

LLF

RADIO ENGINEERING
MICROWAVE RADIO PROPAGATION
SELECTIVE FADING

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A. General	12	1.01 Time variation in the level of received radio signals is called "fading." Fading is the combined effect of many mechanisms which are associated with meteorological variations in the earth's lower atmosphere. The most common, and potentially the most troublesome to microwave transmission, is the type of fading resulting from wave interference among several components, or rays, of a transmitted signal. Ordinarily, only a small portion of the transmitted beam—the direct ray—reaches the receiving antenna. However, sometimes the atmosphere redirects portions of the remainder by the process of refraction so that the redirected portion also reaches the receiver.	
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There the redirected ray combines with the normal direct ray and either enhances or diminishes the resultant, depending on their phase relationships. This phenomenon is called "multipath propagation," and its effect, "multipath fading." Multipath propagation can also be caused by reflections from the earth or from objects along the path. However, in this section it will be assumed that such reflections are reduced to negligible proportions by proper site layout; the problem of reflections is discussed in detail in Sections 940-310-103 and 940-310-104.

1.02 This section is being reissued to improve and expand the methods of calculation applicable to multipath phenomena, to extend coverage to 40 GHz, and to include narrowband AM systems. The nature and extent of this change precludes the use of change arrows.

B. Conditional Qualifications

1.03 Certain formulas and derived graphic illustrations applicable to the quantification of multipath phenomena (contained essentially in Parts 4 and 5 of this section) have been evolved with respect to systems having standard clearance conditions. Clearance in such systems is not excessive; it normally does not exceed the radius of the first Fresnel zone when K , the equivalent earth radius factor, equals $2/3$. Since the standard clearance conditions tend to typify 4- and 6-GHz system design and since ground-related atmospheric effects contribute significantly to multipath propagation, the fade occurrence factor (r), as described in paragraph 4.07, is derived with respect to these standard systems. For this reason, graphic representations such as Fig. 9 (multipath occurrence factor) as well as Fig. 10 and 11 (both of which involve r in the quantification of "time below level") should be considered most accurate in terms of the curves representing 4 and 6 GHz. The 11-GHz curves, for example, were similarly derived. However, 11-GHz systems are extensively employed in mountainous regions of the United States where, by locating microwave towers on mountain tops, midpath clearance hundreds of feet in excess of the first Fresnel zone may be achieved. Such special case paths affording clearances several hundred feet in excess of the first Fresnel zone will experience significantly less selective fading than that implied by the curves of the aforementioned illustrations or otherwise derived in terms of r as defined herein. Design under high clearance conditions will therefore require different equations.

Additionally, while it is known that fading activity increases with increasing microwave frequency, additional measurements may yield improved data for the higher frequency ranges (above 11 GHz). Again, as before, extrapolating from current formulas to the 18-, 29-, and 40-GHz regions might yield values subject to improvement when refined data become available.

C. Description of Fading

1.04 An analysis of selective fading as a result of multipath propagation is perhaps best begun with reference to Fig. 1, which illustrates the variations in the envelope levels of two received signals during heavy fading. The graphs represent two 4-GHz microwave signals transmitted over the same path at the same time and having a frequency separation of 100 MHz (about 2.5 percent in this case). The signal levels in decibels relative to their normal unfaded levels are indicated on the ordinate scales. Several characteristics of heavy fading are apparent on these graphs and are discussed below.

1.05 Even though the two signals are observed at the same time and travel over the same paths, their levels do not vary in quite the same way, particularly in regard to the deeper fades. That is, most of the deeper fades do not occur simultaneously. Because these disparities occur between signals of different frequencies, this type of fading is said to be frequency selective; hence the alternate term "selective fading." Although it happens that none of the deeper fades in this example have entered the -40 dB region, the improvement offered by frequency diversity protection can still be demonstrated. For example, the first half-hour (two left-hand columns) of the top chart contains several relatively deep fades which are not present on the lower chart.

1.06 Multipath fading is spatially selective, too.

To illustrate, assume a single signal transmitted under conditions similar to those producing the fading shown in Fig. 1. Also assume the signal to be received by two receivers having their antennas vertically separated by a distance of about a hundred wavelengths. Under these conditions, the received signals would have fade relationships resembling those of the frequency-separated signals in Fig. 1. Horizontally-separated antennas would yield similar results, but the distances would have to be many times greater

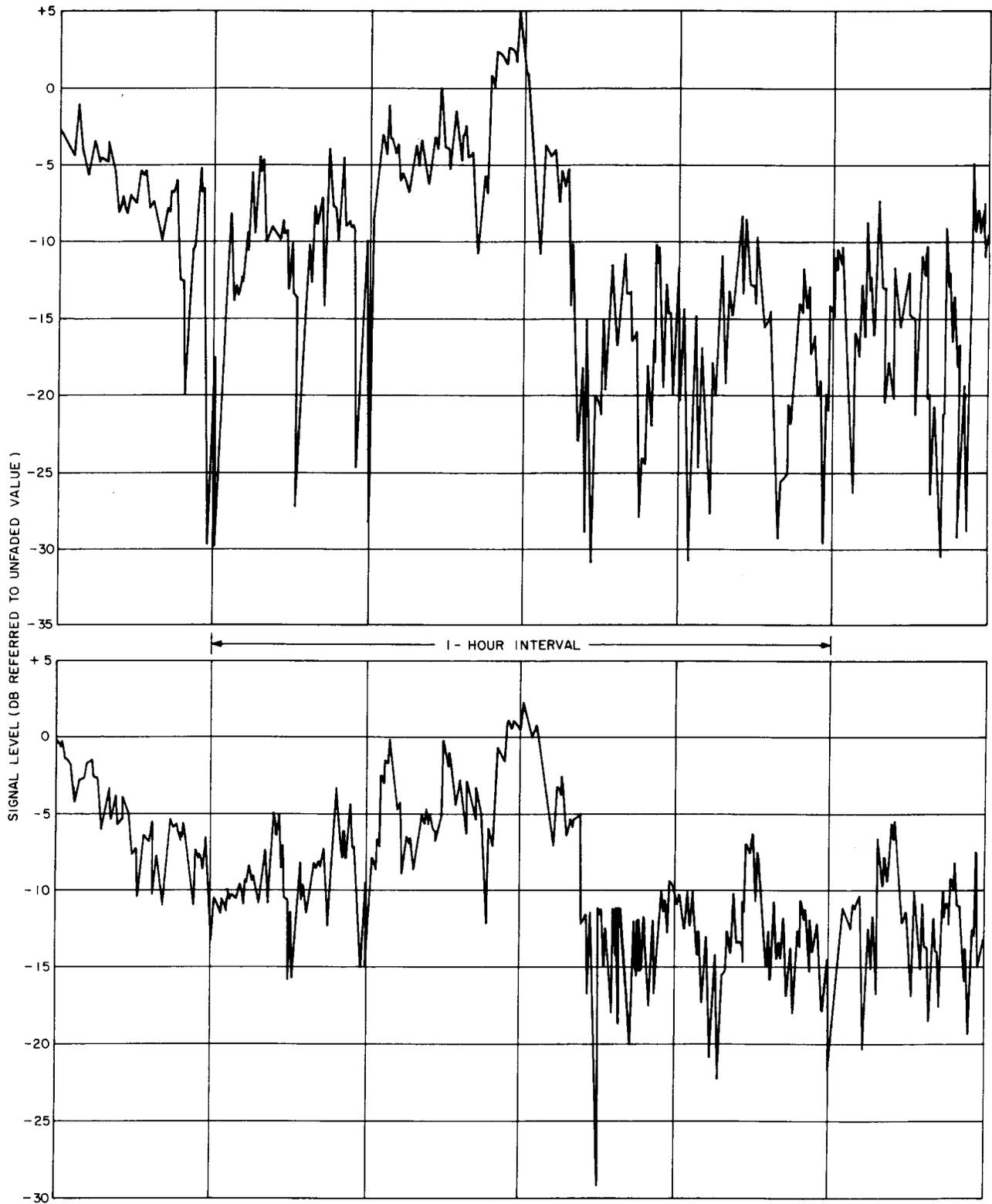


Fig. 1—Heavy Fading on Two Microwave Channels (100-MHz Separation Over the Same Path)

because the structure boundaries in the refractive index tend to be in nearly horizontal layers.

1.07 Also suggested by Fig. 1 is that the number of occurrences and the average duration of the fades are inversely proportional to their depths. That is, there are fewer of the deeper fades, and they are generally of shorter duration than the more shallow ones. While an accurate appraisal cannot be made from this graph, these parameters are elaborated and quantified in Part 4 of this section. Another aspect of multipath fading which is not apparent in Fig. 1 is the fact that the number of fades is related to carrier frequency, although average fade duration, at a given level, remains independent of frequency. These facts are also subsequently considered and quantified.

1.08 Fading activity is variable with the time of day and with the seasons. The late night and early morning hours are usually more conducive to selective fading because the decreased wind activity allows the atmosphere to form into the stratifications which produce multipath propagation. Fading tends to diminish with the morning sun, reaching a minimum at or near noon. On a longer term basis, increased fading activity is generally experienced during the summer months largely because the water vapor content of the atmosphere is at its peak then; the absolute humidity is a major factor in multipath propagation.

1.09 Figure 2 shows typical daily and seasonal variations in fading activity. In it, the vertical lines represent the extremes in signal level received over a 17-mile 4-GHz hop during the 24-hour periods from noon to noon. Signal variations on it are somewhat restricted, owing to the shortness

of the hop; however, the preponderance of fading activity during the late summer months, usual in this country, is evident here.

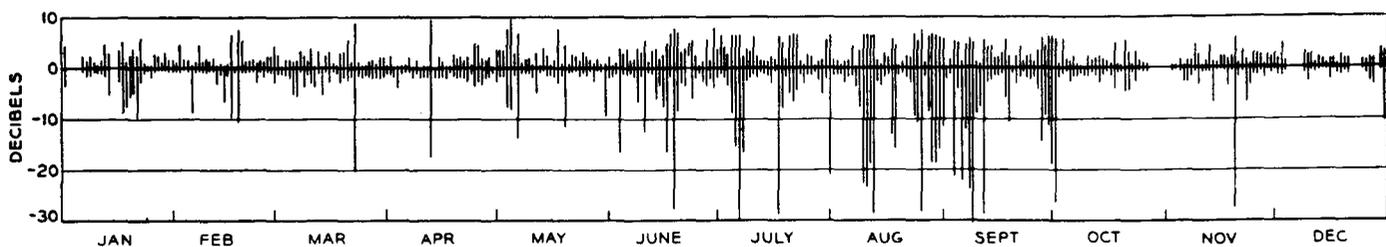
2. BASICS—PHYSICS OF MULTIPATH PROPAGATION

A. Refraction and Reflection

2.01 Radio signals and visible light are both forms of electromagnetic radiation and thus have many properties in common. These similarities are more pronounced as the wavelengths of the radio signals approach that of light. Thus radio signals at microwave frequencies (or wavelengths) behave more like light waves than do those, for example, in the standard AM broadcast band. Two of these properties are refraction and reflection, both of which are deflections of the energy rays from their original paths. A brief discussion of these properties, based on theory and empirical evidence, follows.

2.02 Light and microwave energy may be reflected, or thrown back, from the surfaces of objects in the path. One rule associated with this *specular*, or "mirror-type," reflection is that the angle of reflection is equal to the angle of incidence; that is, the angle formed by the incident, or arriving, ray and the line. Figure 3 illustrates these angles as well as those concerned with refraction, as discussed later. The other rule is that the incident and reflected rays and the normal to the surface are all in the same plane.

2.03 Several conditions are necessary for reflection of this type. One is that the reflecting surface be "smooth." That is, the average depth of the irregularities must be substantially less than the wavelength of the incident ray. Otherwise



NOTE:

EACH VERTICAL LINE REPRESENTS THE EXTREMES OF RECEIVED SIGNAL STRENGTH DURING ONE DAY.

Fig. 2—Typical Seasonal Variations in Fading Activity

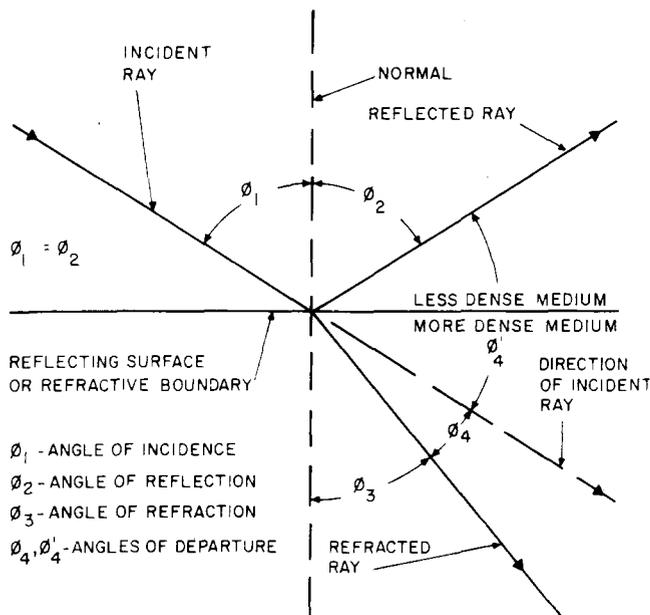


Fig. 3—The Angles and Rays of Reflection and Refractions

the energy will be scattered (also called diffusely reflected). An example of this is that the bottom of a cast-iron skillet makes a good reflector for microwave energy, but not for light. This is because the irregularities in the surface of the skillet are large compared to the wavelengths of light, but small compared to those of microwave energy. Thus, a surface may be "smooth" for one wavelength and "rough" for another. (The wavelengths of light and microwave energy differ by about five orders of magnitude.)

2.04 Another requirement is that the transverse surface dimensions be substantially larger than the wavelength of the incident ray. If this condition is not also met, the ray will tend to be scattered. This type of scattering is called diffraction and will not be discussed here (a dime will reflect light energy, but diffract microwave energy).

2.05 A ray of electromagnetic energy may be either reflected or refracted if it encounters a medium of different density than that of the one through which it has been traveling. **Refraction** results in only a slight departure of the beam from the previous path (always less than 90°), whereas the path of a **reflected** beam may depart any amount between 0° and 180° from its previous direction. As shown in Fig. 3, the angles of

departure referred to here are different from the angles of reflection or refraction. For the purpose of this section, the term "deflection" will be used to include the effect of both refraction and reflection on the direction of the electromagnetic rays.

2.06 The basis for refraction is the fact that electromagnetic energy propagates at different velocities in different media, or in the same medium, if its density varies. This propagation velocity is maximum in a vacuum (the "speed of light") and is lesser in any other medium. Also, it is a constant value for **all** wavelengths in a vacuum, whereas it is dependent on wavelength in other media. The ratio of the velocity in a vacuum to the velocity in a particular medium is called its "index of refraction" and is consequently also a function of wavelength. This frequency dependence, although responsible for the light spectrum produced by a prism and that of a rainbow, is of small magnitude and little importance in selective fading at microwave frequencies.

2.07 Figure 4 is a representation of a microwave beam being refracted by an atmospheric discontinuity. Here, the discontinuity is a boundary between two air masses of different density. As each wavefront of the microwave beam crosses the boundary, the part that has entered the less dense air begins traveling slightly faster than the portion still in the more dense mass. When all of a wavefront has crossed the boundary, it is then traveling in a different direction and thus has been refracted. If the air masses in the figure were interchanged, the beam would be bent in the opposite direction. This is a rather simplified explanation, based on Huygens' principle. Huygens' principle is given broader treatment in Section 940-310-105 and in many texts covering basic optics.

2.08 Both the angle of deflection and the energy in the deflected beam depend upon the angle at which the beam approaches the boundary. If the beam encounters the boundary at a 90° angle, no refraction occurs and almost all of the energy crosses it; a small amount will be reflected, depending on the relative indices of refraction. As the angle is changed from 90° , a larger fraction of energy is reflected and the refracted beam is deflected from the incident direction a greater amount. If the incident beam is in the medium of higher density, an angle will be reached, well short of a grazing angle, after which all of the energy will be reflected. This phenomenon does not exist for

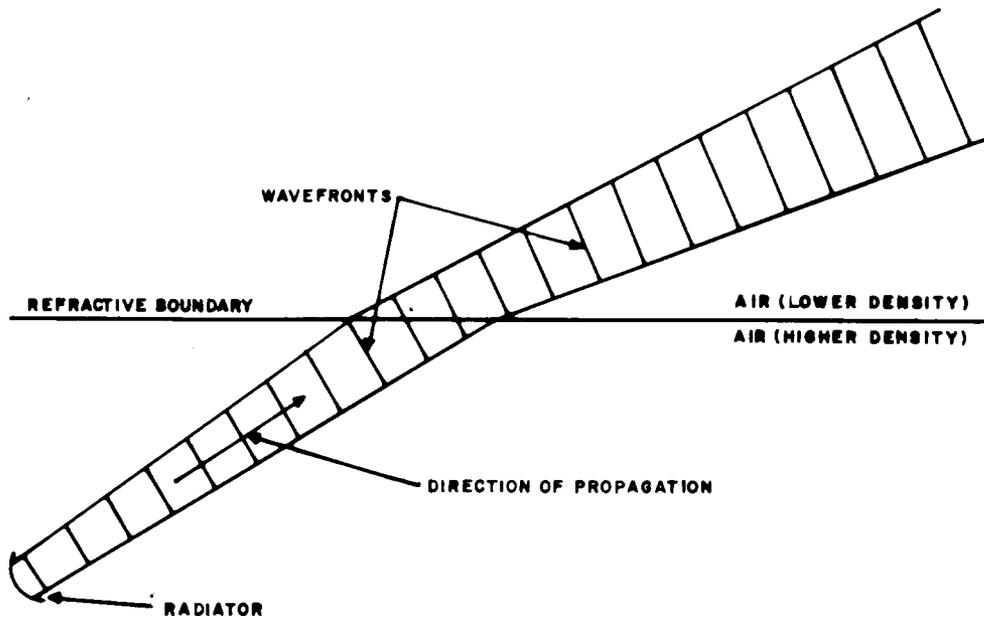


Fig. 4—Refraction of a Microwave Beam Upon Crossing an Atmospheric Discontinuity (Higher-to-Lower Density)

beams originating in the less dense medium; in this case, total reflection is only *approached* as the incident beam approaches a grazing angle.

2.09 A microwave signal during propagation through the earth's atmosphere rarely encounters such well-defined boundaries as suggested by Fig. 4. Rather, the variations in density are more gradual, as in the case of humid air masses merging into dry ones, or cold ones into warm ones. In these cases, the bending is more gradual, forming curves instead of sharp angles.

B. Multipath Propagation

2.10 Ordinarily the refractive index of the lower atmosphere has a constant vertical gradient; that is, it decreases with altitude in a rather constant manner. Sometimes, however, relatively abrupt changes in the gradient exist at random altitudes due to temperature inversions (the temperature begins increasing, rather than decreasing, with altitude) or to sharp changes in humidity. These discontinuities usually form horizontal layers, or strata, and cause part of the transmitted beam to be refracted down to the receiver as diagrammed in Fig. 5. It is this propagation by multiple paths which is considered to be the principal source of selective fading. Discontinuities at altitudes of

more than a mile can potentially be involved in multipath propagation. The height at which discontinuities continue to be influential will depend on antenna beam width, which determines the energy with which the higher altitudes are illuminated.

2.11 The components of a transmitted beam propagating over these multiple paths may be received in different phases because the path lengths are usually different. They can have different amplitudes, too, according to the effects of absorption and scattering and to the refraction efficiencies of the discontinuities. At the receiver, these components will add vectorially; and thus the normal signal level will be reduced or enhanced, depending on this vector sum.

2.12 Consider a 6-GHz signal reaching the receiver by the direct (line-of-sight) path and one of the additional paths in Fig. 5. Since one wavelength at 6 GHz is about 2 inches, a difference in path length of merely 1 inch (or an odd multiple thereof) will cause the two components to be completely out of phase at the receiver. There they will tend to cancel, reducing the signal to a level determined by their relative amplitudes. Such a 2-component signal will produce a very deep fade if the amplitudes are nearly equal.

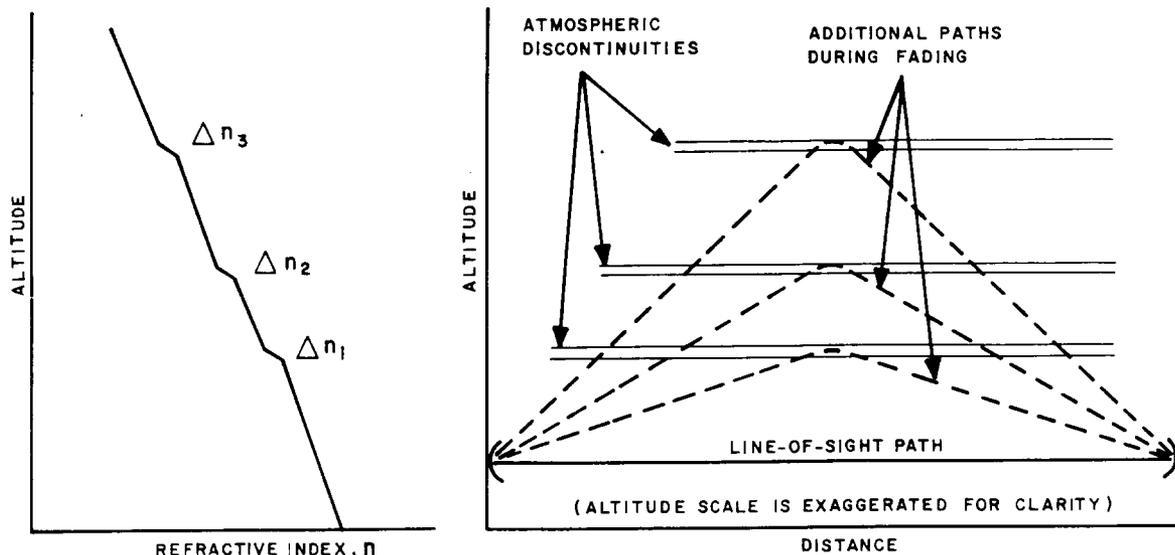


Fig. 5—Multipath Propagation From Refractive Discontinuities in the Atmosphere

2.13 Consider next an additional signal at a frequency only a few percent different (e.g., another channel in the 6-GHz band) but propagated at the same time and over the same two paths. Because this second signal has a different wavelength, its two components will probably not have the same phase relationship as those of the first (i.e., not 180°). They might actually reach the receiver in phase, thus enhancing the signal, while the first signal is reduced. This combination of wavelength and path-length differences is the primary reason for the frequency-selective characteristic of multipath fading.

2.14 Consider further an additional receiver and antenna for the signal of the first example, except at a different location. Depending on the direction and distance of separation, the difference in path lengths to the second receiver would probably be different from that to the first. Therefore, the resultant signal levels would similarly be different at the two receivers. Thus, the fading produced by multipath propagation is spatially selective.

2.15 In practice, the relationships are less simple than these examples, and often many more than two signal paths are involved. Also, the multipath conditions are variable with the seasons, the time of day, and with the meteorological conditions and the quality of terrain (smooth or rough); all of these variables make any precise

prediction of fading impossible. Because of the random nature of fading conditions and their ultimate effect on the received signal, any further analysis is best approached from a statistical point of view. The discussion of the Rayleigh distribution which follows affords such a frame of reference and provides insight regarding the methods used in quantifying multipath phenomena for practical application in improving performance.

3. THE RAYLEIGH DISTRIBUTION

3.01 Lord Rayleigh, the British physicist, formulated a probability distribution function for "the resultant of a large number of vibrations of the same pitch and of arbitrary phase." Expressed somewhat more elaborately, the "Rayleigh" function gives the probability (or time) distribution of the resultant (sum) of a large number of vectors of roughly equivalent size which are constantly and randomly varying in phase. It involves only the magnitude (envelope) of the resultant, the phase distribution being uniform. Because of the similarities between Lord Rayleigh's problem and that of selective fading, the Rayleigh distribution has found use in predicting the fading severity of microwave signals during multipath conditions. The descriptive and predictive power of the Rayleigh curve results in occasional reference to selective fading as "Rayleigh" fading.

3.02 The mathematical expression for the Rayleigh distribution is

$$\Pr(E < E_1) = 1 - \exp[-(E_1/E_{rms})^2].$$

It expresses the probability \Pr that the received signal level E is less than any arbitrary voltage E_1 . E_{rms} , the root-mean-square value of the distribution, is the so-called "free-space" value which represents the normal received signal envelope in the absence of fading. If this probability distribution is considered over an extended period of time, it expresses the fraction of time the received signal E can be expected to fall below the arbitrary voltage E_1 . Figure 6 shows the Rayleigh distribution plotted on a Rayleigh graph scale. The time-fraction is expressed as a percentage, and the ratio E_1/E_{rms} is given in decibels. Inspection of the main (Rayleigh) curve of Fig. 6 reveals that the actual received signal can be expected to fall below the free-space value (0 dB) 60 percent of the time, while a level depressed below -40 dB from normal could be anticipated 0.01 percent of the time.

3.03 Actual microwave reception does not act in strict accordance with the Rayleigh distribution. This is exemplified by the inclusion in Fig. 6 of curves for 4, 6, 11, and 40 GHz, each normalized to its own unfaded level. The curves for 4, 6, and 11 GHz were empirically determined from data taken during two summer months on a hop of 28.5 miles. The curve representing 40 GHz, which serves to extend the example, was generated according to formulae presented in Part 4. Average terrain and climate were assumed, and the path length was also set at 28.5 miles. In practice, paths of this length would not be employed above 11 GHz due to the severe attenuation contributed by rain and fog in the higher frequency ranges.

3.04 During light fading, the criterion of "a large number of vectors of roughly equivalent size" does not usually exist. That is, at these times usually at least one of the components is steady and significantly stronger than the others and/or the number of components is too few to result in a Rayleigh distribution. For a reasonable approximation of the Rayleigh distribution over its whole range, the magnitude of any individual component must be considerably less than the sum of the others' magnitudes and at least several components must be present. Since these conditions are not fulfilled during light fading, empirical curves

depart even more from the Rayleigh distribution. For this reason and because heavy fading is of more concern to the study of performance degradation, the empirical curves are limited to fades deeper than 20 dB.

3.05 The augmented Rayleigh distribution of Fig. 6 serves to reveal several significant characteristics of multipath fading. First, and most apparent, is the fact that the time during which a signal can be expected to fall below a given level decreases with increasing fade margin. Second, the added curves demonstrate that fading activity increases with increasing carrier frequency. While an exact mathematical model of this phenomenon is still being developed, a moment's consideration reveals that at a relatively low frequency of, say, 1 MHz, delays approaching 150 meters (one-half wavelength) are required to produce fading. At a typical microwave path length of 26 miles, it is unlikely that atmospheric aberrations sufficient to cause such delays will exist. If, however, the frequency is increased to 1 GHz, delays in the order of the 15-centimeter half-wavelength become increasingly possible. Finally, if we limit our concern to the region representing fade depths below -20 dB, the slope of the Rayleigh distribution is an almost constant 10 dB per decade of probability or time. Taken at face value, Fig. 6 does not show that fading is a function of path length, that average fade duration at a predefined level is frequency independent, nor does it account for other variables such as terrain and climate.

3.06 As stated above, the slope of the Rayleigh distribution in the region below -20 dB is, for all practical purposes, a constant decade of time per 10 dB. Fortunately, the region below -20 dB is also the area of practical concern regarding fade-produced transmission outages. For this reason, it is possible to develop a simplified, flexible method of quantifying anticipated fading activity.

3.07 If the ratio E_1/E_{rms} is expressed as a fade depth F in dB

$$F = -20 \log(E_1/E_{rms}),$$

the Rayleigh distribution may be closely approximated by the simpler expression

$$\Pr(E < E_1) = 10^{-F/10}.$$

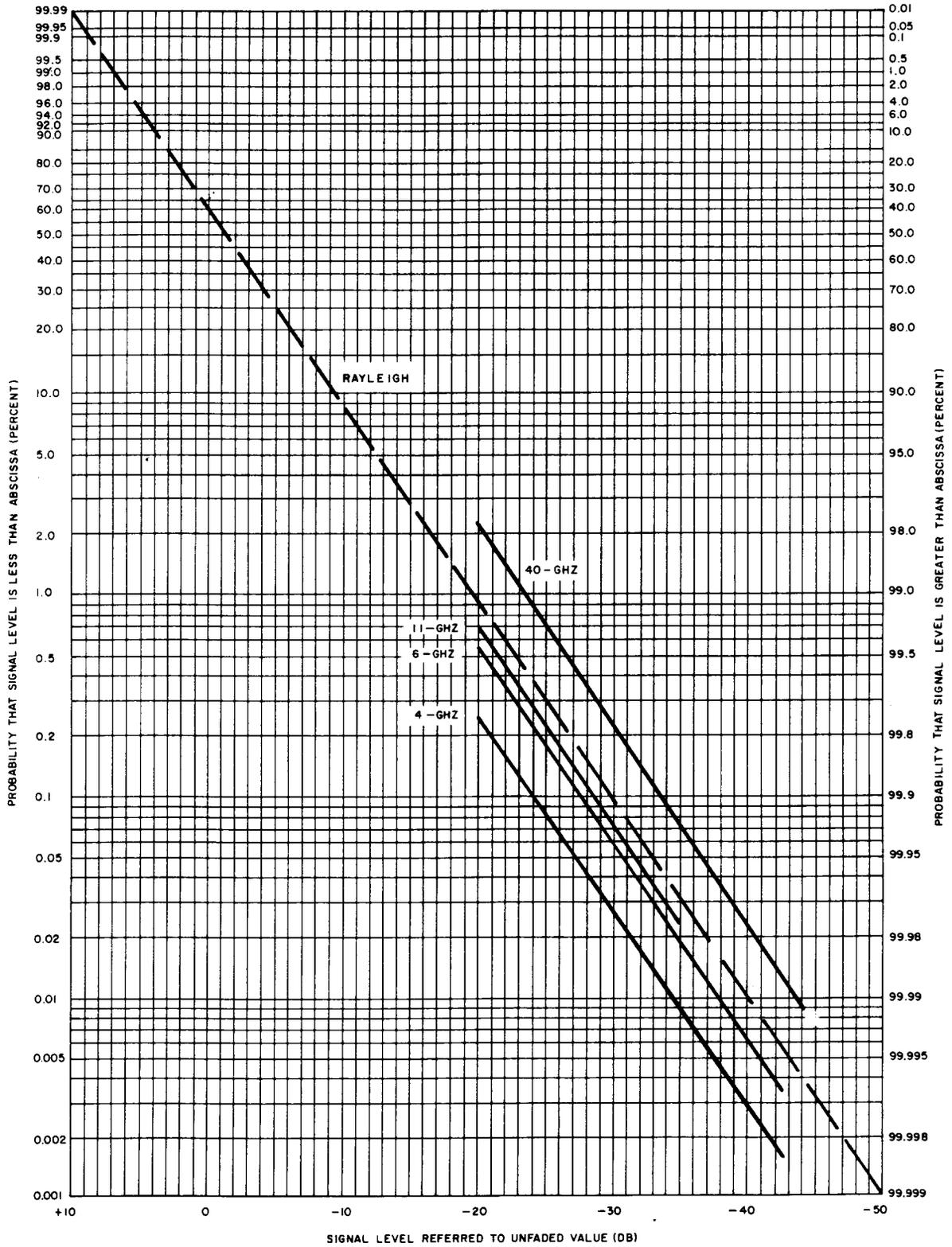


Fig. 6—Probability Distributions (Rayleigh and Empirical Samples)

If the free-space value (E_{rms}) of the received signal is normalized to 1 and fade depths below this level are represented as L (see Fig. 7), the fade depth F in dB becomes

$$F = -20 \log L$$

which permits the probability function to be expressed

$$\text{as } Pr = 10^{\frac{-(-20 \log L)}{10}}$$

which simplifies to L^2 as follows:

$$Pr = 10^{(2 \log L)}$$

$$Pr = 10^{\log(L^2)}$$

$$Pr = L^2.$$

Thus, the characteristic decade of time per 10-dB slope is described as having an L^2 functional dependence. If a finite period of time is multiplied by L^2 , it will then yield the proportionate time during which the received signal can be expected to fall below that level. It is then only necessary to modify this time fraction with a factor representing local situational variables (frequency, distance, climate, length of fading season, etc.) to obtain an accurate appraisal of anticipated failure.

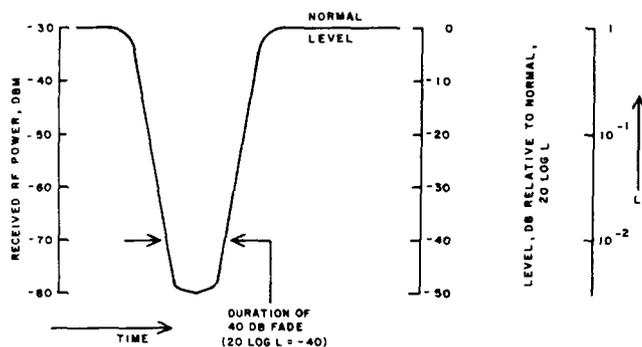


Fig. 7—Definitions of L and Fade Duration (-30 dBm Assumed Normal)

4. ESTIMATING OUTAGE TIME DUE TO FADING

A. Rationale

4.01 Bell System microwave facilities (both long- and short-haul) are designed with a reliability

objective of 99.98 percent. Stated differently, they are engineered with an average outage goal of less than 0.02 percent (about 6300 seconds or 1-3/4 hours per year). This overall objective is based on 2-way service and includes outages from all types of fading as well as equipment malfunction, power failure, and other causes. Also, since it is specified for end-to-end service, it implies different per-hop requirements for long- and short-haul systems. The time during which the received signal is below level at a fade depth equal to the receiver fade margin represents potential service failure time. If reliability objectives are to be met, it becomes necessary to appraise and quantify anticipated multipath fading activity on a per-hop basis. The value thus obtained can then be added to the value of outage time allocated to other causes (equipment failure, obstruction or "earth bulge" fading, rain attenuation, etc.) to arrive at a net value of outage time. If this value is excessive or if the value of multipath fading exceeds that value apportioned to multipath effects in terms of overall transmission availability objectives, compensation becomes necessary. Compensation for multipath degradation is typically achieved by means of space or frequency diversity.

4.02 It has been previously stated, and empirically demonstrated, that while average fade duration is independent of frequency and inversely proportional to fade depth, the rate of fading activity and therefore the total time below a given level increases with frequency. Part 4, expanding upon the equivalence of probability (Pr) and L^2 as discussed in Part 3, provides definitions and methods of procedure for the initial quantification of anticipated fading activity.

B. Definitions and Estimation of Fading

Free-Space Value

4.03 The RF power received over a microwave radio hop is least subject to multipath influence at or near noon, when the atmosphere has reached its most stable condition. Even here, however, there can be fractional dB excursions within a period of seconds (scintillations) as well as slower excursions of a dB or two. The normal value of the received signal is therefore obtained as an average over at least one-half hour at or near noon. This so-called free-space value of the received signal is determined repeatedly at least once a week to identify and exclude periods during

use $T_0 = \frac{1}{50} \times 2 \times 10^{-5}$ per 5.07

which there have been enhanced or depressed signals due to relatively steady atmospheric focusing or defocusing and which therefore cannot be regarded as normal.

Definitions of L and Fade Duration

4.04 During fading, the received RF power can be practically zero for seconds at a time. The terminology to describe this is introduced in Fig. 7 via an example where the free-space value is -30 dBm and a single (idealized) fade decreases the received power temporarily to -80 dBm. Levels in dB relative to normal are denoted by $20 \log L$, where L represents the antenna voltage during a fade, as compared to the normal or free-space value. The time during which a signal is below a level is called the duration of fade of that level, which is illustrated in Fig. 7 by the duration of a 40-dB fade. Since this illustration is intended to define terms, the relative durations as implied by the curve are not proportioned to scale but are defined below.

Average Fade Duration

4.05 Average durations of fades are independent of microwave frequency and are proportional to L or depth of fade. Typical numerical values are given by: t (typical) = 410 L seconds, where $L < 0.1$. This is graphically illustrated in Fig. 8. As an example, the average duration of a 40-dB fade ($L = 10^{-2}$) is 4.1 seconds at all microwave frequencies.

Time Below Level

4.06 The sum of durations of all fades of a particular depth is called "time below level" (T). It is proportional to L^2 since, in addition to fade duration, the number of fades is also proportional to L. The numerical value of time below level is given by:

$$T = T_0 L^2, L < 0.1.$$

In this expression, T_0 is the time period (a summer month, for example) over which the summation of fade durations is made. The units of T are also those of T_0 with seconds normally being used (one 31-day month = 2.68×10^6 seconds). A realistic evaluation of time below level must, however, account for local situational parameters; thus the practical expression for time below level is

"TMP"
$$T = r T_0 L^2, L < 0.1$$

where r, the fade occurrence factor, accounts for situational variables.

4.07 The fade occurrence factor r accounts for frequency, distance, climate, the occasional nature of fading, and, ultimately, terrain roughness (if this latter quantity requires separate consideration). Figure 9 serves to illustrate the multipath occurrence factor as a variable of path length and frequency. The significance of the curves for 18, 29, and 40 GHz is confined to academic interest, since at these frequencies path lengths are sufficiently short to avoid serious multipath fading. The fade occurrence factor r, for a heavy fading month, is expressed as:

$$r = c(f/4)D^3 10^{-5}$$

where

- c = 4 over-water and Gulf coast,
- = 1 average terrain and climate,
- = 1/4 mountains and dry climate,
- f = frequency in GHz,
- D = path length in miles.

As an example, values of time below level (T) as a function of fade depth for a 26-mile (typical length) path and average terrain and climate ($c=1$) are shown in Fig. 10 for a heavy fading month. The lines have the decade of time per 10-dB slope typical of multipath fading, specified by the L^2 functional dependence. The values of T at -40 dB are 47, 71, and 129 seconds at 4, 6, and 11 GHz, respectively. Based on an average fade duration of 4.1 seconds as determined previously, this corresponds to 11 fades of 40 dB at 4 GHz, 17 fades at 6 GHz, and 31 fades at 11 GHz.

C. Terrain Roughness Modification

4.08 The coefficient c, as described above, is simplified in that it incorporates and ties together the effects of both terrain and humidity. While this is adequate for first estimates of expected fading in many cases, differentiation between paths having identical climate but differing terrain can be done via modification of c for specific terrain

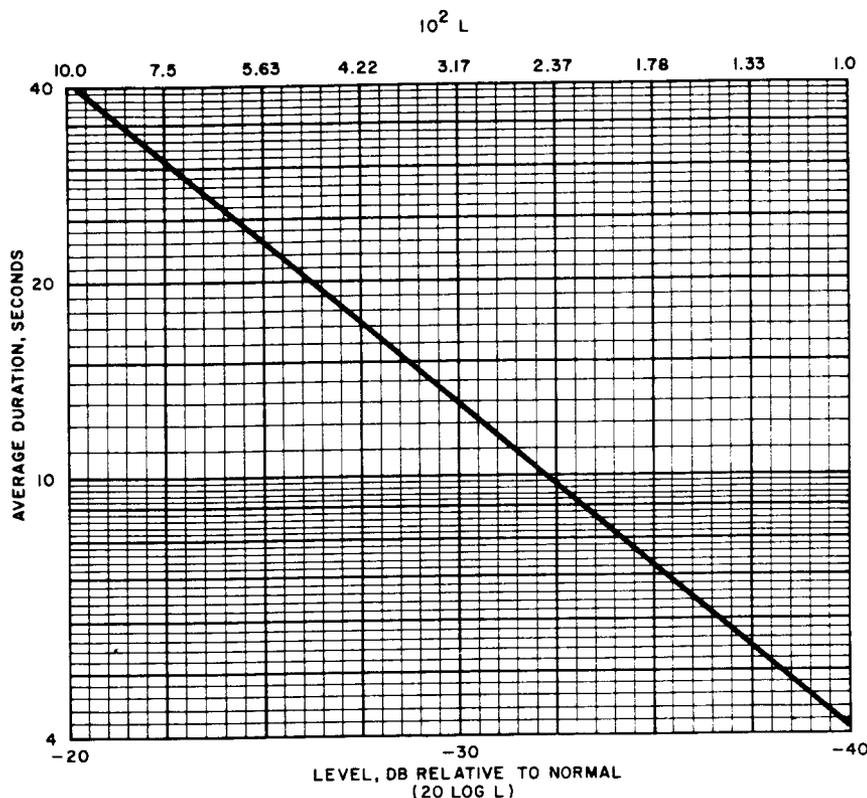


Fig. 8—Average Fade Durations ($\langle t \rangle = 410L, L < 0.1$)

roughness. The terrain roughness parameter introduced for this purpose serves to quantify common knowledge that paths over rough terrain fade less than paths over smooth terrain, presumably because stable atmospheric layering is less likely to occur over rough terrain.

4.09 Terrain roughness is calculated from terrain heights above a reference level (sea level, for example) obtained from the path profile at 1-mile intervals, with the ends of the path excluded. The standard deviation of the resulting set of numbers is the terrain roughness, denoted by w . Table A demonstrates the method of calculation used to obtain values of w . The path length in this example is 19 miles. Applicable values of w range from 20 feet (considered as smooth) to 140 feet (rough). These values of 20 and 140 should be used when calculated values of w are less than 20 or larger than 140. A value of 50 has been defined as normal, and in this case, the value of c will remain at 1 for average climate. Modified for roughness, the equations for c become:

$$c = 2 (w/50)^{-1.3}, \text{ coastal areas}$$

$$= (w/50)^{-1.3}, \text{ average climate}$$

$$= 0.5 (w/50)^{-1.3}, \text{ dry climate.}$$

5. DETERMINATION OF NEED FOR PROTECTION

A. General

5.01 In Part 4, the overall reliability objective for Bell System microwave facilities was established at less than 0.02 percent or about 6300 seconds per year or less. The practical realization of this goal requires that each hop in a particular system be examined to assure that the proportionate outage time assigned to multipath fading is not exceeded. In Part 5 of this section, the concepts of Part 4 are applied to a per-hop analysis in terms of short- or long-haul system requirements. As herein described, a somewhat simplifying assumption is made regarding the occurrence of simultaneous fading; i.e., it is assumed that simultaneous fading on distinct hops does not occur. Since two or more simultaneous outages translate as a single outage, the slight error thus introduced is conservative in that it overestimates the outage. Design

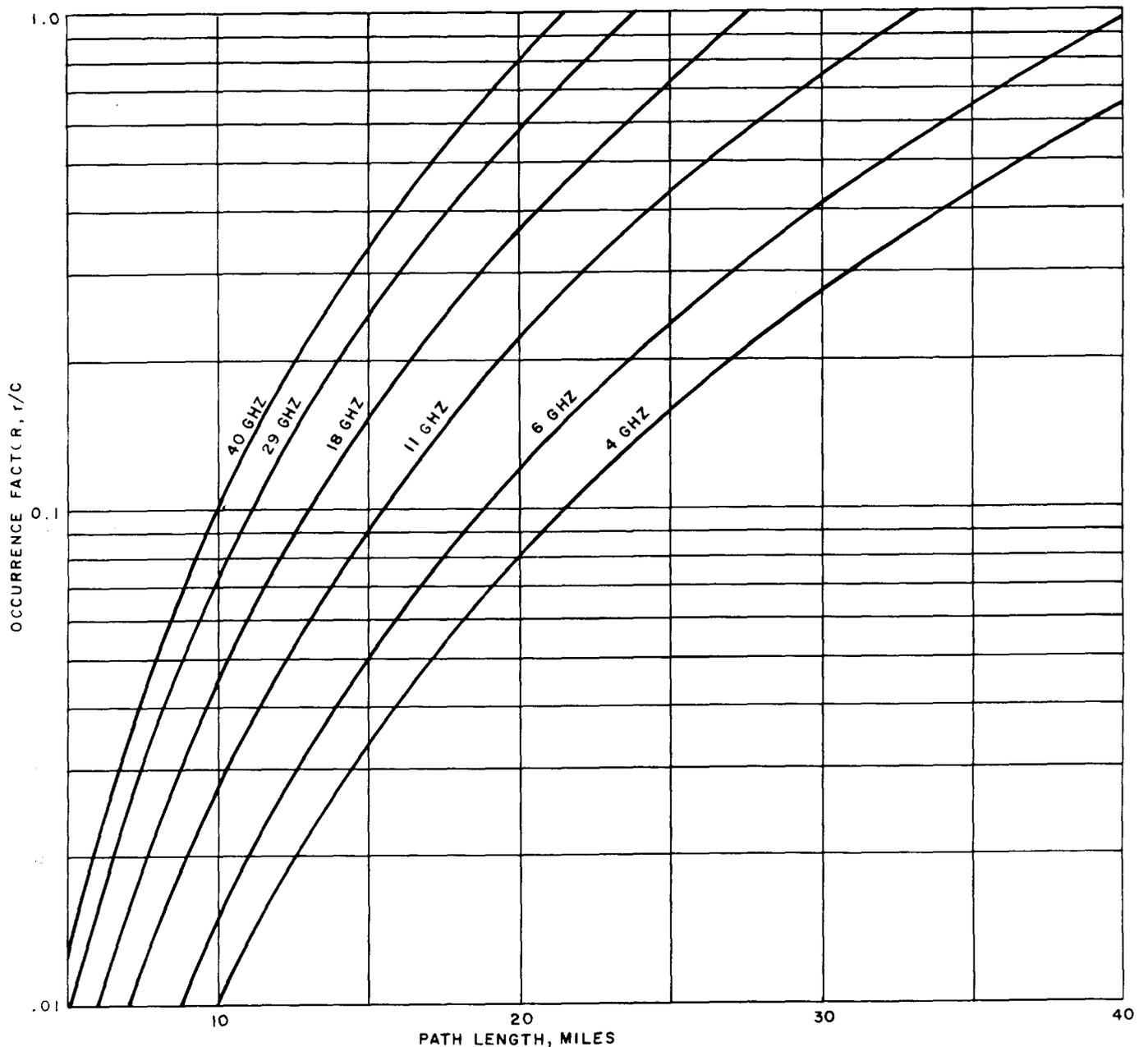


Fig. 9—Multipath Occurrence Factor for a Heavy Fading Month

objectives will therefore tend to exceed actual requirements. In the 18-, 29-, and 40-GHz microwave bands, attenuation from condensed atmospheric moisture (rain and fog) is severe. For this reason, hop lengths are sufficiently short to preclude the need for multipath compensation. The 11-GHz band is also subject to rain attenuation. Here, however, hop lengths can be sufficiently long to result in selective fading. Consequently, that percentage of total outage time allocated to rain

fading must be offset by additional reduction of the effects of selective fading. The subject of rain fading is covered in Section 940-310-106 and should be considered in any 11-GHz design effort.

B. Short-Haul Objectives

5.02 Short-haul objectives limit service failure time to 0.02 percent, 2-way annual, on a 250-mile route due to all causes. Of this amount,

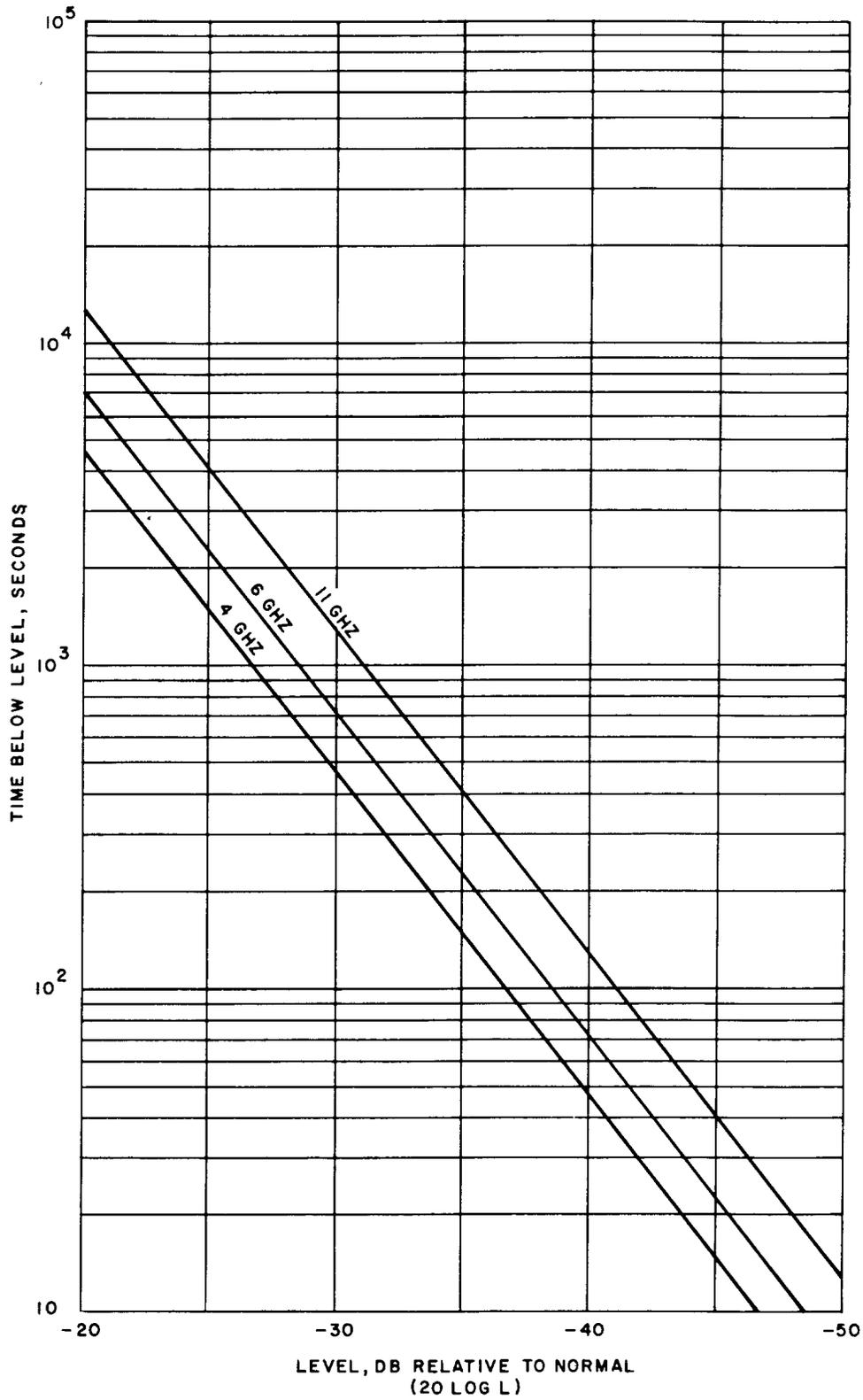


Fig. 10—Time Below Level in a Heavy Fading Month ($D = 26$ Miles, $c = 1$, $T_0 = 31$ Days = 2.68×10^6 Seconds)

TABLE A
COMPUTATION OF THE TERRAIN ROUGHNESS FACTOR

The terrain roughness factor (w) is, as stated in 4.09, the standard deviation of the path profile (σ). Expressed mathematically,

$$w = \sigma = \left[\frac{\sum (x - M)^2}{n} \right]^{1/2},$$

where "x" is the vertical distance in feet of the path profile as measured from some horizontal reference at one-mile intervals, excluding the station locations; "n" is the number of such measurements; and "M" is the arithmetic mean, or average, of the measurements.

The above equation for "w" may be altered so that the number of subtractions will be greatly reduced at the expense of larger squared terms:

$$w = \sigma = \left[\frac{\sum (x^2)}{n} - M^2 \right]^{1/2}.$$

It should be noted that $\sum (x^2) \neq (\sum x)^2$.

Thus, for the 19-mile hop "A" in the sample calculations, w is computed as follows; preparation of a table similar to that below helps keep computations under control.

NUMBER OF MEASUREMENT	DISTANCE MEASUREMENT	SQUARE OF DISTANCE MEASUREMENT
(n)	(x) feet	(x ²) feet ²
1	600	360,000
2	625	390,625
3	515	265,225
4	440	193,600
5	480	230,400
6	450	202,500
7	400	160,000
8	420	176,400
9	460	211,600
10	420	176,400
11	450	202,500
12	480	230,400
13	450	202,500
14	420	176,400
15	390	152,100
16	480	230,400
17	520	270,400
18	550	302,500
$\Sigma = 18$	$\Sigma = 8,550$	$\Sigma = 4,133,950$

$$M = \Sigma \frac{x}{n} = \frac{8,550}{18} = 475 \text{ ft}$$

$$w = \sigma = \left[\frac{4,133,950}{18} - (475)^2 \right]^{1/2} = 63.5$$

one-half is allocated to causes associated with equipment, maintenance, and plant errors. The allocation to fading is therefore 0.01 percent, 2-way annual. There can be, however, obvious exceptions to this. For example, unavailability on a route where all hops are exceptionally short will be due mainly to equipment outages and may be so allocated.

5.03 In the past, it was customary to further apportion the 0.01-percent, 2-way annual value assigned to fading between multipath and obstruction fading—otherwise known as “earth bulge” fading. However, the occurrence of intolerable obstruction fading can be decreased by increasing clearance (higher towers or shorter hops) or by increasing the system gain margin. Reliability records show that there has been a gradual decrease in the occurrence of obstruction fading over the years. In the construction of new hops or in the upgrading of older ones in locations where obstruction fading is known to occur (or by related experience is expected to occur), increased clearances (or limits on path lengths) are assumed to be used. Consequently, no allocation to obstruction fading is made; the entire 0.01-percent, 2-way annual fading allocation is applied to multipath fading. The one-way annual multipath fading allocation for 250 miles becomes 0.005 percent or approximately 26 minutes per year (1600 seconds per year). The corresponding allocation to a hop D miles long is $1600 \times D/250$ seconds per year or 165 seconds per year one way for an average 26-mile hop.

C. Short-Haul Appraisal

5.04 The estimated annual time below level for comparison with the 165-second objective is obtained from the equation for T ($T = r T_0 L^2$, $L < 0.1$) in paragraph 4.06, with T_0 describing the length of the fading season. As a geographic average, the value of T_0 in this estimate is equal to the number of seconds in three months. This assumes that all significant fading is contained in two heavy- and two medium-fading months, which is equivalent to three heavy-fading months or 8.04 $\times 10^6$ seconds. Figure 10, presented in conjunction with paragraph 4.07, provides the time below level for a typical heavy fading month. Continuation of this example provides the annual time below level curves of Fig. 11. Examination of Fig. 11 reveals that at -40 dB, the annual average case values are now 142, 212, and 387 seconds at 4, 6, and 11 GHz, respectively, or three times the 47-, 71-, and 129-second values of T obtained in 4.07.

Figure 11 also includes the per-hop annual objectives for both short haul (165 seconds) and long haul (20 seconds). Examination of the short-haul objective at a -35 dB fade reveals that the time below level exceeds the 165-second objective by factors of 2.7, 4, and 7.3 at 4, 6, and 11 GHz, respectively. Protection against multipath fading is therefore needed when the fade margin is -35 dB. At a fade margin of -40 dB, the 4-GHz channel in the example can, however, get by without protection.

5.05 The above example assumed T_0 as the geographic average of three heavy-fading months. The length of the fading season is, however, influenced by temperature and is essentially a warm weather phenomenon. The value of T_0 must therefore be modified as a function of average annual temperature which, in turn, is related to geographic location. Paragraph 5.07 provides the procedure, together with a contour map of the United States, for specific computation of T_0 .

D. Long-Haul Considerations

5.06 For long-haul radio the overall objective is also 0.02 percent, but the route length is 4000 miles. Previously, the recommended long-haul multipath allocation to a hop D miles long was $1600 \times D/2000$ seconds per year or 20 seconds per year for the average 26-mile hop. This was based on the assumption of significant fading on only half of the hops. Better estimates of fading can now be made, and the recommended allocation now is $1600 \times D/4000$ or 10 seconds per year for the average 26-mile hop.

E. Length of Fading Season

5.07 Multipath fading is a warm weather phenomenon. Assuming that the length of the warm portion of the year is proportional to the average annual temperature, the value of T_0 to be used to estimate the annual time below level is

$$T_0 = (t/50) 8 \times 10^6 \text{ sec}, 35 \leq t \leq 75$$

where t denotes the average annual temperature of the locality in question given in °F, as determined from Fig. 12. In the average case (Fig. 11), T_0 is equal to the number of seconds in three months, and T_0 reduces to this when t is 50°F. The temperature contours in Fig. 12 show that 50°F is appropriate for middle latitudes in the United

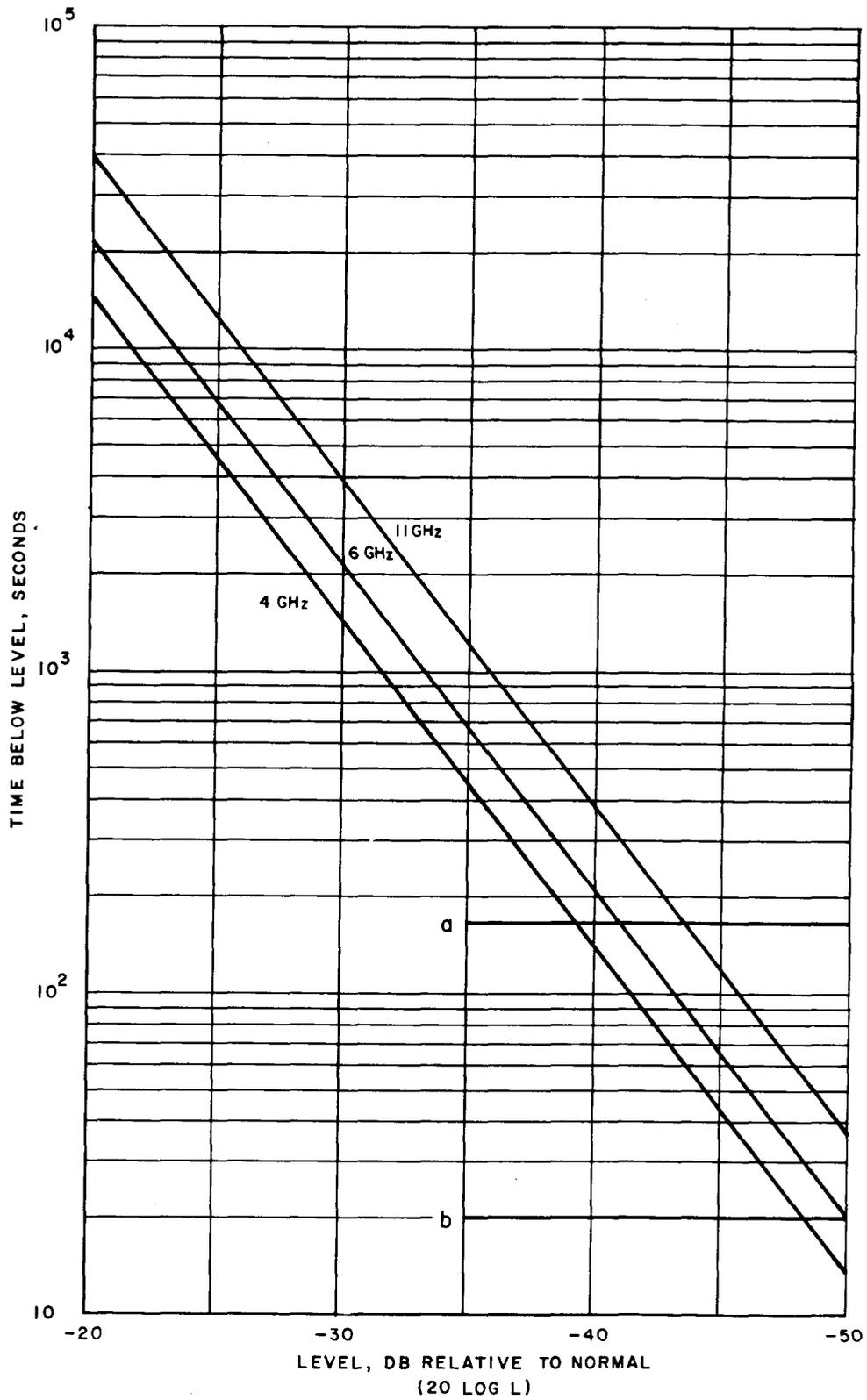


Fig. 11—Annual Time Below Level (Average Case) Objectives: (a) Short Haul, 165 Seconds/Year (b) Long Haul, 20 Seconds/Year

States and for Ohio in particular. Data from Ohio have often been used to describe average fading. The range of average annual temperatures (Fig. 12) is from 35°F in northern North Dakota to 75°F in southern Florida. The corresponding fading season lengths range from 70 percent to 150 percent of average. The adjusted value of T_0 therefore ranges from 2 months to 4-1/2 months.

6. SELECTIVE FADING AND NARROWBAND SYSTEMS

A. General

6.01 The emphasis of this section has, thus far, been directed to conventional FM systems which, at the time of writing, characterize microwave transmission media. The use of frequency modulation in microwave radio systems arises primarily from difficulties related to the design of linear amplifiers having adequate gain and power output to handle wideband AM signals at microwave frequencies. The application of a complex amplitude-modulated signal to an amplifier having inherent amplitude nonlinearity results in the generation of spurious frequencies or modulation products which will be present in the output and which cannot be tolerated. A constant amplitude FM signal is, however, relatively insensitive to this type of nonlinear distortion and can thus be transmitted through amplifiers which have compression or amplitude nonlinearity with little penalty.

6.02 The IF bandwidth employed in existing microwave radio systems is typically 20 or 30 MHz. In an FM system, a 30-MHz bandwidth is required in order to carry 1800 telephone message channels or three L-carrier mastergroups. (One mastergroup contains 600 4-kHz voice channels and occupies 2.4 MHz.) Three mastergroups is the per-channel loading in TH-1, TH-3, and TN-1 systems. The need for spectrum conservation together with ever-increasing communications demands has necessitated the development of alternatives to current FM systems having increased information-carrying capacity. A new method, known as the AR-6A (analog radio, 6 GHz, type A) system, employs an amplitude-modulated single-sideband technique wherein a baseband multimastergroup signal is translated to a 6-GHz radio channel. The narrowband terminology, incidentally, refers to the nature of the intelligence (as contained in 4-kHz, AM, SSB channels) within the microwave channel, which again is 20 or 30 MHz wide as in existing FM systems. (The AR-6A

channel will be 30 MHz wide, while a later version, operating at 4 GHz, will utilize a 20-MHz channel width.)

B. Narrowband Radio and Wired Carrier Systems

6.03 The use of multiplexed, up-converted groups of AM sidebands to amplitude-modulate a microwave carrier (which is itself transmitted as a single sideband) results in an increased similarity between radio systems and conventional wired carrier telephone systems such as type "L" carrier. With the application of similar techniques to microwave radio, it becomes possible to realize the increased information-carrying capacity of wired carrier systems. The L-3 and L-4 carrier systems, using coaxial cable as the transmission medium, require a bandwidth of only 8 MHz to carry 1800 message channels, as compared to the aforementioned 20 MHz in FM radio. Thus, in the narrowband system, it is possible to contain six mastergroups (3600 message channels) together with necessary guard bands, noise slots, and pilot signals in a single 20-MHz channel, thereby doubling the capacity of the system. A 30-MHz channel will contain ten mastergroups (6000 message channels), resulting in an improvement in excess of three (6000/1800) times that of current FM systems.

6.04 The analogy between carrier systems and narrowband radio is not limited to a coincidence of message capacity and modulation methods, but also includes a commonality of problems. One of the major problems associated with transmission lines is attenuation-versus-frequency distortion, which results in level misalignments of information-carrying frequencies within the band. Inasmuch as the distortion-producing parameters of a transmission line can change with time or be influenced by environmental factors such as temperature, equalizing and regulating networks can be inserted which compensate for nonlinearity. The resultant "flat" line prevents loss of information in the otherwise attenuated portion of the frequency spectrum.

6.05 Selective multipath fading within a 20- or 30-MHz channel carrying AM narrowband information is analogous to attenuation-versus-frequency distortion of a transmission line. The difference rests in the essential predictability (attenuation is known to vary as the square root of frequency) of wired carrier systems as opposed to the compounded problems created by the unpredictability

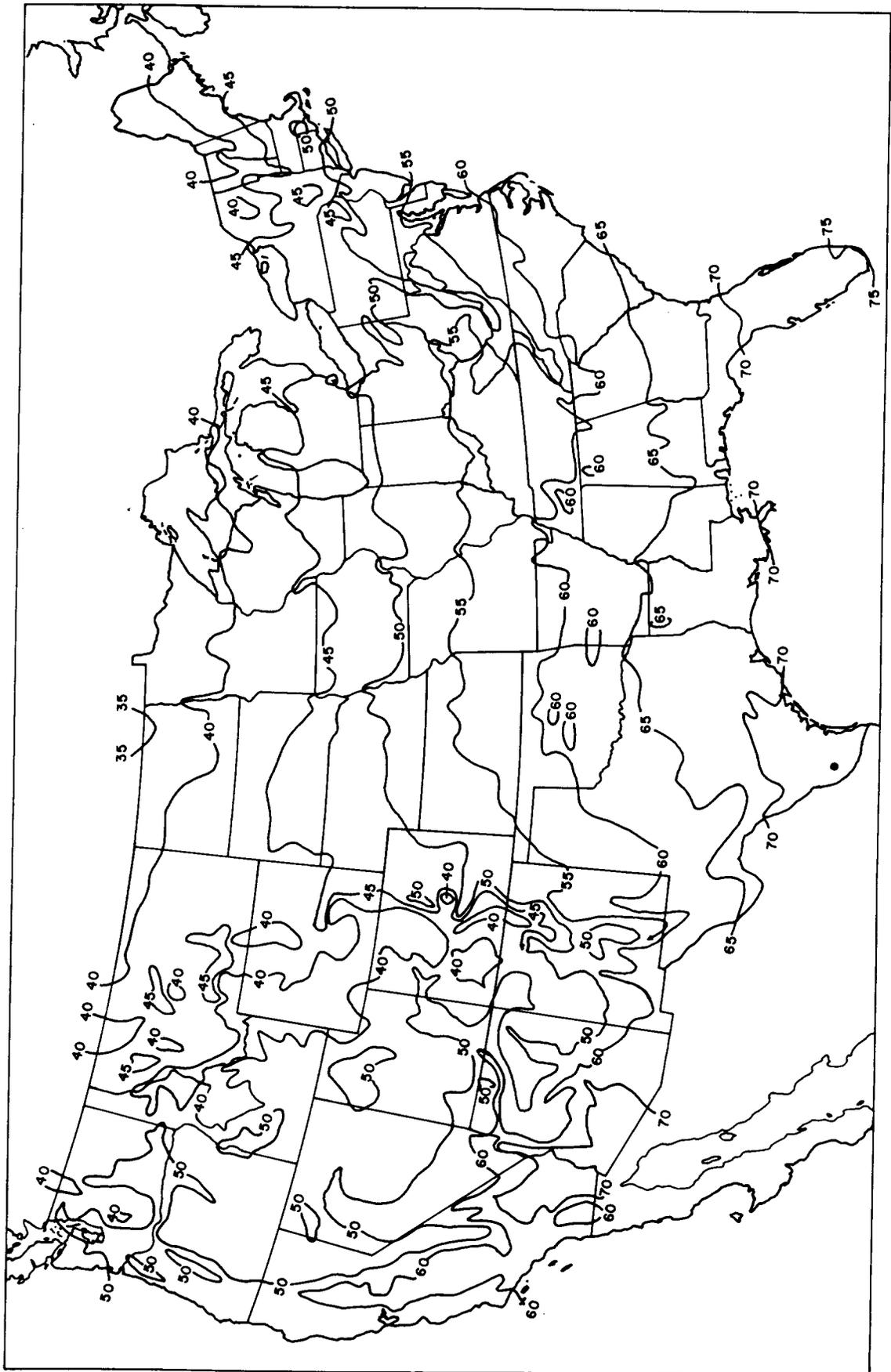


Fig. 12—Average Annual Temperatures in °F

of a radio link. Selective fading can occur randomly at any point in the band; it can remain fixed for a given period or sweep across the band spectrum. Its level will also be changing. Whatever the case, the desired uniform transmission characteristic will be corrupted. The nature of an FM signal, which among other factors contains both sidebands of information, is such that it is less susceptible to intrachannel distortion of this type. For such an FM system during deep fades, a single pilot tone (or noise slot) is sufficient to monitor channel conditions and indicate when a switch to a diversity antenna or protection channel should take place; i.e., the entire channel can be regarded as a singular entity. In a narrowband AM system, selective fading can result in loss of message channels within the affected portion of the main channel spectrum or can distort the channel profile from its ideal flat attenuation-versus-frequency characteristic.

6.06 In dealing with narrowband radio propagation, two major factors attributable to multipath phenomena must be considered and offset. The first results from relatively deep inband selective fading, causing those message channels in the faded portion of the channel spectrum to be reduced in signal level. The second is time-variant deviation of the channel amplitude-versus-frequency characteristic which, because it is continually changing, must be dynamically compensated. Deep fading is monitored by the use of three separate pilot tones (and associated noise slots) located approximately at band center and 2.4 MHz (one mastergroup) in from the respective band edges. Under conditions of deep fading, protection switching of the entire channel will take place if any one of the three band segments has failed. Dynamic equalization, driven by special tones separated from message frequencies, will correct for level misalignments.

INTRACHANNEL PHENOMENA

A. General

6.07 The following discussion provides a characterization of radio channel loss variations as typical of a microwave channel assigned to narrowband service. The data herein presented was extracted from that obtained during two experiments conducted, respectively, in 1970 and 1971. The objective of the first experiment was directed toward the quantification of spectral and temporal behavior of amplitude distortion occurring within a channel as a result of destructive multipath

interference. The 1971 experiment demonstrated the realizable advantages of a space diversity system in counteracting these deleterious effects. To the extent that the second experiment duplicated conditions of the first, confirmation of initial results was also obtained. Since the purpose of this discussion is the exposition of salient facts and conclusions, graphic data found most illustrative in support of given topics will be selected from either experiment, except in cases requiring strict parametric continuity.

B. Experiment Structure

6.08 Experimental data was obtained by the generation, transmission, and continuous recording of a tone field consisting of 62 coherent tones. The tones, which were uniformly spaced at 550-kHz intervals, spanned a bandwidth of 33.55 MHz. The tone field, centered at 70.4 MHz, was used to amplitude-modulate a 6-GHz microwave carrier which was transmitted as a single sideband having an essentially flat envelope over a 26.4-mile radio path. At the receiver, the amplitudes of selected tone subsets were continuously monitored and recorded together with timing and tone identification data by means of a multiple input data acquisition system. The data base, compiled during a 59-day period in the case of the first experiment and three summer months in the second, was held within manageable limits by restricting the highest recording rate (five samples per second) to periods of heavy fading, as well as by other methods. By selectively operating upon this large volume of information, significant aspects of multipath behavior were extracted and characterized. Additional objectives of the initial experiment were to prove the feasibility of defining intrachannel distortion selectivity by means of a 3-tone amplitude difference technique and to determine the adequacy of this analysis in terms of level misalignments for the parameters of bandwidth and fade depth.

C. Definitions and Methodology

6.09 In order to reveal the variety and nature of selective fading acting upon a channel, a series of time-sequential amplitude-frequency plots were made across the 33.55-MHz bandwidth. An examination of these sequential scans established that the distortion profiles most frequently exhibited simple slopes, simple curvatures, or combinations of the two. Higher-order structures (cusps, for example) which exceeded second-order analysis

occurred only for the deeper fades. Ideally, the form chosen to represent such selective fading events should be characterized by simplicity and generality. Therefore, the detailed variation across the amplitude-frequency characteristic was defined in terms of linear and quadratic distortion. These could be parameterized by monitoring the amplitudes of three symmetrically spaced reference tones $A(f_1)$, $A(f_2)$, and $A(f_3)$ across a channel of $2\Delta f$ as illustrated in Fig. 13. The bandwidth ($2\Delta f$) was 20.35 MHz in the first (1970) experiment and 19.8 MHz during the second. Again referring to Fig. 13, linear or first-order amplitude distortion (ΔA) is defined as

$$\Delta A = A(f_3) - A(f_1)$$

and represents the *slope* in dB across a channel of width $f_3 - f_1 = 2\Delta f$. Quadratic amplitude distortion, so called since its expression contains second-order terminology ($\Delta^2 A/2$), is defined as

$$\frac{\Delta^2 A}{2} = \frac{A(f_1) + A(f_3)}{2} - A(f_2)$$

and represents the component of curvature or *bow* in dB across the $2\Delta f$ channel. For the example shown in Fig. 13, the fade depth $A(f_2)$ is -34 dB, and $A(f_3)$ and $A(f_1)$ are respectively -23 dB and -33 dB. Consequently, the channel, for this brief instant, had 10 dB of slope and 6 dB of bow. The observed experimental distributions for slope $|\Delta A|$ and bow $|\Delta^2 A/2|$ were accumulated for various ranges of center channel fade depth as well as for seven different bandwidths. Conditional data, i.e., conditioned on the faded level in dB of $A(f_2)$, serve to more clearly demonstrate at what fade depth the slope and bow mathematical representations applied.

D. Characteristics of Inband Fading and Distortion

Overview and Time Below Level

6.10 Following initialization procedures during which calibration reference levels based on normal or free-space path loss were established, an overview of daily fading activity was generated and is presented in Fig. 14. The lower half of the figure shows the daily distributions of the fraction of total time the received amplitude was faded 20 dB for tones 1, 25, and 62. The upper half of this figure is for the 30-dB level. (Tone 25 was used rather than tone 32 to avoid certain spurious modulation effects which were detected earlier.) Several observations can be made from

Fig. 14. First, as is typical of line-of-sight fading, the deep fading at these levels occurred in unpredictable bursts. Second, higher fading activity occurred in more concentrated bursts and for deeper fades. Finally, individual tones exhibited increasingly different fading activity for the deeper fades. This tone dispersion is an indication of the increasing frequency selectivity of deep fades as contrasted to the relatively flat (across the band) fading at levels of 20 dB or less.

6.11 Figure 15 shows the actual fade depth distributions for tones 3, 24, and 60 for the month of August. The tones display the same characteristic decade of time per 10-dB slope as described previously in Part 3 of this section. A question which arises at this time is how the division of a channel into three segments, each of which is now subject to fading, alters the concepts previously set forth in Part 4 of this section. The formula for time below level ($T = r T_0 L^2$) given in paragraph 4.06 is applicable to any of the three tones. It has been demonstrated that mutual exclusivity is not an unreasonable assumption for deep fades having a frequency separation of 5 to 10 MHz, which applies to the three pilot tones of a narrowband channel. Thus, for the limiting case, the total time below level within the channel becomes $3T$ or, expressed as a time fraction in accordance with the three tones of Fig. 15, $3 \times 2.0 \times 10^{-5} = 6.0 \times 10^{-5}$ at 40 dB. Experience arising from additional experimental work, however, indicates that a more realistic or practical value for tones having 5- to 10-MHz separation and fade margins slightly above, i.e., less deep than, those typical of FM systems was actually 2.6. Thus the practical formula for time below level becomes $2.6T$. Another way of viewing this is to say that the number of requests for protection switching will now increase by this amount.

The Space Diversity Improvement

6.12 An additional consideration here is the degree of improvement in outage time offered by a space diversity protection system as envisioned for narrowband systems. This is best illustrated by Fig. 16, which represents a permutation of the three band segments represented by three frequencies F_1 , F_2 , and F_3 as received simultaneously on the main (top) and diversity (bottom) antennas. As an example, assume a hop having an outage time of 100 seconds per month protected by a space diversity system providing an available improvement

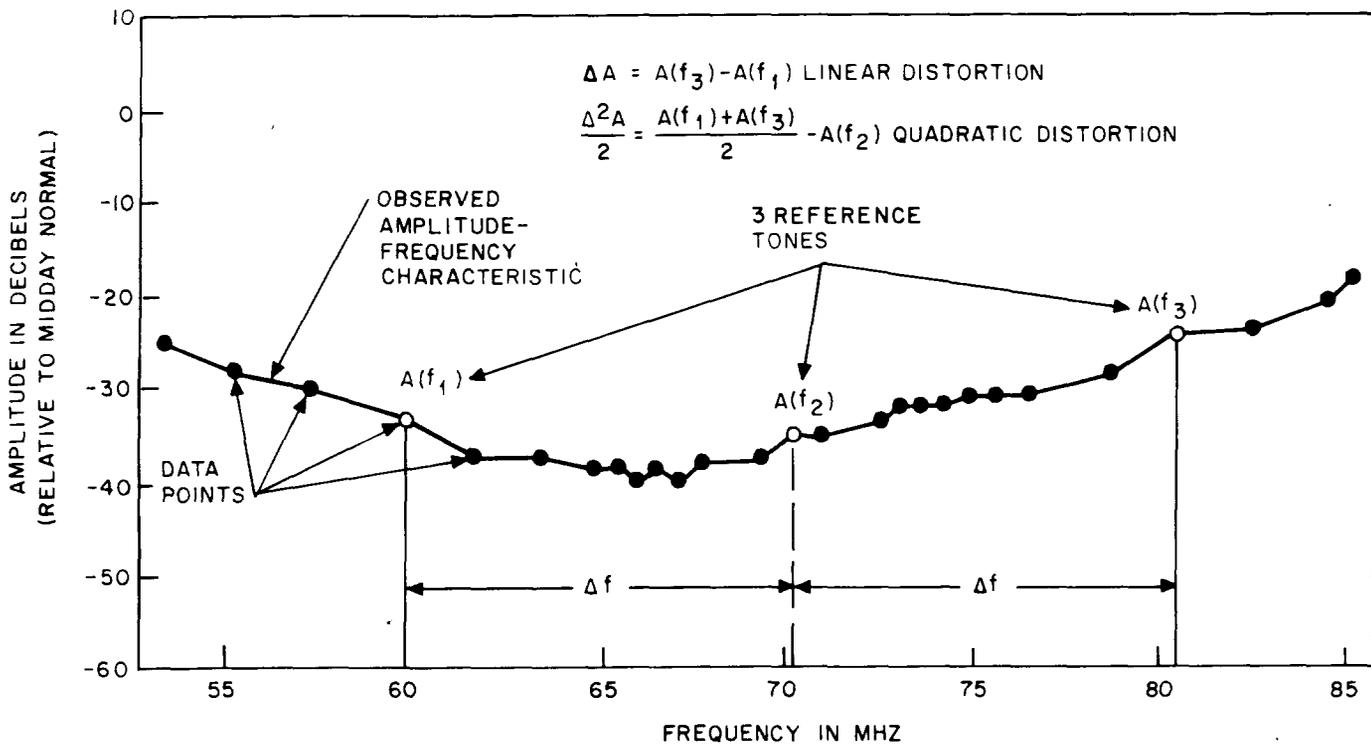


Fig. 13—Selectivity Characterization of the Observed Amplitude-Frequency Characteristic

or I_0 (see Section 940-310-115) of 100 in terms of an FM system. This states that the probability of a single frequency experiencing a simultaneous fade on both antennas exists for only 1/100 of the total time. Thus the actual failure time of each single frequency with respect to itself is reduced to 1 second. Since there are now three frequencies, the possibility exists that one of the two additional frequencies might be faded below level on the secondary antenna when a switch is made for the first. Thus each column of Fig. 16 provides the failure time for each frequency with respect to itself and the remaining two, yielding an outage probability of 3 seconds. The sum of the three columns reveals that the limiting case failure time increase will be nine times that of a conventional FM system having the same I_0 .

Linear and Quadratic Distributions

6.13 The distributions for slope and bow (linear and quadratic) distortions occurring across a 19.8-MHz channel width are shown in Fig. 17. The abscissa is the amount of distortion in dB, and the ordinate is the fraction of time (2.6784×10^6 seconds, representing the month of August).

The distributions exhibit slopes of a decade of probability of occurrence per 10-dB change in distortion, with the linear distortion $\Delta A \geq 18.5$ dB and the quadratic distortion $\Delta^2 A/2 \geq 7$ dB for 10^{-5} of the time or about 27 seconds. The significance of 10^{-5} rests in its approximation of relevant time fractions for high-quality single-hop propagation considerations.

6.14 The linear and quadratic distortion distributions conditioned on the fade depth of the midchannel tone $A(f_2)$ are shown in Fig. 18 and 19, respectively. Note that the time base for each curve is different and is the total time the middle tone was faded the indicated amount. The bandwidth is again 19.8 MHz—Fig. 17, 18, and 19 all being derived from the 1971 experimental data base. Figures 18 and 19 reveal the increase in distortion values with increasing fade depth.

6.15 The increase in distortion as a variable of bandwidth is indicated in Fig. 20 and 21. Figure 20 provides a summary of the linear distortion distributions, while Fig. 21 summarizes the quadratic distributions. The unusual (crossover) behavior of the quadratic distortion for the 33.5-MHz bandwidth

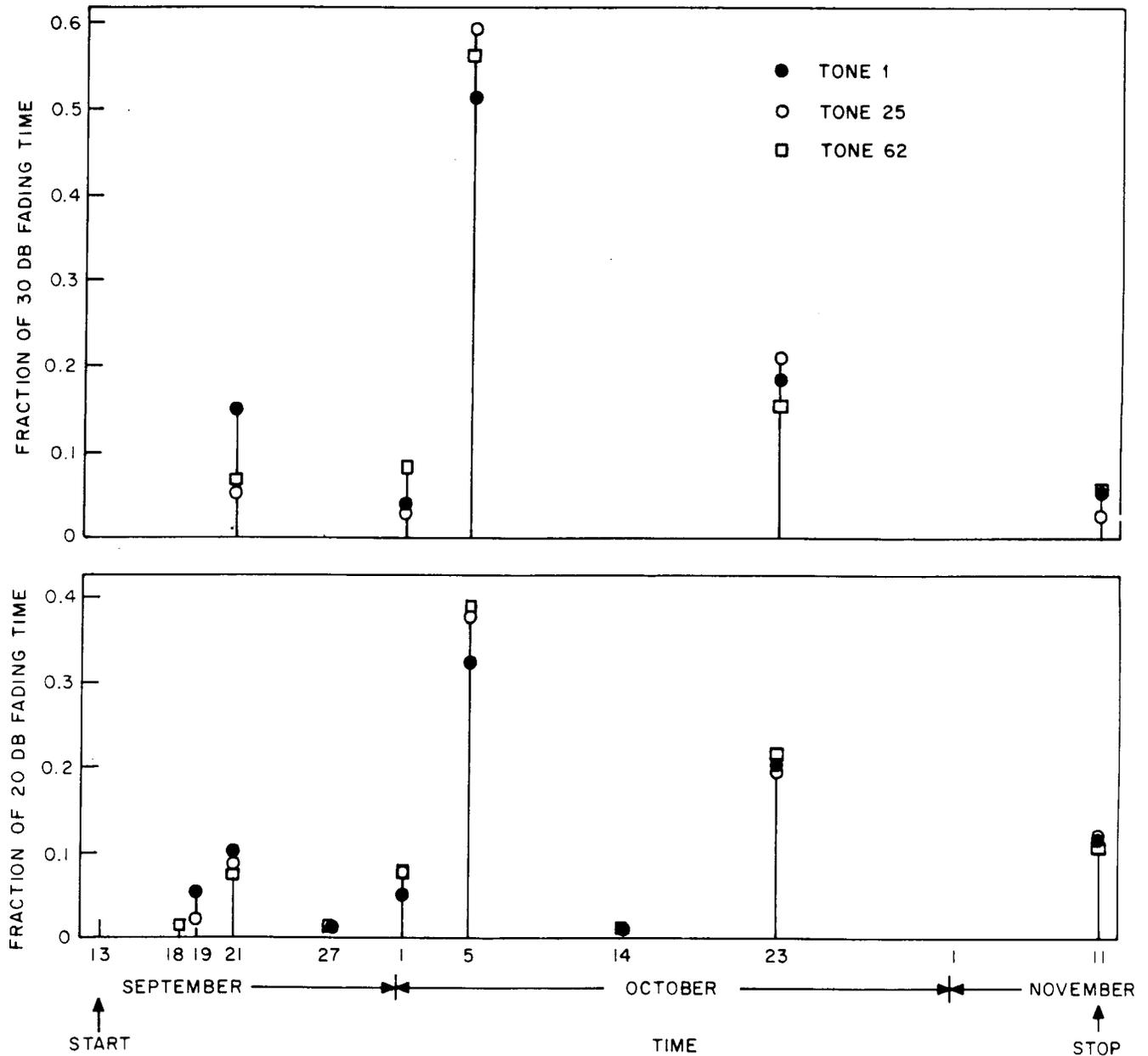


Fig. 14—Daily History of 20- and 30-dB Fading Activity for Tones 1, 25, and 62 During the Entire 1970 Measurement Period

indicates that definition of the selective fading amplitude characteristic by means of three tones becomes inadequate when bandwidths as large as this are spanned. Here again it will be noted that the slopes of the linear and quadratic distortion curves for the larger bandwidths exhibit a decade decrease in probability for 10-dB increase in distortion.

E. Conclusions

6.16 The following conclusions provide a summary of pertinent information discussed in Part 6 of this section or otherwise derived from the experimental data.

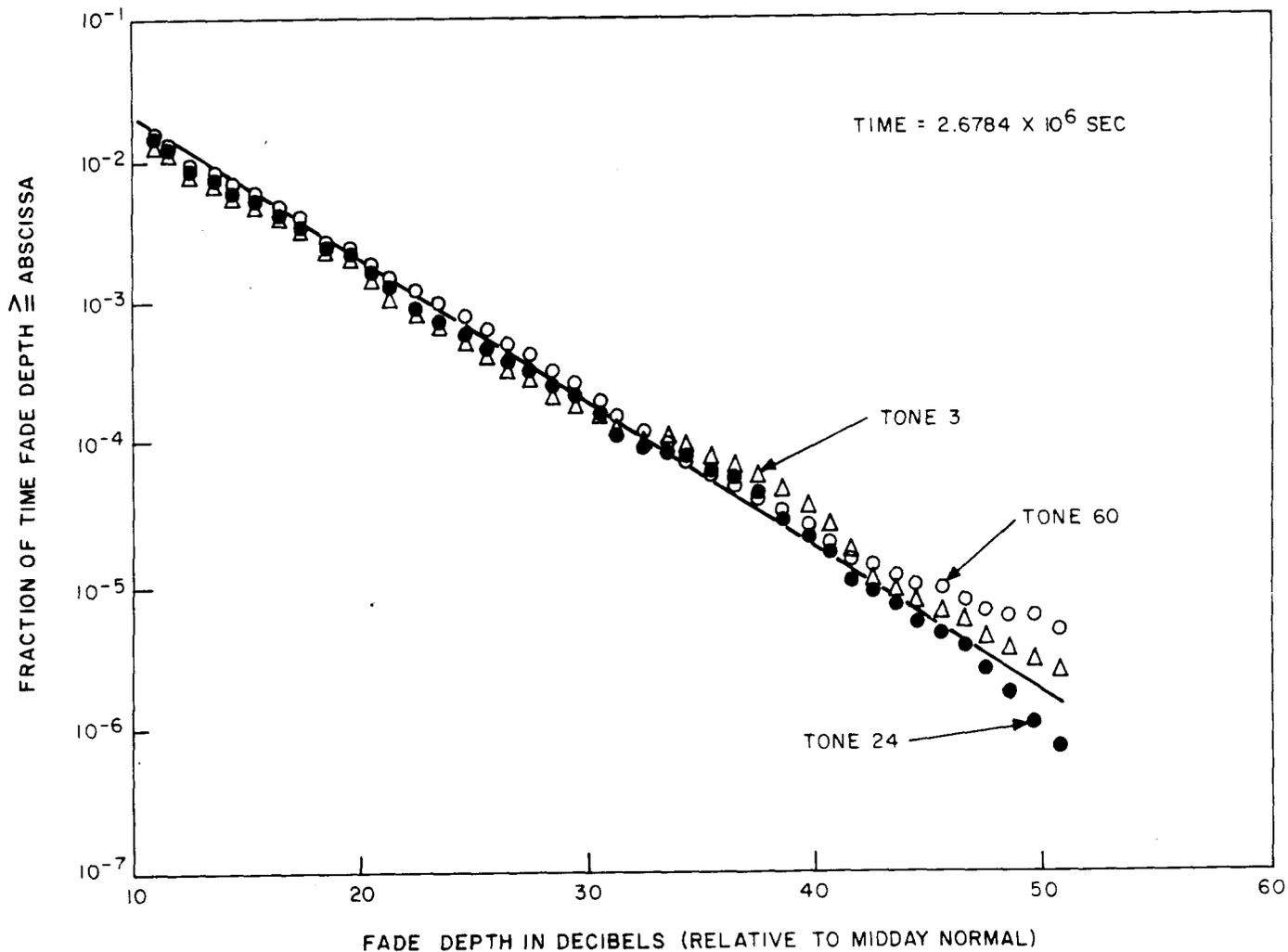


Fig. 15—Fade Depth Distributions for Tones 3, 24, and 60 for the Month of August

(T) F ₁	(T) F ₂	(T) F ₃
(B) F ₁	(B) F ₂	(B) F ₃
1 SEC	1 SEC	1 SEC
(T) F ₁	(T) F ₂	(T) F ₃
(B) F ₂	(B) F ₁	(B) F ₁
1 SEC	1 SEC	1 SEC
(T) F ₁	(T) F ₂	(T) F ₃
(B) F ₃	(B) F ₃	(B) F ₂
1 SEC	1 SEC	1 SEC
SUBTOTALS 3 SEC 3 SEC 3 SEC		
GRAND TOTAL 3X3 = 9 SECONDS FAILURE TIME		
UNPROTECTED TIME BELOW LEVEL = 100 SEC/MONTH		
(T) = TOP ANTENNA (B) = BOTTOM ANTENNA		
DIVERSITY IMPROVEMENT I ₀ = 100		

Fig. 16—Increase in Failure Time Resulting From Permutation of Three Independent Frequencies Protected by a Space Diversity System

(a) The practical value of time below level for narrowband channel failure considerations is 2.6 times the value of time below level (T) as calculated in paragraph 4.06 for standard systems. The degree of improvement in failure time offered by a space diversity system was shown to have a worst case value of 1/9 when compared to an FM system.

(b) For fade depths less than 30 dB and bandwidths from 5 to 20 MHz, the distortion frequency selectivity is described (within 2 dB) by linear and quadratic components of amplitude distortion.

(c) For fade depths greater than 30 dB occurring within bandwidths greater than 5 MHz, the amplitude distortion (bow) exceeds second-order components of frequency selectivity.

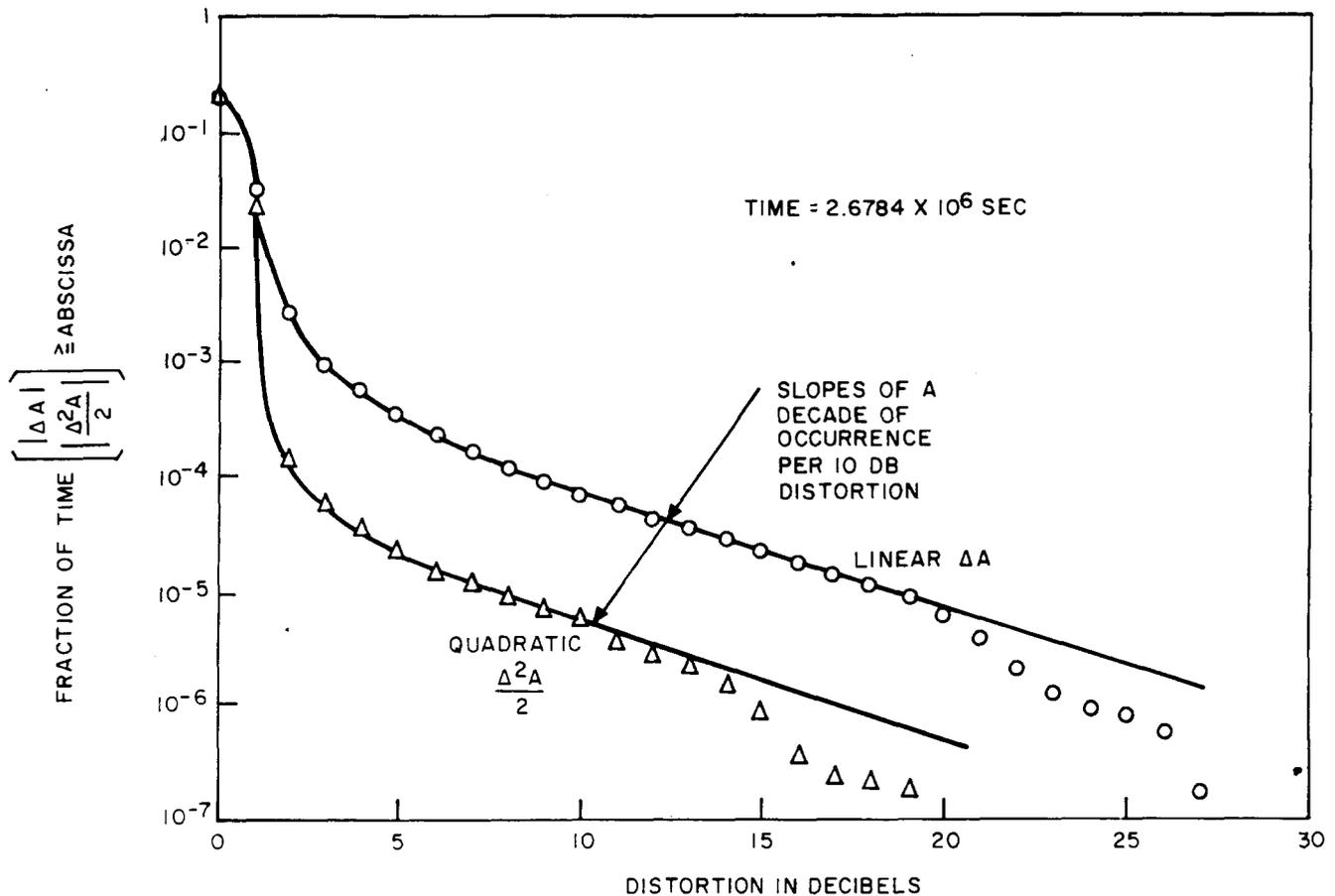


Fig. 17—Unconditional Linear and Quadratic Distortion Distributions for the 19.8-MHz Channel

- (d) For bandwidths greater than 5 MHz, the derived statistical distributions of linear and quadratic distortion parameters exhibit slopes of a decade decrease in probability of occurrence per 10-dB increase in distortion.
- (e) For a channel bandwidth of 19.8 MHz, the linear and quadratic distortion exceeded 18.5 dB and 7 dB, respectively, for 10^{-5} of the observation time.
- (f) The maximum rates of change for the linear and quadratic distortion were 90 and 60 dB per second, respectively.

The information concerning the influence of selective fading on a narrowband channel was derived primarily from experimental descriptions appearing

in the *Bell System Technical Journal*. If desired, reference may be made to the following:

Babler, G. M., "A Study of Frequency Selective Fading for a Microwave Line-of-Sight Narrowband Radio Channel," *Bell System Technical Journal*, March, 1972, pp. 731-757.

Babler, G. M., "Selectively Faded Nondiversity and Space Diversity Narrowband Microwave Radio Channels," *Bell System Technical Journal*, February, 1973, pp. 239-261.

The incipient nature of narrowband technology at the time of writing suggests that increasingly formalized and refined data will become available as experience is gained. Revisions to this section may be anticipated when improved information becomes available.

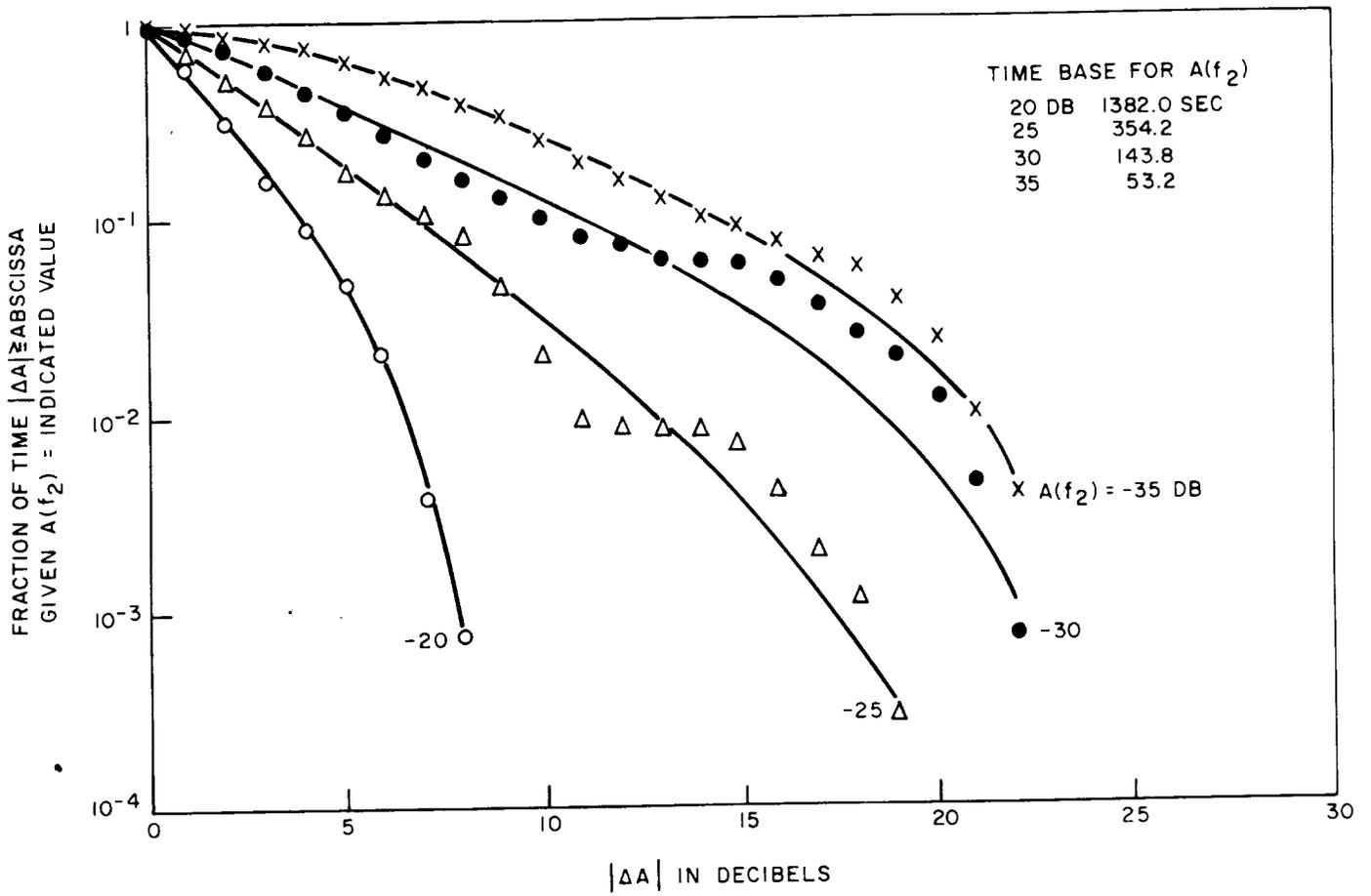


Fig. 18—Conditional Linear Distortion Distributions for the 19.8-MHz Channel

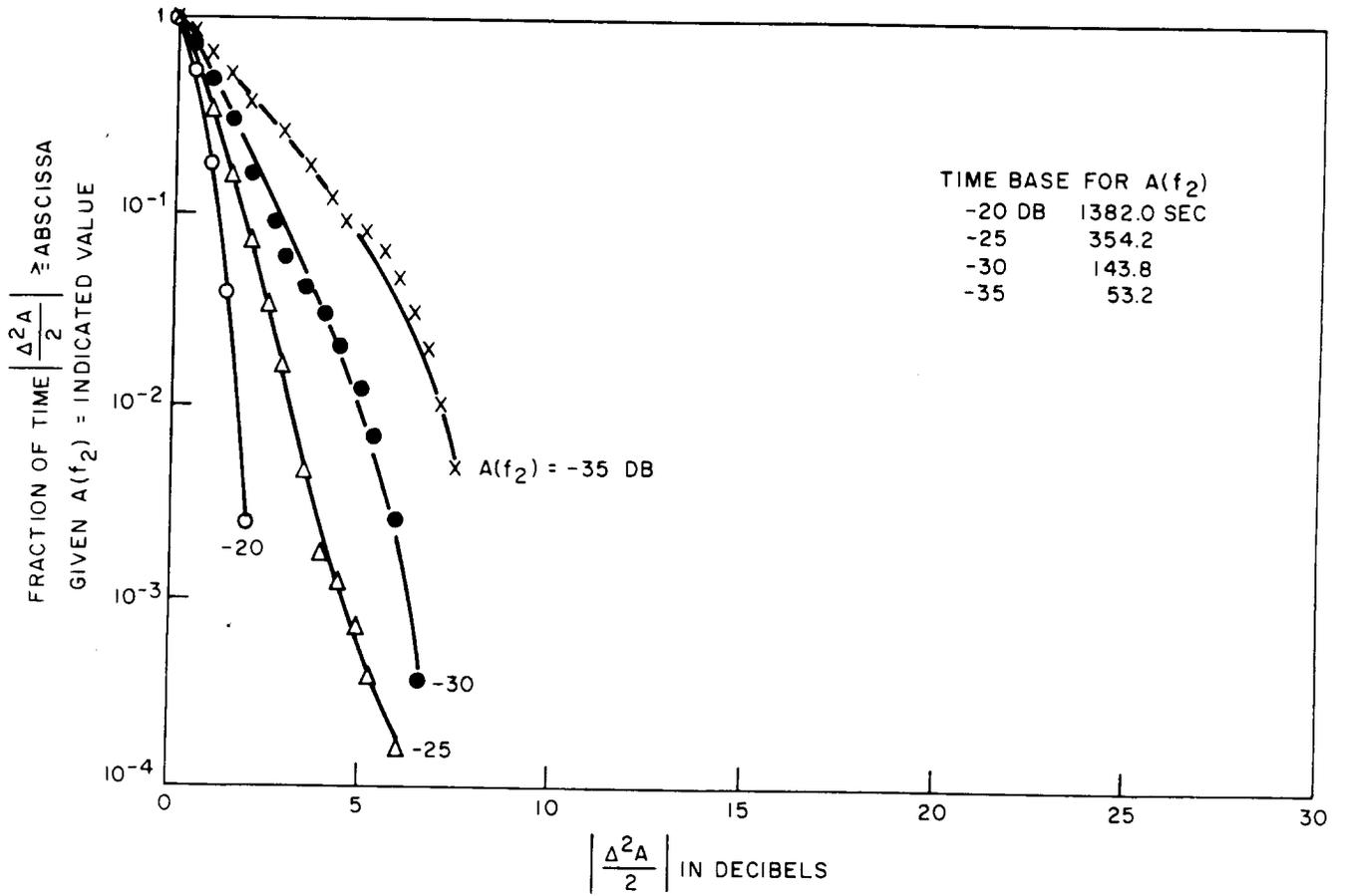


Fig. 19—Conditional Quadratic Distortion Distributions for the 19.8-MHz Channel

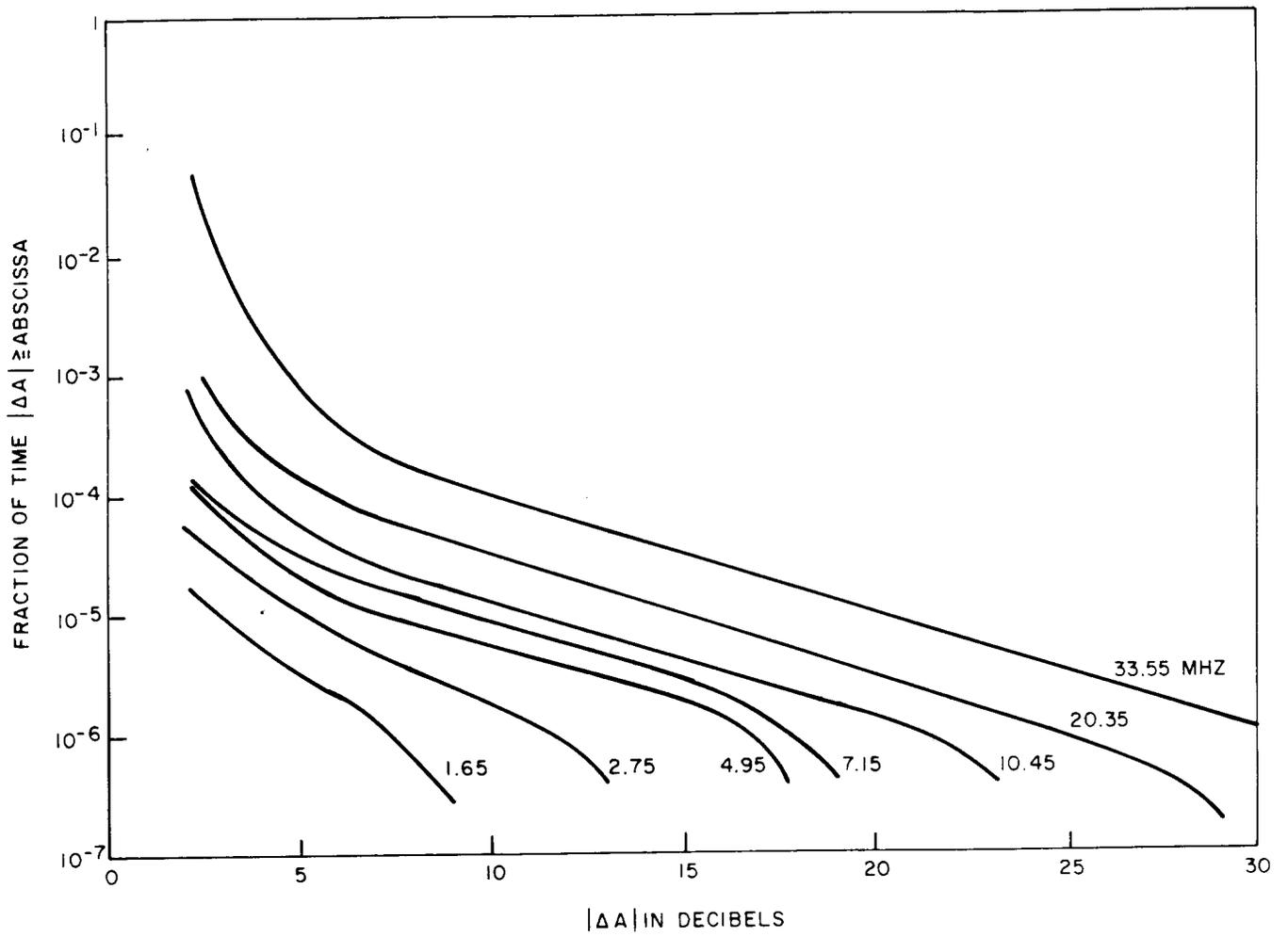


Fig. 20—Summary of Unconditional Linear Distortion Distributions for Different Bandwidths

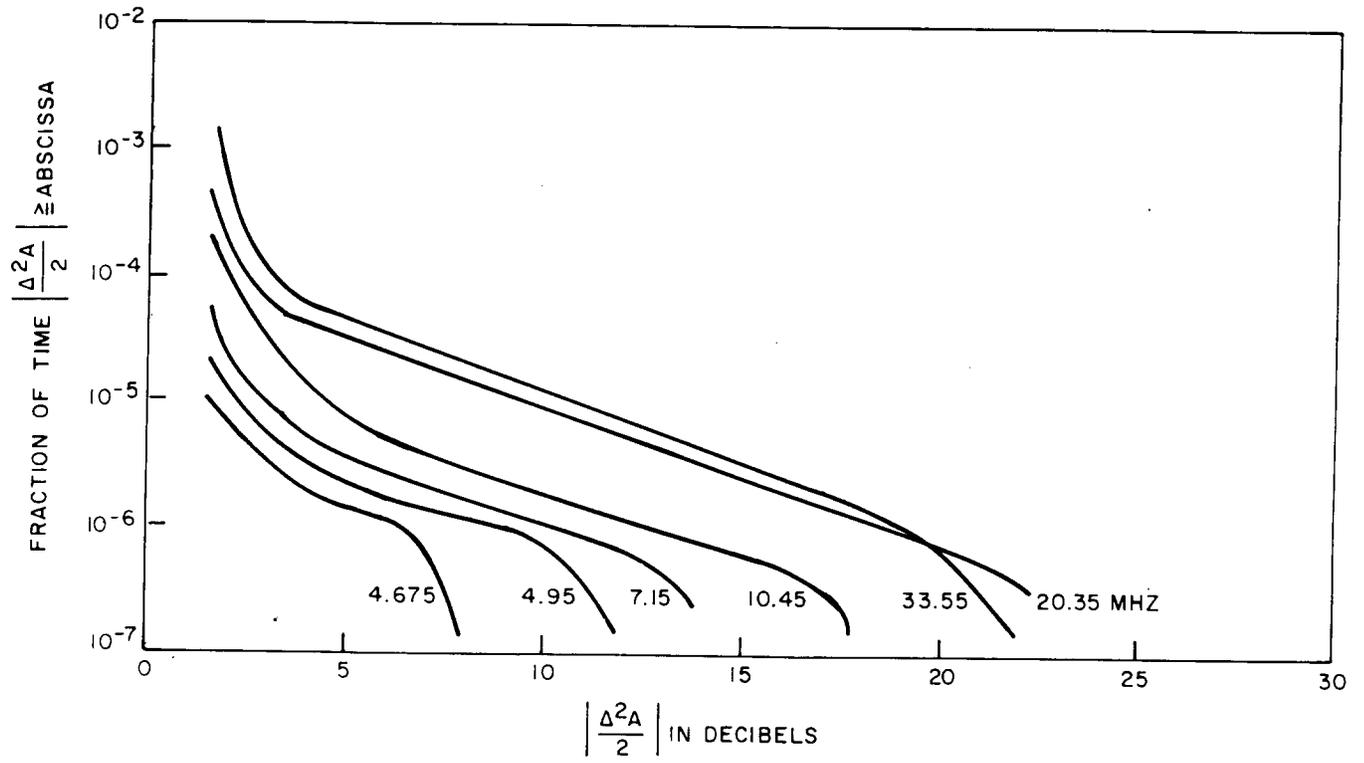


Fig. 21—Summary of Unconditional Quadratic Distortion Distributions for Different Bandwidths