to determine relative signal-to-noise performance directly by measuring the peak-to-peak magnitude of the composite signal voltage (sync tip to white) transmitted.

Fig. 9 may also be used to obtain relative modulation performance. For this purpose, the following factors must be considered; (1) the magnitude of the signal generating the interference ("black" or "white" carrier magnitude); (2) whether the interference is proportional directly or to the square of the carrier magnitude; (3) relative interference sensitivity in black or white portions of the picture; and (4) deviations from the Weber-Fechner law as the brightness is varied over its full range. The relationships among these factors were used to establish that for all cases of interest, bar patterns due to cross modulation are always more interfering in either black or white portions of a picture than in an intermediate gray area.

Table III shows the relative system performance for the five carrier frequency wave forms of Fig. 9. For comparison purposes, the signal-to-noise and signal-to-bar pattern ratios are all related to Fig. 9(f).

Table II — Television Viewing Tube Characteristics Assumed for L3 Signal-to-Noise Analyses

1. Brightness-grid voltage characteristic of viewing tubes follows 5/2 power law: $B \alpha e_g^{5/2}$.
2. Maximum high light brightness of viewing tubes will be 150 foot lamberts.
3. Contrast ratio of viewing tubes will be 150:1.
4. Viewing tubes will have interference sensitivities which vary with brightness in accordance with the characteristic of Fig. 10.
5. The visibility of bar patterns will decrease with frequency in accordance with the characteristic of Fig. 11.
6. Deviations from the Weber-Fechner law may be assumed to follow the curve of Fig. 12. This law states that "the minimum change in stimulus necessary to produce a perceptible change in response is proportional to the stimulus already existing."

It is obvious from Table III that the signal is transmitted most efficiently at an excess carrier ratio of one half. The wave form of Fig. 9 (f), which illustrates excess carrier of one half, is the one used in L3. Television terminal circuit problems arising from this choice of carrier frequency wave form are discussed in another paper.[9]

2.16 *Signal Levels and Repeater Spacing*

In a broadband system like L3, the problem of determining the repeater spacing is made complex by the large number of parameters that must be considered. The approach to this problem that has been used to advantage in the L3 design is to assume several reasonable values of repeater spacing and determine for each the system performance achievable with various combinations of important parameter values. This method also permits evaluation of the effects on repeater spacing due to variations in parameters so that it is possible to form judgements as to the most economic design.

TABLE III — RELATIVE PERFORMANCE OF ALTERNATIVE TELEVISION WAVEFORMS

Waveform*	Relative Signal-to-Noise Ratio in db†	Relative Signal-to-Modulation Ratio (Bar Patterns) in DB‡	
		Group 1	Group 2
9b no dc	+10.2	+11	+11.3
9c neg. mod.	+6	+9.5	+12.5
9d ECR = 2	+12	+14	+15.5
9e ECR = 1	+6	0	+6
9f ECR = 1/2	0	0	0

* The waveforms are numbered to correspond to those given on Fig. 9.
† All values referred to E.C.R. = ½; plus values indicate poorer performance.
‡ All values referred to E.C.R. = ½; Group 1 products are those whose magnitudes are directly proportional to the carrier magnitude. Group 2 products are those whose magnitudes are proportional to the square of the carrier magnitude.

One of the important factors in setting repeater spacing is the magnitudes at which signals are transmitted in the system and the relation between these magnitudes and signal-to-noise and repeater overload performance. In the all telephone system (1,860 channels), the telephone levels (db with respect to the transmitting toll test board) were set to optimize signal-to-noise performance. To avoid penalizing the channels in the upper part of the band where random noise tends to be much higher than at low frequencies, the levels of the three mastergroups are staggered. At the output of any repeater in the high frequency line, the nominal level of mastergroup No. 1 is −21 db, that of mastergroup

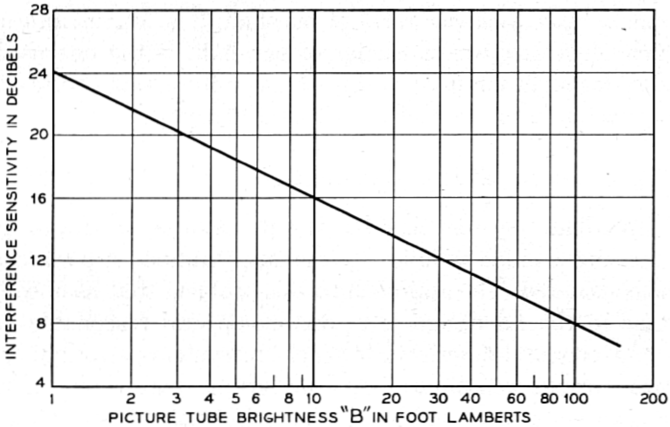


Fig. 10 — Picture tube interference sensitivity assumed for L3.

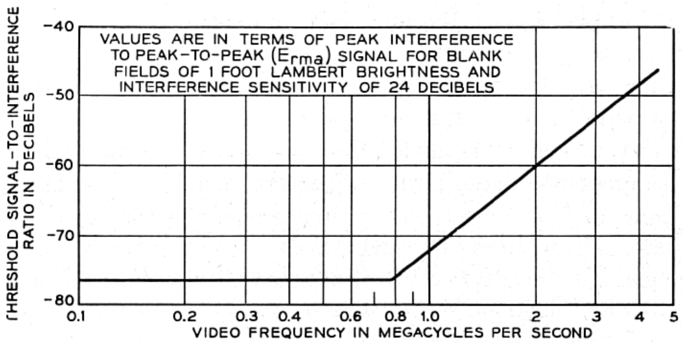


Fig. 11 — Threshold values for bar patterns.

No. 2 is −16 db and that of mastergroup No. 3 is −11 db. As a consequence of setting levels in this way, the random noise in the message channels is approximately 2 db higher on the average than modulation noise. It can be shown that with both second and third order modulation products contributing, and with third order somewhat predominant, this relation between random noise and modulation noise produces optimum signal-to-noise performance. With these levels, the 1,860 channel telephone system has approximately 6 db margin against repeater overload which, for L3 purposes, has been defined as the point at which the repeater modulation coefficients just depart from their constant small-signal values. The signal-to-noise objective of +29 dba at the −9 db level is met with about 2 db margin.

When the system is used to transmit television and message signals simultaneously, the level of the telephone channels in mastergroup No. 1 at the repeater output is the same as that of mastergroup No. 1 in the all-telephone application, −21 db. The most convenient measure of the television signal is the power of the unmodulated carrier at the output of a repeater. Its value is +6 dbm. Due to the inter-relations

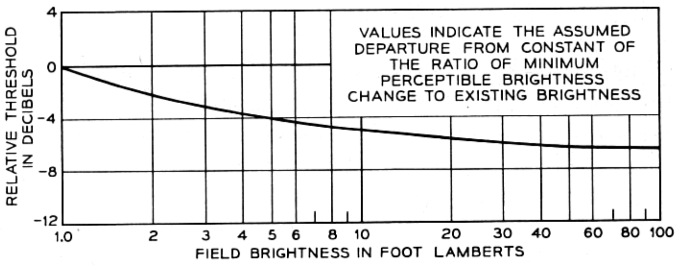


Fig. 12 — Assumed deviation from Weber-Fechner law.

between the two signals, the limitations on achievable maximum transmission levels or magnitudes arise from certain types of second order modulation products rather than from optimizing signal-to-noise performance as in the all-telephone application. One of these types consists of sum products of cross modulation between telephone and television signal components. These form bar patterns and, in so far as signal-to-interference ratio is concerned, are independent of the television signal magnitude. Thus, adjusting such products to equal the appropriate requirement has the effect of setting the maximum permissible magnitude or level of the telephone signal. The second type of limiting product is due to difference frequencies formed by cross modulation among the television signal components. These fall into the telephone channels and, after the telephone level has been set as described above, permit calculation of the maximum permissible television signal magnitude.

With signals set at −21 db level for telephone and +6 dbm unmodulated carrier for television, all of the critical products discussed in section 2.15 above and illustrated on Fig. 8 have adequate margin. The 40 db signal-to-noise objective for 4,000-mile television transmission is met with about 2 db margin and long haul (4,000 mile) message channels meet the +29 dba at the −9 db level objective with about 5 db margin. A margin of about 5 db is also realized with respect to repeater overload performance.

The single frequency pilots are adjusted to have the following values of power at the output of a transmitting amplifier:

7266 kc	−16 dbm
8320 kc	−26 dbm
All others	−36 dbm

With these values, modulation products produced by cross modulation among the pilots and message and television signals all meet the appropriate objectives.

2.17 *Frogging of Message Circuits*

When signals, either message or television, are transmitted over long distances through many amplifiers in tandem, the accumulation of modulation products along the line becomes an important system problem for two reasons: (1) the accumulation of certain types of third order products tends to follow a direct or in-phase law and (2) the distribution of modulation products over the band produces more modulation noise in certain parts of the band than in others. Both of these cumulation problems are alleviated if, at intervals along the line, the signals are shifted with respect to one another in the band, a process known as frogging.

In the L3 system, signal-to-noise performance is substantially improved by frogging the supergroups at intervals of about 800 miles. In the 1,860 channel all-message application, the busy hour signal-to-noise performance of 4,000-mile circuits is alike to within two db with all channels meeting the objective of +29 dba at the −9 db level. In contrast, if frogging were not specified, a substantial number of circuits (10 to 20 per cent would fail to meet the objectives while the performance of other channels would be better than required by six db or more.

When the system is used for combined message-television signals, the message circuits are frogged in supergroup blocks at approximate 800-mile intervals except for supergroups Nos. 113 and 114 which must be frogged at 400-mile intervals. This procedure is necessary to prevent second order sum and difference products of message and television signal components from cumulating excessively, expecially those products which involve television signal components close to the television carrier. Frogging these supergroups more frequently than others results in a 3 db improvement in television signal-to-noise performance.

2.18 *Special Services Transmission*

During the early design stages, requirements based on the transmission of message and television signals were used to set repeater spacing, to determine the bandwidth and frequency allocations and to fix important design parameters of the amplifiers. Concurrently, the objectives for the transmission of telegraph, program, and telephotograph signals were studied and before the system design crystallized, analyses were made to assure that these special services objectives would be met.

In a few instances it was found that the special services objectives tended to dominate and the system requirements and design were adjusted accordingly. For the most part, however, channels which meet message circuit objectives are satisfactory for special services transmission. In L3, telegraph and telephotograph signals may be transmitted without restriction provided the proportion of these signals does not materially exceed the proportion now installed in the plant. Program signals may be transmitted in the 1,860 all-message arrangement without restriction but when television transmission is provided, program circuits are restricted to supergroups Nos. 113 and 114. This restriction is due to the fact that program circuits are usually more than 4 kc wide; interferences of high magnitude which normally fall between 3,300 and

4,000 cycles or below 300 cycles in message channels of supergroups other than Nos. 113 and 114 would fall close to 4,000 cycles in a program circuit where there is high susceptibility to interference.

2.19 *Uncertainties*

In the early stages of system design, firm decisions have to be made on such matters as repeater spacing, bandwidth, and component characteristics. These decisions must be based on a detailed signal-to-noise analysis which in turn involves many judgements of repeater performance parameters, tolerable system requirements and the effects of signal mechanisms on system performance. It would be easy and safe to engineer the system to provide enough signal-to-noise margin to cover the uncertainties in each of these judgements. Conservative engineering of this type could easily have justified a repeater spacing of three miles instead of the four miles actually chosen. Instead, an effort was made to estimate a "mid-range" or most probable value for each performance, requirement or mechanism factor entering into the signal-to-noise design. In addition, a "probable" uncertainty was estimated for each critical parameter. This was usually taken as one third of the maximum foreseeable error in the estimate. Finally, these uncertainties in electron tube modulation, realizable feedback, network impedances, channel requirements, interaction laws between signals and a myriad of other factors were all translated by the signal-to-noise analysis into their effect in db on the television channel signal-to-noise performance. On this basis, the "probable" uncertainties were summed on an rss basis to find the "probable" uncertainty in the overall design. Whereas the direct addition of the probable uncertainties gave a figure of about 20 db uncertainty in the design, the rss addition indicated about six db uncertainty. It was then argued that during the ensuing years of development the probability of finding all the judgements to be wrong in the same sense was extremely small. On the other hand it was deemed reasonable to provide enough margin so that there would be perhaps a 75 per cent chance of not exceeding the margin. Six db of margin was therefore provided, half by clear margin and half by having available economically feasible changes in system design such as a decrease in the telephone channel frogging interval. Any further error in judgement would then have to be taken up by degrading performance below the desired objectives. As the system design proceeded, the early judgements were changed in considerable measure. Likewise, numerous additional system parameters were introduced. However, at no point in the system planning was the balance of factors such that there was less than three db clear margin.

Margin handled in this way becomes a carefully husbanded asset of the whole system. In designing or analyzing a part of the system a major effort must be made to achieve the performance introduced into the initial determination of repeater spacing and bandwidth. The design of each individual part of the system cannot be allowed a margin which can be used up as the individual designer chooses.

2.20 *Equalization Design*

The term "equalization" is used to describe the process of obtaining flat gain and delay characteristics for the system transmission. The system and equipment designs to accomplish this function represent two of the major engineering features of the L3 system. In an overall sense, equalization includes the following: (1) determining deviation objectives for the gain and delay characteristics of the system and its component parts; (2) designing the auxiliary repeater so that the most economical over-all system equalization is obtained; and (3) specifying the location, form and control methods for the mop-up equalizers that are used at intervals along the system. Equalization and its related process, regulation, are the subject of a companion paper;[10] therefore, in this paper only those aspects of equalization will be covered which are necessary for an appreciation of the over-all system design.

2.21 *Transmission Objectives*

The requirements on the gain characteristic of a band used for multichannel telephony depend on two message channel objectives. One of these is that the gain of a message channel must not vary by more than two db over the 4-kc band. To meet this requirement, broad changes in the transmission characteristic of the message band are held to less than 0.5 db for 150-mile links. The second objective stems primarily from the need to transmit telephotograph signals. Since these signals are relatively intolerant of level changes, the transmission characteristics of working lines and protection lines are made alike to within ±0.25 db.

The requirements on the gain and delay characteristics of the television band are based on the subjective determination that an echo delayed by about two microseconds or more in a representative picture is considered tolerable by 95 per cent of the viewers when the peak-to-peak voltage of the echo signal is 39 db below the peak-to-peak signal voltage.[11] The translation of this echo objective to allowable variations in the gain and delay characteristics is straight forward if idealized sinusoidal deviations extending across the whole band are assumed.

In practice, the characteristics of the transmission deviations in a long repeater system are very complex and therefore, the idealized objectives are only a tentative guide in system design. Since we do not have a thoroughly satisfactory method of evaluating complex echo patterns, the exact nature of the final television mop-up arrangements will be determined after subjective tests on the interfering effects of echoes resulting from the complex transmission deviations of representative links of the system.

2.22 *The Mop-Up Plan*

The deviations from ideally flat gain and delay transmission characteristics may be classified in three broad categories; (1) fixed deviations; (2) slowly varying deviations; and (3) rapidly varying deviations. The distinction that is made between slow and rapid in the last two categories relates to the frequency of adjustment needed to meet system objectives. Those variations which require adjustment more often than once a week are considered rapid and those requiring adjustment at longer intervals are considered slow.

Corresponding to each of the three classifications of deviations is a set of equalizers, fixed, manually adjustable, or automatic under control of the pilot or a temperature sensitive element. Networks capable of fulfilling the functions of each are distributed along the line according to carefully prepared rules which enable system objectives to be economically met. The locations of these equalizers, their functions and general characteristics are illustrated in Fig. 13.

2.221 *Fixed Equalizers*

To the extent that the auxiliary repeater is designed so that its nominal gain compensates for the loss of four miles of coaxial, it may be considered as the first step of fixed equalization. In addition to the amplifier, the auxiliary repeaters are equipped with artificial lines, which are used to build out the loss of short sections to the equivalent of four miles of cable, and basic equalizers which provide for differences in the loss characteristics of different types of cable.

The second and final step of fixed gain equalization is known as a design deviation equalizer. Its function is to correct accumulated deviations due to the failure of the average auxiliary repeater to exactly

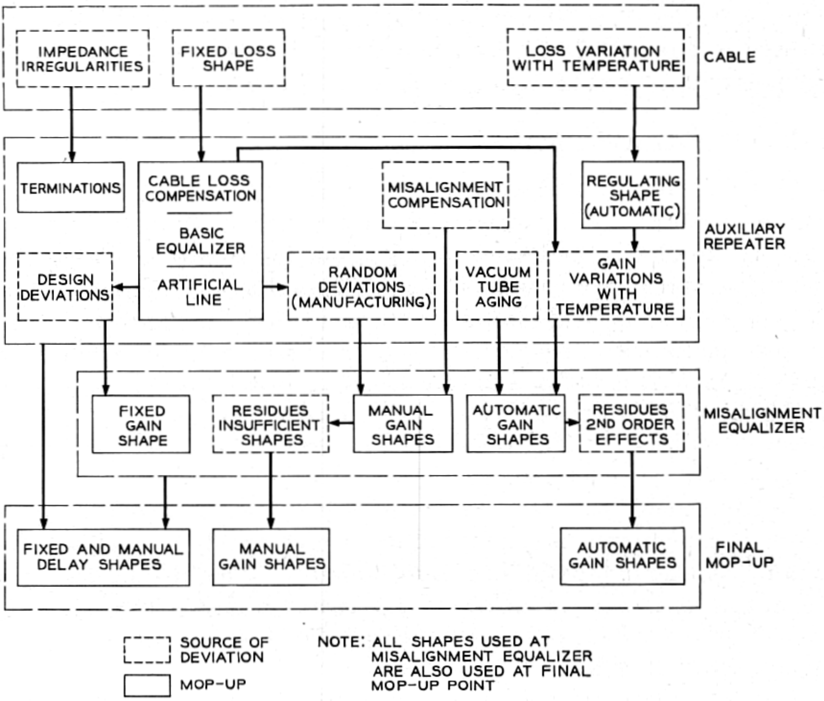


Fig. 13 — L3 coaxial system, equalization plan.

compensate for cable loss. These equalizers will be used at every mop-up point, at 40 to 120-mile intervals.

When television is transmitted, fixed delay equalizers are used at approximately 150-mile intervals. These equalizers compensate for the delay distortion introduced by the cutoffs of the auxiliary repeater sections.

2.222 *Manually Adjustable Equalizers*

The manually adjustable gain equalizers consist of networks whose loss-frequency characteristics are related to one another by a Fourier series type of representation. The number of terms of the series required to meet system objectives varies with different types of mop-up points and depends on the system application being provided for, all-message or combined message-television service. Equalizers of this type are used in mop-up points at 40 to 120-mile intervals along the line.

Manually adjustable delay equalizers are provided at approximately 150-mile intervals when television signals are transmitted. These equalizers supplement the fixed delay equalizers described above and are needed to trim the delay characteristic of the line in finer detail than would be possible with fixed equalizers.

2.223 *Automatic Equalizers*

The first step of automatic-gain equalization is provided at each auxiliary repeater. The nominal gain characteristic of the repeater is designed to match the loss characteristic of the coaxial at 55° F. The cable loss varies with changes in temperature; the variations, however, have a predictable characteristic, being very closely proportional in db to the square root of frequency. To compensate for these changes, the gain characteristic of the amplifier at auxiliary repeaters is adjustable and follows the loss of the cable under the control of a thermistor. Two types of circuits are used to control the current fed to the thermistor as described in a later section.

In the second step of automatic gain equalization, networks are provided to match system gain variations caused by electron tube aging and by changes in repeater hut temperatures. The loss characteristics of these equalizers are controlled by thermistors which in turn are controlled by the 308-kc and the 2064-kc pilots. These equalizers are used every 40 to 120 miles.

In the final step of automatic gain equalization, networks are provided to compensate for second order effects of the first three rapid variations described above, namely, cable loss variations, and repeater gain variations due to hut temperature changes and electron tube aging. The loss characteristics of these networks are under control of thermistors acted on by the 556-kc, 3096-kc and 8320-kc pilots. These equalizers are located at approximately 150-mile intervals.

The thermistors which control the loss-frequency characteristics of automatic equalizers are driven by regulators through a simple form of analog computer. The design and operation of this circuit is described in a companion paper.[10]

There is no automatic control of the delay characteristic in the system except that provided by the automatic gain equalizers. Every effort is made to have these equalizers match the transmission changes outside the band so that resulting delay changes in the band are minimized.

2.23 *Equalization System Considerations*

Whether the system is being equalized for telephone or television it is immediately apparent that the channel requirements described earlier applied after 4,000 miles of transmission imply that, with no equalization, stability of the transmission characteristics of the individual repeaters would have to be of the order of a few ten thousandths of a db. Obviously, stabilities of this magnitude with changes due to temperature, electron tube aging and manufacturing processes cannot be achieved. Therefore, the equalization system design must be based on an economical balance between the cost of achieving repeater accuracy and stability and the cost of providing and maintaining an elaborate system of fixed, manual, and automatic equalizers.

The equalization problem involves so many variables that no attempt has been made to evolve a unified theoretical basis for evaluating the factors entering into this economic balance. However, in planning and designing the L3 system a number of principles and points of view have been developed which have guided the equalization planning.

2.231 *Misalignment*

The transmission objectives described above are determined on the basis of delivering satisfactorily equalized signals at terminals. In addition to this function the equalizers must limit the signal excursions along the line so that excessive noise or modulation is not accumulated in the repeater system. The amount of signal misalignment that can be allowed to accumulate before the first mop-up equalizer depends of course on the signal-to-noise allowance that has been made for this purpose. The amount of signal-to-noise performance allotted to misalignment must represent a balance between the reduced repeater spacing and increased complexity of equalizers that it costs and the increased spacing between mop-up equalizers and increased repeater deviations that it allows.

The engineering method for arriving at this balance represents an interesting example of system design by successive approximations. For example, the total gain area available (over an infinite frequency range) in a coupling network is inversely proportional to the capacity across the network and one of the important design choices is the extent to which one tries to utilize this area in the transmitted frequency band. The degree to which the available gain is concentrated in-band is called the resistance integral efficiency. In the very early stages of the amplifier design it was necessary to choose resistance integral efficiencies and frequency characteristics for the coupling networks. In a definite but complicated way these parameters are related to the sensitivity of the networks to element variations. Efficient networks give improved signal-to-noise performance but also increase the sensitivity to element changes. By examining deviation curves for a number of specific network designs, tentative choices were made of 50 per cent resistance integral efficiency for the coupling networks and an allocation of about half the cable slope to the pair of coupling networks and the remainder to the feedback network. With an amplifier employing these networks a detailed study was made of the noise and modulation penalties at two frequencies resulting from misalignment in several lengths of line. This study indicated that with certain refinements in the repeater design the misalignment in twenty or more auxiliary repeater sections could be tolerated with a signal-to-noise penalty of about 2 db which was judged to be a reasonable allotment for this purpose. In addition, this study brought out: (1) that randomizing the variations of an element between its normal manufacturing limits resulted in a 4/1 reduction in the required misalignment allowance as compared with accepting large numbers of elements at one extreme of their limit; and (2) a small amount of gain adjustment at each repeater in the vicinity of the high magnitude television carrier would reduce the required misalignment allowance by about 2/1. Refinements on this plan for handling misalignment had to wait until the signal-to-noise and repeater design were crystallized. However, the study referred to above provided a powerful tool for evaluating proposed element deviations during the design period.

When the exact signal levels and the most limiting modulation products became known and when the repeater characteristics and final element deviations were determined it became possible to make a refined study of misalignment in terms of the noise and modulation impairment associated with specific signals and distortion products. At this point performance margins associated with specific interferences could be used to allow more or less misalignment of the particular signal components forming the interference. Likewise, amplifier deviations with specific frequency characteristics could be evaluated exactly in terms of their effect on the number of repeaters between mop-up equalizers. By studies of this type it was determined that the "A" or misalignment equalizers could be spaced at intervals not to exceed thirty-two auxiliary repeater sections.

2.232 *Distribution of Element Deviations*

The methods of statistical quality control used to monitor the process of manufacture provided the necessary techniques for obtaining the desired randomization of deviations. A companion paper[12] presents the techniques that were developed to apply the broad field of knowledge on quality control to the specific needs of the L3 system. The most important point to appreciate in this connection is that the control of the process of manufacture (as well as the end electrical requirements) of individual elements is being used as a basic factor in the design of the system.

2.233 *Repeater Accuracy*

In developing the equalization plan it is a logical and straight forward operation to provide shapes and ranges in the equalizers that will compensate for the random variations of known elements. Likewise, real but indeterminate parasitic elements can be taken into account by specifying the final characteristics of the line amplifier feedback network and the equalizer fixed shapes (design deviation equalizers) on the basis of measurements on a rigidly controlled group of amplifiers that are deemed to be representative of the final product. However, having once specified the equalization on this basis the design elements and indeterminate parasitic elements must be held to the values and ranges upon which equalizer location, shapes and ranges are specified. This point of view has led to rigid mechanical control and the omission of component adjustments in the line amplifier which represent a departure from other transmission systems. These features are discussed in detail in the companion amplifier paper.[8]

2.3 NEW YORK-PHILADELPHIA TRIAL

The first installation of L3 has been made between New York and Philadelphia. Since the middle of 1952, this installation has been used to test components, to verify values of important system parameters used in system analyses, and to gather data for the further design and development of equalizers.

Random noise measurements have confirmed theoretical values (Fig. 5) to an accuracy of better than 2 db. In general, the measurements have indicated that the theoretical values have been conservative.

Measurements of system modulation performance, made with single frequency tones, also confirm the theoretical values used in analyses. Third order modulation measurements are in almost complete agreement with theory while second order measurements have been generally two to three db more favorable than the analytic values used.

Transmission measurements have confirmed that equalizer networks designed so far are satisfactory for systems to be installed in the near future. Further measurements are required to determine automatic

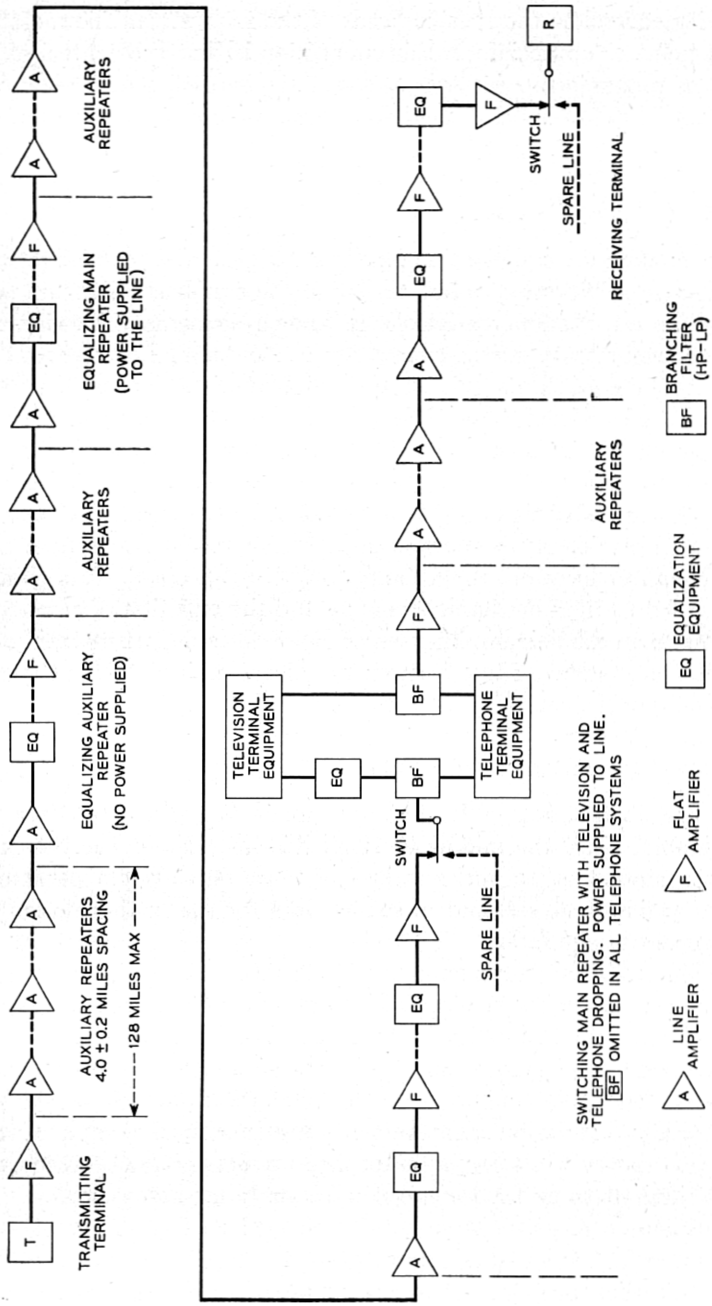


Fig. 14 — General layout of L3 repeaters.

equalizer shapes to correct for the second order effects of temperature changes and electron tube aging. Also under active study are the problems associated with final mop-up for long television systems.

3.0 System Description

3.1 GENERAL

In the preceding sections on system design the functions of the auxiliary repeaters and the need for additional repeaters with varying amounts of equalization have been brought out. Fig. 14 shows the transmission layout of a typical L3 system. The auxiliary repeaters contain amplifiers and regulating equipment to compensate for the basic cable loss and its variation with temperature. Since such repeaters are dependent on the cable for their primary source of power they are called auxiliary repeaters.

At points in the system where additional first order equalization is required to reduce misalignment the complexity of the repeater equipment increases and such repeaters receiving power over the cable are called equalizing auxiliary repeaters.

The distance which power may be transmitted over the cable to the auxiliary repeaters is limited; therefore, repeaters at specified intervals must be capable of supplying power to the cable. These are called main repeaters. They may be equalizing main repeaters where only first-order equalization is required or switching main repeaters where lines are switched or circuits dropped.

3.2 AUXILIARY REPEATER

3.21 *Transmission Circuit*

The auxiliary repeater is the basic unit of the system and its design determines to a great extent the performance and economics of the system. A block diagram of such a repeater for transmission in two directions on two coaxials is shown in Fig. 15. The power separation filter (PSF) is a six terminal high pass-low pass filter designed to separate the high frequency transmission signals on the coaxial from the low frequency current transmitted on the center conductor to furnish primary power to the repeater power equipment. At the input to the repeater the low-frequency current is diverted to a power supply while the high-frequency current follows a path through passive networks to the input of the amplifier.At the output, the signal from the amplifier and the low-frequency current from the power supply are recombined in the power separation filter for transmission to the next repeater.

The power separation filters are basically simple designs, but the realization of the theoretical design was complicated by the following: (1) the components in the low frequency section must pass currents of about 1.5 amperes without change in characteristics, and must withstand potentials as high as 2,000 volts rms without generating corona noise; and (2) the components in the high frequency section must be such that the loss over the transmission band (300–8,350 kc) is small and stable and of such a shape that it is easily equalized. To meet these requirements stable inductors and capacitors with a minimum of parasitic resonances in the band were designed.

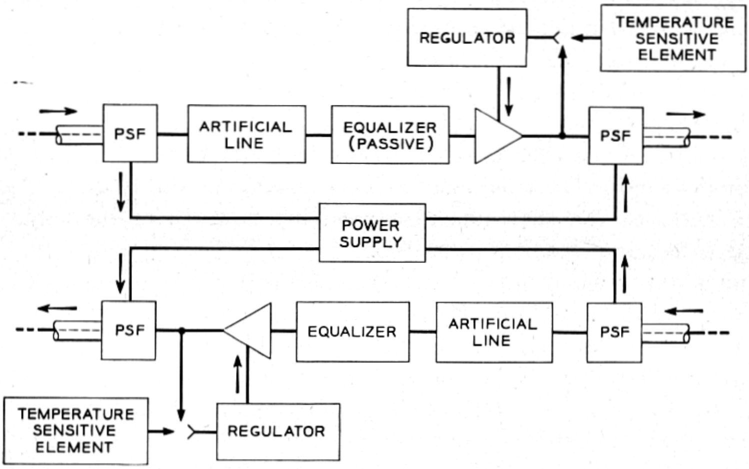


Fig. 15 — Auxiliary repeater.

The artificial line shown preceding the input to the amplifier is a passive network to build out the loss-frequency characteristic of a short cable section to be equivalent to the loss-frequency characteristic of 4.0 ± 0.2 miles of 0.375″ cable or 2.87 ± 0.15 miles of 0.27″ cable. These lines are provided in several different sizes, so that, where it is impossible physically to locate the repeater within the specified accuracy of 0.4 mile this accuracy can be obtained electrically. The design of the network is such that an accurate and stable characteristic is obtained with a minimum number of components.

The equalizer is a means for compensating for small variations in the transmission characteristics of coaxial cables due to variations in the physical construction of the cable. In the case of the most generally used cable, this equalizer inserts only a small flat loss.

The amplifier is of the feedback type whose gain frequency characteristic is closely equivalent to 4.0 miles of 0.375″ coaxial cable plus the loss of the other passive elements in the repeater. This unit is demountable without tools for maintenance and is sealed in a die cast housing as protection against moisture and dust. The detailed electrical and mechanical design are covered in a companion paper.[8]

The regulator may be one of two types. The first, called the auxiliary regulator, adjusts the gain-frequency shape of the amplifier in accordance with the magnitude of the 7,266–kc pilot transmitted along the line. The second type, the thermometer regulator, adjusts the gain-frequency shape of the amplifier under control of an element representing an average value of cable temperature. This element is a thermistor buried in the ground near the cable. Such a control is, obviously, not as accurate as pilot controlled regulation, but it is adequate for use at one-half of the auxiliary repeaters and its simplicity results in considerable saving in first cost and power requirements. The regulators are demountable units similar to the amplifiers. Their detailed electrical and mechanical design are covered in a companion paper.[10]

The pilot alarm unit is provided with auxiliary regulators to indicate pilot deviations beyond a predetermined limit. Its operation will be described a lattle later in connection with the discussion of alarm and control arrangements for the entire system.

3.22 *Power Supply*

Primary ac power for the auxiliary repeater is supplied on a constant current basis from the main repeater over the center conductors of the two associated coaxials. Power generating and control equipment used at the main repeater will be discussed in Section 3.6. At the auxiliary repeater, power supply equipment is required to convert the primary power to suitable voltages for heater, plate and bias use as shown on Fig. 16. Half of the input to the power supply is taken from each center conductor and the output of the power supply is used to power the entire two-way repeater.

The heater voltages are obtained by simple transformation which is complicated only by the fact that accurate and low loss transformers are required and the primaries of these transformers must withstand high ac potentials without generating corona noise which might be transmitted through the power separation filter to the input of the amplifier. Two separate transformers are used to split the load between the two center conductors even though the secondaries are connected together to feed the repeater. This arrangement eliminates one crosstalk path

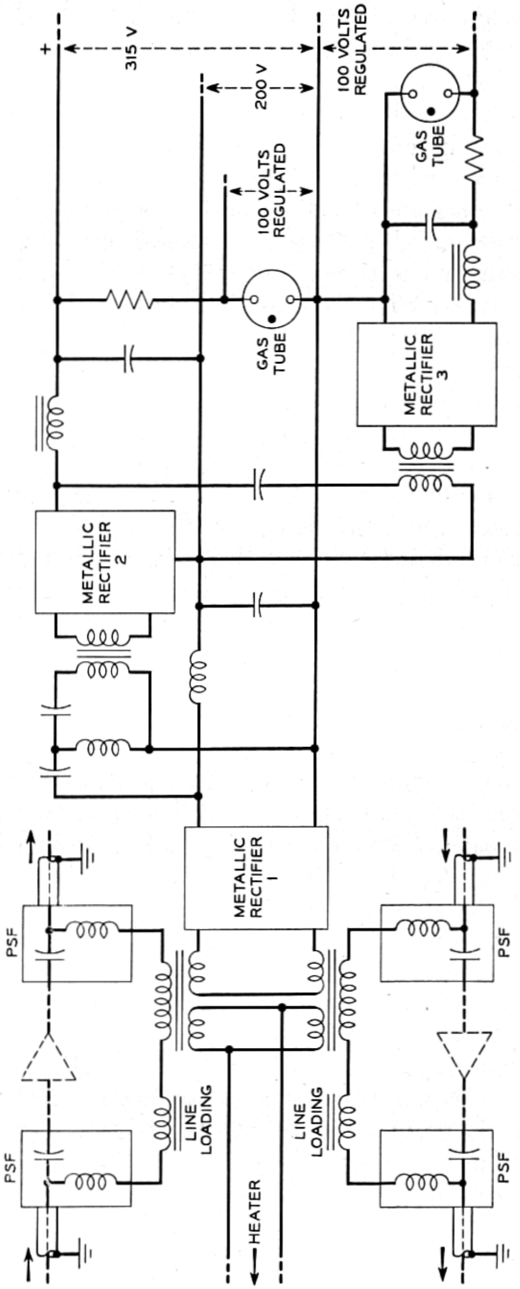


Fig. 16 — Auxiliary repeater power supply.

at low frequencies where it is difficult and expensive to design power separation filters to meet the system requirements.

The dc plate and bias supply voltages for amplifiers and regulators could be obtained by conventional rectifier circuits except for one complication which such arrangements introduce. This complication is the fact that a rectifier terminated in a low-pass filter (conventional ripple filter) reflects a highly distorted current wave into the primary circuit. If the primary current is so distorted the various power supplies in the series circuit will be fed with other than a sine wave of current and will supply different voltages depending on the wave form. Since the heater power depends on the rms value of current while the dc output depends on the peak value of voltage, it is easily seen that the relationship between these two will change with the wave form of the applied current. Furthermore, the line loading to be discussed later must be calculated on the basis of a pure sine wave; appreciable harmonics in the line current tend to make it impossible to predetermine the loading to any reasonable degree of accuracy.

It was found that these problems could be avoided and the power factor of the power supply made very nearly unity if the rectifier (RECT 1) was terminated in a constant resistance load rather than a low-pass filter. This was provided by paralleling the conventional low-pass filter with a high-pass section terminated in the proper resistance load. To avoid wasting the power in this load a second rectifier was added (RECT 2). The dc output of this circuit is used in series with the main dc supply to provide the higher voltage required for the output stage of the amplifier. This rectifier must also be terminated resistively although its effect on the main current wave is less than that of the first rectifier, and the power dissipated is smaller. Since there was a further use for a small amount of power for bias in the regulators, RECT 3 was added to produce a regulated voltage in conjunction with a conventional gas tube circuit. This rectifier and its load provide the termination for the high pass section of the filter circuit for RECT 2. A second gas tube circuit is used to obtain a regulated bias supply for amplifiers and regulators from the 315-volt source. The loads on both gas tube circuits are fixed so regulation for variation in input voltage only is required. For this reason a low current, highly stable gas tube could be used.

3.23 *Power Loading*

The power transmission circuit of a power loop is essentially a resistance-capacity network at the power frequency. The line and the power supply resistance are the resistance component and the line and power separation filter capacity to ground make up the shunt capacity. If the circuit were used in this form the primary current at each repeater would be different since it would be the vector sum of the current in the succeeding section and the current in the shunt capacitance. This is undesirable as the objective is to make all power supplies alike. A familiar solution is applied to this problem by inserting an inductive reactance in series with the line. A value of this reactance is chosen for each repeater to compensate for the current through the effective shunt capacitance and thus make the currents through each of the power supplies as nearly alike as possible.

To simplify the loading adjustment in the L3 system a continuously variable loading inductor was developed. This arrangement allows more accurate adjustment of loading without the complications of changing wiring taps in a high voltage circuit. The design of such an inductor presented formidable obstacles as a large range of variation was desired (20–120 mh), and relatively high currents and voltages were involved. The device used consists of the two inductors which may be rotated with respect to each other, so that the coupling between their magnetic circuits varies ideally between zero and 100 per cent. One inductor is inserted in each side of the power circuit and a net result is obtained which is equivalent to varying each inductor.

3.24 *Physical Description*

The type of auxiliary repeater generally used is shown in Fig. 17. It consists of a 6-foot cable duct framework upon which the component panels are mounted. It is completely wired in the factory. The lower third of the bay contains the power supply equipment while the upper part contains two transmission panels. One panel is provided for each direction of transmission and all of the transmission components of the circuit are found on these panels. The demountable units, amplifier, regulator, and pilot alarm unit are interconnected with plugs and jacks, so that they may be removed for maintenance. The other units are interconnected by screw-type terminals and cable as it is expected that they seldom will require maintenance.

Other types of repeaters will be available to meet special conditions such as manholes where sealed apparatus cases will be required to prevent damage due to water submersion, or telephone offices where standard 11′-6″ frameworks are usually desired.

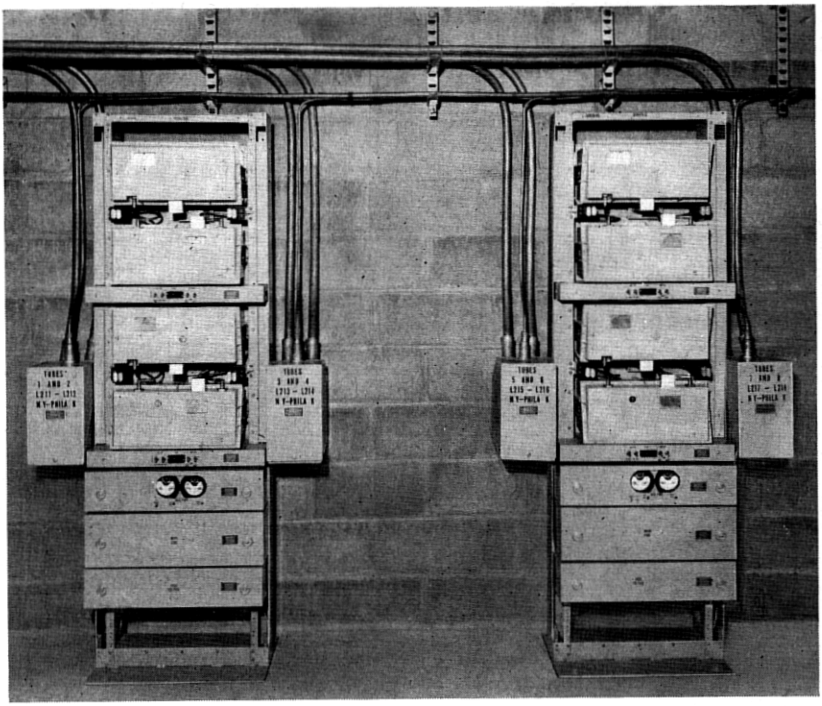


Fig. 17 — Typical auxiliary repeater in concrete block nut.

3.3 EQUALIZING AND SWITCHING REPEATERS

3.31 *Components*

The equalizing auxiliary and main repeaters use the same general types of transmission equipment as the auxiliary repeater except for the equalizers. They differ principally in the quantity of equalization equipment provided and the bay arrangements. Table IV lists a summary of the basic transmission units in each repeater.

At these repeaters a line amplifier is used as a receiving amplifier to compensate for the previous section of cable. Flat amplifiers are used as transmitting amplifiers and to compensate for the loss introduced by the equalizers. They have a flat gain-frequency characteristic and no provision for pilot control of their gain. Their design is very similar to that of the line amplifier and is covered in the companion amplifier paper.[8]

TABLE IV—SUMMARY OF HIGH-FREQUENCY LINE EQUIPMENT AT REPEATER STATIONS

	Auxiliary	Equalizing Aux.	Auxiliary Main	Switching Main (Telephone only)	Switching Main (Telephone — TV
Line amplifier	1	1	1	1	1
Flat amplifier	0	2	2	5	5
Auxiliary or thermometer regulator	1				
Manual equalization (Number of terms)		10	10	15	25
Automatic equalizers	1	3	3	6	6
Regulators for equalization (kc)		7266 308 2064	7266 308 2064	7266 308 2064 3096 556 8320	7266 308 2064 3096 556 8320
Design deviation equalizer		1	1	1	1

The functions of the fixed, manual and pilot controlled equalizers are noted in Section 2.22 of this paper and discussed in detail in the companion equalization paper.[10]

3.32 *Equalizing Auxiliary Repeaters*

This type of repeater will be found after a maximum of thirty-two auxiliary repeaters provided power feed to the cable, dropping, or switching is not required (Refer to Fig. 14). The major components provided are covered in Table IV. In addition to these items, power separation filters, basic equalizers and artificial lines identical with those in auxiliary repeaters are used. A pilot alarm unit is also included to monitor each of the three regulators and transmit an alarm when any one of the controlling pilots has deviated beyond a given limit.

Power for these repeaters is obtained from the cable just as in the case of the auxiliary repeater and much of the same type of equipment is used. However, due to the larger amount of power required and the layout of the repeater the auxiliary repeater power units have been repackaged to provide the optimum arrangements for leads carrying high current or critical bias supply circuits.

The design of panels used in this repeater was dictated by the general scheme conceived for the switching main repeater where the maximum amount of equipment is required. This arrangement involves the use of both sides of a duct-type frame. A single panel (again called the transmission panel) is used, but an amplifier is mounted on one side and a regulator is mounted on the other. This requires access to both sides of the bay, but results in an overall saving in the number of bays and overall floor space.

All of the transmission components and a heater and bias supply unit are mounted in one 7′ bay for each coaxial. The plate and primary ac power for two of these bays is mounted in another 7′ bay.

3.33 *Equalizing Main Repeater*

This repeater contains exactly the same transmission equipment as the equalizing auxiliary repeater (see Table IV). It differs in the function noted before, that is, it is equipped to feed power to the cable. The equipment to perform this function will be described later in the paper. Since the repeater can feed power to the cable it can also supply the power for its own operation. This power is derived from the primary ac supply used for the line by means of conventional metallic rectifiers for dc circuits and transformers for the ac heater supplies. These power supplies are not a part of the power loop containing auxiliary repeaters, so no special arrangements are required to obtain good waveform or high power factor.

The equipment arrangement uses the same units as the equalizing auxiliary repeater, but here conventional 11′-6″ frames are used.

3.34 *Switching Main Repeater*

Usually, this type of repeater is supplied at the point where circuits are dropped or terminated. In order to permit switching from a working line to a spare line in case of trouble, see Section 3.4, more complex equalization is required so that the lines will be as nearly alike as possible when the switch takes place. Furthermore, the signal delivered to the terminal must meet equalization limits that will result in a satisfactory grade of service.

Where the repeater is part of a system required to transmit only message circuits the basic equipment shown in Table IV (telephone only case) is required. In addition to these units facilites are provided which indicate and alarm pilot levels and provide for patching and other maintenance arrangements. Since this repeater always feeds power to the cable it uses the same power arrangements as the equalizing main repeater.

When the system is being used for the combined telephone and television signal this repeater is the same as the "all telephone system" repeater except that it has additional equalization equipment to adjust the system for the more stringent television requirements. Furthermore, line connecting equipment consisting of branching filters and additional equalization is required. Branching filters are used to separate the telephone and television bands so that they can be transmitted to their respective terminal equipment. These are combined high-pass low-pass structures complicated by strict requirements on stability of the gain-frequency and delay-frequency characteristics. Delay equalization for the line sections must also be provided in the television branch and a large part of this is combined with the branching filters. Other components required for long television systems are adjustable gain and delay equalizers and associated amplification.

The same type of equipment is used as that described for the other repeaters except that a number of additional transmission panels are required to mount the additional amplifiers and regulators associated with the equalizers. Two 11′-6″ bays are used to contain the equipment for one through coaxial. One bay contains the receiving equipment which precedes the line switch. The other bay contains the transmitting equipment (transmitting amplifier and hybrid) and any line connecting equipment for combined systems. Fig. 18 shows a typical main repeater installation.

3.4 AUTOMATIC SWITCHING*

In order to preserve transmission in the event of the failure of a component of the system and for transmission maintenance purposes, one coaxial in each direction is operated as a standby. An automatic switching system is provided to permit substitution of the standby line for any of the working lines. The lines are switched at the input to the transmitting amplifier and at the output of the receiving amplifiers and equalizers. (See Fig. 14).

At the receiving end of a switching section, equipment is provided whose function is to recognize failure of a working line and initiate the switching circuits. Information as to the transmission conditions of the system exists in the pilot regulators, the output of which controls a sensitive relay with high and low limit contacts. The operation of one of these relays provides the switching system with the information that transmission has failed or been seriously impaired. It is necessary to make a switch as rapidly as possible in the case of a total failure in order to reduce the effect upon the transmission circuits. As the relays take appreciable time to operate, the receiving switch equipment is designed

* Material written by P. T. Sproul.

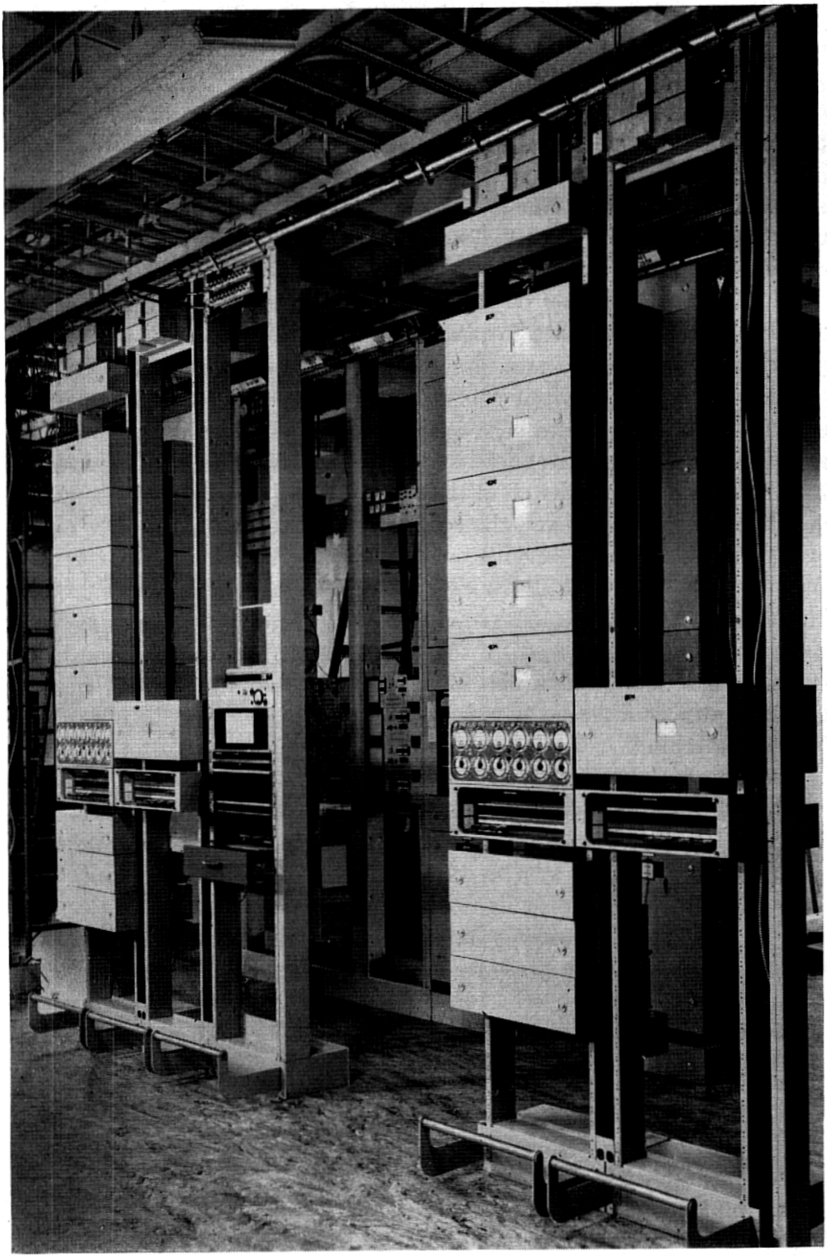


Fig. 18 — Typical main repeater installation.

to operate directly from the dc output of the regulator associated with the 7,266-kc line pilot. This permits complete switch operation in about 15 milliseconds.

Upon receipt of information from the regulators that one or more of the pilots have gone out of limits, the switch initiator signals the transmitting switch control equipment at the transmitting end of the switching section as to which line has failed. Signalling is accomplished by the use of tones in the 280 to 296-kc range which are transmitted over all coaxials in parallel in the reverse direction. Use of the coaxials for transmission of these signals obtains maximum speed of operation of the switch. All paths are used in parallel to preclude failure of the switch if one channel in the opposite direction would be inoperative.

The transmitting switch control equipment causes the transmitting end of the standby line to be switched in parallel with the line in trouble and then signals the switch initiator that this has been done. This verifier tone actuates the line switch at the receiving end to complete the switch.

When the trouble clears, the switch is released as the initiator checks every minute to see if service on the working line can be restored. In the event of a prolonged trouble, the switch can be locked manually and the initator will no longer attempt to restore to normal. Release of the switch is accomplished by the transmission of a release tone to the transmitting end while a checking tone returned by the transmitting end indicates completion of release and readies the switch initiator for further switching.

For maintenance purposes, manual operation of the switching equipment is provided. In effect, manual switches are made by simulating a failure. Alarm features are provided to indicate to the operating personnel failure of the coaxial system or failure of the switching equipment. Care has been taken in the design to insure that failure of the switching equipment in no way affects transmission except by removing the protection afforded by the presence of the switching facility.

One 11′-6″ bay is required for the switch control equipment for each direction of an 8-coaxial system. The line switches are mounted in the miscellaneous bay of the main repeater lineup.

3.5 TERMINALS*

Television terminal equipment, which is required to modulate the video frequency signals to and from the high-frequency line, is described in a companion paper[9] and therefore, will not be discussed here.

* Material written by C. G. Arnold.

The telephone terminals consist of modulators (and related transmission equipment) and carrier and pilot generating equipment. The transmission components of a terminal for an all message system are shown on Fig. 19. The channel, group and supergroup equipment are designs previously used in the L1 system. The designs of the submastergroup and mastergroup units employ circuit arrangements similar to those used in the supergroup equipment. The greater bandwidths, higher frequencies and more severe stability requirements required new components and improved circuit and layout techniques.

Fig. 20 shows the modulation steps and location in the frequency spectrum of the supergroups, submastergroups and mastergroups when the L3 system is used for telephone and television or all telephone. Mastergroup one comprises the first ten sixty-channel supergroups. This mastergroup is placed directly on the line in the 564 to 3,084-kc frequency band for both the telephone-television and all-telephone cases. When the system is used entirely for telephone, two additional mastergroups are formed by modulating mastergroup one up into the desired frequency bands.

Mastergroup No. 1 is subdivided into two submastergroups. The lower six supergroups, comprising submastergroup one are modulated directly up from the basic supergroup located in the 312 to 552-kc band. The modulation and carrier supply equipment for these supergroups are the same units that are employed in the L1 system. The upper four supergroups comprising submastergroup two are obtained by modulating four supergroups located in the same frequency range as the top four supergroups in submastergroup one into the top part of mastergroup one.

The supergroup numbering system used for L3 has been adopted for easy identification of supergroups in their high-frequency positions. Each supergroup is given a three digit number. The first digit identifies the mastergroup, the second digit identifies the submastergroup, and the third digit identifies the L1 supergroup from which it was originally derived.

In the 1860 channel all-telephone allocation, supergroup No. 112, which corresponds to the basic L1 supergroup No. 2, may be used for high quality, long haul message circuits. When the system is used for telephone and television, supergroup No. 112 is restricted to circuits under 200 miles in length because of intolerable second order cross modulation between these signals and the television signal.

With these groupings of channels new modulating and carrier supply equipment is required for submastergroup No. 2 and mastergroups Nos.

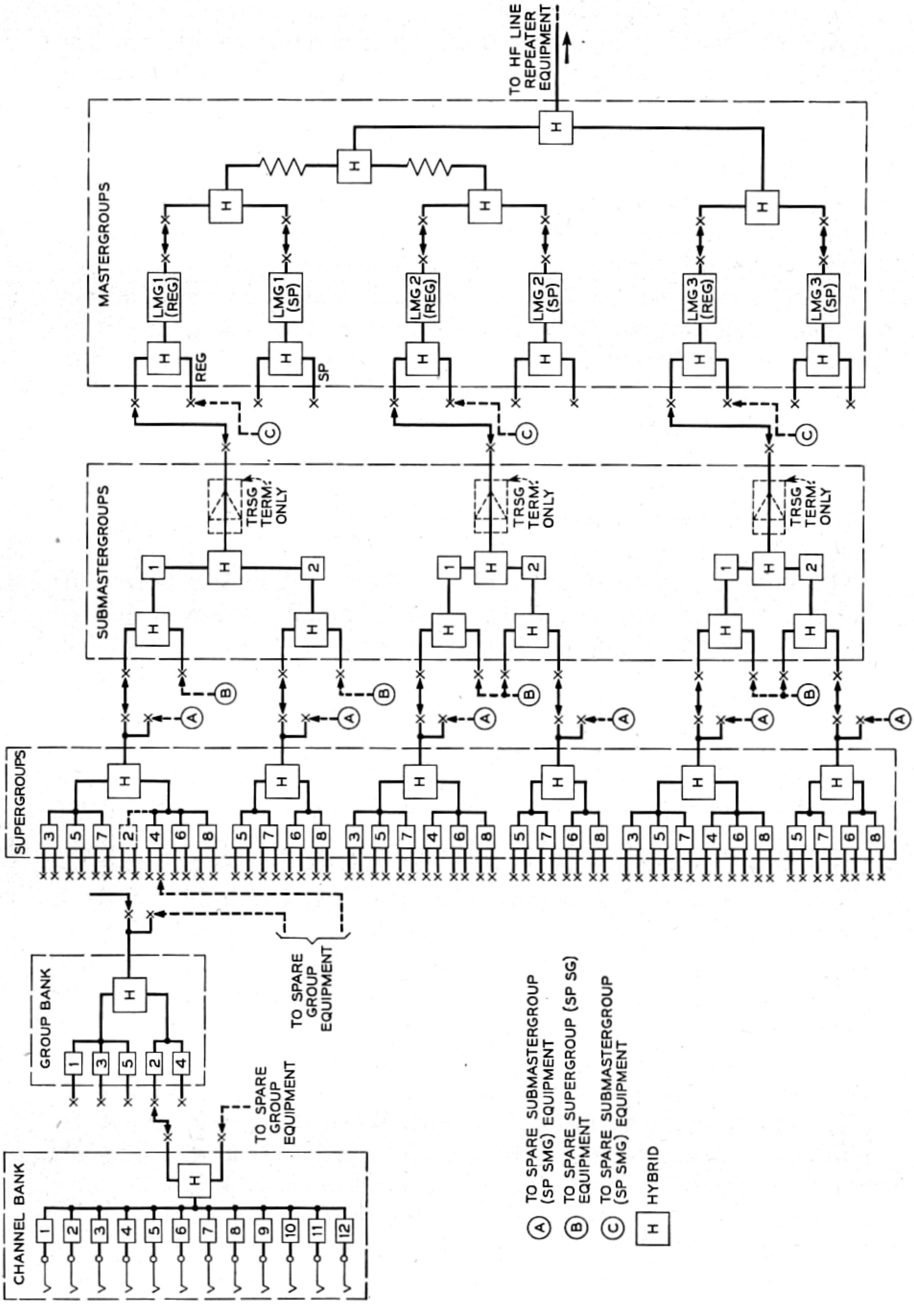


Fig. 10 — Terminal transmission

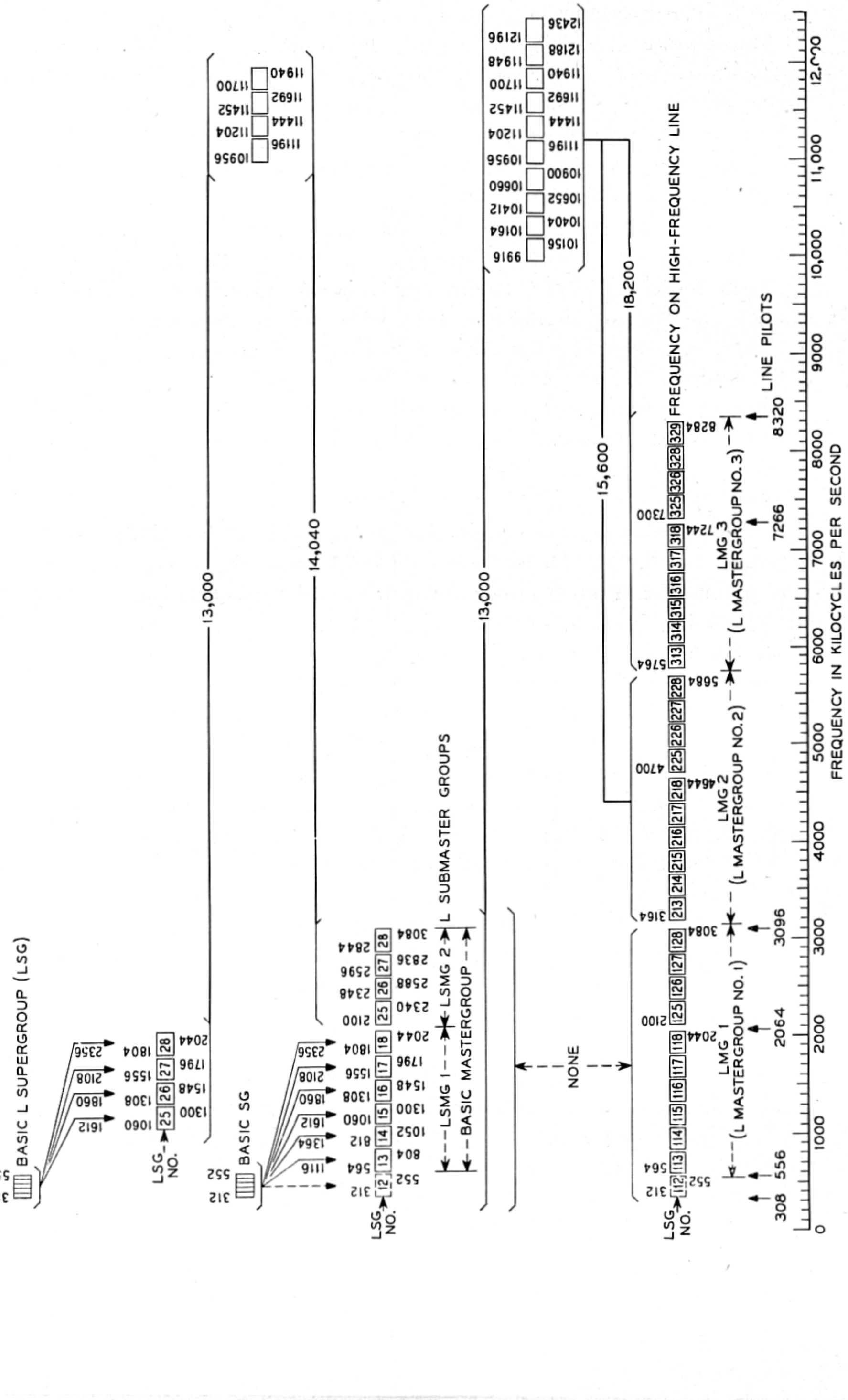


Fig. 20 — Frequency translations in the terminal for an all-message system.

2 and 3. The frequency allocation and modulation steps shown on Fig. 20 were chosen so that good performance could be obtained with relatively inexpensive filters used for suppressing unwanted sidebands and to develop lower sideband signals appearing right side up for transmission over the high-frequency line. The carrier frequencies used in the modulation steps were chosen so that some of the same filters could be used in the submastergroup two and mastergroup two and three modulators. The clear bands between the submastergroups and the mastergroups were chosen to permit the use of economical blocking filters at repeaters where circuits are to be dropped from the high-frequency line and to provide frequency space for the line pilots.

It will be noticed in Fig. 19 that facilities are provided for patching spare equipment into service for maintenance reasons or in the event of a failure in working units. Alarm features are incorporated in the submaster group and mastergroup units to indicate trouble conditions and initiate maintenance procedures.

The carriers required for the channel, group and supergroup units are supplied by equipment developed for the L1 system. The arrangements for supplying the new carrier and pilot frequencies are shown in Fig. 21.

A problem of primary importance in carrier supply design is the accuracy of the frequencies. There is both an absolute accuracy and a relative accuracy requirement. For transmission of some types of signals there is a requirement that the difference in frequency between a carrier at two terminals be less than 2 cycles per second. This extreme accuracy is achieved by using the oscillator at one terminal to control the frequency of oscillators at other points. A line pilot generated at the terminal in which the master oscillator is located is used as a reference frequency at points along the line where other terminals are located and by this means carriers are held to a relative accuracy of ± 1 part per 30 million.

In order that requirements for high quality television transmission may be realized on a 4,000-mile circuit, the output of the pilot supply must be extremely constant with both time and temperature changes. Deviations in the magnitudes of line pilots are maintained to less than 0.05 db.

Since a failure in the L3 carrier and pilot supply could cause interruption to service on an extremely large number of circuits, many precautions have been taken to make the equipment reliable. In addition, standby units, which are automatically switched in place of the regular units in the event of failure, are provided to improve the over-all reliability of the system.

The terminal equipment is normally mounted on standard 11′ 6″ duct-type bays. The submastergroup and mastergroup equipment required to handle 1,860 channels occupies two complete bays and portions of two others. One carrier and pilot supply is mounted in three bays.

3.6 POWER GENERATION AND TRANSMISSION

Power is transmitted to the auxiliary repeater over the inner conductors of each pair of coaxials as noted earlier. A maximum of twenty-one auxiliary repeaters can be fed from a main repeater. This limit is determined by the maximum potential the cable can safely withstand. Shorter spacings are dictated by geographical and plant layout considerations.

The power supplied to the coaxials at the main stations is generated by a motor-alternator set which consists of the alternator, an induction motor, a dc motor and its exciter, all coupled together on the same shaft. Normally, commercial power is used to drive the induction motor. When this source fails or the voltage goes out of prescribed limits the drive is transferred to the dc motor which operates from a 130-volt battery. If the commercial power is unusable for more than 2½ minutes an emergency engine alternator is started and after a five minute warm-up period it replaces commercial power in driving the regular induction motor.

The constant current to the coaxials is supplied through a power control circuit which accurately regulates it to within ±1 per cent of the desired value. A simplified schematic of the power control unit is shown on Fig. 22. The unit consists of two motor driven continuously variable transformers which supply power to the line transformer. The course control variable transformer is relay controlled and maintains the line current within ±3 per cent of the prescribed value. The range of this transformer is sufficient to permit reducing the voltage to zero in order to turn down power on the system for maintenance purposes. The fine control variable transformer is regulated by an electronic regulator to maintain the line current within ±1 per cent of the desired value.

The change in the line current in response to commercial power transients and transients introduced by changes in the motors driving the alternator requires careful consideration. By increasing the inertia of the motor alternator set with a fly wheel and carefully designing the frequency response of the above described power control regulator a satisfactory transient response has been obtained.

For the maximum length power section the potential applied to

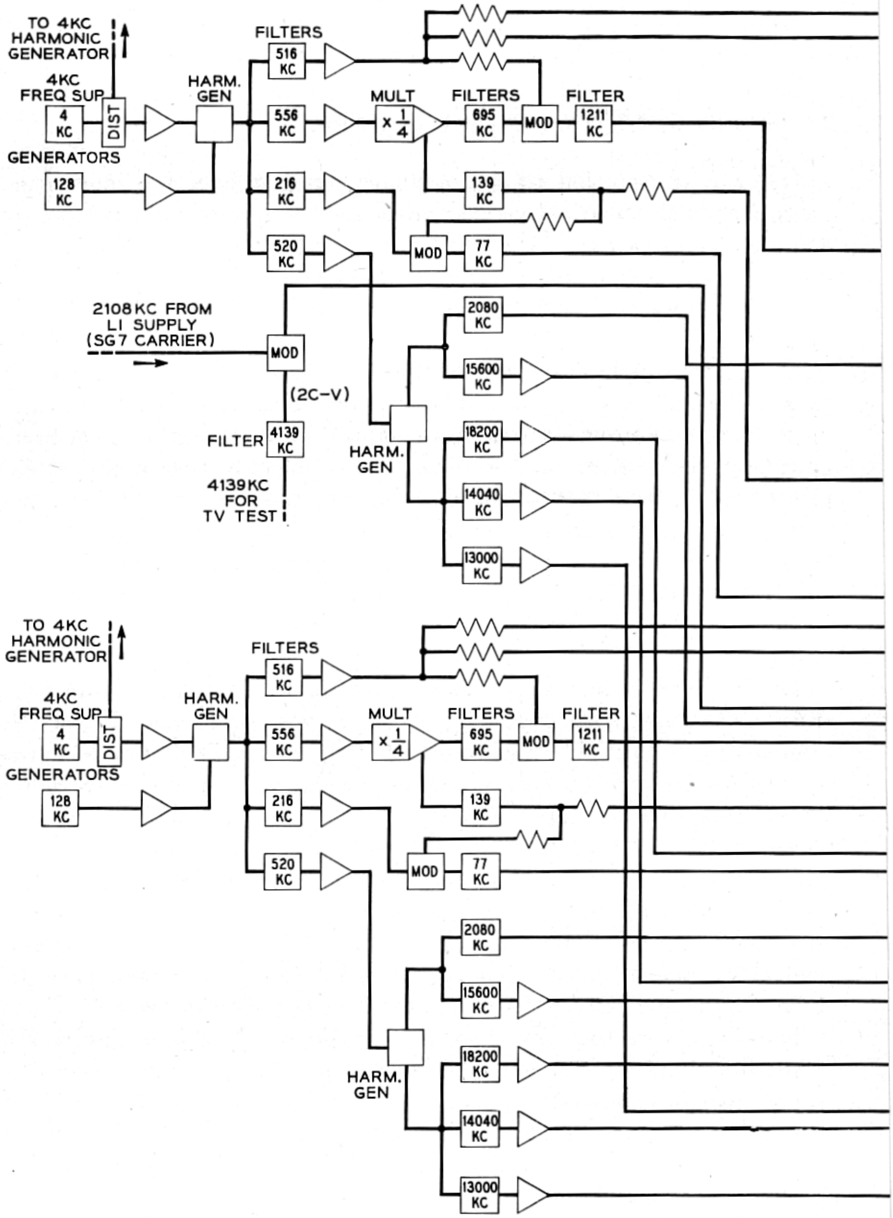
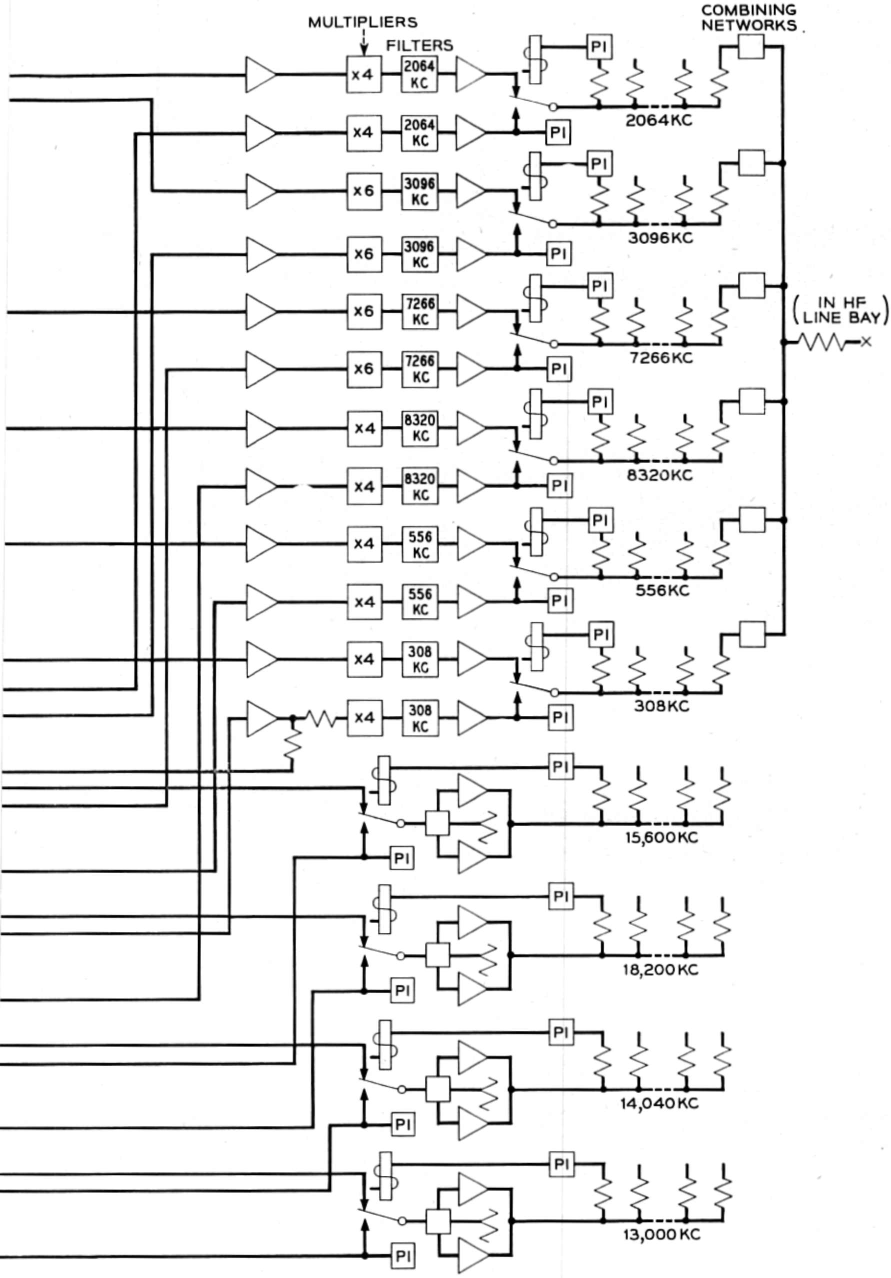


Fig. 21 — Arrangements for supp



arrier and pilot frequencies.

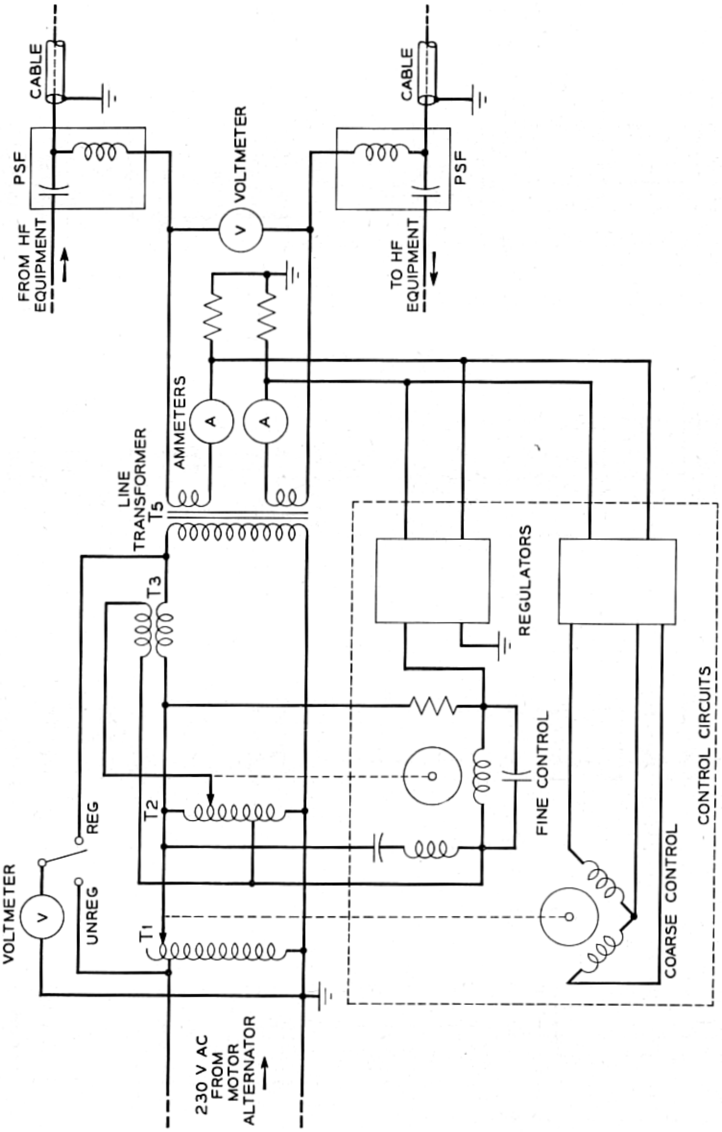


Fig. 22 — Simplified schematic of the power control circuit through which regulated power is fed to the coaxial circuits.

the cable at the main stations is about 2,000 volts rms from center conductor to ground. This potential diminishes about 100 volts per repeater section in going out from the power feed point or as the power section is shortened. (The maximum potential applied to the cable in L1 systems is about 800 volts rms between center conductor and ground). Extensive tests on the installed cable showed that corona develops in the cable at potentials varying in a random fashion between 1,200 and 1,600 volts rms. This would allow power feed points to be placed at a maximum spacing of about 100 miles. By replacing the nitrogen, with which the cables are normally filled, with a large molecule gas, sulfurhexafluoride (SF_6), the corona potential of the cable is increased well above the maximum operating potential. Only the cable sections exposed to potentials greater than 1,200 volts will be filled with the new gas. Elaborate and thorough tests have demonstrated that no deterioration of the cables will result from the use of this gas. Some additional precautions are required in entering manholes and using high temperature torches for soldering when the SF_6 gas might be present.

3.7 ALARM EQUIPMENT

Since the auxiliary repeaters and certain of the main repeaters are unattended it is necessary that arrangements be provided to indicate at the attended stations when some piece of equipment fails to perform satisfactorily.

Auxiliary repeaters using pilot regulators are equipped with microammeter relays which monitor the operation of the regulator continuously. These relays provide an indication of the operation of the regulator and the power of the 7,266-kc pilot at the output of the repeater. When conditions change from the nominal by a specified amount the relay contacts close and are locked magnetically. This bridges an alarm pair in the cable and operates an alarm at the nearest attended repeater. By means of Wheatstone bridge measurements from this repeater over the same alarm pair, the repeater in trouble can be located and a maintenance crew dispatched to make the necessary equipment replacements. The relays can also be reset over the same alarm pair to aid in the location process or to clear alarms which were initiated at unaffected repeaters by deviations in the pilot due to troubles at preceding repeaters.

At main repeaters, microammeter relays are provided on all six pilots used to control the equalization of the system. Deviations in these pilots operate the automatic switching equipment and initiate the usual office alarms. Alarms are also provided to indicate fuse operation, transfers from regular to standby equipment, and the condition of electron tubes in the terminal equipment amplifiers.

Provisions for connection to special alarm systems are made at main repeaters which are not fully attended. These systems extend the alarms to the nearest attended repeater and enable the attendant to determine in considerable detail the condition at the remote repeater. The attendant may also perform certain operations such as switching a working line to a spare line at the remote repeater.

3.8 MAINTENANCE

Maintenance of the L3 system requires equipment and methods for routine checking of the system and trouble location. Normally the auxiliary repeaters will be visited at intervals of about three months, when checks will be made of the power voltages and currents, the electron tube bias and change in bias with a fixed change in heater voltage (activity), and the pilot magnitudes. At these times amplifiers and regulators which fail to meet prescribed limits will be replaced, the 7,266-kc pilot will be brought to its normal value by adjusting the regulator gain, and the amplifier gain control in the output beta circuit will be adjusted by observing the 3,096-kc pilot.

For these routine tests and adjustments two portable test sets are provided. The power test set plugs into the repeater, amplifier, or regulator and provides for measuring power supply voltage and currents and electron tube cathode-grid voltages to an accuracy of ± 1 per cent. The pilot indicator makes it possible to measure the 7,266 and 3,096-kc pilots to an accuracy of ± 0.1 db.

For trouble locations at auxiliary repeaters a portable transmission measuring set has been designed. It is capable of measuring the power in a 500-cycle band at any place in the frequency spectrum from 50 to 11,000 kc to an accuracy of ± 0.5 to ± 0.02 db depending on its specific use and the care used in calibration.

At main repeaters, line sections will be checked for noise and modulation performance and equalizers will be adjusted at intervals of one week to several months. In addition, loss and gain measurements on sections of the office suspected of being in trouble will be made. For all general tests except equalization line up, point by point measuring equipment is provided, consisting of a 50 to 10,000-kc oscillator, the tuned transmission measuring set referred to above, a milliwatt power meter accurate to ± 0.035 db and a complement of attenuators, pads and comparison switches.

Fig. 23 — An engineer testing pilot transmission in an L3 repeater hut.

The adjustment of the manual gain equalizers to an accuracy of ± 0.02 db in a rapid and direct way is accomplished by special equipment described in the companion equalization paper.[10] A visual gain and delay transmission measuring test set, capable of measuring gain to ± 0.05 db and delay to ± 0.02 microseconds, has been developed for observing the line performance and adjusting delay equalizers when the system is used for television.

A maintenance center is provided at about 200-mile intervals along the line to service the equipment removed from repeaters. At these points facilities are provided for the following: (1) electron tube testing; (2) regulator repair and adjustment; (3) transmission measurements on passive components; and (4) amplifier testing of sufficient scope to permit changing tubes and to determine whether an amplifier is suitable for further service in the line.

ACKNOWLEDGEMENTS

A system as complex as the L3 system is the result of a large scale cooperative development effort involving many Departments in Bell Laboratories. More than a hundred engineers and technicians have contributed to the design over a period of seven years. In the system planning aspects of the development covered by this paper particular mention should be made of the large contributions of L. G. Abraham, C. H. Bidwell and S. E. Miller.

BIBLIOGRAPHY

1. Abraham, L. G., Progress in Coaxial Telephone and Television Systems, Transactions of the A.I.E.E., **67**, pp. 1520–1527, 1948.
2. Crane, R. E., Dixon, J. T. and Huber, G. H., Frequency Division Techniques for a Coaxial Cable Network, Transactions of the A.I.E.E., **66**, pp. 1451–1459, 1947.
3. Holbrook, B. D., and Dixon, J. T., Load Rating Theory for Multichannel Amplifiers, Bell System Tech. J., **18**, pp. 624–644, Oct., 1939.
4. Bennett, W. R., Cross-Modulation Requirements on Multichannel Amplifiers Below Overload, Bell System Tech. J., **19**, pp. 587–610, Oct., 1940.
5. Mertz, Pierre, Data on Random Noise Requirements for Theater Television, S.M.P.T.E., J., **57**, pp. 89–107, Aug., 1951.
6. Baldwin, M. W. Jr., The Subjective Sharpness of Simulated Television Images, Bell System Tech. J., **19**, pp. 563–586, Oct., 1940.
7. Baldwin, M. W. Jr., Single Frequency Video Interference Data, Proceedings of the J.T.A.C., Annex 8, **2**, Dec., 1948.
8. Morris, L. H., Lovell, G. H., and Dickinson, F. R., The L3 Coaxial System — Amplifiers, see pp. 879–914 of this issue.
9. Rieke, J. W., and Graham, R. S., The L3 Coaxial System — Television Terminals, see pp. 915–942 of this issue.
10. Ketchledge, R. W., and Finch, T. R. L3 Coaxial System — Equalization and Regulation, see pp. 833–878 of this issue.
11. Mertz, Pierre, Fowler, A. D., and Christopher, H. N., Quality Rating of Television Images, I.R.E., Proc., **38**, pp. 1269–1283, Nov., 1950.
12. Dodge, H. F., Kruger, M. K., and Kinsburg, B. J., The L3 Coaxial System — Quality Control Requirements, see pp. 943–968 of this issue.