Interference between Satellite Communication Systems and Common Carrier Surface Systems

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Various published papers have discussed in quite general terms the problem of interference between satellite systems and ground systems. These studies have been largely qualitative, rather than quantitative, in nature. The magnitude of the interference between a satellite system and ground system, however, depends greatly on the frequency plans involved, the character and degree of modulation used, and the parameters of the equipment. Bell Telephone Laboratories has under construction experimental satellite equipment designed to operate in the heavily used 4- and 6-kmc common carrier bands, and the present paper is directed to the potential interference between this satellite equipment and ground point-to-point systems.

Interference involving a satellite station and the TD-2 and TH systems is analyzed specifically, and it is shown that the separation between systems must be of the order of 100 to 120 miles or more when the antenna of the common carrier transmitter or receiver is pointed directly at the satellite ground station. If the antenna is beamed 90 degrees or more from the satellite site, the minimum distance may be of the order of 10 miles even when line-of-sight propagation exists between locations. This assumes the use of the Bell System's horn-reflector antenna on the terrestrial system. With a parabolic dish antenna the latter distance must be increased to about 40 miles and adequate blocking must exist in the interference path. These distances provide adequate freedom from mutual interference for both telephone and television modulating signals.

I. INTRODUCTION

Satellite systems will of necessity use ground transmitter powers of several thousand watts. Present microwave systems in the United States operating in the common carrier band utilize transmitters of the general order of one watt output power and in this sense are consequently only about one-thousandth as interfering as a satellite ground transmitter. Furthermore, the inherent noise per cycle of bandwidth at the input of the satellite ground receiver will be about 20 db less than that of the present-day commerical common carrier receiver, thus making it correspondingly more sensitive to interference from other systems.

Several general studies of interference[1,2] have used criteria of interference intended to encompass all varieties of ground radio relay systems, but inevitably the decision as to whether interference between particular sites is tolerable or intolerable must be made on the basis of the specific radio systems involved and the frequency bands in which they operate.

The F.C.C., as a result of its studies, has recommended for consideration a number of bands between 3700 and 8400 mc, including the two common carrier bands 3700 to 4200 mc for the spacecrafts and 5925–6425 mc for the earth stations.[3]

The experimental satellite equipment presently under construction by Bell Telephone Laboratories will operate in the top 100 megacycles of the 4- and 6-kmc common carrier frequency bands mentioned above and thus, potentially, interference may occur between the satellite system and the many ground commerical systems operating in these bands.

The Western Union Company has a radio relay system operating in the 4-kmc band, and a transcontinental system in the 6-kmc band is under construction. There are also a relatively large number of short haul common carrier systems in the 6-kmc band. However, the most extensive user of each of these two bands in the United States is undoubtedly the Bell System which had in operation at the beginning of 1961 approximately 300,000 one-way broadband channel miles of microwave systems. A large fraction of this service utilizes the TD-2 system[4] operating in the 3700- to 4200-mc band, and, at present, a small fraction utilizes the recently developed TH system[5] operating in the 6-kmc band. For this reason the interference study described herein is directed quite specifically to the TD-2 and TH systems, but the basic philosophy is readily applicable to other microwave systems.

Such a complicated network of microwave routes as presently exists in the United States and Canada with its numerous sources of inter- and intra-system radio interferences has necessitated most careful attention to this problem in order that the interference at baseband at the end of a long circuit would be in reasonable balance with other sources of system impairment, such as intermodulation between elements of the system load and the noise arising in the converters. This problem has been discussed at some length in an earlier paper,[6] and the philosophy developed therein will be applied in the present paper to interference involving satellite systems.

The experimental equipment under construction by Bell Laboratories will transmit from ground to spacecraft in the 6-kmc frequency band, and in the reverse direction in the 4-kmc band, so that the only appreciable interferences between ground stations are those from satellite ground transmitters into TH receivers and from TD-2 transmitters into satellite ground receivers. For completeness, consideration is also given to the two complementary interferences that would exist if the frequencies were interchanged. Possible interference from the spacecraft into ground receivers is discussed briefly.

Contours of permissible minimum separation between satellite ground station and TH and TD-2 microwave stations are presented in this paper. It should be emphasized at this point that the results are based on values of parameters for the three systems that are pertinent at the present time. Changes that may be made in the future such as increases in transmitter power, improvements in receiver noise figure or change in frequency plan would, of course, alter the conclusions reached herein.

While the contours are based on propagation under "average" terrain conditions, it is believed that they should be of considerable value in the early phases of site selection. However, in any particular case, if the profile of the path so indicates, the power of the interference should be calculated and compared with the objectives given later in Table III.

II. OBJECTIVES

Microwave systems with which we are concerned may handle television or multichannel data and telephone signals, and in the latter case the signal load may range from busy-hour full load to light early-morning load. Interference objectives must be sufficiently stringent to protect the systems under all normal conditions; moreover, interference powers should be sufficiently less than the total receiver input noise so as not to impair significantly the fading margin of the interfered-with system.

Basically the amount of RF interference that can be tolerated depends on the interference that it produces at baseband frequencies. The spectrum of the interference at baseband frequencies resulting from RF interference between two FM or PM waves is made up of beats between each frequency component of the spectrum of one RF wave and each frequency component of the other. The frequency of any baseband component is that of the frequency difference between the two RF components that produced it; and finally the power of the baseband component depends on the powers of the RF components.

Therefore the baseband interference spectrum can, for convenience, be thought of as the result of (a) a tone resulting from the beat between the two carrier frequencies, (b) the sidebands of one wave beating against the carrier of the second and vice-versa, and (c) the sidebands of one beating against the sidebands of the other. The beat tone ideally may appear as sinusoidal interference in a video signal, or as a tone in some particular telephone channel. Actually, because of the very low frequency noise normally present on FM transmitters using klystron deviators, the tone is more like a "burble" spread over a number of channels, the particular channels affected at any time depending on the difference frequency between the carriers at that instant. The second and third classes of interference appear normally as unintelligible crosstalk.

The relative magnitudes of carrier and sidebands at any time depend on the degree and type of modulation applied to the radio transmitter. Consequently the RF interference objectives must be sufficiently restrictive that the baseband interference is adequately low for all conditions of modulation. The procedure here will be to develop objectives on the basis of full load telephone considerations and then to make certain that they are adequate for all other loads and signals, whether telephone or television. In general, the interference objective set by telephone considerations is sufficiently controlling so that it is satisfactory for other types of signals.

All long-haul microwave systems are subject to a number of sources of transmission impairments. For example, a 4000-mile TD-2 system may have approximately 140 sources of thermal-type noise due to the converters, an equal number of sources of cross modulation due to repeater phase and amplitude nonlinearity, 280 sources of waveguide echoes, 280 sources of intersystem co-channel interference, together with a number of somewhat less important contributions.

Good engineering practice indicates that for telephone service, the rms sum of these impairments should, during busy hours, be not over 38 dba0, i.e., 38 dba* at a point of zero-db transmission level. This is equivalent to -43 dbm in a 4-kc band, and the signal-to-noise ratio is 27 db where the signal in each telephone channel is random noise equal in power to an rms talker, one quarter active, or -15.8 dbm in a 4-kc band, using values obtained from the Holbrook and Dixon paper.[7]

* The unit dba identifies a particular weighting characteristic for which 82 dba is equivalent to one milliwatt of thermal noise in a 3-kc band.

The division of this total permissible impairment into all the various individual sources cannot be done by any set rule. The total number of significant sources of noise impairment in a 4000-mile system, as enumerated above, totals very roughly one thousand. Therefore if each were given an equal share of the total, the individual allotment would be 8 dba0. Since interference and cross modulation are generally more annoying than thermal-type noise, it is normally a desirable goal that the baseband noise due to the converters in a repeater should be slightly greater than inter-modulation, which in turn should exceed the baseband interference from RF crosstalk. Then during a fade of the desired carrier, the converter noise and interference in any telephone channel will rise together and the interference will not predominate over the noise.

The distance between any satellite system site and a potentially involved interfering or interfered-with TD-2 and TH station may vary from a few miles to more than 100 miles. Thus, propagation between them may range from line-of-sight, in which free-space propagation normally exists for a very large fraction of the time over a full year, to tropospheric scatter propagation, in which the long-term distribution of path loss is normal in db and in which the chance of the received signal being, let us say, 32 db or more above the median value is about 0.01 per cent.

For this reason two interference objectives are proposed. The first applies to line-of-sight interference paths in which the propagation is very close to that of free-space nearly 100 per cent of the time. Up-fades greater than about 5 db occur less than about 0.3 per cent of a year's time, and down-fades of the interfering carrier simply decrease the baseband interference. This is referred to herein as the "100 per cent" objective, and it is intended that it be met for line-of-sight paths during free-space transmission.

For interference signals which are constantly fading both up and down, such as on tropospheric scatter paths, a second objective is proposed, which should be exceeded only 0.01 per cent of the time. This objective in terms of baseband noise may obviously be higher than the "100 per cent" objective, and it appears reasonable to let the 0.01 per cent objective be 15 db more lenient than the "100 per cent" objective. The "100 per cent" objective is so chosen that the unintelligible crosstalk type of interference in the worst telephone channel in the full-load telephone case may be expected to be 9 dba0 during nonfading periods. It may be 24 dba0 or greater 0.01 per cent of the time when the interfering signal path is well beyond line-of-sight. This may be compared with the contribution of about 10 dba0 per repeater due to noise arising in the converters of a 4000-mile system during nonfading conditions. Interference may also manifest itself as tones in certain telephone channels or in television transmission. The magnitudes of these effects will be discussed in a subsequent section.

III. FREQUENCY PLAN

Interference between two FM or PM systems depends upon such parameters as frequency deviation, top baseband frequency, and upon the frequency separation between the carrier frequencies of the systems involved.

The CCIR recommends for the 6-kmc common carrier band a plan based on a spacing of 29.65 mc starting at 5945.20 mc, and this is identical with the plan used in the United States by the Bell System for the TH system and also by Western Union for its 6-kmc system. Thus eight satellite assignments, each about 50-mc wide, can be obtained in the same band with a minimum of mutual interference by placing the satellite carriers midway between the common carrier assignments as shown on Fig. 1.

Coordination in the 4-kmc common carrier range is less satisfactory. The TD-2 system, when a route is fully developed, will have a channel

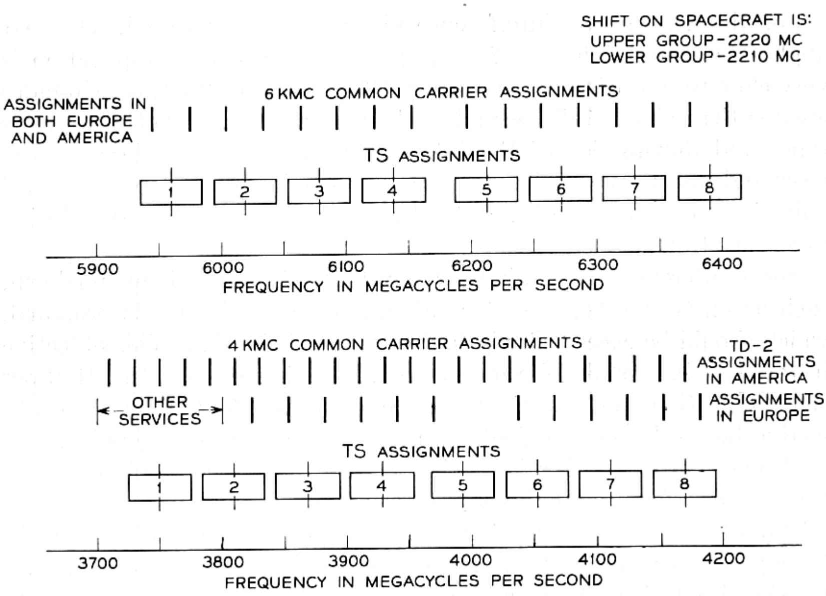

Fig. 1 — Frequency plan.

every 20 mc from 3710 to 4170 mc, while in Europe a spacing of exactly 29 mc is used.

A frequency shift from the 6-kmc to the 4-kmc band must obviously be made on the spacecraft, the optimum value of the shift for each of the channels depending to a considerable extent on problems outside the scope of this paper.

However, one possibility might be to use a shift of 2220 mc for the upper four channels, and 2210 mc for the lower four channels. The satellite assignments in the 4-kmc band would then be as shown on Fig. 1, and this plan is assumed in the present study. It will be noted that the satellite carrier frequencies would, in all cases, be very close to certain of those used in the TD-2 system. The effect on interference of moderate departures in frequency from the plan shown on Fig. 1 is discussed below.

IV. INTERFERENCE BETWEEN TWO FM OR PM WAVES

Signal and interference are customarily specified in units of watts per cycle of bandwidth. Since there is a linear relationship between signal power per cycle and carrier deviation in mean square radians per cycle of bandwidth, it is convenient in this paper to express both signal and interference in the latter units.

The method used herein to compute quantitatively the baseband interference due to the presence of a weak interfering FM or PM wave can be demonstrated by the limiting case when neither interfered-with nor interfering carrier is modulated. Let the peak amplitudes of the two carriers be E and kE, respectively, where k is small relative to unity, and let the frequency difference between them be f. The interfering carrier phase modulates the stronger carrier by $k \cos 2\pi ft$ radians, and the baseband interference power is proportional to $k^2/2$ mean square radians.

However, the present problem is most closely approximated by two carriers separated an appropriate amount in frequency and modulated with random noise so as to simulate a number of telephone channels arranged in frequency division multiplex. This problem has been treated for the case of pure frequency modulation by several writers.[8,9]

The Appendix gives an expression for the interference in integral form that is valid when the interfering carrier is substantially weaker than the interfered-with carrier. This integral is difficult to deal with numerically. However, following the argument used in the Appendix a practical, but basically exact, method of evaluating the interference has been developed, subject to the same premise of weak interference. This method consists simply of normalizing the level of the unmodulated power or voltage of the stronger carrier to a reference value of 0 db, and expressing the spectrum of each of the two waves in db below this reference value. The two spectra thus described are convoluted (adding the db values). The interference thus computed in a very narrow band, such as one cycle, is varying with time, and in this case to obtain the mean square value, or power, the result must be decreased by 3 db.

This procedure, then, gives the distributed interference spectrum in mean square radians per cycle of bandwidth, together with a sine wave component at the difference frequency, whose power is expressed in mean square radians. The noise signal simulating a typical talker can be expressed in the same units as the distributed baseband interference, and thus the baseband signal-to-interference ratio can be obtained. Since the noise signal, for the loading constants assumed herein, is 65 dba0, the interference can be expressed in dba0 by subtracting the signal-to-interference ratio in db from 65. Baseband signals are usually pre-emphasized so that the higher frequencies phase modulate the carrier and the lower ones frequency modulate it. In this study, pure phase modulation is assumed for simplicity of analysis for all baseband frequencies.

Nominal values of the parameters determining the spectra for the three systems considered here are given in Table I.

For both the TD-2 and the TH carriers the frequency deviation is sufficiently low that, for purposes of this study, sidebands of order greater than unity are sufficiently small that they may be neglected.

The spectral power per cycle of bandwidth for first order sidebands

TABLE I

Item	Symbol	System		
		TD-2	TH	TSX-1*
Top baseband frequency	f_b	2 mc**	10 mc	2 mc**
RMS frequency deviation due to noise load	f_d	0.71 mc	0.71 mc	5 mc

* This is the designation for the Telstar experimental satellite equipment being constructed at Bell Telephone Laboratories. The ground station will be located in Andover, Maine. The spacecraft will have active repeater equipment for one broadband channel. Transmission to the spacecraft will be at a frequency of about 6390 mc. Transmission from spacecraft to ground will be at about 4170 mc. The parameters given in Table I above for the TSX-1 equipment represent values that appear to be reasonable at the time of preparation of the paper.

** The top frequency of 2 mc is appropriate to 480 telephone channels arranged in frequency division multiplex.

only, relative to the unmodulated carrier, for a low index of modulation is[10]

$$P_i = \frac{\exp\left[-3f_d^2/f_b^2\right]}{2f_b} \frac{3f_d^2}{f_b^2} \quad \text{for} \quad |f| < f_b \qquad (1)$$

$$\text{and zero for} \quad |f| > f_b$$

where f is any frequency relative to that of the unmodulated carrier.

In the case of the TSX-1 system, the deviation with noise load is sufficiently great that the wide deviation approximation may be used. Assume the power of the carrier when unmodulated is unity. When the phase deviation, as defined in (4) below, is substantially greater than unity, the power per cycle of the PM wave at a frequency $\pm f$ from that of the carrier frequency is very closely

$$P = \frac{1}{\sqrt{2\pi} f_d} \exp\left(-f^2/2f_d^2\right). \qquad (2)$$

There is also a carrier spike present whose power relative to that of the unmodulated carrier of unity power is

$$P(\text{spike}) = \exp\left(-3f_d^2/f_b^2\right). \qquad (3)$$

Fig. 2 shows the spectra for the three systems with noise loading as computed using the parameters and formulae given above.

The mean square phase deviation, D, of the carrier is related to the above defined constants in the following way:

$$D = 3f_d^2/f_b^2 \text{ mean square radians.} \qquad (4)$$

The applied signal power, S, per cycle of bandwidth is

$$S = D/f_b = 3f_d^2/f_b^3 \text{ mean square radians per cycle of bandwidth.} \qquad (5)$$

The signal power in db is given by 10 log S and is tabulated in Table II for the three systems of interest, using the constants from Table I. The symbol dbR/cbw will be used to denote mean square radians per cycle of bandwidth expressed in decibels.

The application of the method of determining the interference in a specific case will illustrate the procedure. Let us consider, as an example,

TABLE II

Signal Power	TD-2	TH	TSX-1	Units
10 log S	−67.3	−88.2	−50.3	dbR/cbw

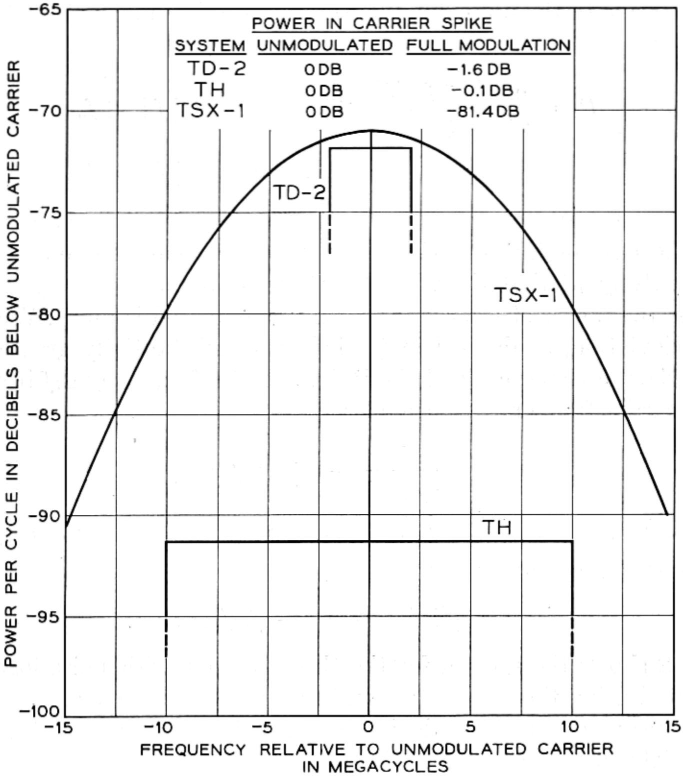

Fig. 2 — Spectra of phase-modulated waves.

interference into the satellite system from the TD-2 system and compute, specifically, the dba value of interference corresponding to a particular ratio of unmodulated TD-2 carrier power to unmodulated satellite carrier power at the input to the TSX-1 receiver, such as −35 db. The unmodulated carrier frequencies in this case will be nearly cochannel.

Fig. 2 shows that in the case of the satellite system modulated with random noise, the sideband power per cycle near the carrier will be 71 db below the unmodulated satellite carrier power. The power of the TD-2 carrier in turn was assumed to be 35 db below the carrier power of the interfered-with TSX-1 carrier.

The TD-2 carrier spike then beats with each component of the TSX-1 spectrum to produce baseband interference as described above. Consider specifically the beat between the unmodulated TD-2 carrier and the TSX-1 spectral power one kilocycle removed therefrom. The resulting interference that will fall in a bandwidth of one cycle at a baseband frequency of one kilocycle can be obtained, as described above, by adding the db values of the appropriate points on the two spectra and subtracting 3 db from the result. This gives an interference value of $-71 + (-35) -3$, or -109 dbR/cbw.

From Table II we find that the TSX-1 signal power is -50.3 dbR/cbw. The signal-to-noise ratio in a narrow band then is 55.7 db, which is equivalent to approximately $+9$ dba0. This establishes the position of the linear relationship shown on Fig. 3, for interference from the TD-2 system into the TSX-1 system.

If the speech load on the satellite system is very low, then the continuous portion of baseband interference of the satellite system due to the TD-2 system can be obtained by convoluting the TSX-1 carrier spike and the TD-2 spectrum. By following the above procedure it can be shown that the baseband interference is 0.9 db less than when the TSX-1 system was fully modulated.

Interference from the satellite system into the TH system behaves quite differently. With the frequency plan shown on Fig. 1, the unmodulated carriers are approximately 15 mc apart, and only when the satellite system is substantially fully loaded will there be appreciable interference into the TH system.

Assume a ratio of TH carrier to satellite carrier power of 68 db. The maximum interference into TH falls at 10 mc and is the result of a beat between the TH carrier and satellite sidebands 10 mc removed, i.e., 5

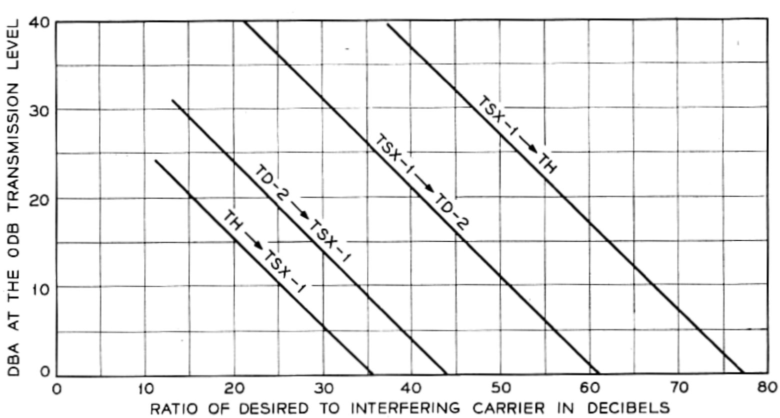

Fig. 3 — Expected message channel interference, all-message case.

mc from the satellite carrier itself. Fig. 2 shows the spectral power is 73 db below the TSX-1 unmodulated carrier or 141 db below the TH carrier. Therefore the interference on the TH carrier corresponds to phase modulation of −144 dbR/cbw. The TH signal power (see Table II) is −88.2 dbR/cbw. The signal-to-interference ratio is 56 db and the interference is +9 dba0.

Interference into the TSX-1 system from the TH system increases rapidly with baseband frequency. In order not to jeopardize the potential use of the satellite system above 2 mc, interference is computed at 5 mc but is referred to the signal as specified in Table I, thus giving a conservative value for the minimum allowable separation.

Finally, interference from the TSX-1 system into the TD-2 system is a maximum at the bottom baseband frequencies since the two systems are nearly co-channel. Computations are made in a manner similar to that for interference in the reverse direction. Fig. 3 shows the relationships between baseband interference to the ratio of desired carrier to interfering carrier for these four cases. These relationships are linear, and are valid for carrier ratios greater than about 10 db.

In the frequency plan shown on Fig. 1, the satellite channels are uniformly spaced between TH assignments. If a plan were used with a spacing different from 15 mc, the magnitude of the interference would, of course, be affected. Fig. 4 shows the computed baseband interference spectrum as a function of carrier spacing, and it will be noted that the increase due to reducing the separation to 10 mc is only about 2 db at the top baseband frequency.

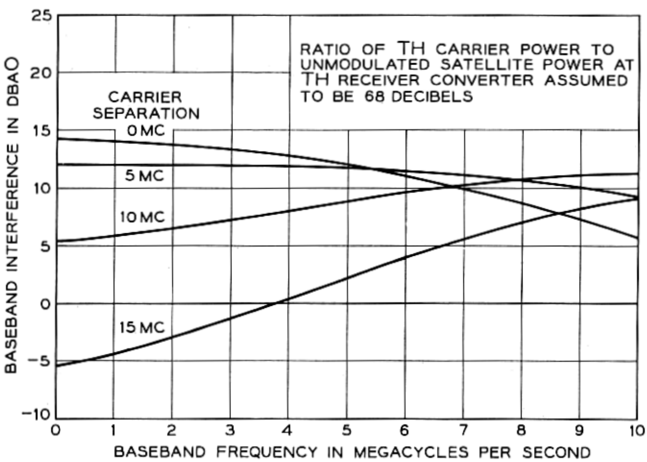

Fig. 4 — Interference — satellite transmitter into TH system.

Table III

System		Normal Received Carrier	Required Interference Ratio	Interfering Carrier Objectives at receiver-converter	
Interfering	Interfered-with			100%	0.01%
TH	TSX-1	−98 dbm	27 db	−125 dbm	−110 dbm
TSX-1	TH	−27	68	−95	−80
TD-2	TSX-1	−98	35	−133	−118
TSX-1	TD-2	−38	52	−90	−75

V. PERMISSIBLE INTERFERENCE

On the basis of the normal received carrier power for the TD-2 and TH systems and the minimum received satellite carrier, permissible interference carrier powers at the input to the receiver-converter of the interfered-with system can be obtained (Table III). The values tabulated in the "required interference ratio" column in Table III are from Fig. 3, and correspond to a baseband interference value of 9 dba0.

The above objectives have been based on busy-hour telephone interference. During such periods the power in the carrier of the satellite system is negligible, but under light loads it may be strong enough to make the beat note between it and the carrier of the ground common carrier system a serious source of interference. Ideally this interference would be a pure tone, but actually it will be spread over a group of telephone channels, its location depending on the frequency difference between the two carriers at any moment

An order of magnitude estimate of this interference can readily be made as follows for the case of interference from the TD-2 system into the satellite system when the latter is very lightly loaded:

a. Permissible carrier to interference ratio from Table III	= +35 db
b. Resulting tone interference	= −38 dbR
c. Signal (noise load) from Table II	= −50.3 dbR/cbw
d. Signal in a 3-kc band	= −15.5 dbR
e. Signal-to-interference ratio	= +22.5 db
f. If the interference is assumed to have the character of noise and spread over one channel only, it will read	= +42.5 dba0.

This, it will be noted, is 4.5 db above the total 4000-mile objective. Actually it will probably be spread over a number of telephone channels, depending upon the steadiness of the carriers, but still it is a potentially important interference source. The interference from the satellite system into the TD-2 system computed in the same manner will have the same value.

This source of interference can be decreased substantially by applying a very low frequency baseband signal to the transmitter to keep the carrier in motion even when the total speech load is low.[11]

The above objectives have been based on telephone channel interference considerations. It appears possible to produce interference into the satellite system when the interfering carrier is weakly modulated, thus having a strong carrier spike, and when at the same time the interfered-with carrier is handling a television picture with a large gray area, thus also having a large component of energy in a fairly narrow band.

For example, assume the television signal content in the TSX-1 channel is such that there is a concentration of energy one mc removed from an assumed interfering TD-2 carrier. A sinusoidal baseband tone will result whose peak-to-peak amplitude relative to the peak-to-peak amplitude of the desired baseband signal for full deviation is given by the ratio of the carrier powers involved in db, plus the FM improvement. The assumed carrier ratio from Table III is 35 db; the FM improvement for a TSX-1 deviation of 20 mc is 26 db. Therefore, the signal-to-tone ratio is 61 db as shown later in Table IV. Bearing in mind that line-of-sight signals during fading conditions may "up-fade" as much as 5 db, this TV signal-to-tone ratio would then be reduced to about 56 db. This is of the same order of magnitude as the tolerable tone interference ratio in a television picture.

The various impairments that may be expected using the interference ratios given in Table III are summarized in Table IV. Since the ground satellite station in the TSX-1 experiment transmits in the 6-kmc band

TABLE IV

System		Telephone Interference		TV Sp-p/Tp-p	Loss of Fade Margin
Interfering	Interfered-with	Full Load	No Load		
TH	TSX-1	+9 dba0	nil	53 db	0.3 db
TSX-1	TH	9 dba0	nil	80	1.6
TD-2	TSX-1	9 dba0	42.5 dba0*	61	0.1
TSX-1	TD-2	9 dba0	42.5 dba0*	64	2.2

* This interference will appear in a few telephone channels only, and there is also considerable uncertainty in the values given.

and receives in the 4-kmc band, it is evident that TD-2 interference into TSX-1 is controlling from the standpoint of interference to television.

The loss of fading margin is computed on the basis of the increase in peak noise voltage at the converter when the interfering carrier is present. A noise peak factor of 12 db is assumed for the noise at the converter. The interference values used in computing loss of fading margin are the "100 per cent" values, so-called, on Table III since the use of the "0.01 per cent" values seemed unduly conservative.

An examination of Table IV appears to indicate that relaxing any of the RF interference objectives will result in undesirable impairment increases in one or more of the categories listed.

VI. REQUIRED PHYSICAL SEPARATION

The separation between satellite station and common carrier station should be such that the received signal does not exceed the values stated on Table III. This separation depends, of course, upon the transmitter power, path loss and antenna discrimination involved.

In this study the satellite transmitter power is assumed to be 2 kw. The transmitter power in the TH system is 5 watts. Because of atmospheric effects it is expected that the minimum useful elevation of the satellite antenna above the horizontal will be limited to about 7.5°. If so, the effective gain of the satellite antenna in the horizontal direction may be expected to be 0 db above isotropic or less. The gain of the conven-

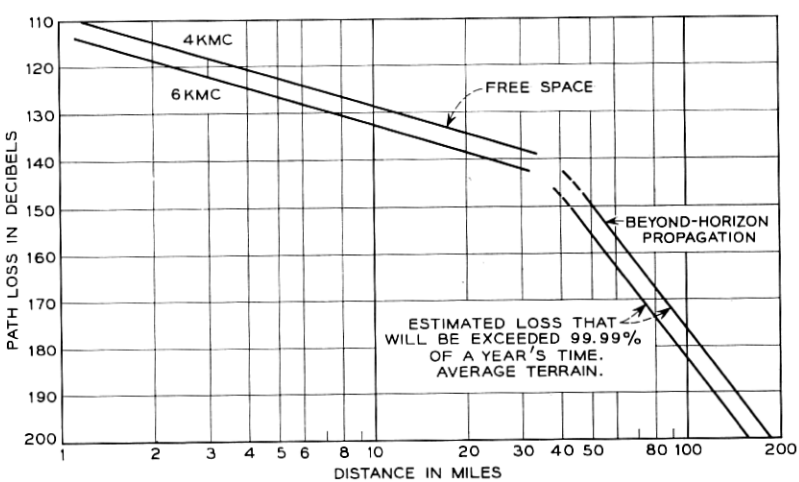

Fig. 5 — Path loss — line-of-sight and beyond-horizon.

tional horn-reflector antenna used with the TD-2 and TH microwave systems at a given angle off-beam is conveniently expressed as the on-beam gain (about 40 db above isotropic at 4 kmc) reduced by the relative directivity pattern of the antenna, a typical example of which is shown later as Fig. 6. Thus, the net response of the horn-reflector in the backward direction is +40 −70, or 30 db below isotropic.

Typical path-loss curves between isotropic antennas as a function of distance are shown on Fig. 5. For distances up to about 30 miles, free-space loss values are plotted; from about 40 miles to 140 miles, scatter propagation over average terrain is assumed. The scatter loss curve is that which will be exceeded 99.99 per cent of a year's time as estimated by K. Bullington of Bell Telephone Laboratories.[12]

The interfering carrier power in dbm is given by

$$P_R = P_T + A_T - L + A_R \tag{6}$$

where P_T = effective transmitter power

A_T = transmitter antenna gain in the direction of the interfered-with receiver

L = path loss (from Fig. 5)

A_R = receiving antenna gain in direction of the interfering transmitter.

As an example, interference from the TD-2 system into the TSX-1 system will be considered. Transmitter power and on-beam antenna gain for the TD-2 system are approximately +27 dbm and 40 db, respectively. The required separation when the antenna of the interfering transmitter is pointed at the satellite site will be such that propagation will presumably be by scatter and hence the 0.01 per cent objective of −118 dbm given in Table III will apply. The total required path loss will be then 185 db, corresponding to 123 miles.

If the satellite receiving station is off the beam of the TD-2 transmitting antenna, the energy radiated thereto is decreased by the antenna discrimination, and the required separation is therefore decreased. Fig. 6 shows the measured directivity pattern of an individual horn-reflector antenna relative to its forward gain, and it will be noted that the backward gain is 70 db below the on-beam gain. Tentatively applying the line-of-sight objective of −133 dbm from Table III, and substituting the appropriate values into (6), we have

$$-133 = +27 + (40-70) - L + 0$$

from which L = 130 db. Reference to Fig. 5 shows that this loss corre-

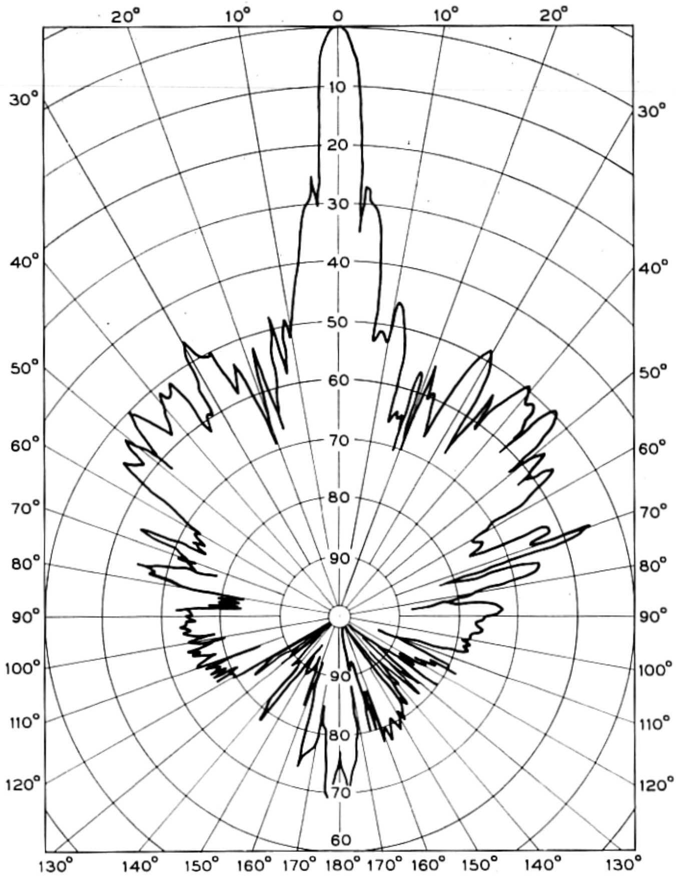

Fig. 6 — Measured pattern in db of horn-reflector antenna at 3740 mc.

sponds to a separation of about 11 miles. Thus, this distance is adequate when the horn-reflector antenna is beamed directly away from the satellite site, even with line-of-sight propagation.

The measured antenna pattern shows a large number of nulls, the position and depth of which will vary from antenna to antenna. Therefore, in developing contours of minimum permissible separation, it has seemed a reasonable and conservative approach to use not the measured patterns but instead an envelope drawn through the maximum values of the pattern as in Fig. 8 of Ref. 6. An additional element of conservatism lies in the fact that the TSX-1 antennas will use circularly polar-

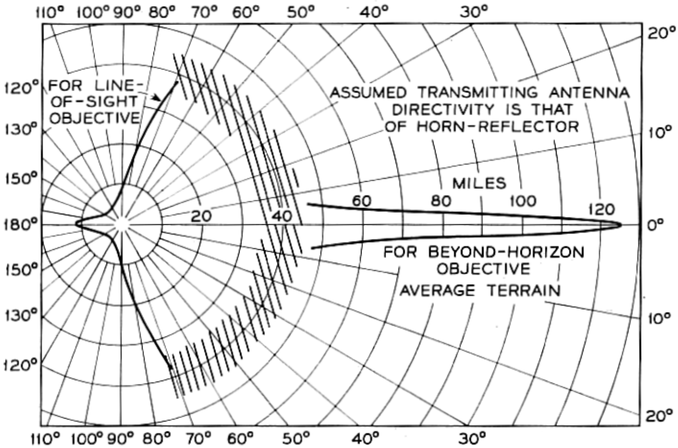

Fig. 7 — Contours of minimum permissible separation between TD-2 transmitter and satellite ground receiver.

ized waves, whereas plane polarized waves are used by the ground systems.

Fig. 7 shows a contour of minimum permissible separation between a TD-2 transmitter and a satellite receiver as a function of the angle between the bearing of the TD-2 antenna and the bearing of the satellite site, based on a smoothed envelope of the antenna discrimination pattern of Fig. 6. For angles greater than 90°, the separation can be as low as about 5 miles. For angles less than about 5° it must be 60 miles or greater. Distances in the order of about 40 miles are cross-hatched because of the uncertainties in propagation. Specific cases that fall in this range should be examined individually to ascertain whether line-of-sight or beyond-horizon objectives should be applied.

Figs. 8, 9 and 10 show similar contours of minimum permissible separation for the three other interference combinations.

It should be emphasized that these values of separation may vary substantially, depending on the local terrain. If the path is obviously line-of-sight, the "100 per cent" objective shown on Table III should be used and met on a free-space propagation basis. In the case of stations only somewhat beyond line-of-sight, it must be kept in mind that ducting may occur occasionally and the signal may become strong enough to give interference much stronger than expected under true scatter conditions. In this situation the chance of exceeding the 0.01 per cent objective given on Table III must be estimated for the specific case involved, due allowance being made, of course, for the directivity of the antennas; if the estimated probability is 0.01 per cent or less, the locations may be considered safe.

The close permissible spacing indicated when the horn-reflector antenna is oriented 90° or more from the direction of the satellite station is, of course, due to its very low backward response. An 8-foot parabolic

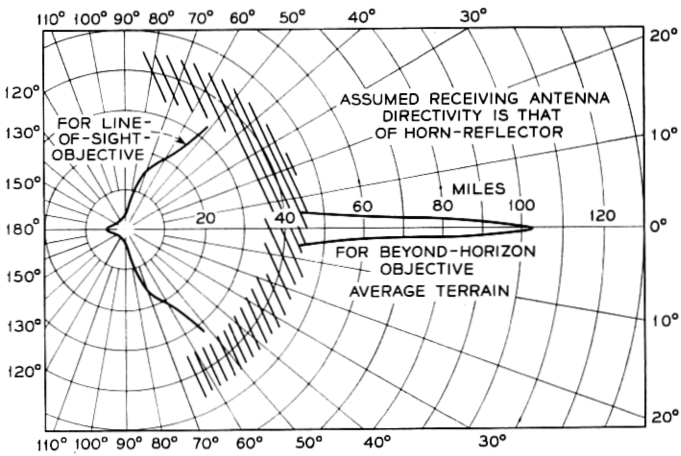

Fig. 8 — Contours of minimum permissible separation between satellite ground transmitter and TD-2 receiver.

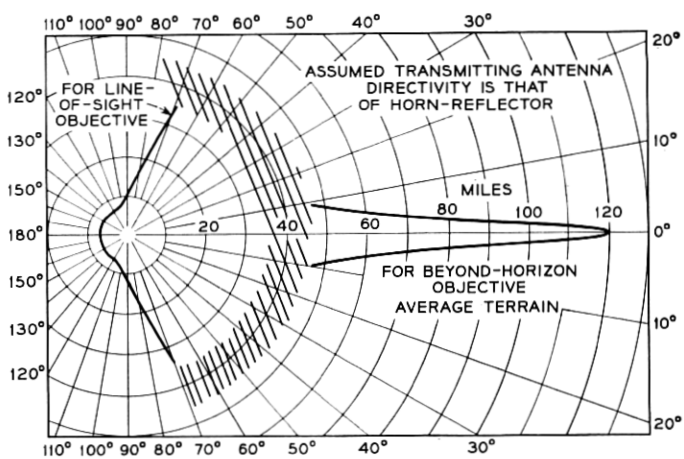

Fig. 9 — Contours of minimum permissible separation between TH transmitter and satellite ground receiver.

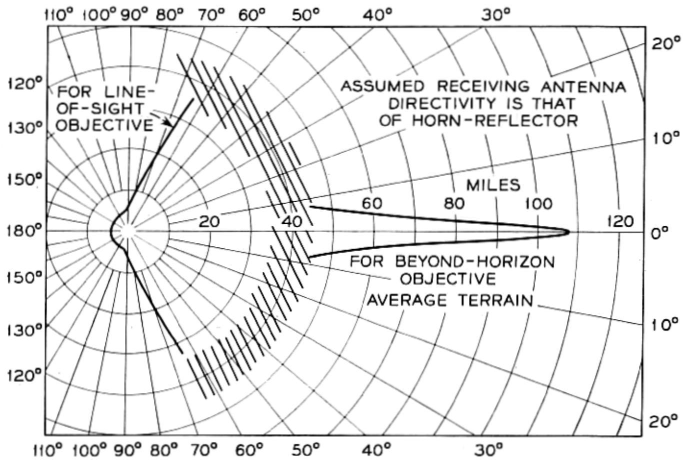

Fig. 10 — Contours of minimum permissible separation between satellite ground transmitter and TH receiver.

antenna may be expected to provide some 20 db to 30 db less discrimination in this general direction. The application of the line-of-sight objective would then result in a minimum distance so great that it would be highly improbable that line-of-sight transmission could take place. The application of the "0.01 per cent" objective indicates, however, a minimum separation of 30 to 40 miles.

In this case, it would be necessary to make certain that propagation is by scatter. The process of estimating propagation over relatively short non-line-of-sight paths involves a detailed study of the exact profile and knowledge of climatic conditions. This subject is outside the scope of the present paper.

While these contours indicate that separations of the order of 5 to 10 miles are possible under the conditions assumed, it should be emphasized that these conclusions are valid only in the absence of significant reflection paths between the interfering and interfered-with sites. Thus, reflecting objects such as houses or trees in the foreground of the horn-reflector antenna may degrade its directivity pattern in the backward direction so that the values shown on Fig. 6 are not attained. Normally it may, however, be expected that such reflections can be made adequately low by careful examination of the terrain illuminated by the ground system antenna.

Transient reflections may be produced by objects in the sky such as airplanes and birds. Also, reflections from rain clouds and precipitation represent a possible way in which interference might reach the satellite ground receiver. However, calculations of the probable magnitude of the effects of such reflections indicate that with station separations of the order of 10 miles or more, interference of this kind from TD-2 into TSX-1 will not exceed the objective of -118 dbm for any appreciable percentage of time.

VII. INTERFERENCE FROM SPACECRAFT TO GROUND RECEIVERS

Another possibility is, of course, interference from the spacecraft transmitter into ground microwave systems. For example, assume a power of one watt and an isotropic antenna on the spacecraft, and on-beam gain of 40 db for the ground antenna. The interference at the receiver converter would have a value of -90 dbm with the spacecraft at a distance of about 370 statute miles, therefore just meeting the "100 per cent" objective for interference from the satellite system into the TD-2 system under these assumed conditions. On this same basis, the maximum power on the spacecraft could be increased to 100 watts if the distance from the spacecraft to the earth were increased ten-fold.

In the case of the horn-reflector antenna, the beamwidth is sufficiently narrow that any particular spacecraft would be in the beam of a given antenna for only brief and infrequent intervals.

APPENDIX

Using an approach similar to that developed in Ref. 13, Messrs. S. O. Rice and L. H. Enloe of Bell Telephone Laboratories have shown independently that the distributed portion, W(f), of the interference spectrum is given by

$$W(f) = k^2 \int_0^\infty \exp[-R_w(0)](\exp[R_w(\tau)] - 1) \cdot [\cos(2\pi f - \omega_0)\tau + \cos(2\pi f + \omega_0)\tau]\, d\tau \tag{7}$$

where the amplitude of the stronger carrier is unity and

k = ratio of the weaker to the stronger carrier; this must be small compared to unity

f = any baseband frequency

$\omega_0/2\pi$ = frequency difference between the two carriers

$R_w(\tau)$ = sum of the autocorrelation functions of the two applied noise signals.

If the noise signals applied to the carriers have powers w_1 and w_2 mean square radians per cycle of bandwidth for the weaker and stronger carriers, respectively, and f_1 and f_2 are the top baseband frequencies of the noise signals applied to the same two carriers, then

$$R_w(\tau) = R_{w_1}(\tau) + R_{w_2}(\tau) \tag{8}$$

$$= \frac{w_1 \sin 2\pi f_1 \tau}{2\pi\tau} + \frac{w_2 \sin 2\pi f_2 \tau}{2\pi\tau}. \tag{9}$$

Also, let

$$w_2 f_2 = D_2 = \text{mean square phase deviation of the stronger carrier}$$

and

$$w_1 f_1 = D_1 = \text{mean square phase deviation of the weaker carrier;}$$

then

$$R_w(0) = D_1 + D_2. \tag{10}$$

In addition to the distributed interference, there is a sinusoidal component of magnitude

$$k\, e^{-\frac{1}{2} R_w(0)} \sin \omega_0 t \text{ radians.} \tag{11}$$

The expression $W(f)$ as given by (7) is not readily evaluated except over a somewhat limited range of parameters. However, the quantity $\exp[R_w(\tau)]$ in (7) is the product of the two autocorrelation functions $\exp[R_{w_1}(\tau)]$ and $\exp[R_{w_2}(\tau)]$. It therefore follows from the convolution theorem for Fourier integrals that the power spectrum of the interference can be obtained by convoluting the power spectra of the two phase-modulated waves. Thus, baseband interference spectrum in mean square radians is given by twice the value obtained by convoluting the spectral power of the two waves, both in a resistance of one ohm. This provides the method* used in this paper for computing interference.

* While the paper was in page proof it was brought to the writer's attention that the convolution method of computing interference between two PM waves had previously been described in a paper (in Japanese) entitled "On the Interference Characteristics of the Phase Modulation Receiver for the Multiplex Transmission," Shinji Hayashi, The Journal of the Institute of Electrical Communication Engineers of Japan, **35,** pp. 522–528, November 1952.

REFERENCES

1. Fine, H., and Dixon, J. T., Suggested Criteria for Limiting Satellite Power in Channels Shared with Ground Systems, Office of the Chief Engineer, Technical Research Division, FCC, TRR Report No. 5.2.1, June 1, 1961.
2. Downing, J. J., Interference Considerations for Communications Satellites, Seventh National Communication Symposium Record, 1961, pp. 302–309.
3. Final Preliminary Views of the United States of America, as Submitted by the Federal Communications Commission, Frequency Allocations for Space

Radiocommunication, September 7, 1961. Hearings on Space Communications and Allocation of Radio Spectrum before the Communications Subcommittee on the Committee on Commerce, United States Senate, August 1, 23 and 24, 1961 — United States Government Printing Office, Washington, D. C.

4. Roetkin, A. A., Smith, K. D., and Friis, R. W., The TD-2 Microwave Radio Relay System, B.S.T.J., **30,** October 1951, p. 1041.
5. Mc Davitt, M. B., 6000-Megacycle-per-Second Radio Relay System for Broadband Long-Haul Service in the Bell System, AIEE Trans., **76,** Part 1, January 1958, p. 715.
6. Curtis, H. E., Radio Frequency Interference Considerations in the TD-2 Radio Relay System, B.S.T.J., **39,** March, 1960, p. 369.
7. Holbrook, B. D., and Dixon, J. T., Load Rating Theory for Multi-Channel Amplifiers, B.S.T.J., **18,** October 1939, p. 624.
8. Medhurst, R. G., Hicks, Mrs. E. M., and Grossett, W. G., Distortion in Frequency-Division-Multiplex FM Systems Due to an Interfering Carrier. Proc. I.E.E., **105,** Part B., No. 21, May 1958.
9. Hamer, R., Radio-Frequency Interference in Multi-Channel Telephony FM Radio Systems, Proc. I.E.E., **108,** Part B, No. 37, January 1961.
10. Stewart, J. L., The Power Spectrum of a Carrier Frequency Modulated by Gaussian Noise, Proc. I.R.E. **42,** October 1954, pp. 1539–1542.
11. U. S. Patent 2,352,254, Frequency Modulated Wave Transmission, June 27, 1944, H. E. Curtis.
12. Response of the A. T. & T. Co. before the Federal Communications Commission, Docket No. 13522, February 27, 1961.
13. Bennett, W. R., Curtis, H. E., and Rice, S. O., Interchannel Interference in FM and PM Systems Under Noise Load Conditions, B.S.T.J., **34,** May 1955, pp. 601–636.