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Transmission Specifications for Private Line Metallic Circuits

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NOTICE

This Technical Reference is published by American Telephone and Telegraph Company as a guide for the designers, manufacturers, and consultants of customer-provided systems and equipment which connect with Bell System communications systems or equipment. American Telephone and Telegraph Company reserves the right to revise this Technical Reference for any reason, including, but not limited to, conformity with standards promulgated by ANSI, EIA, CCITT, or similar agencies; utilization of new advances in the state of the technical arts; or to reflect changes in the design of equipment or services described therein. The limits of responsibility and liability of the Bell System with respect to the use of customer-provided equipment or systems are set forth in the appropriate tariff regulations.

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FOR

PRIVATE LINE METALLIC CIRCUITS

0. IMPORTANT PREFATORY NOTICE

This preliminary Technical Reference is being published to provide information to customers, consultants, designers, and manufacturers of customer-provided systems and equipment that may be used in connection with Bell System private line metallic circuits.

Historically, the Telephone Companies have provided short distance private line channels over metallic wire pairs. These metallic circuits have been used by customers employing their own transmission equipment for voice, teletypewriter, facsimile, data, alarm, metering, supervisory control and signaling communications. In many instances, customer-provided equipment may have been designed so as to require metallic continuity for successful operation of such equipment. Where such channels are furnished today or in the future for connection to such customer-provided equipment, the customer should be fully aware that the Telephone Company has no obligation to continue to provide the private line channel on a metallic basis.

The local telephone company tariffs do not provide, as a standard offering, private line circuits with metallic continuity. The Telephone Companies implement private line services by the most efficient means possible, whether by wire, radio, carrier or combinations thereof. The tariffs are thus filed in such a form as to describe communications services that can be provided over the telephone network without specific requirement for provision of a particular type of facility. Indeed, in the normal rearrangements of the

Telephone Company facilities, the service may from time to time be provided over a variety of facilities.

The rapid growth of short haul carrier systems between central offices, the continuing need to add new central offices and to transfer areas between serving central offices, and the increasing use of carrier technology on lines between the central office and customer's location are reducing the availability of metallic wire pairs. To avoid the risk of obsolescence of customer-provided equipment, customers who connect their equipment to Telephone Company channels are encouraged to secure equipment compatible with the total telecommunications network. Equipments compatible with the total telecommunications network are those designed in conformance with Technical References such as:

- 30-Baud Private Line Channels, Interface Specification, (PUB 41001)*
- 45-,55- and 75- Baud Private Line Channels, Interface Specification, (PUB 41002)*
- 150-Baud Private Line Channels, Interface Specification, (PUB 41003)*
- Transmission Specifications for Voice Grade Private Line Data Channels, (PUB 41004)*
- Private Line Interconnection, Voice Applications, Preliminary, (PUB 43201)*

This Technical Reference on metallic circuits is applicable to situations where the Telephone Company implements the private line channel with a cable pair and does not include in the channel additional transmission equipments such as transformers, amplifiers and carrier systems. Presently this is the

* Bell System Technical References may be purchased by writing to:

Western Electric Company, Inc.
Commercial Relations
P.O. Box 1579
Newark, New Jersey 07102

case for most local private line channels provided for morse, teletypewriter, teletypesetter, data, remote metering, supervisory control and miscellaneous signaling purposes.

The material in this Technical Reference is not appropriate for voice grade channels and is not appropriate for less than voice grade channels where the Telephone Company uses channel deriving equipments or provides the signal battery. The Technical References cited above should be used for information on the connection of customer-provided equipments to these channels.

In order to protect Telephone Company personnel and equipment from harm and in order to prevent interference with the signal transmission of other users of the telecommunications network, signals applied to metallic circuits should meet the signal level criteria objectives presented in this Technical Reference. It is requested that manufacturers and users initiate whatever procedures are necessary to correct any inconsistencies which may exist in their equipments. It is strongly recommended that all new equipment designs comply with these objectives.

This Technical Reference is to be used only to the extent it is applicable to the specific service obtained under tariff. The material contained in this Technical Reference should not be interpreted to supersede, in any way, any of the provisions set forth in the tariffs including those provisions which restrict the type of signals which may be applied to a specific channel or the purpose for which a specific channel may be utilized. Attention is specifically directed to those provisions of the tariffs which set forth limitations on bandwidth and pulsing rates.

1. INTRODUCTION

1.1 General

This preliminary Technical Reference defines the interface between customer-provided equipment and a private line metallic circuit used by the customer for transmission of dc and/or ac signals. In addition, this Technical Reference provides information on the transmission characteristics of metallic circuits, along with the signal level restrictions and the design and maintenance considerations associated with the use of such circuits.

1.2 Arrangements

The basic metallic circuit is a cable pair, or equivalent dc path, used to provide service between customer locations. Metallic circuits are limited to short distance service (e.g., the area served by a single Telephone Company central office) in accordance with local Telephone Company practice. End-to-end metallic circuits are generally not provided when the terminating points are served by different Telephone Company central office buildings. Two points which are physically close together may be served by different central office buildings so even physical proximity is not an indication that metallic facilities will be available.

Metallic circuits are generally routed through a Telephone Company central office although some may not, depending upon the availability of pairs and the relative locations of the central offices and customer terminals. While the basic metallic circuit provides two-point service, multipoint service can be provided by appropriate junction of a number of legs, usually at a Telephone Company central office.

1.3 Variations From Basic Circuit Arrangements

If additional service features beyond those contained in this Technical Reference are required, special arrangements should be made with the local Telephone Company. Special arrangements over and above the basic metallic circuits provided in the local Telephone Company area may result in additional charges to the customer.

2. SERVICE AND MAINTENANCE CONSIDERATIONS

2.1 Responsibility of the Customer

The following is representative of tariff regulations which delineate the responsibility of the customer:

"Where private line service is available under this tariff for use in connection with terminal equipment or communications systems, provided by a customer, authorized user or joint user, the operating characteristics of such equipment or systems shall be such as not to interfere with any of the services offered by the Telephone Company. Such use is subject to the further provisions that the equipment or systems provided by a customer, authorized user or joint user does not endanger the safety of Telephone Company employees or the public, damage, require change in or alteration of, the equipment or other facilities of the Telephone Company; interfere with the proper functioning or such equipment or facilities; impair the operation of the Telephone Company's facilities or otherwise injure the public in its use of the Telephone Company's services. Upon notice from the Telephone Company that the equipment or system provided by a customer, authorized user or joint user is causing or is likely to cause such hazard or interference, the customer shall take such steps as shall be necessary to remove or prevent such hazard or interference."

"The customer shall be responsible for payment of a service charge for visits by the Telephone Company to the premises of the customer or authorized or joint users where the service difficulty or trouble report results from the use of equipment or facilities provided by the customer or his authorized users or joint users."

2.2 Responsibility of the Telephone Company

The following is representative of tariff regulations which delineate the responsibility of the Telephone Company:

"The Telephone Company shall not be responsible for installation, operation or maintenance of any terminal equipment or communications systems provided by a customer, authorized user or joint user. Private line service is not represented as adapted to the use of such equipment or systems and where such equipment or system is connected to Telephone Company facilities the responsibility of the Telephone Company shall be limited to the furnishing of facilities suitable for private line service and to the maintenance and operation of such facilities in a manner proper for such private line service; subject to this responsibility the Telephone Company shall not be responsible for (i) the through transmission of signals generated by such equipment or system, or for the quality of, or defects in, such transmission, or (ii) the reception of signals by such equipment or system, or (iii) address signaling where such signaling is performed by customer-provided tone-type signaling equipment."

"The Telephone Company shall not be responsible to the customer or authorized user or joint user if changes in protection criteria or in any of the facilities, operations or procedures of the Telephone Company render any facilities provided by a customer, authorized user or joint user obsolete or require modification or alteration of such equipment or system or otherwise affect its use or performance."

2.3 Maintenance Access

Because trouble locating procedures may require separation of the cable pairs from the terminal equipment, it must be possible to quickly and easily disconnect the customer's terminal equipment at some point such as the interface connector block. In large concentrations of metallic circuits, maintenance access jacks are sometimes provided at the telephone offices and/or at the customer's premises according to local Telephone Company practices. If system operational considerations prohibit the use of jacks for maintenance access, this factor should be carefully reviewed with the Telephone Company at the time of the service request so that those channels may be accorded proper treatment. The need for quick and easy accessibility to the interface connector block and/or terminals on a 24-hour basis is a prerequisite for proper maintenance.

2.4 Reliability

Although reliability of metallic circuits is normally high, rapid restoration of failed circuits by patching to an alternate route is generally not practical for these circuits. The main factors contributing to circuit failure or interruption are such events as storms, automobile accidents, malicious destruction, plant rearrangement, and construction activities.

2.5 Trouble Reporting Procedure

Even though there is an adequate maintenance operation for these channels, there will be occasions when trouble is experienced. When this occurs, the customer should check for proper operation of his equipment and facilities. If the tests indicate the trouble is in the Telephone Company-provided equipment or facilities, it should be promptly reported to the Telephone Company as instructed by the local Telephone Company.

3. INTERFACE

3.1 Physical

The interface between the customer-provided terminal and the Telephone Company metallic circuit will, in general, be a terminal block arranged for convenient connection of the conductors to the customer-provided equipment. The terminal block will be provided by the Telephone Company and space must be provided by the customer for the Telephone Company to install the terminal block in a suitable location to permit maintenance testing of the circuit when the customer's equipment is disconnected. The customer is responsible for the connection of his equipment to the terminal block. The customer is also responsible for disconnecting his equipment at the interface to allow Telephone Company repair personnel to make maintenance tests.

3.2 Electrical

Each metallic circuit will consist of a pair of wires, without signal battery, which are insulated from each other and from ground, each having metallic continuity end-to-end. The wire resistance will depend on the length of the circuit and available wire sizes as described in Section 4.1. The leakage resistance of the wires to ground or to each other will usually be more than 100,000 ohms, but may approach 10,000 ohms under adverse conditions.

4. TRANSMISSION CONSIDERATIONS

4.1 General

A metallic circuit is suitable for the transmission of signals having dc and/or ac components which meet the criteria of Section 5 and which conform to the restrictions (e.g., bandwidth, pulsing rate, etc.) set forth in the tariff under which the service is obtained. The metallic circuit is routed over the same types of cable pairs used in providing local voice grade service. These pairs are usually nonloaded, but may, in some instances, be inductively loaded (e.g., 88 mH coils spaced about 6000 ft.) for improved voiceband transmission.* While the pass band is equivalent to other nonconditioned voice grade facilities (approximately 3000 Hz), no amplifiers are included in the circuit, and, hence, the 1000 Hz loss is not usually specified. In general, an end-to-end connection may be expected to have a loss characteristic which increases with increasing frequencies in the upper half of the band.

There is no well-defined upper limit to the loop resistance which may be encountered. Since leakage resistance may be as low as 10,000 ohms, operation over loop resistances in excess of 5,000 ohms may not provide an adequate margin between loop resistance and the worst case of insulation leakage. The wire size for copper conductors may range from 19-gauge to 26-gauge (26-gauge is typical), with the dc resistance (at 68°F) ranging from about 85 ohms per loop mile to 450 ohms per loop mile. Corresponding wire gauges for aluminum conductors are used in some areas. The time variation in loop resistance will be a function of the local climate and will depend on whether the circuit is routed over aerial, underground, or buried cable. Capacitance between conductors of a cable pair is nominally 0.083 µF per mile but may be in the range of 0.06 to 0.10 µF per mile. Depending on availability, a given metallic circuit may be routed over several cable sections having different wire sizes and different types of loading.

Signal propagation time will be a function of signal frequency, circuit length, and type of facility. When signal propagation time is a sensitive system parameter, the subject should be reviewed with the local Telephone Company at the time of the service request.

*Load coils are present on most circuits exceeding 3 to 6 miles in length

If the signal propagation time, bandwidth or other circuit characteristics described in this Section must be controlled (that is, when feasible), special facilities and additional charges to the customer are usually required.

4.2 Metallic and Longitudinal Voltages* - Circuit Noise

When metallic circuits are connected to balanced terminal equipments of approximately 900 ohms, metallic circuit noise at the interface can be expected to be low, usually less than 20 dBrnC.** Depending on the environment, circuit length and system grounding arrangements, longitudinal voltages of considerable magnitude may be encountered. The most likely longitudinal voltages are those resulting from power system inductive influences at the fundamental and harmonic frequencies of the power system. Under extreme conditions, the induced ac power frequency longitudinal voltage (noise) may be as high as 100 volts. The average induced ac longitudinal voltage (noise) is usually less than 10 volts. DC longitudinal voltages will generally be less than 3 volts.

4.3 Foreign Voltage Protection

Where telephone lines are exposed to lightning, power circuit contact, or induction, protective devices are installed at the central office and on the customer's premises. Spark gap lightning protection devices intended to limit the voltage from any one wire to ground to approximately 600 volts are the typical protection devices installed on the customer's premises. The gap on one wire will often break down before the other causing the voltage on the wire whose gap does not break down to appear as a transient impressed across the input of the customer's terminal equipment. Because of normal variations in gap breakdown, transient voltages up to approximately 800 volts peak may

* See Section 5.3.3 for definition of metallic and longitudinal voltages.

** A 1000 Hz tone at a level of -90 dBm gives a 0 dBrn reading regardless of weighting. The notation dBrnC is used when readings are made with the C-message weighting network.

develop across the input terminals of the customer's equipment. Where customer-provided equipment and wiring require grounding, it is important that the grounding connections be made to a National Electrical Code approved ground electrode (e.g., waterpipe) to which the Telephone Company protector is grounded (see Section 4.4). Because the grounding connections may be long and thus have high surge impedances, longitudinal voltages considerably larger than 800 volts may appear between the customer's equipment and the common ground. Accordingly, it is recommended that customer-provided equipment be capable of withstanding minimum transverse surges of 800 volts peak and minimum longitudinal surges of 5000 volts peak. Typical transverse lightning surges may be assumed to have about a 10-microsecond rise rise time to crest and a decay time to half crest value of about 1000 microseconds.* Longitudinal surges, which are caused by high magnitude, steep rising, lightning currents flowing in grounding conductors, are not likely to have durations longer than a few tens of microseconds.

4.4 Grounding

It is expected that the customer's equipment, if powered from commercial power, will be grounded in accordance with applicable electrical codes, such as the NEC. Self-powered or passive customer's equipment need not be grounded.

Provisions should be made within the customer's equipment for connecting together all internal signal grounds. This connection should be isolated from both the grounding (green) conductor run with the power supply primary conductors and the chassis or frame of the customer-provided equipment. The customer's signal ground may be obtained with a proper connection to the ground electrode (e.g., metallic cold water pipe), using a single No. 14 AWG or larger copper conductor. The run should be short, straight, and a continuous piece of wire. Proper attention should be given to providing the

* Bodle, D. W. and Gresh, P. A., "Lightning Surges in Paired Telephone Cable Facilities", BSTJ, Vol. 40, No. 2 (March 1961), pp. 547-576.

lowest possible resistance connection at each end of the ground wire. When the metallic circuit is equipped with a Telephone Company provided station protector, it is imperative that the customer's ground wire be connected to the ground electrode at the same location as the Telephone Company protector ground wire but not using the Telephone Company ground clamp. The ground wire must not be fused.

5. SIGNAL RESTRICTIONS

5.1 General

The customer is responsible for providing protection, internal to his equipment and facilities, against hazardous and interfering voltages and currents from his equipment and facilities being applied to the Telephone Company conductors. There are two sets of signal restrictions which must be met: (1) safety limits - covered in Section 5.2 and (2) noise influence limits - covered in Section 5.3. A fundamental difference between these two sets of signal restrictions should be noted. The safety restrictions pertain to the peak voltage of the signal waveform whereas the noise influence restrictions pertain to the rms voltage of the signal components within a given frequency band. The significance of this difference is discussed in the following sections. It should also be noted that these two sets of signal restrictions are independent and that satisfying one set does not insure that the other set is satisfied.

This Technical Reference does not cover any additional restrictions such as bandwidth and pulsing rate limitations which might be imposed by the tariff under which the service is obtained.

5.2 Restrictions Due to Safety Considerations

5.2.1 Restrictions on Operating Voltages and Currents

For the purpose of providing adequate protection to Telephone Company personnel and plant facilities, the voltages applied to the conductors at the metallic circuit interface must be limited to the following:

> Magnitude of the peak of the voltage between any conductor and ground < 70.7 volts.

This limitation applies to all signal waveforms with the following two exceptions:

> Continuous (uninterrupted) dc voltage*: magnitude of the peak of the dc voltage between any conductor and ground < 135 volts.
>
> Interrupted dc voltage* (duration of each interruption greater than one second): magnitude of the peak of the dc voltage between any conductor and ground < 135 volts.

It should be noted that rectangular pulse-type signals must meet the 70.7 volts peak to ground requirement unless they satisfy the interrupted dc requirement of at least one second of zero voltage. For a continuous single frequency tone signal, the 70.7 volts peak to ground requirement is equivalent to 50 volts rms.

Figure 1 illustrates the above restrictions for rectangular pulses, a single frequency tone, and an arbitrary signal and shows the effect of the voltage limitations when these signals are superimposed on various amounts of dc. Also included in the figure are the limitations for a steady state dc voltage and for interrupted dc voltages.

The maximum permitted voltage between two conductors is limited to a value such that the voltage requirement between each conductor and ground is satisfied. For example, if the voltage source is center-tapped to ground, the maximum permitted voltage between conductors would be twice the maximum permitted voltage between a conductor and ground. If the signal source is not grounded, then the conductor to conductor voltage must not exceed the conductor to ground limits specified above.

The maximum permitted voltage is also restricted by noise influence considerations as described in Section 5.3. Either restriction (safety or noise

* Peak ripple of dc voltage must be less than 5 volts.

influence) may be controlling depending upon factors such as signal waveshape and grounding arrangements. However, safety considerations are controlling if there are no frequency components (including harmonics and spurious signals) above 10 Hz. Noise influence considerations are controlling if there are no frequency components of the signal below about 150 Hz (including dc).

The current applied to the conductors by customer-provided equipment must be limited as follows:

> line current, including contributions by both ac and dc components, per conductor < 0.350 amperes rms.

That is, the effective value of the current waveform, for any waveform, must be less than 0.350 ampere. This restriction is necessary to limit the temperature rise of the conductors and other circuit components to an acceptable level and to prevent the operation of standard protection devices. The use of multiple conductors to limit the current per conductor to this value is not desirable since a conductor or pair could go open or become grounded resulting in excess current on one or more conductors of the circuit.

Operation with currents of 350 milliamperes per conductor is not always permitted. For example, where loaded cable is used the maximum current is restricted to approximately 150 milliamperes. Therefore, it is recommended that equipments designed for general use not apply currents greater than 150 milliamperes per conductor.

5.2.2 Limitation of Abnormal Voltages

In order to prevent voltages substantially higher than normal from being impressed on the metallic circuit in the event of some equipment failure, it is important that any transformers, relays, or other apparatus connected between the metallic circuit and sources of power meet the applicable dielectric strength requirement of the American National Standards Association (dielectric strength of twice the line voltage plus 1000 volts).

A note of caution concerning power line surges. Customer equipment powered from commercial power sources may have surges up to 5 KV across the power line. Secondary arrestors can limit this voltage to about 2 KV. Responsibility for determining the probable hazard in any specific case rests with the customer.

All conductors on the customer's side of the interface that may possibly be exposed to lightning surges or power voltages in excess of 300 volts rms shall be equipped with Underwriters Laboratories listed station protectors.

5.2.3 Limitation of Abnormal Currents

Current limiting devices in the form of fuses and protective series resistance must be provided by the customer according to the following table:

Open Circuit Voltage dc or ac (rms)	Maximum Fuse Rating		Series Resistance
0 - 15	5 amps	or	1 ohm per open circuit volt
15 - 30	3 amps		
30 - 50	1-1/3 amps		
over 50	1 amp	and	1 ohm per open circuit volt

These current limiting devices are needed to control abnormal currents resulting from faults within customer-provided equipment or faults in the metallic circuit to a level where fires due to arcing in Telephone Company equipment and facilities are unlikely.

The open circuit voltage in the above table refers to the larger of (1) the voltage between conductors and ground and (2) the voltage between the two conductors. When fusing is used, a fuse should be associated with each ungrounded conductor. The fuse should blow within five minutes when carrying 150 percent of its rated current. When series resistance is required, the resistance should be sufficient to limit to one ampere current on the

Telephone Company conductors resulting from faults within customer-provided equipment. In addition, the protective series resistance should be such to insure that the current will not exceed one ampere when grounds and/or shorts are applied in any combination to the Telephone Company side of the interface. The protective series resistance should be capable of carrying one ampere continuously. The required resistance normally should be applied equally to the two sides of the circuit in order to preserve circuit balance. If one side of the circuit is grounded, the required resistance should be inserted in the ungrounded side.

5.3 Restrictions Due to Noise Influence Considerations

In addition to the safety considerations of Section 5.2, it is necessary that certain signal level criteria be met to prevent signals applied to metallic circuits from interfering with other communications services. In general, the amount of interference depends upon:

(1) the magnitude of the signal,

(2) the repetition rate of the signal,

(3) the waveshape of the signal,

(4) the balance to ground of the signal, and

(5) the number of channels keyed coherently.

In order to be applicable to all types of signals, the signal restrictions are specified in terms of the rms voltage in each of four frequency bands: 10 Hz - 10 kHz, 10 kHz - 25 kHz, 25 kHz - 40 kHz, and above 40 kHz. Four frequency bands are specified in order to account for the differences in susceptibility to crosstalk of various communications services. For example, the limitation for the 10 Hz - 10 kHz band is based on the susceptibility of voiceband data, message and program circuits to interference from signals applied to a metallic circuit in the same cable.

5.3.1 Single Frequency Signals

To prevent interference into other circuits, it is necessary that the balanced single frequency rms voltage applied to a metallic circuit not exceed the limits given in the following table. Other types of operation are discussed below; the restrictions applicable in these cases are tighter than those of Table I.

TABLE 1

Frequency Band	Maximum Balanced rms Voltage to Control Crosstalk
	SEE SAFETY WARNING BELOW
10 Hz to 10 kHz	1000 volts rms at 10 Hz decreasing logarithmically with logarithmically increasing frequency to 100 volts rms at 100 Hz. This rate is equivalent to 20 dB per frequency decade or approximately 6 dB per doubling of frequency 100 volts rms at 100 Hz decreasing logarithmically with logarithmically increasing frequency to 0.05 volts rms at 10 kHz. This rate is equivalent to 33 dB per frequency decade or approximately 10 dB per doubling of frequency
10 kHz to 25 kHz	0.05 volts rms
25 kHz to 40 kHz	0.012 volts rms
Above 40 kHz	0.0025 volts rms

SAFETY WARNING:

THE MAXIMUM VOLTAGE WHICH MAY BE APPLIED TO THE CONDUCTORS IS THE SMALLER OF THE LIMITS GIVEN IN THIS TABLE AND THE SAFETY LIMITS WHICH REQUIRE THAT THE MAGNITUDE OF THE PEAK VOLTAGE BETWEEN ANY CONDUCTOR AND GROUND MUST NOT EXCEED 70.7 VOLTS OR, UNDER CERTAIN CONDITIONS, 135 VOLTS (SEE SECTION 5.2)

Figure 2 shows a graphical representation of these limits.

The 10 Hz - 10 kHz restriction for a balanced single frequency signal can be expressed mathematically as follows:

$$20 \log_{10} E(f) \leq 80 - 20 \log_{10} f \quad \text{or} \quad E(f) \leq 10^4/f \qquad 10 \text{ Hz} \leq f \leq 100 \text{ Hz}$$

$$20 \log_{10} E(f) \leq 106 - 33 \log_{10} f \quad \text{or} \quad E(f) \leq 10^{5.3}/f^{1.65} \qquad 100 \text{ Hz} \leq f \leq 10 \text{ kHz}$$

where f = frequency in Hertz

$E(f)$ = rms voltage at frequency f

It should be noted that the safety limit of 70.7 volts peak to ground restricts the conductor to conductor voltage of a balanced single frequency tone signal to 100 volts rms*. Table I, Figure 2, and the equations for the 10 Hz - 10 kHz band include limits above this value only to enable the low frequency components of multiple frequency signals and unbalanced signals to be weighted properly. In no event may the safety limits of Section 5.2 be exceeded.

5.3.2 Multiple Frequency Signals

The signal restrictions of Table I are maximum single frequency balanced voltage limits and as such apply directly only to a signal consisting solely of a single frequency tone. The limitations do not permit two or more tones to be applied simultaneously to the metallic circuit at the maximum values permitted for each individual tone. If the signal contains more than one frequency (e.g., multiple tones, pulsed signals, etc.) it is necessary to combine the voltages of all the frequency components in each band by taking the square root of the sum of the squares of the rms values of the component voltages. The resultant rms voltage for each band must be less than the limitations given above for each band. For components in the 10 Hz to 10 kHz band, it is necessary to weight the different voltages before combining them as described above. Weighting is performed by referencing all signal components to an arbitrarily chosen reference frequency. Each component voltage is multipled by a weighting factor which is calculated by dividing the requirement voltage at the reference frequency by the requirement voltage at the frequency of the signal component. The square root of the sum of the squares of all of the weighted signal components must be less than the requirement voltage at the referency frequency.

* Voltage source center-tapped to ground (see Section 5.2).

These procedures for determining compliance with the signal level restrictions can be expressed mathematically as follows:

$$\sqrt{\sum_i [\, W(f_i)\, E(f_i) \,]^2} \leqslant E_r(f_r) \qquad 10\ \text{Hz} \leqslant f_i \leqslant 10\ \text{kHz}$$

$$\sqrt{\sum_i [\, E(f_i) \,]^2} \leqslant 0.050 \qquad 10\ \text{kHz} < f_i \leqslant 25\ \text{kHz}$$

$$\sqrt{\sum_i [\, E(f_i) \,]^2} \leqslant 0.012 \qquad 25\ \text{kHz} < f_i \leqslant 40\ \text{kHz}$$

$$\sqrt{\sum_i [\, E(f_i) \,]^2} \leqslant 0.0025 \qquad f_i > 40\ \text{kHz}$$

where $E(f_i)$ = rms voltage of the signal component at frequency f_i

$W(f_i)$ = weighting factor for frequency f_i

= $E_r(f_r)/E_r(f_i)$

$E_r(f_r)$ = rms voltage restriction for the chosen reference frequency f_r

$E_r(f_i)$ = rms voltage restriction for frequency f_i

If 100 Hz is chosen as the reference frequency for the 10 Hz to 10 kHz band computations, the limitation for this frequency band can be expressed as:

$$\sqrt{\sum_i [\, W(f_i)\, E(f_i) \,]^2} \leqslant 100 \qquad 10\ \text{Hz} \leqslant f_i \leqslant 10\ \text{kHz}$$

$$\text{where } W(f_i) = \begin{cases} f_i/100 & 10\ \text{Hz} \leqslant f_i \leqslant 100\ \text{Hz} \\ f_i^{1.65}/10^{3.3} & 100\ \text{Hz} \leqslant f_i \leqslant 10\ \text{kHz} \end{cases}$$

and f_i is the numerical value of the frequency, in Hertz.

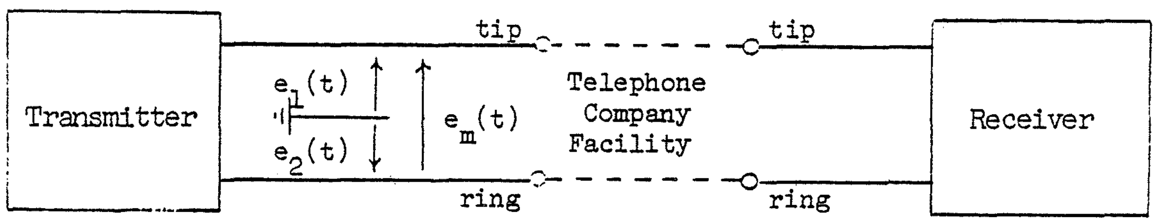
Appendix I contains several examples of computations for multiple frequency signals.

5.3.3 Unbalanced Signals

The signal limitations and procedures for single and multiple frequency signals described in the previous sections are for balanced signals, i.e., the voltage to ground on one conductor is equal in magnitude and opposite in sign to the voltage to ground on the other conductor of the pair.

Tests have shown that the crosstalk coupling between cable pairs increases (crosstalk increases) when the circuit termination is changed from balanced to unbalanced. In order to compensate for this increased coupling between pairs, it is necessary that the signal levels be reduced for unbalanced operation from the values permitted for balanced operation*. The following mathematical procedure provides for the necessary reduction in signal level for unbalanced operation by computing from the unbalanced signal an equivalently interfering balanced signal. This equivalently interfering balanced signal can be used with the procedures of the previous two sections to determine compliance with the signal limitations.

Consider the following representation of a connection of transmission equipment to the Telephone Company conductors.



Using the voltage references shown in the above diagram, the metallic voltage, $e_m(t)$, and the longitudinal voltage, $e_\ell(t)$, applied to the pair are as follows:

$$e_m(t) = e_1(t) - e_2(t) \qquad e_\ell(t) = \frac{e_1(t) + e_2(t)}{2}$$

The frequency components of the metallic and longitudinal voltages can be mathematically combined to obtain equivalently interfering balanced voltage components. The equivalently interfering balanced rms voltage, $E(f_i)$, at each frequency f_i for unbalanced signals is the square root of the sum of the square of the rms voltage of $e_m(t)$ for that frequency and 396 times the square of the rms voltage of $e_\ell(t)$ for that frequency.

* Reduction in level is not required for signal components below 10 Hz, including dc; safety limits of Section 5.2 are controlling for these signal components.

$$E(f_i) = \sqrt{[\, E_m(f_i)\,]^2 + 396\, [\, E_\ell(f_i)\,]^2} \qquad f_i \geqslant 10 \text{ Hz}$$

where $E_m(f_i)$ = rms voltage of the metallic signal component at frequency f_i

$E_\ell(f_i)$ = rms voltage of the longitudinal signal component at frequency f_i

The equivalently interfering balanced rms voltage, $E(f_i)$, at each frequency can be used with the equations given in the previous sections to determine if the signal meets the signal limitations. Making this substitution in the previous equations, the signal limitations, generalized to be applicable for all types of signals, can be expressed mathematically as:

$$\sqrt{\sum_i \{ W(f_i) \sqrt{[\, E_m(f_i)\,]^2 + 396\, [\, E_\ell(f_i)\,]^2}\, \}^2} \leqslant E_r(f_r) \qquad 10 \text{ Hz} \leqslant f_i \leqslant 10 \text{ kHz}$$

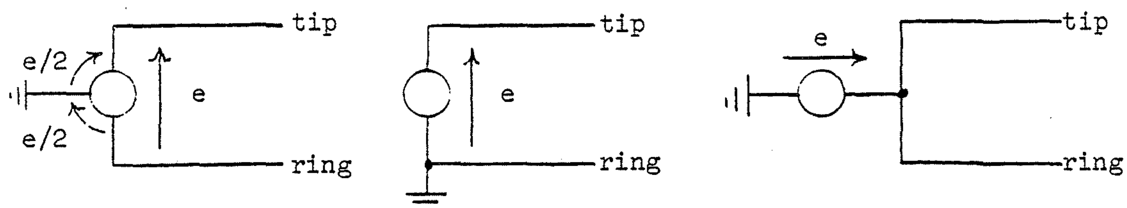
$$\sqrt{\sum_i \{ [\, E_m(f_i)\,]^2 + 396\, [\, E_\ell(f_i)\,]^2 \}} \leqslant 0.050 \qquad 10 \text{ kHz} < f_i \leqslant 25 \text{ kHz}$$

$$\sqrt{\sum_i \{ [\, E_m(f_i)\,]^2 + 396\, [\, E_\ell(f_i)\,]^2 \}} \leqslant 0.012 \qquad 25 \text{ kHz} < f_i \leqslant 40 \text{ kHz}$$

$$\sqrt{\sum_i \{ [\, E_m(f_i)\,]^2 + 396\, [\, E_\ell(f_i)\,]^2 \}} \leqslant 0.0025 \qquad f_i > 40 \text{ kHz}$$

Computations should be made of the signal at both ends of the circuit since the signal at either end may be controlling, depending upon the configuration of the terminal equipments. It is important that these computations include all harmonics and spurious signal components which contribute to the total signal. Appendix II contains several examples of computations for multiple frequency unbalanced signals.

Three cases of signal balance are worthy of comparison. These are illustrated by the following transmission arrangements:



Balanced

One Conductor Grounded

A Ground Return Arrangement

The balanced arrangement applies a metallic voltage [$e_m(t) = e$] to the conductors whereas the ground return arrangement applies a longitudinal voltage [$e_\ell(t) = e$]. In the one conductor grounded situation, both a metallic voltage [$e_m(t) = e$] and a longitudinal voltage [$e_\ell(t) = e/2$] are present. Since unbalanced signals cause more interference to other circuits in the same cable than balanced signals of the same voltage, the signal restrictions given previously require that unbalanced signals be applied at reduced levels. Using the voltage sources shown in the diagrams above, if E volts rms is the maximum voltage permitted for a particular signal connected in the balanced arrangement, then E/10 volts rms is the maximum voltage permitted for the one conductor grounded arrangement and approximately E/20 volts rms is the maximum voltage permitted for the ground return arrangement (applies to frequency components above 10 Hertz). Figure 3 shows a graphical representation of the voltage limitations (noise influence and safety limits combined) for these three arrangements for the specific case of a signal consisting solely of a single frequency tone.

Designers who contemplate the use of unbalanced and grounded operation should carefully consider the cautions and recommendations given in the following paragraphs.

It is strongly recommended that unbalanced operation not be used. However, if unbalanced operation must be used, extreme caution should be exercised, since, in addition to reductions in permissible signal levels, unbalanced systems are much more susceptible to interference from other circuits. This is caused by the increase in coupling by as much as 20 dB between a balanced circuit and an unbalanced circuit, and by as much as 60 dB between two unbalanced circuits as compared to two balanced circuits. It should be noted that the reduction in signal level required for unbalanced operation is to protect balanced circuits from interference caused by unbalanced circuits. This reduction in signal level does not protect unbalanced circuits from interference from balanced circuits or other unbalanced circuits. The interference to unbalanced circuits can be significant since the combined effect of the reduction in signal level and the increase in coupling is to reduce the signal to noise ratio by about 60 dB compared with balanced operation. Therefore, it is recommended that if unbalanced operation must be used, it should be confined to very low frequency tones (e.g., less than about 20 Hz) or very low dc pulsing rates (e.g., less than about 20 pulses per second). It is further recommended that the method of applying any unbalanced signals to the metallic circuit be such that harmonics and spurious signal components having frequencies above a couple of hundred Hertz be balanced to ground.

There are two corrosion considerations* which should be recognized with respect to grounded and ground return systems. The first concerns the corrosion

* Corrosion occurs where postive current leaves a metallic structure. The first consideration discussed involves corrosion of cable sheaths and other buried metallic structures whereas the second consideration discussed involves the corrosion of cable conductors.

hazard to buried structures such as cables, pipe lines, and railroad tracks which results from currents flowing in the earth. While the major problem arises from dc ground currents (even small values of dc current), ac ground currents are also corrosive, but to a lesser extent. Therefore, it is strongly recommended that ground return operation not be used. It is recognized that in some applications eliminating the use of ground return may be very difficult or even unavoidable; however, reasonable alternatives should be sought whenever possible. It is particularly important that designers of equipment find alternatives to the use of ground return circuits which involve intermittent high currents or any value of continuous current. The objective is to eliminate all types of ground return operation.

The second corrosion consideration concerns the electrolytic effects which are likely to lead to interruption of service in instances when moisture penetrates a cable sheath. In order to mitigate this problem, it is requested that any steady state potentials applied by grounded signal sources to the conductors be negative with respect to ground.

5.5.4 Coherent Keying

While the foregoing signal level restrictions are based upon multiple disturbers being present in a given cable, a reduction in signal level is required when several metallic circuits employing pulse-type transmission are keyed coherently. Typically, the noise interferences from pulse-type disturbers appear as a series of short pulses in the disturbed pair since the crosstalk coupling differentiates the signals. If the pulses of the disturbing signals occur randomly, the interferences would be a series of pulses, the pulses from one disturber randomly occurring between pulses of the other disturbers. In this case, it would appear that multiple signals would be only slightly more interfering than one signal.

However, if a number of metallic circuits are keyed coherently, the noise from each source is approximately the same and adds on a voltage basis. Experience has shown that in order to hold the noise level in a cable to approximately the same value, the signal limits of Table I, which apply to each disturber, must be reduced by multiplying the voltage signal limits by a factor of $1/\sqrt{N}$ where N is the expected number of transitions occurring simultaneously. In order to reduce the number of transitions occurring simultaneously, it is recommended that customer-provided equipment which may transmit over a large number of metallic circuits at the same time be arranged to stagger the transitions in time over a nominal signal element. For example, the outputs could be divided into four groups and a delay of one-fourth of a signal element provided between successive groups.

5.6 Comparison of Signal Restrictions with Previously Established Voice Grade Criteria

The signal restrictions for the frequency bands above 10 kHz are essentially the same as those specified in the tariffs for voice grade channels, but are expressed in terms of rms voltage instead of power. The signal restrictions for the frequency band below 10 kHz are significantly different from the restrictions given for voice grade channels which were determined from a combination of considerations including carrier system overload, crosstalk between cable pairs, etc. Since the signals used on metallic circuits are not suitable for direct transmission over Telephone Company carrier systems, the restrictions for metallic circuits are based solely on cable crosstalk and safety considerations. In general, the major differences between the restrictions are:

(1) The maximum overall signal level is specified in terms of peak voltage (safety limits, see Section 5.2) rather than total power.

(2) The signal level restrictions in the various frequency bands are specified in terms of rms voltage (noise influence limits, see Section 5.3) rather than power.

(3) Higher signal voltages are permitted at the lower frequencies for metallic circuits than for voice grade channels.

Instead of the power restrictions, voltage specifications are given which apply to a wide range of input impedances of customer-provided equipment. For comparison with the voice grade criteria, a power scale is included on the right of Figure 2 for the specific case of 600-ohm terminations.

5.5 Signal Waveshaping

The noise influence restrictions of Section 5.3 require most signals which have fast risetimes to be waveshaped. Although no explicit risetime requirements are given, the voltage restrictions on the high frequency signal components severely restrict the permissible waveforms.

For example, consider an ideal square wave signal applied in a balanced manner to the conductors. This signal can be completely characterized by two parameters:

(1) peak-to-peak voltage, E_{pp} volts

(2) baud rate (fundamental frequency, f_o, in Hertz equals one-half the baud rate)

A square wave signal, like any periodic waveform meeting certain conditions, can be represented as a sum of harmonically related sinusoidal components by using Fourier techniques.

SQUARE WAVE: $$e(t) = \sum_{\substack{n=1 \\ n \text{ odd}}}^{\infty} \frac{2\,Epp}{n\,\pi} \sin[2\pi n f_o t]$$

The frequency of the n^{th} harmonic = $n\,f_o$

The rms voltage of the n^{th} harmonic = $\frac{\sqrt{2}\, E_{pp}}{n\, \pi}$

Thus, a square wave signal can be considered as being composed of harmonically related single frequency tones and the methods of Section 5.3.2 can be applied to determine the necessary restrictions on the peak-to-peak voltage in order to satisfy the noise influence restrictions. The results of these computations are shown in Figure 4 which gives the maximum permitted peak-to-peak voltage for a balanced ideal square wave signal for baud rates between 1 and 1000 bauds in order to satisfy the noise influence restrictions in each frequency band. Since the restrictions for each frequency band must be met, the peak-to-peak voltage must be less than that shown for the above 40 kHz band, the most severe limitation for an ideal square wave signal.

As can be seen from Figure 4, the higher the frequency band, the more severe the restriction on the voltage of a square wave signal. This effect suggests waveshaping as a means to permit higher voltages to be applied to the conductors than those shown by the lowest line in Figure 4. There are many types of waveshaping but only two will be considered in detail here:

(1) employing a low pass filter to filter out the unwanted high frequency components

(2) sloping the transitions by converting the square wave into a trapezoidal waveform.

Since metallic circuits are generally not suitable for the transmission of frequencies above approximately 3000 Hz, harmonics of the input signal above 3000 Hz could be eliminated by means of a low pass filter. This would increase the maximum permitted peak-to-peak voltage to the values shown in Figure 5 for ideal filters having a cutoff of 1000 Hz, 3000 Hz, and 10,000 Hz. The maximum permitted peak-to-peak voltage will be less for physically realizable filters depending upon the rate of rolloff and other factors.

Noise interference reduction by employing a low pass filter below 10 kHz is effective since the harmonics of an ideal square wave signal roll off at 6 dB/octave while the signal limitation in this region has a slope of 10 dB/octave. As a result, the higher frequency harmonics of an ideal square wave signal, which are more interfering than the lower frequency harmonics, can be reduced by using a low pass filter.

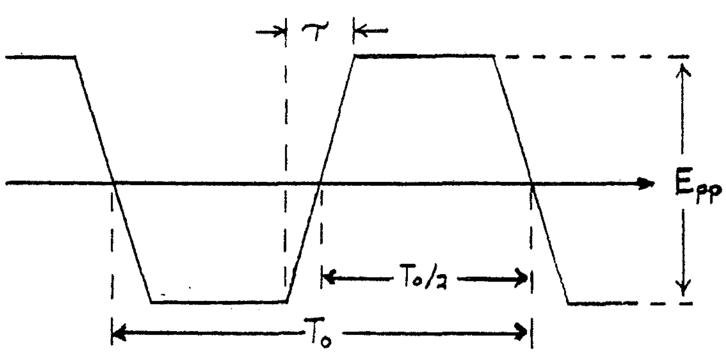
In some systems, it may be more desirable to directly slow down the rate of rise of the transitions than to employ a low pass filter. Some methods of implementation result in the square wave signal being converted into essentially a trapezoidal waveform. An ideal trapezoidal waveform can be characterized by three parameters:

(1) peak-to-peak voltage, E_{pp} volts

(2) baud rate (fundamental frequency, f_o, in Hertz equals one-half the baud rate)

(3) ratio of the time spent in the transition region to the bit width time, $K = \tau/(T_o/2)$

The following diagram illustrates the three parameters:



$$\text{BAUD RATE} = \frac{1}{T_o/2} = 2\ f_o$$

$$K = \frac{\tau}{T_o/2} = 2\ \tau f_o$$

$$0 \leq K \leq 1$$

Figure 6 shows the maximum permitted peak-to-peak voltage for a balanced <u>ideal</u> trapezoidal wave to meet the 10 Hz to 10 kHz signal limitation for K equal to 0.25, 0.05, 0.01, and 0.002. Also shown are the limiting cases of a triangular wave (K=1) and a square wave (K=0). While the signal limitations for the upper three frequency bands (especially the above 40 kHz band) are more restrictive than the limits shown in Figure 6, a suitable low pass filter can be employed to attenuate the higher frequency harmonics so that these restrictions are satisfied. However, the employment of a low pass filter will not substantially improve the noise performance in the 10 Hz to 10 kHz band for trapezoidal signals having a large value of K since they have a rolloff greater than the slope of the requirement (a triangular wave, for example, rolls off at 12 dB/octave). For these trapezoidal signals, the lower frequency harmonics of the signal are more interfering than the higher frequency harmonics.

Several notes of caution are in order. Figures 4, 5, and 6 were drawn for <u>specific</u> cases of <u>ideal</u> signal waveforms and are intended to show the relative effects of different kinds and amounts of waveshaping. Separate computations as described in Section 5.3.2 must be made on the actual signal to be applied to a metallic circuit to establish if the signal meets the voltage requirements. Secondly, Figures 4, 5, and 6 were drawn for balanced arrangements. If the voltages applied to the conductors are not balanced to ground, the maximum permitted voltage due to noise influence considerations is reduced as described in Section 5.3.3. In addition, the maximum permitted voltage due to safety considerations is reduced depending on the grounding arrangements as described in Section 5.2.1.

In summary, the following techniques are recommended for the generation of signals which meet the noise influence voltage limitations.

(1) use balanced operation

(2) employ a low pass filter to eliminate unnecessary high frequency components

(3) control the rate-of-rise of the signal

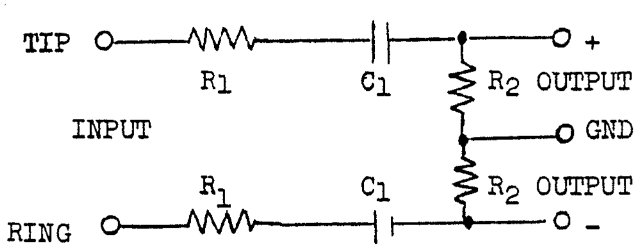
6. MEASUREMENT TECHNIQUES - NOISE INFLUENCE

6.1 General

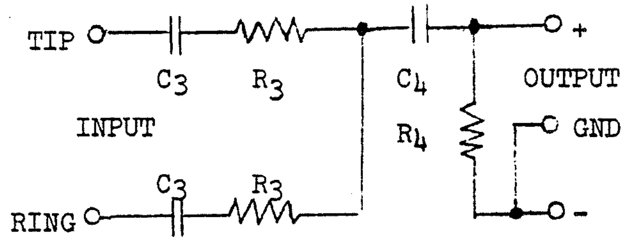
The mathematical procedure outlined in Section 5.3 and Appendices I and II may in some cases be awkward to perform on a real signal. An alternate approach is to make measurements of the signal using an rms voltmeter with a suitable weighting network and bridging arrangement ahead of it. Four weighting networks are required; one for each frequency band listed in Table I of Section 5.3. For the three upper frequency bands, the weighting network should be either a band-pass filter or a high pass filter. For the 10 Hz to 10 kHz band, the frequency response of the weighting network should be the inverse of the signal limitations. Two measurement arrangements are necessary: one to measure the metallic component of the signal and one to measure the longitudinal component of the signal.

6.2 Bridging Arrangements

The measurements should be performed on a high impedance bridging basis as shown in Figure 7 since most dc transmission systems require transmission equipment at each end connected by an appropriate length of cable (or simulated transmission line or dc resistive equivalent) to function properly. Incorrect measurements will result, in most cases, if the transmission equipment is terminated in a resistance (e.g., 600 ohms) with measurements made across this resistance. Two bridging arrangements are needed - one for metallic measurements and one for longitudinal measurements. There are many types of bridging networks which may be suitable for these measurements. Two relatively simple circuits are illustrated below:



Metallic Measurements



Longitudinal Measurements

These bridging arrangements have a loss versus frequency response similar to a simple high pass filter with a 20 dB/decade rolloff for frequencies below the cutoff frequency and a fixed loss above the cutoff frequency. The cutoff frequency for the bridging circuits used for the 10 Hz to 10 kHz frequency band measurements should be above 10 kHz so that the 20 dB/decade rolloff provides part of the required weighting as described in Section 6.3. Since a flat inband frequency response is needed for the three frequency bands above 10 kHz, the cutoff frequency should be below 10 kHz for these measurements. Thus, different bridging networks are needed for the 10 Hz to 10 kHz band than those needed for the bands above 10 kHz. Therefore, a total of four bridging networks are required. The component values should be chosen so that the networks provide a relatively high input impedance over the frequency range to be measured in order not to load down the transmission system being measured. The high input impedance requirement results in a substantial amount of loss being introduced into the measurement system. This loss can be compensated by connecting an amplifier to the output of the bridging network. However, since most available electronic filters and rms voltmeters which are needed to complete the measurement system are grounded and unbalanced, a differential amplifier is needed for the metallic measurements to balance out longitudinal components. For longitudinal measurements, an unbalanced amplifier can be used in place of the differential amplifier. Commercially available differential amplifiers such as the Hewlett Packard Model 2470A Data Amplifier having a frequency bandwidth of at least 40 kHz appear to be satisfactory for the lower three frequency bands. According to Hewlett Packard, the Model 2470A Data Amplifier has a frequency characteristic which is 3 dB down at 50 kHz and 9 dB down at 100 kHz. This makes it marginal for measurements in the above 40 kHz frequency band. For accurate measurements of the signal components above 40 kHz, it is recommended that a differential amplifier having a bandwidth of at least 1 MHz be used.

Circuit values which have been found suitable for use on many transmission systems are as follows:

	10 Hz to 10 kHz Band	Above 10 kHz Bands
Metallic Measurements		
R_1	5.1×10^3 ohms	2.0×10^4 ohms
C_1	1.0×10^{-9} farads	2.4×10^{-9} farads
R_2	3.0×10^2 ohms	6.0×10^2 ohms
Longitudinal Measurements		
R_3	1.0×10^4 ohms	2.0×10^4 ohms
C_3	2.0×10^{-6} farads	2.0×10^{-6} farads
R_4	6.0×10^2 ohms	6.0×10^2 ohms
C_4	1.0×10^{-9} farads	5.1×10^{-9} farads

Over the frequency range to be measured, all four networks have an input impedance of at least 10,000 ohms. The input impedance increases with decreasing frequency below the cutoff frequency for all four networks. The value of the input impedance for these passive bridging networks is a compromise between loading down the circuit if the impedance is too low or adding too much loss so that noise becomes an important consideration if the impedance is too high. The 1000 Hz loss for the 10 Hz to 10 kHz band networks is 54.5 dB for a metallic signal connected to the metallic bridging network and 48.5 dB for a longitudinal signal connected to the longitudinal bridging network. For the frequency bands above 10 kHz, the loss of the networks for frequencies above 10 kHz is 30.7 dB for a metallic signal connected to the metallic bridging network and 24.8 dB for a longitudinal signal connected to the longitudinal bridging network.

6.3 <u>10 Hz to 10 kHz Frequency Band</u>

A filter is required in order to pass only the frequencies within the 10 Hz to 10 kHz frequency band. The inband response of the filter must be equal to the inverse of the signal limitation. In designing the filter, approximations must be made since the slope of the requirement between 100 Hz and 10 kHz is not an integer multiple of 20 dB/decade. A voltage transfer function which approximates the inverse of the requirement quite well between 10 Hz and 10 kHz and leads to a relatively simple network is:

$$T(f) = \frac{K\left(1 - j\frac{223.87}{f}\right)}{\left(1 - j\frac{4466.8}{f}\right)\left(1 - j\frac{30,000}{f}\right)}$$

The second column of Table II gives the required frequency response of the filter referenced to 1000 Hz. The deviation of the above transfer function with respect to the requirement is given in the third column of the table.

TABLE II

Frequency (Hz)	Gain Relative to 1000 Hertz (dB)	Deviation from Requirement (dB)
10	-53.00	0.01
15	-49.48	0.02
20	-46.98	0.04
30	-43.46	0.08
40	-40.96	0.14
50	-39.02	0.22
70	-36.10	0.41
100	-33.00	0.79
150	-27.19	-0.68
200	-23.07	-1.37
300	-17.25	-1.75
400	-13.13	-1.63
500	- 9.93	-1.36

Frequency (Hz)	Gain Relative to 1000 Hertz (dB)	Deviation from Requirement (dB)
700	- 5.11	-0.76
1000	0.00	0.00
1500	5.81	0.86
2000	9.93	1.35
3000	15.75	1.71
4000	19.87	1.60
5000	23.07	1.26
7000	27.89	0.31
10000	33.00	-1.24

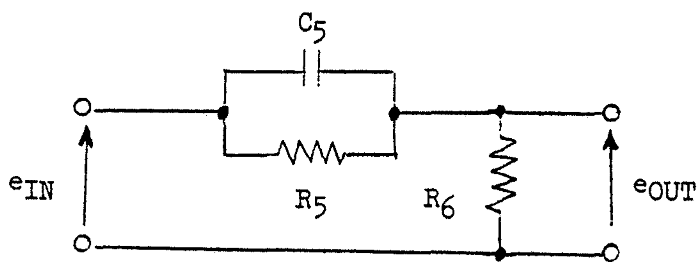
As can be seen from the table, the maximum deviation from the requirement is less than 2 dB. If desired, closer approximations to the requirement can be obtained by using a more complicated transfer function having additional breakpoints.

The $K/(1 - j\frac{30,000}{f})$ part of the transfer function provides a 20 dB/decade loss slope for frequencies below 30 kHz and a loss of $20 \log_{10} (K)$ dB for frequencies above 30 kHz. This part of the transfer function can be easily implemented as part of the bridging arrangement as described in Section 6.2. For the circuit values given in Section 6.2, the cutoff frequency is 2.95×10^4 Hz for the metallic network and 2.84×10^4 Hz for the longitudinal network. It should be noted that the 30,000 Hz value for the cutoff frequency is not a critical number. It should, however, be high enough so that it provides a loss slope below 10 kHz of 20 dB/decade.

By making use of the 20 dB/decade slope below 10 kHz provided by the bridging arrangement, the additional filtering needed to approximate the required weighting is simplified to the following voltage transfer function:

$$T(f) = \frac{(1 - j\frac{223.87}{f})}{(1 - j\frac{4466.8}{f})}$$

This voltage transfer function can be realized by the following relatively simple network:



$R_5 = 1.14 \times 10^4$ ohms

$C_5 = 6.24 \times 10^{-8}$ farads

$R_6 = 6.00 \times 10^2$ ohms

The cutoff frequencies and thus the three circuit components are relatively critical in order to properly approximate the 33 dB/decade slope between 100 Hz and 10 kHz. The loss of this network at 1000 Hz is 13.0 dB. Splitting the transfer function into two parts as described above has the additional advantage of reducing the required dynamic range of the differential amplifier from over 85 dB to approximately 30 dB.

A low pass filter with a frequency cutoff of approximately 10 kHz can be employed to attenuate the out of band frequencies of the signal above 10 kHz so that only the appropriate frequencies are measured. Commercially available electronic filters such as the Krohn-Hite Model 3202 Variable Filter having a maximally flat eighth order Butterworth response or better appear to be satisfactory.

The complete measurement system as described above for the 10 Hz to 10 kHz frequency band is shown in Figure 8.

6.4 <u>Frequency Bands Above 10 kHz</u>

Measurements of signal components in the three upper frequency bands can be made in a manner similar to that described above. However, the measurement is simplified since weighting is not involved. A filter is required in order to pass only those frequencies within the given frequency band.

Examination of the filter requirements for the middle two frequency bands shows that one is slightly greater than an octave wide and one is slightly less than one octave wide. Because of the difficulty of obtaining bandpass filters having a frequency width of one octave with a relatively flat inband response (within a dB or two) and a relatively sharp rolloff out of band (eighth order or better), it is suggested that high pass filters be used instead of bandpass filters for the upper three frequency bands. The three tenths of a dB or less error which results from this approximation is compensated for by relaxing the signal limitations as described below. It should be noted, however, that this approach is satisfactory only if it is desired to know if the signal meets or exceeds the limitations, and not by how much.

The procedure is to first make a measurement of the frequency components above 40 kHz by employing a high pass filter having a 40 kHz cutoff frequency. If the above 40 kHz limitation is met, the cutoff frequency is reduced to 25 kHz and a second measurement is taken. The signal is considered to meet the 25 kHz to 40 kHz signal limitation if the second measurement meets the limitation relaxed by 0.18 dB (i.e., less than 0.0123 volts rms). If this limitation is met, the cutoff frequency should be reduced to 10 kHz and a third measurement should be made. The signal is considered to meet the 10 kHz to 25 kHz signal limitation if the third measurement meets the limitation relaxed by 0.25 dB (i.e., less than 0.0515 volts rms). If any of the measurements exceed the limitations, then the signal exceeds the criteria. If this is the case, reducing the cutoff frequency as described above for the other frequency bands will not give accurate results for these frequency bands. Filters such as the Krohn-Hite Model 3202 Variable Filter having a maximally flat eighth order Butterworth response or better and a bandwidth extending to at least 1 MHz appear to be satisfactory.

The values to relax the signal limitations were determined by assuming the case where the signal being measured just meets the signal limitations for each frequency band. The rms values of the voltage above 25 kHz and 10 kHz when the signal limitations are satisfied are given as follows:

$$E_{rms}\ (\text{frequencies above 25 kHz}) = \sqrt{(0.0025)^2+(0.012)^2} \cong 0.01226 \text{ volts rms}$$

$$\Delta \text{ dB} = 20 \log \left[\frac{0.01226}{0.01200}\right] \cong 0.18 \text{ dB}$$

$$E_{rms}\ (\text{frequencies above 10 kHz}) = \sqrt{(0.0025)^2+(0.012)^2+(0.050)^2} \cong 0.05148 \text{ volts rms}$$

$$\Delta \text{ dB} = 20 \log \left[\frac{0.05148}{0.05000}\right] \cong 0.25 \text{ dB}$$

Figure 9 shows the complete measurement system for the three frequency bands above 10 kHz.

6.5 RMS Responding Voltmeter

Measuring equipments such as spectrum analyzers are not appropriate because of the spectrum of frequencies generated by most pulse-type signals. A true rms responding voltmeter is needed to properly combine the frequency components into a useful measurement. For most signals to be measured (e.g., rectangular pulses), the output voltage of the filter consists of a number of very sharp pulses since the filter in essence differentiates the signal. In order to measure accurately the rms voltage of such a signal, an rms voltmeter with a high crest factor (the ratio of the peak voltage to the rms voltage of the signal which will be measured correctly) is required. Commercially available rms voltmeters such as the Hewlett Packard Model 3400A RMS Voltmeter having a 10 to 1 crest factor at full scale and a 100 to 1 crest factor at one-tenth scale appear to be satisfactory.

One method to check if the crest factor rating of a rms responding voltmeter is satisfactory for the signal being measured is to (1) read the rms voltage indicated by the voltmeter, (2) determine the peak value of the signal by an oscilloscope or peak responding voltmeter measurement, and (3) determine the ratio of the peak voltage to the measured rms voltage. This ratio should not exceed the crest factor specified for the rms responding voltmeter for a valid measurement. This technique is valid for rms responding voltmeters whose voltage indication is low when the crest factor is exceeded.

6.6 Combining Metallic and Longitudinal Measurements

In order to determine if a given signal meets the noise influence criteria, it is necessary to make eight measurements - a metallic and a longitudinal measurement for each frequency band. The metallic measurement and the longitudinal measurement for each frequency band must be mathematically combined to obtain an equivalently interfering balanced signal which can be compared with the signal requirements.

$$\text{Equivalent Balanced rms Voltage at Frequency } f = \sqrt{\left[K_{m_f} E_m\right]^2 + 396\left[K_{\ell_f} E_\ell\right]^2}$$

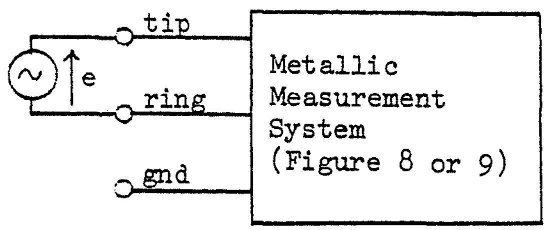
where E_m = rms voltage meter reading for metallic measurement

K_{m_f} = metallic calibration constant for frequency f

E_ℓ = rms voltage meter reading for longitudinal measurement

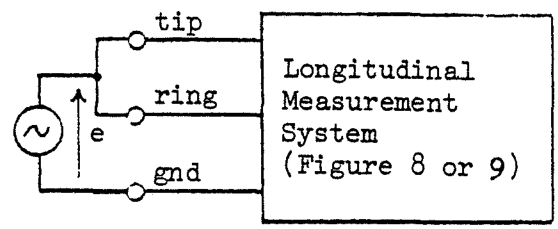
K_{ℓ_f} = longitudinal calibration constant for frequency f

The calibration constants are needed to convert the meter reading to the actual rms voltage at the chosen frequency. One relatively simple method to determine the calibration constants is to apply a sinusoidal signal to the measurement system and take the ratio of the input voltage to the output voltage indicated by the rms voltmeter. A metallic signal should be applied to the metallic measurement system and a longitudinal signal should be applied to the longitudinal measurement system as shown below to determine K_{m_f} and K_{ℓ_f} for <u>each</u> frequency band.



$$K_{m_f} = \frac{\text{input sinusoidal rms voltage}}{\text{rms voltmeter reading}}$$

ARRANGEMENT TO DETERMINE K_{m_f}



$$K_{\ell_f} = \frac{\text{input sinusoidal rms voltage}}{\text{rms voltmeter reading}}$$

ARRANGEMENT TO DETERMINE K_{ℓ_f}

For the frequency bands above 10 kHz, any frequency within the band may be used for the sinusoidal signal to determine K_{m_f} and K_{ℓ_f}. For the 10 Hz to 10 kHz frequency band, any frequency between 10 Hz and 10 kHz may be used. However, the frequency chosen is the frequency at which the equivalent balanced rms voltage must be compared with the requirement. For example, if a 1000 Hz tone is used to determine K_{m_f} and K_{ℓ_f}, the equivalent balanced voltage computed for a measurement on a transmission system must be less than 2.239 volts rms (1000 Hz limit) for the signal to meet the signal limitation.

6.7 Determining Compliance with Noise Influence Signal Criteria

Measurements of the signal should be made at the interface of the customer-provided equipment with the metallic circuit. Measurements of the signal should be made at both ends of the circuit since the signal at either end may be controlling, depending upon the configuration of the terminal equipments. The signal at each end of the circuit must meet the signal limitations for all four frequency bands in order to comply with the noise influence criteria.

Since the parameters of a metallic circuit (e.g., loop resistance and capacitance, input impedance, etc.) will vary from circuit to circuit, it is recommended that manufacturers of customer-provided transmission equipment test their equipment in the laboratory with the metallic circuit replaced by its dc resistive equivalent. If the equipment meets the signal limitations when operating over the resistive equivalent of a metallic circuit, it will meet (except for very unusual situations) the signal requirements when connected to any given metallic circuit. If the signal does not meet the resistive test, it does not necessarily mean that it will not meet the signal limitations when connected to the cable facilities used to derive the metallic circuit. This results from the beneficial waveshaping provided by cable capacitance. However, this should be a warning that the transmission system may not be satisfactory for all metallic circuits.

A final note of caution concerning measurements. Many of the signal levels to be measured are very low, especially after the bridging network. Care must be exercised in the selection of the measurement equipments to insure an adequate signal to noise ratio. In addition, the waveforms at the input to the various equipments which make up the measurement system have a high peak value compared to the rms value. It is important to insure that the peak value of the voltage waveform does not overload the equipments. This can be easily checked by using an oscilloscope or an equivalent device to measure the peak value of the voltage waveform at the inputs to the various measurement equipments.

7. MEASUREMENT TECHNIQUES - SAFETY

7.1 Peak Voltage

Several relatively simple measurements are required to determine compliance with the safety criteria. A peak responding voltmeter or an oscilloscope should be used to make measurements of the voltage between tip and ground and between ring and ground. The magnitude of the reading for each measurement should be less than 70.7 volts peak. If the reading exceeds 70.7 volts peak, the signal waveform should be examined on an oscilloscope to determine whether it conforms to one of the two exceptions given in Section 5.2.1. In no case should the magnitude of the peak voltage exceed 135 volts conductor to ground.

7.2 RMS Current

An rms responding milliammeter should be used to make measurements of the current flowing in the tip and ring conductors. If the rms responding milliammeter is not capable of measuring dc current, a separate dc current measurement should be made. The rms value of the total signal can be obtained by the following formula:

$$I_{rms} = \sqrt{I_{dc}^2 + I_{ac}^2}$$

The computed value must be less than 350 milliamperes in order to satisfy the current requirement. However, it is recommended that the current per conductor be less than 150 milliamperes (see Section 5.2.1).

Appendix I

Computation Examples - Multiple Frequency Signals

Example 1:

A well balanced transmitter whose voltage source is center-tapped to ground uses a metallic signal composed of the following frequencies:

Frequency	Voltage (rms)
50 Hz	60.0 volts
100 Hz	30.0 volts
1 kHz	2.00 volts
4 kHz	.150 volts
15 kHz	.0450 volts
20 kHz	.0350 volts
30 kHz	.0080 volts
35 kHz	.0060 volts
50 kHz	.0010 volts

There are four signal components in the 10 Hz to 10 kHz band and they must be weighted as follows (using 100 Hz as the reference frequency):

Frequency	Weighting Factor*			x	rms Voltage	=	Weighted rms Voltage
50 Hz	50/100	=	0.50	x	60.0	=	30.0
100 Hz	100/100	=	1.00	x	30.0	=	30.0
1 kHz	$(1000)^{1.65}/(10)^{3.3}$	=	44.7	x	2.00	=	89.4
4 kHz	$(4000)^{1.65}/(10)^{3.3}$	=	440.	x	0.150	=	66.0

* See Section 5.3.2

$$\text{rms} = \sqrt{(30.0)^2 + (30.0)^2 + (89.4)^2 + (66.0)^2}$$

$$= 119 \text{ volts (equivalent 100 Hz voltage)}$$

Since 119 volts rms exceeds the 100 Hz limit of 100 volts rms, the signal level limitation is exceeded for this frequency band.

The two signal components in the 10 kHz to 25 kHz band are combined as follows:

$$\text{rms} = \sqrt{(.045)^2 + (.035)^2}$$

$$= 0.057 \text{ volt (equivalent single frequency voltage)}$$

Since 0.057 volt exceeds the 0.050 volt rms limitation for the 10 kHz to 25 kHz band, the signal level limitation is exceeded in this frequency band.

The two signal components in the 25 kHz to 40 kHz band are combined as follows:

$$\text{rms} = \sqrt{(.008)^2 + (.006)^2}$$

$$= 0.010 \text{ volt (equivalent single frequency voltage)}$$

Since 0.010 volt is less than the 0.012 volt rms limitation for the 25 kHz to 40 kHz band, the signal level in this frequency band is satisfactory.

Since there is only one signal component in the frequency band above 40 kHz, it can be compared directly with the requirement. The 0.0010 volt rms signal at 50 kHz is below the 0.0025 volt rms requirement and the signal level limitation for the band above 40 kHz is satisfied.

Since the signal exceeds the limits in at least one frequency band (2 bands in this example), the system must be modified to meet the required limitations before it can be connected to the Telephone Company facilities.

Example 2:

It is desired to simultaneously apply two balanced single frequency tones to the circuit at the same signal level. What is the maximum voltage per tone for the signal consisting of tones at 200 Hz and 500 Hz?

Using 100 Hz as the reference frequency, the maximum voltage can be obtained from the following expression of the 10 Hz to 10 kHz limitation.

$$\sqrt{[\ W(200\ Hz)\ E(200\ Hz)\ ]^2 + [\ W(500\ Hz)\ E(500\ Hz)\ ]^2} \leqslant 100$$

$$W(200\ Hz) = (200)^{1.65} / (10)^{3.3} \cong 3.138$$

$$W(500\ Hz) = (500)^{1.65} / (10)^{3.3} \cong 14.23$$

$$\text{let}\quad E_{rms} = E(200\ Hz) = E(500\ Hz)$$

substituting values into the inequality gives:

$$\sqrt{[\ (3.138)(E_{rms})\ ]^2 + [\ (14.23)(E_{rms})\ ]^2} = 14.57\ E_{rms} \leqslant 100$$

Solving this inequality gives a maximum rms voltage per tone of 6.86 volts.

It should be noted that this maximum voltage for each tone is less than the maximum permitted voltage for a 200 Hz single frequency tone (31.9 volts rms) or a 500 Hz single frequency tone (7.03 volts rms).

Appendix II

Computation Examples - Unbalanced Signals

Example 1:

A given transmitter applies a signal consisting of two tones superimposed on a dc voltage to the facility in a manner such that the voltages between ground and each conductor are:

$$e_1(t) = -5 + 1 \cos[2\pi(100)t] + 3 \cos[2\pi(250)t + \pi/2]$$

$$e_2(t) = -5 + 1 \cos[2\pi(100)t] - 1 \cos[2\pi(250)t + \pi/2]$$

The metallic and longitudinal voltages are computed as follows:

$$e_m(t) = e_1(t) - e_2(t) = 4 \cos[2\pi(250)t + \pi/2]$$

$$e_\ell(t) = \frac{e_1(t) + e_2(t)}{2} = -5 + 1 \cos[2\pi(100)t] + 1 \cos[2\pi(250)t + \pi/2]$$

There are three frequency components contained in these signals, namely zero frequency (dc), 100 Hz, and 250 Hz. Since frequencies below 10 Hz are not considered in noise influence computations, the dc component is left out of the following analysis. Note, however, that the safety limitations of section 5.2 must be met for $e_1(t)$ and $e_2(t)$. The rms values of the 100 Hz and 250 Hz components of $e_m(t)$ and $e_\ell(t)$ are given below.

$$E_m(100\text{ Hz}) = 0 \qquad E_\ell(100\text{ Hz}) = 1/\sqrt{2}$$

$$E_m(250\text{ Hz}) = 4/\sqrt{2} \qquad E_\ell(250\text{ Hz}) = 1/\sqrt{2}$$

The equivalently interfering balanced rms voltage at 100 Hz is

$$E(100\ Hz) = \sqrt{[\ E_m(100\ Hz)\ ]^2 + 396\ [\ E_\ell(100\ Hz)\ ]^2}$$

$$= \sqrt{[\ 0\ ]^2 + 396\ [\ 1/\sqrt{2}\ ]^2} = 14.07\ volts$$

The equivalently interfering balanced rms voltage at 250 Hz is

$$E(250\ Hz) = \sqrt{[\ E_m(250\ Hz)\ ]^2 + 396\ [\ E_\ell(250\ Hz)\ ]^2}$$

$$= \sqrt{[\ 4/\sqrt{2}\ ]^2 + 396\ [\ 1/\sqrt{2}\ ]^2} = 14.35\ volts$$

These equivalently interfering balanced rms voltages must be weighted to determine compliance with the criteria. Using 100 Hz as the reference frequency for weighting, the computations are:

Frequency	Weighting Factor	x	rms Voltage	=	Weighted rms Voltage
100 Hz	1		14.07		14.07
250 Hz	4.535		14.35		65.08

$$rms = \sqrt{(14.07)^2 + (65.08)^2} = 66.59\ volts\ (equivalent\ 100\ Hz\ voltage)$$

Since 66.59 volts is less than the 100 Hz (reference frequency) requirement of 100 volts, the signal restrictions are met and the system may be connected to Telephone Company facilities.

Example 2:

A given transmitter keys the facility (open and closes a contact) with a 300-baud square wave signal which results in the following voltages on the conductor pairs:

Tip conductor to ground, contact open:	+10 volts
Tip conductor to ground, contact closed:	-10 volts
Ring conductor to ground:	-10 volts

(the signal is applied to one conductor of the pair while the other conductor is held at a fixed potential).

Representing the square wave signal in terms of a Fourier Series, the voltages between ground and each conductor are:

$$e_1(t) = \sum_{\substack{n=1 \\ n \text{ odd}}}^{\infty} \frac{2\,E_{pp}}{n\pi} \sin[2\pi n f_o t] \qquad \text{where } E_{pp} = 20 \text{ volts}, \quad f_o = 150 \text{ Hz}$$

$$e_2(t) = -10$$

The metallic and longitudinal voltages are:

$$e_m(t) = e_1(t) - e_2(t) = 10 + \sum_{\substack{n=1 \\ n \text{ odd}}}^{\infty} \frac{2(20)}{n\pi} \sin[2\pi n(150)t]$$

$$e_\ell(t) = \frac{e_1(t) + e_2(t)}{2} = -5 + \sum_{\substack{n=1 \\ n \text{ odd}}}^{\infty} \frac{2(10)}{n\pi} \sin[2\pi n(150)t]$$

The following table tabulates the rms voltages at each frequency (excluding zero frequency) for $e_m(t)$ and $e_\ell(t)$. The fourth column of the table gives the equivalently interfering balanced rms voltage for each frequency using the relationship:

$$E(f_i) = \sqrt{[\,E_m(f_i)\,]^2 + 396\,[\,E_\ell(f_i)\,]^2}$$

The last column of the table gives the weighted rms voltage for each frequency using 100 Hz as the reference.

f_i Frequency Hertz+	$E_m(f_i)$ rms Voltage*	$E_\ell(f_i)$ rms Voltage*	$E(f_i)$ rms Voltage	$W(f_i)$ Weighting Factor	Weighted rms Voltage
150	9.00	4.50	90.0	1.952	175.
450	3.00	1.50	30.0	11.96	359.
750	1.80	.90	18.0	27.79	500.
1050	1.29	.65	12.9	48.41	624.
1350	1.00	.50	10.0	73.29	733.
⋮	⋮	⋮	⋮	⋮	⋮

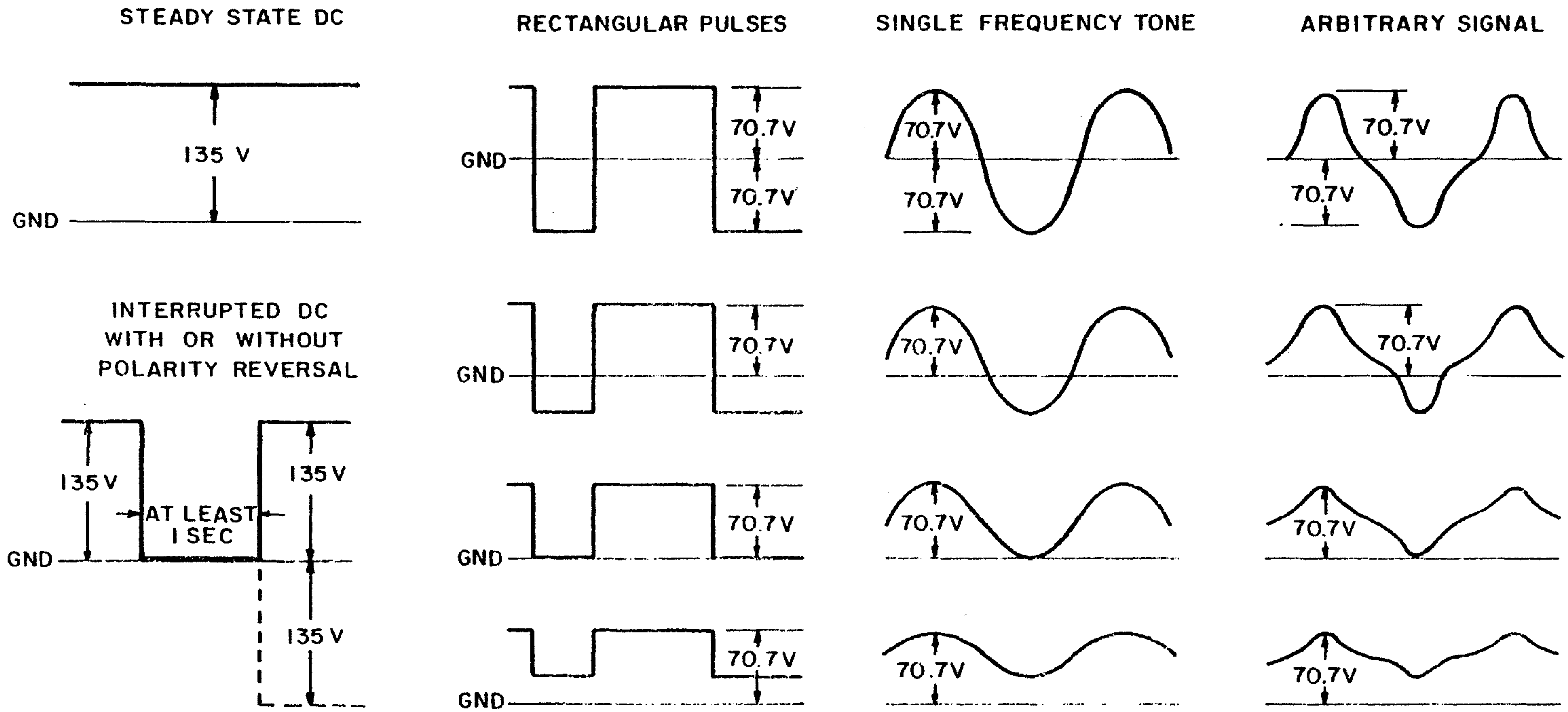
$$\text{rms} = \sqrt{(175)^2 + (359)^2 + (500)^2 + (624)^2 + (733)^2 + \ldots}$$

Since this signal exceeds the 10 Hz to 10 kHz limitation (in fact, the fundamental frequency alone exceeds the limitation), this system must be modified to meet the signal limitations before it can be connected to Telephone Company facilities.

+ The frequency in Hertz of the n^{th} harmonic of a square wave signal having a fundamental frequency of f_o Hertz is equal to nf_o.

* The rms voltage of the n^{th} harmonic of a square wave signal having a peak-to-peak voltage of E_{pp} volts is equal to:

$$\frac{\sqrt{2}E_{pp}}{n\pi}$$



MAXIMUM VOLTAGE CONDUCTOR TO GROUND

FIGURE 1

SAFETY LIMITATIONS APPLIED TO TYPICAL SIGNAL WAVEFORMS

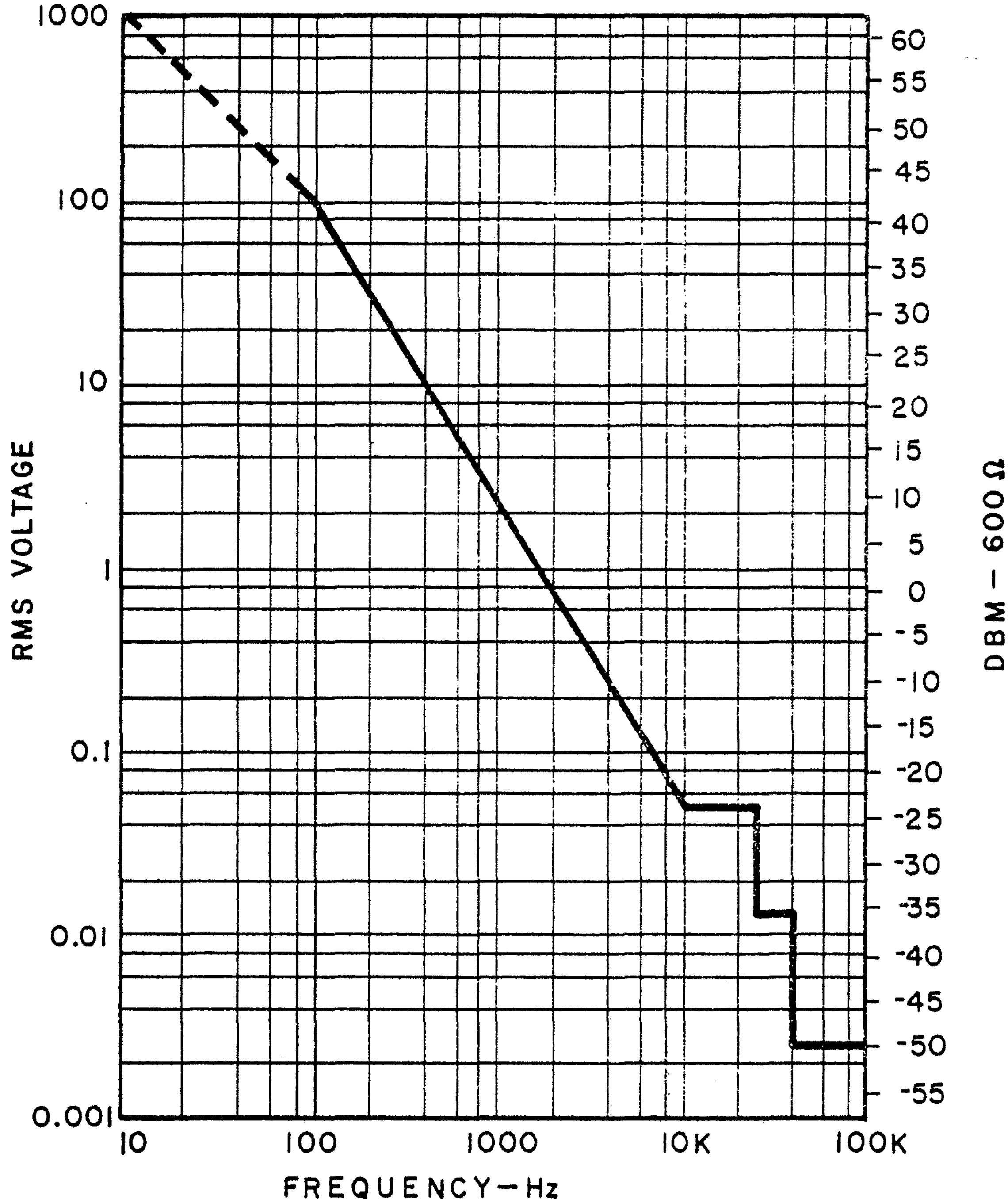


FIGURE 2

NOISE INFLUENCE SIGNAL LIMITATIONS

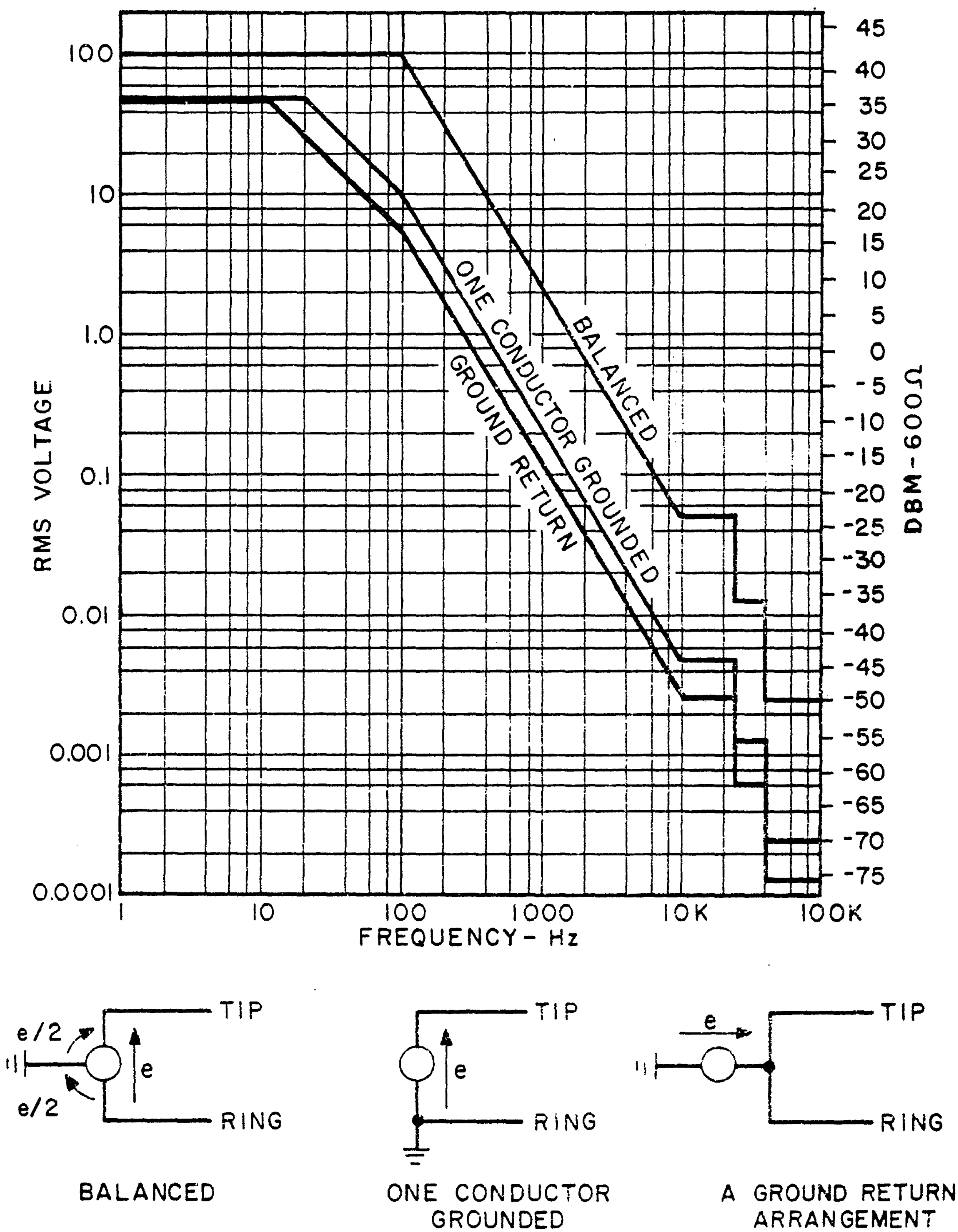


FIGURE 3

MAXIMUM VOLTAGE FOR
A SINGLE FREQUENCY TONE SIGNAL

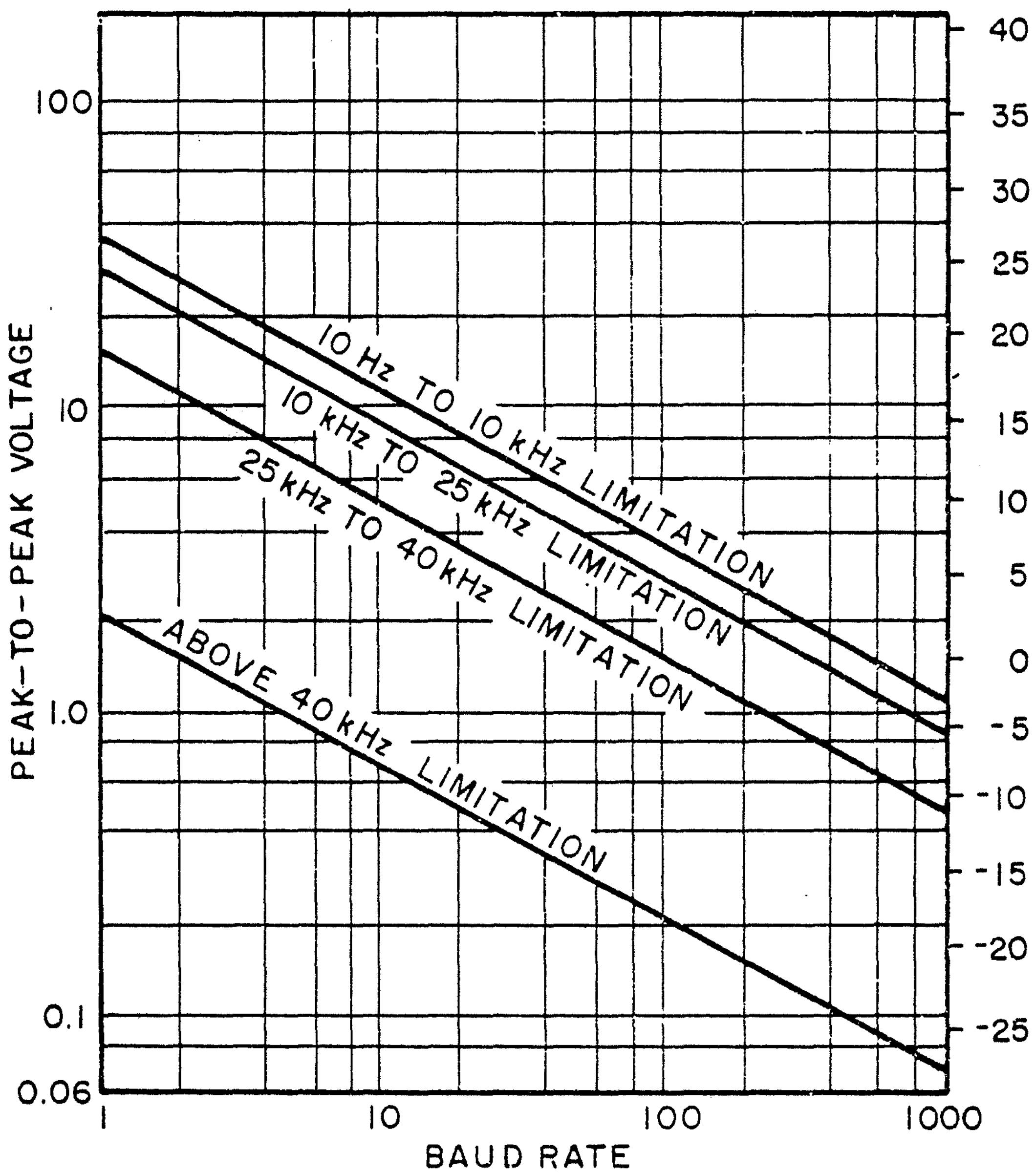


FIGURE 4

MAXIMUM BALANCED VOLTAGE FOR AN IDEAL SQUARE WAVE SIGNAL

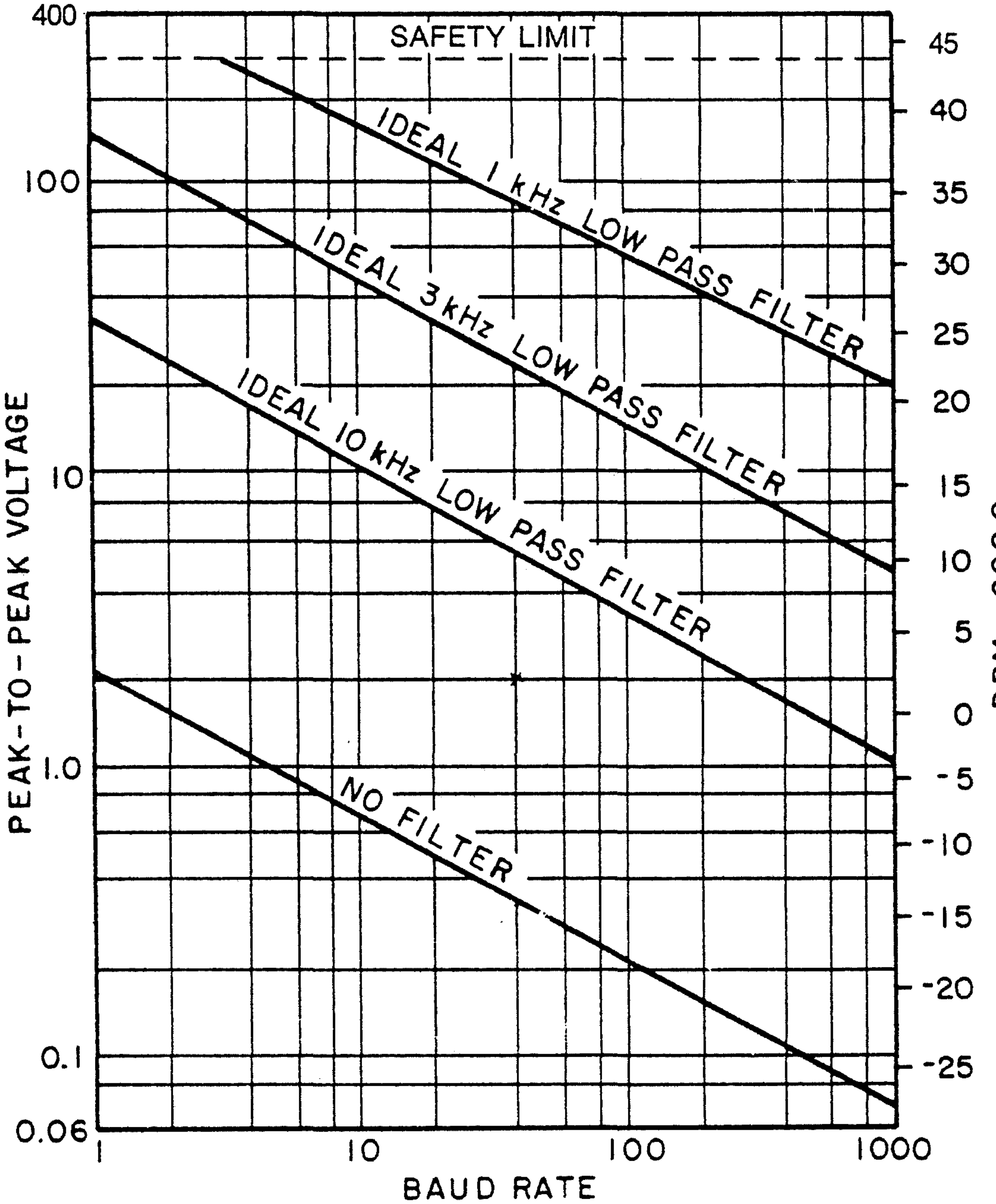


FIGURE 5

MAXIMUM BALANCED VOLTAGE FOR
AN IDEAL SQUARE WAVE SIGNAL
WAVESHAPED WITH AN IDEAL LOW PASS FILTER

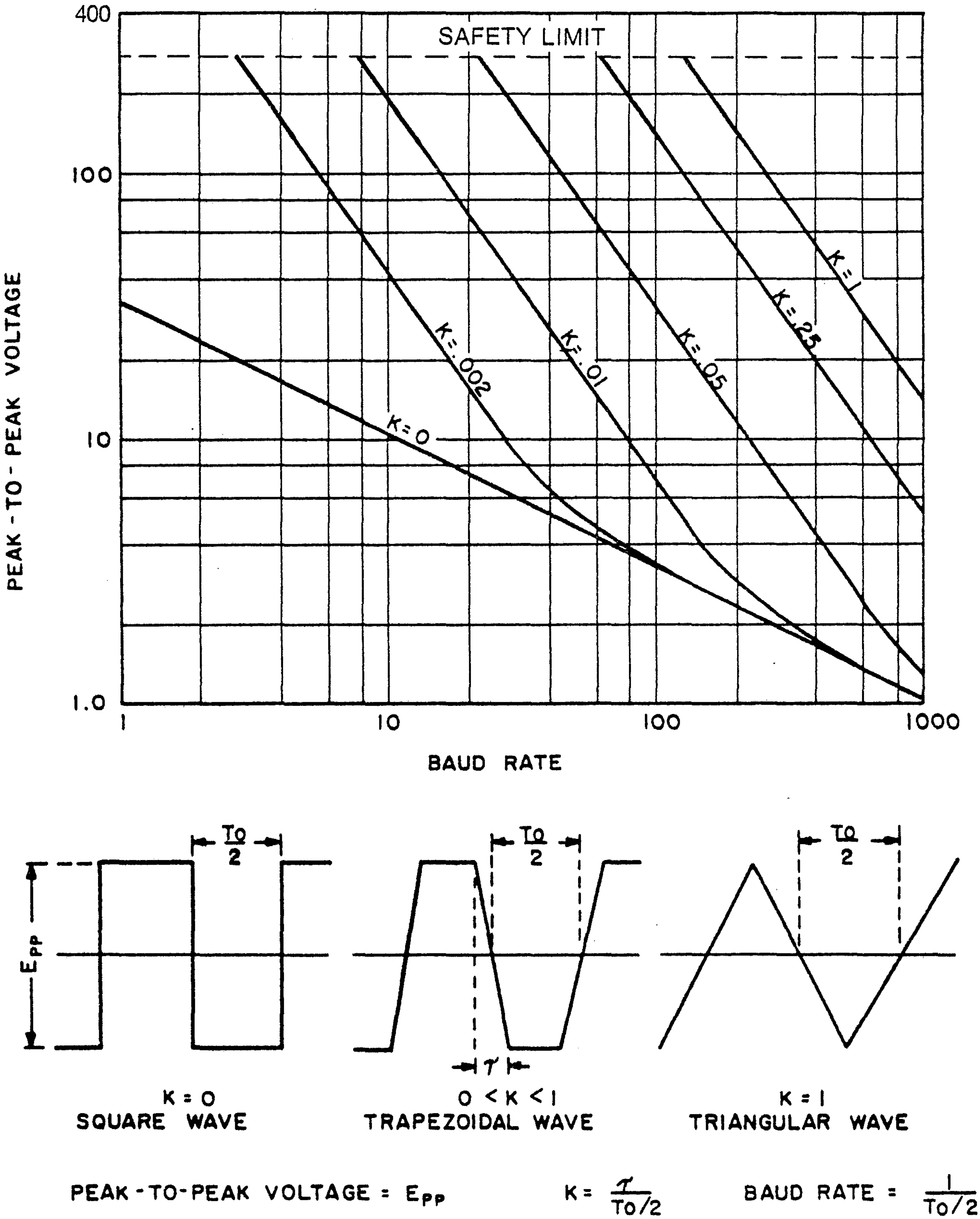
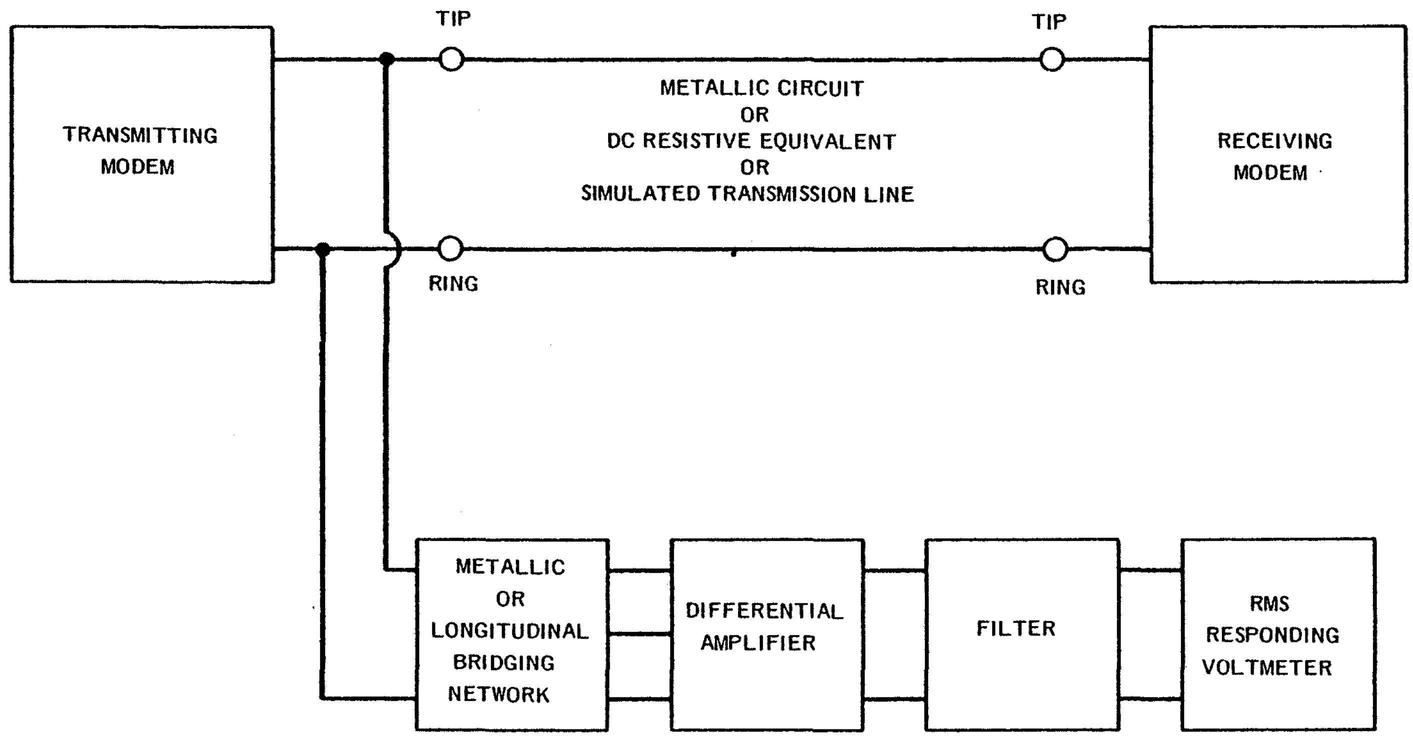


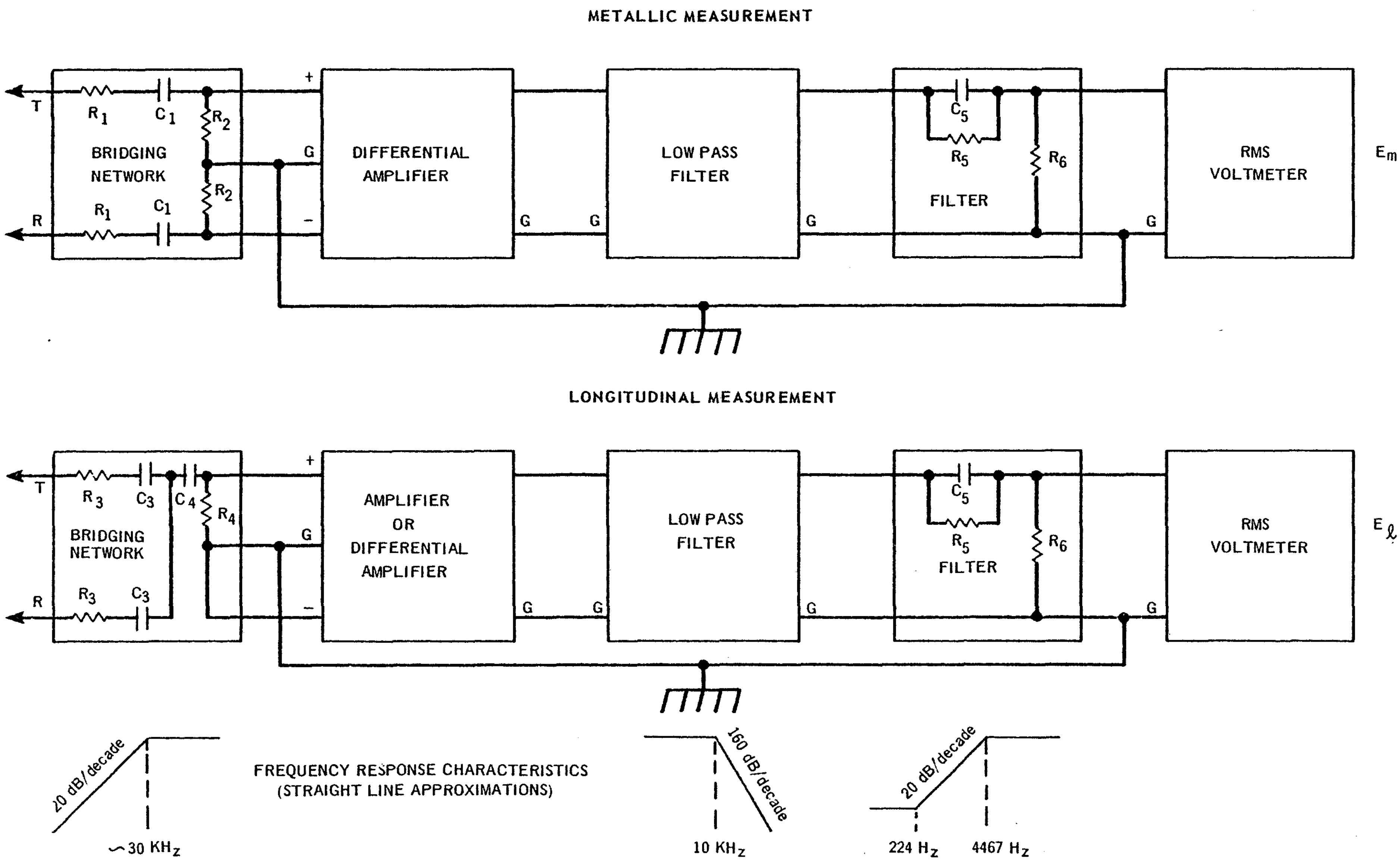
FIGURE 6

MAXIMUM BALANCED VOLTAGE FOR IDEAL SIGNAL WAVE FORMS TO MEET THE 10Hz TO 10KHz SIGNAL LIMITATION



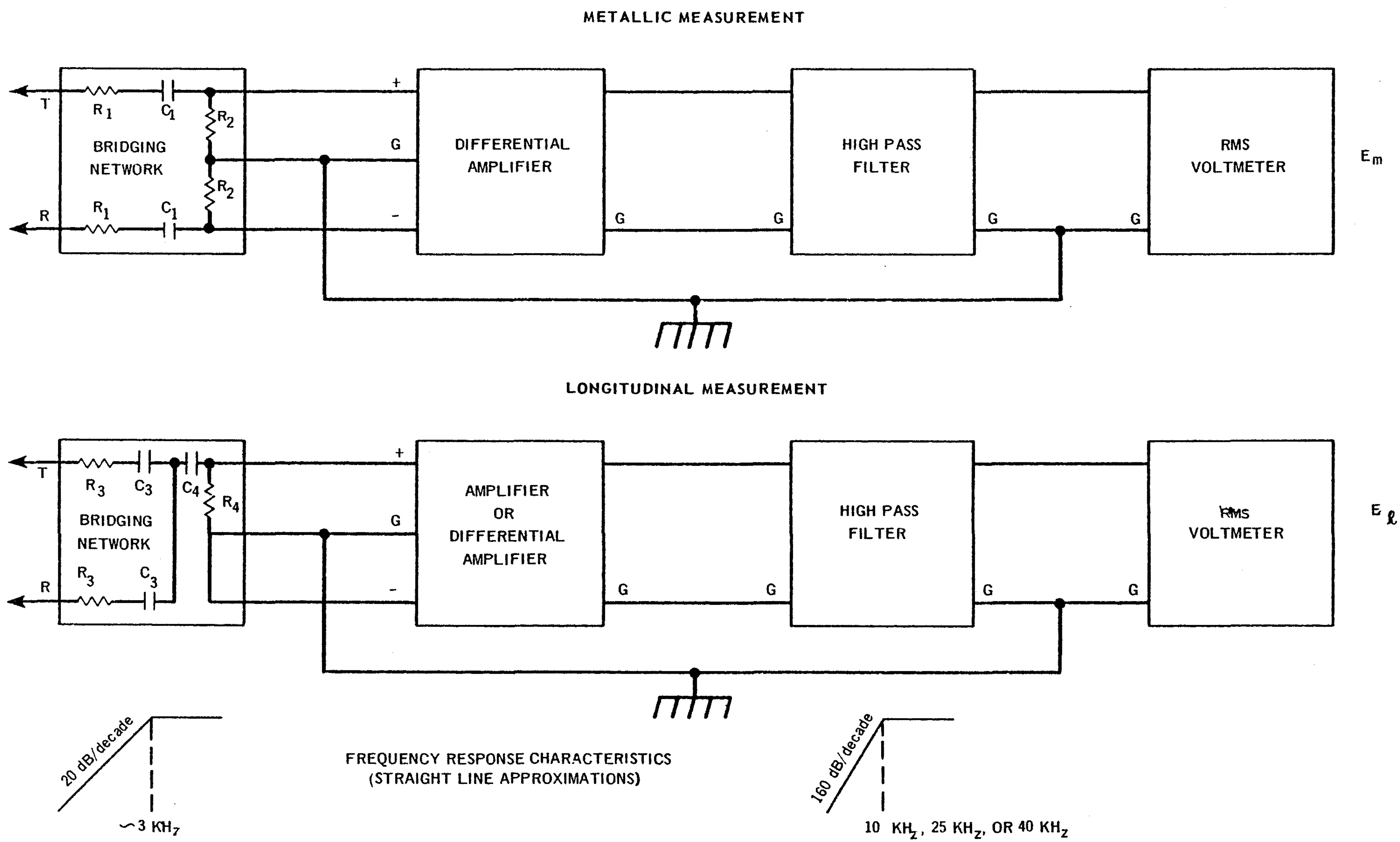
MEASUREMENT ARRANGEMENT

Figure 7



MEASUREMENT METHOD FOR THE 10Hz TO 10 KHz FREQUENCY BAND

Figu



MEASUREMENT METHOD FOR THE THREE FREQUENCY BANDS ABOVE 10 KHz

Figure 9