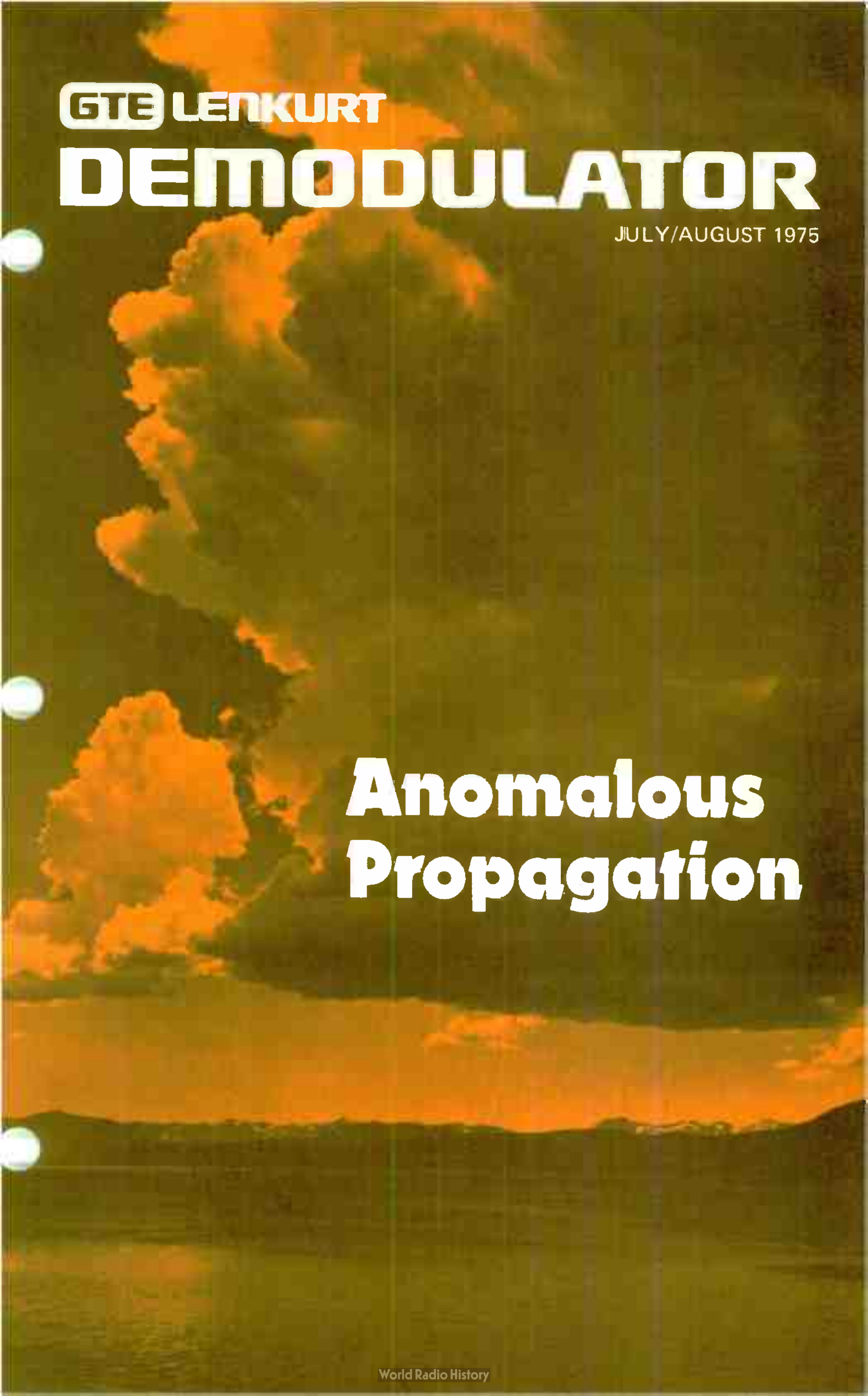
GTE LENKURT

DEMODULATOR

JULY/AUGUST 1975



Anomalous Propagation

Anomalous Propagation – Part 1

Most microwave paths are subject to at least a small amount of multipath and attenuation fading throughout the year. This type of fading is normal and is taken into consideration in system design. Paths located in areas which support the formation of ground-based atmospheric layers may be influenced by a wide range of anomalous (abnormal) propagation effects, some of which defy traditional diversity or other conventional corrective techniques.

In its passage between transmitter and receiver, a microwave signal is subject to any number of obstacles that impede its progress to the intended destination. Many of these obstacles (such as buildings and mountains) are allowed for in the original design of the microwave path. Others, such as conventional types of atmospheric fading, are alleviated by system design and the use of diversity. There is, however, an area where conventional techniques normally used to combat fading are virtually ineffective; this is the area of abnormal, or anomalous, propagation, characterized in its most extreme form by the catastrophic phenomenon known as blackout fading.

Before launching into an in-depth discussion of anomalous propagation, it would be beneficial not only to discuss some of the terminology associated with fading, but also to review some of the characteristics, causes, and remedies of conventional fading phenomena. Since radio waves at microwave frequencies exhibit characteristics and properties similar to those of light waves, certain optical principles are useful in describing radio wave propagation; the most important of these are the principles of reflection, diffraction, and refraction. Individually, or in combination, these properties can significantly affect the reception of the microwave signal at the receiver, thus influencing overall per-hop or system reliability.

Reflection

Reflection of the microwave wavefront is a common source of received signal variation. Reflections occur when radio waves strike a smooth surface such as water, smooth earth, or the boundary between adjacent atmospheric layers of different densities. If both reflected and direct waves reach the receiving antenna, the ensuing cancellation may significantly reduce the received signal strength. Depending on the length of the reflected path compared to the direct path, the reflected wave may arrive at the receiving antenna either in phase, out-of-phase, or partially out of phase with the direct wave. Under conditions where the reflecting surface is very smooth and the reflected wave and direct wave are of equal amplitude and exactly out of phase at the receiver, the reflected wave may temporarily almost completely cancel the direct wave and cause a deep drop in received signal strength.

Diffraction

Microwave paths (and antenna heights) are ordinarily selected to provide line-of-sight clearance between the transmitting and receiving antennas. However, a direct path does not always guarantee good radio transmission. If the wavefront passes too near an obstacle, such as a hilltop or large building, the partial obstruction will result in an increase in transmission loss. If the microwave ray (the centerline route taken by the wavefront between antennas) is blocked (by inverse bending, for example), energy still arrives at the receiver by diffraction. The actual amount of obstruction or diffraction loss is dependent upon the Fresnel zone radius of the wavefront compared to the area obstructed and the reflectivity of the obstruction. The Fresnel zone radius at lower frequencies (VHF to 2 GHz, for example) is much larger than at higher microwave frequencies, and therefore sustains much lower obstruction or diffraction losses during inverse bending periods.

Refraction

Refraction occurs because radio waves travel at different speeds through media of varying density. In free space (a vacuum), the speed of a microwave signal is theoretically constant and maximum, but in the atmosphere, where the atmospheric density is higher due to the presence of gas and water molecules, the radio wave travels slower.

In a "standard" atmosphere, the pressure, temperature, and water vapor content (humidity) all decrease linearly with increasing altitude. Atmospheric density, the single parameter which combines the resultant effect of these variables, also decreases with altitude. Radio waves passing from dense air to thinner air undergo a change of direction in proportion to the difference in densities, since the portion of a wave front that enters the thinner air layer first begins to travel faster than the portion still in the dense air. The result of this process is a microwave path that is bent or refracted towards the denser atmosphere. In a uniform atmosphere, where the change in density is gradual, this bending or refraction of the radio wave is essentially continuous, so that the microwave beam is gently curved away from the upper to the lower atmosphere. The beam then generally tends to follow the curvature of the earth. This causes the radius of the earth to appear to the microwave beam to be larger than the true radius. When an extreme drop in atmospheric density with height (a negative refractive index gradient) occurs, or when the gradient is positive, climatic conditions are conducive to anomalous propagation.

The k Factor

The amount and direction of bending undergone by the microwave beam is defined either by the refractive index gradient or, more often, by the effective earth's radius factor, k. This factor, multiplied by the actual earth radius, gives the radius of a fictitious earth curve. The curve is equivalent to the relative curvature of the earth; that is, it is equal to the actual earth's curvature minus the curvature of the beam of microwave energy. Any change in the amount of refraction caused by atmospheric conditions can then be expressed as a change in k.

During standard atmospheric conditions, the range of k is from 1.2 in dry, elevated areas and 4/3 in typical inland areas, to 2 or 3 in humid coastal areas. The earth appears to become increasingly flat as the value of k increases (see Figure 1). When k equals infinity the earth appears to a microwave beam to be perfectly flat since the beam curves at exactly the same rate as the earth. If the value of k becomes less

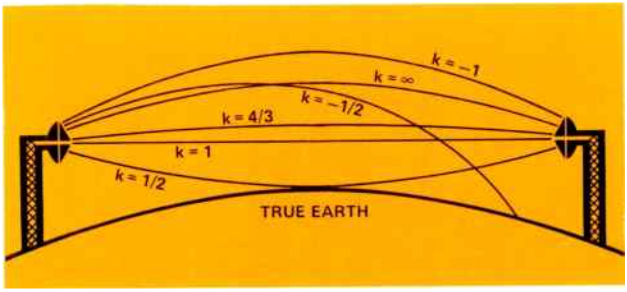


Figure 1. The degree and direction which a microwave beam bends can be defined in terms of the equivalent earth radius factor, k.

than one, the beam curves upwards or opposite to the curvature of the earth; to the microwave beam, the earth appears to "bulge." The effect of earth's bulge may be to partially obstruct the transmission path, causing an obstruction or diffraction. The curvature for various values of k can be calculated from the relationship:

$$h = \frac{d_1 d_2}{1.5k}$$

where h = the change in vertical distance from a horizontal reference line, in feet,

- d_1 = the distance from a point to one end of the path, in miles,
- d_2 = the distance from the same point as above to the other end of the path, in miles, and
- k = the effective earth's radius factor.

Exempting multipath fading (easily overcome with diversity techniques), changes in k from 1 to infinity have little influence upon the received signal level of a properly engineered microwave path. Anomalous propagation occurs outside of this "normal" range of k. With k less than 1, the path could become obstructed and vulnerable to extreme multipath fading. When negative values of k occur, the path may become trapped and susceptible to blackout fading.

Superstandard Refraction

Superstandard refraction, (also called superrefraction), results from such meteorological conditions as a rise in temperature with increasing height (temperature inversion) or a marked decrease in total moisture content in the air with increasing height, either of which will cause a reduction in the atmospheric density with height. Under these circumstances, k increases, resulting in a flattening of the effective earth's curvature.

One of the conditions which may cause this type of abnormal refraction is the passage of cool air over a warm body of water. Evaporation of the water will cause an increase in humidity, and the low temperature near the surface is a sign of a temperature inversion. Low temperatures and high humidities greatly increase the atmospheric density near the surface, causing an abnormally high downward bending of the wavefront. In moderate instances of superrefraction, k approaches infinity and a microwave beam which is propagated parallel to the earth will remain parallel until obstructed or otherwise attenuated. An extreme case of superrefraction will bend the wavefront downward with a radius smaller than that of the earth (negative k), causing a blackout fade if the receiver is beyond the point at which the wavefront refracts into the ground (the radio horizon).

Substandard Refraction

Substandard or less than standard refraction occurs with certain meteorological conditions which cause the atmospheric density to actually increase with height. This condition, described earlier as earth's bulge or inverse beam bending, causes an upward curvature of the microwave beam as shown in Figure 1, where k = 1/2. A substandard atmospheric condition may occur through the formation of fog created with the passage of warm air over a cool air or a moist surface. This will cause the atmospheric density to be lower near the ground than at higher elevations, causing an upward bending of the beam.

Comparison of Common Fade Types

Fading, the variation in the strength of a received microwave signal, is usually due to atmospheric changes and ground and water reflections in the propagation path. Figures 2 and 3 show selective and nonselective fading types that can influence the propagation reliability of a line-of-sight microwave radio system. Two or more types may occur simultaneously, complicating the received rf signal level as shown by the level recorder pattern. For example, rapid multipath fading often accompanies most other types of fading (except rainfall and blackout).

Fade types 2a through 2e result from one or more interference rays arriving at the receive antenna in and out of phase with the desired beam. These types of fades are selective, in that different frequencies within the transmitted band are affected differently; any type of diversity (frequency, space, hybrid, etc.) is almost totally effective in eliminating baseband hits or outages if adequate fade

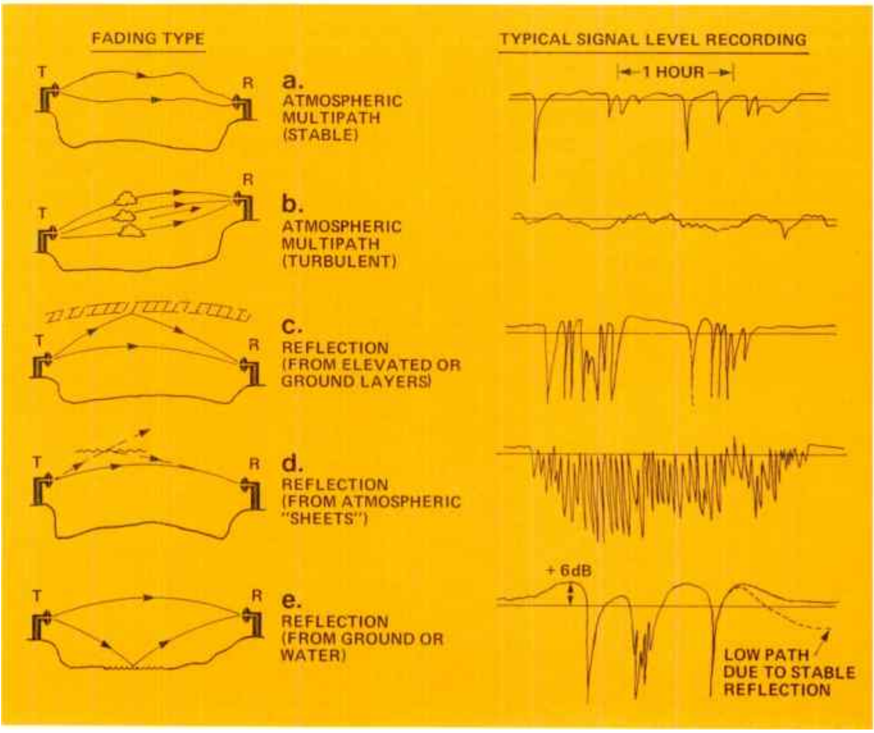


Figure 2. Selective fading types.

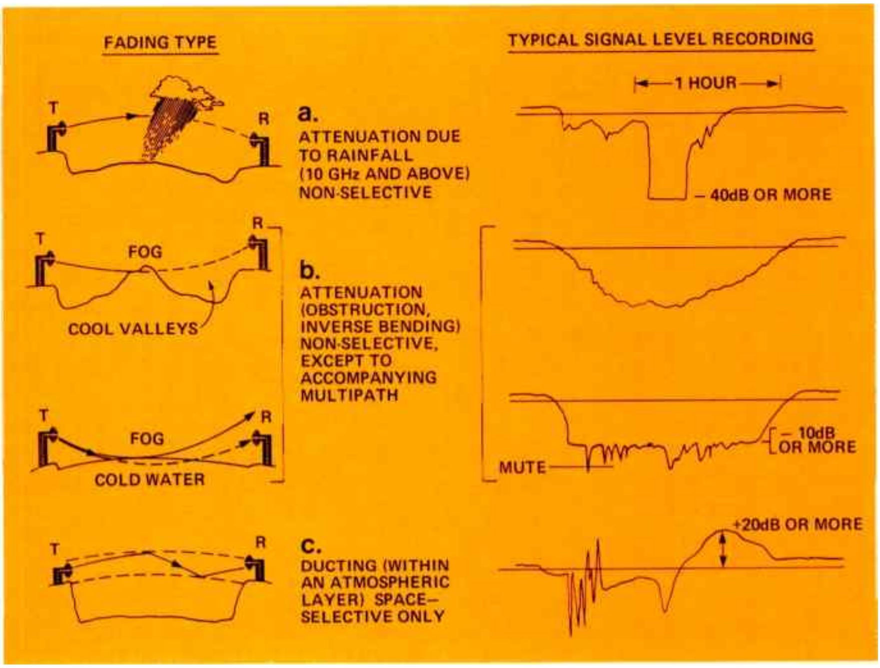


Figure 3. Non-selective fading types.

margin is provided. The power or attenuation fade types 3a through 3c are generally non-selective; normal frequency and space diversity techniques provide little or no improvement over a nondiversity configuration in propagation reliability.

Atmospheric multipath fading appears in both stable and turbulent form. Stable multipath fading (Figure 2a) occurs when only a small number (perhaps two or three) of secondary reflected or refracted paths (from the atmosphere or multiple low-amplitude ground reflection points) are received simultaneously with the desired path. The resulting fading characteristic is relatively slow, but occasional fast, deep fades can occur. Turbulent multipath (Figure 2b) causes fast but low-magnitude fades with fewer outages. Both types of atmospheric multipath fading have a time-versus-depth fade distribution; a 40-dB fade margin in poor propagation areas, for example, could approach about one hour per year of total outage time. Increased fade margin reduces outage time: for each 10-dB increase in fade margin, the outage time drops by a factor of about 10. Multipath fading is highly selective, and reduces baseband outage time by a factor of 100 or more. Such fading is also quite sensitive to antenna orientation and antenna size (larger antennas have better selectivity against slightly off-path secondary multipath rays).

Reflections from boundaries between elevated atmospheric layers and sheets are shown in the fade charts of Figures 2c and 2d. Elevated layer boundaries resulting from sharp changes in either temperature or humidity (or both) may form nearly perfect reflection planes at microwave frequencies. Layers are usually quite stable, perhaps moving slowly, in a vertical direction; in- and out-of-phase reflections occur as this layer moves. Sheets (high-altitude, undulating layers perhaps 10 feet thick and 6 miles long) are constantly changing, and the wild, fast, deep fades (Figure 2d) occurring at night are often attributed to them. During severe reflection fading, the direct path is usually depressed by obstruction or antenna decoupling, increasing its susceptibility to the interference ray. Larger antennas and vertical polarization may help in such cases. Any type of diversity (the greater the spacing the better – 2% frequency or 40-foot antenna spacing are common) essentially eliminates baseband outages caused by reflections from layers and sheets.

Specular reflections from ground or water may occur as shown in Figure 2e. A stable signal reflected from a reflection point may combine with the desired signal either to increase the receive level as much as 6 dB, or to completely cancel the desired signal, perhaps causing a 50 dB or greater fade. In a varying atmosphere, the receive level chart displays a rolling pattern. A path "hung-up" on a stable reflection may remain depressed 10-20 dB for days or weeks. Increased fade margin is of some benefit, and the reflection point could be shielded by planting trees, by erecting a screen, or by relocating the antennas. Antennas can be tilted slightly upward to provide increased discrimination to the reflected ray. Larger antennas with smaller beamwidths are useful, especially at the low end of a high/low path (where one antenna is considerably elevated above the other). Diversity essentially eliminates outages caused by this type of fading, and optimum antenna spacings may be computed for a given path. Vertical polarization is also effective if the reflection (grazing) angle is larger than 0.1 degrees.

Attenuation due to rainfall is shown in Figure 3a. Although fades caused by rainfall are occasionally observed at lower frequencies (10-20 dB fades at 6 GHz have been recorded), this type of fade generally causes outages only on paths above 10 GHz. The outages are usually caused by blockage of the path by the passage of rain cells (thunderstorms, etc.), averaging 5 miles in diameter and 5-15 minutes in duration. The fading chart shows fairly slow, erratic level changes, with rapid path failure as the cell intercepts the path. The fades are nonselective (all paths in both directions are affected simultaneously). Vertical polarization appears less susceptible to rainfall attenuation than horizontal at certain frequencies. Increased fade margin is of some help in rainfall attenuation fading; margins as high as 45 to 60 dB have been used in some highly vulnerable 11-13 GHz links for increase reliability. When permitted, crossband diversity is totally effective – the lower 6-GHz path is stable (affected only by turbulent multipath fading) during periods when the upper 11-GHz path is obstructed by rain cells. Route diversity (paths separated by more than five miles) has also been used successfully. In some 13-GHz intercity video systems, a direct VHF link (receiving a weak but usable direct TV signal) is automatically switched on upon loss of the microwave link during rainstorms.

Attenuation fading due to partial path obstruction in a substandard atmosphere is nonselective. Increased fade margin and antenna heights are the prime solutions, although outages are usually caused by the accompanying severe multipath fade and not by the diffraction fade alone. The lower frequency bands (2 GHz) exhibit less obstruction or diffraction loss than the higher bands for a given amount of inverse bending, so they are recommended where tower heights and fade margins cannot be increased.

Ducting

Paths trapped in ground or elevated ducts may exhibit wide, slow level changes, up to 30 dB above median in some instances, and thus may be compared to a gigantic waveguide coupling the transmit and receive antennas (see Figure 3c). Because ducts are often narrow, space diversity is sometimes helpful in reducing their effects. Frequency diversity is of little use except as protection against the accompanying multipath fading. In extreme cases of ducting, the microwave path may have to be rerouted around the ducting area, but outages caused by this mechanism are rare.

Blackout Fading

The occurrence of blackout fading is rare compared to other types of fading, but when it takes place, its effects are total and catastrophic. Traditional schemes used to improve the reliability of a microwave link, such as increased fade margin and conventional diversity, have only minimal influence with this type of fading.

Catastrophic path propagation failures due to blackout fading have been reported for more than 30 years. Some investigators call any lengthy depression of the microwave signal a fadeout, but this does not clearly identify the specific fade mechanism involved. For example, a non-outage fadeout could result from the partial obstruction of a path during substandard propagation periods. The terms ducting, trapping, blanking, drop-out, antenna decoupling, defocussing, and space-wave fadeout have also been adopted in describing various blackout events, but these terms could also be associated with phenomena other than the specific ground-based, superrefractive gradients (sharply decreasing density with height) causing the true blackout fade.

Common Denominators

Although propagation blackout fades occur in widely separated parts of the world, most have the following unique properties in common:

(1) The propagation failure is absolute, and no reasonable increase in fade margin can adequately resolve it.

(2) The microwave links are close to or traverse areas characterized by shallow, standing bodies of warm water such as swamps, shallow bays, and irrigated farmland, and may be located parallel to coastlines.

(3) The weather just prior to the blackout fade is unseasonably warm and humid; the fade coincides with a marked change in temperature and increase in humidity. The fades usually take place in the late evening, although some occur during daylight hours with the passage of a cold front.

(4) Most of the path lengths are in the 20-30 mile range, and, although antenna heights adequate to prevent a complete diffraction outage during subrefractive periods are usually provided, most have less than 150 feet of clearance over water or moist ground during normal propagation periods.

(5) The catastrophic outages occur simultaneously in both directions of transmission and in both diversity paths (except that in rare instances space diversity receivers showed that the fade exhibits some height selectivity).

The received signal level recording during a blackout fade shows a unique pattern, different from any other fade type (Figures 4a and 5). All other types (selective or nonselective) will show widely varying fade depths from path to path and from day to day, depending upon terrain reflectivity or water roughness, rainfall intensity, path clearance, amount of obstruction, atmospheric turbulence, or the transmitted frequency. Blackout depends only on the thickness, refractive index gradient, and the frequency of occurrence of the ground-base atmospheric layer which, in turn, establishes whether or not the receive antenna is within the radio horizon of the transmit antenna. Blackout is generally a go/no-go phenomenon: either the path is well established or it is totally lost. Except for occasional changes in the thickness or refractive index gradient during blackout that may cause wide swings in received level, the fade depth is nearly always far greater than any reasonably assigned fade margin.

Blackout is most often confused with the diffraction (obstruction) fade that takes place with inverse bending (see Figure 3b and 4b), although the atmospheric refraction characteristics for these two fade types are reversed. Blackout fading results from the presence of an intervening superrefractive atmosphere, which is sometimes invisible except for boundary haze, and sometimes visible in the form of warm

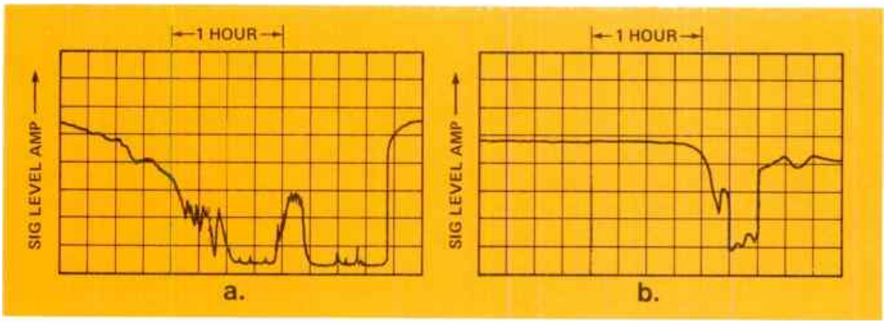


Figure 4. (a) Blackout fading on a low clearance path over shallow, warm water (superrefractive atmospheric layer). (b) Diffraction fading on a low clearance path over deep, cool water (subrefractive atmospheric layer).

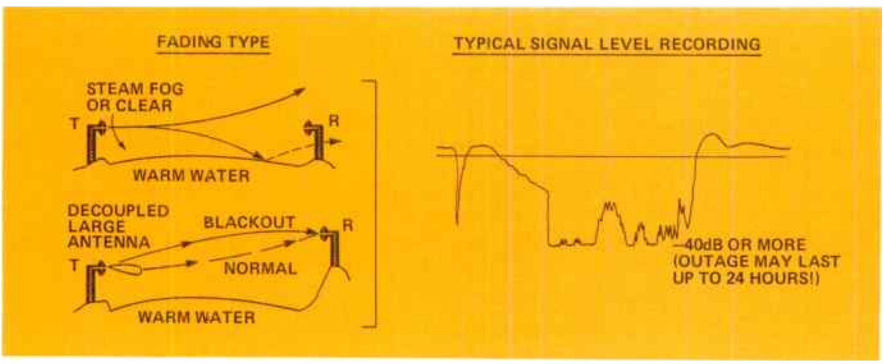


Figure 5. During blackout fading, the microwave path is trapped or arrives outside the main lobe of the antenna. This type of fading is usually non-selective, but may occasionally be space-selective.

water "steam" fog or mist that refracts the microwave wavefront downward or into the ground (or water) before it reaches the receive antenna. Usually, no part of the transmitted signal arrives at the receive antenna (see Figure 5). In contrast, inverse bending is the product of a subrefractive atmosphere (often cold-water fog) that may refract the wavefront upward before it reaches the receive antenna. But in this mechanism, a microwave path, although obstructed, continues to exist to the receive antenna, and a stable but depressed signal is still available, in contrast to the total outage typical of the blackout fade. Rapid multipath fading often accompanies the earth's bulge fade, so diversity protection is required in preventing baseband hits during this period. Again, in contrast, while the blackout fade often shows path instability, it is rarely accompanied by multipath fading, although some characteristics during blackout resemble multipath fading.

For example, if the radio horizon during blackout occurs just in front of the receive antenna, small changes in the thickness of refractive index gradient of the layer may cause the microwave signal to whip in and out of range of the receive antenna. The resultant fade pattern would be similar in appearance to interference fading with slightly varying path clearance with changes in k. But the blackout recording does not exhibit the 6 dB rolling upfade (increase in signal reception) characteristic of two-path reflection fading.

Multipath fading can precede blackout, but usually only over reflective terrain or water and under two exacting conditions. In the first instance, the direct path is partially obstructed by a low layer and a secondary super-refracted path reflected from the terrain arrives to cause interference fading. In the second case, the layer is unusually thick, and the two super-refracted rays arrive at the receive antenna as a direct path and a secondary reflection from the ground.

The Atmosphere

Blackout fading results from the formation of unusually steep, negative atmospheric density gradients; a dramatic drop in humidity, or an increase in temperature with height, for example. As the microwave beam is propagated through a blackout atmosphere, the lower part of the wavefront is slowed by the dense air with respect to the upper part, causing a tilting of the wavefront toward the ground or water. The amount of tilt is very small, but over a 20-mile distance the amount of accumulated bending could refract the propagated beam into the ground before it reaches the receive antenna. The beam may then be absorbed by foliage or crops, or scattered by rough terrain, but is most often specularly reflected by smoooth terrain or water (in which case it will reappear again at a greater distance).

Atmospheric density and refractive indexes are important in determining k factors for establishing path clearances. The density of the atmosphere, in terms of its refractive properties, is a function of pressure, temperature, and humidity in the following approximate relationship:

$$N = \frac{79P}{T} + \frac{3.8 \times 10^5 eH}{T^2}$$

where: N = Atmospheric refractive index (N-units)
P = Pressure, millibars
T = Temperature, °K (273 + °C)
e = Saturation vapor pressure, millibars
H = Relative humidity, %/100

The refractive index gradient dN/dh may be determined from the refractive index measured at the surface (N_S) through the relationship:

$$dN/dh = -7.32\ \epsilon^{.005577 N_s}$$

and:

$$k = [1 + (dN/dh)/157]^{-1}$$

The k factors most commonly used in microwave path engineering are listed in Figure 6. The surface refractive index is related to a reduced-to-sea-level value of refractivity in approximately the following manner:

$$N_O = N_S\ \epsilon^{h/7}$$

where N_O and N_S are the refractive indexes at sea level and on the surface, respectively, ϵ = 2.71828, and h is the altitude above mean sea level (AMSL) of the surface, in kilometers. For example, N_O = 301 would equate to a standard refractive index, N_S, at Denver (elevation 1.63 km) of 239 N-units.

All of these relationships are shown in Figure 7. The wide range of refractive index gradients present in a ground-base atmospheric layer may be seen in the vertical profiles. The standard −40 N-units/km median gradient is typical of inland microwave path propagation in the U.S. With higher ground humidities, a steeper −58 N-units/km (k=1.6) is usual around the Gulf of Mexico and other coastal areas, while in dryer elevated regions (such as in the Rocky Mountain states) dN/dh is typically −30 N-units/km (k=1.25).

The seasonal and diurnal median values and ranges of N_O, N_S, and dN/dh that take place throughout the U.S. and around the world are found in books published by the Department of Commerce *(OT Report 75-59, Refractivity Gradients in the Northern Hemisphere, ESSA Monograph 1, A World Atlas of Atmospheric Radio Refractivity*, and *NBS Monograph 22, Climatic Charts and Data of the Radio Refractive Index for the United States and the World).* Charts are also provided that show the frequency of occurrence of ground-base trapping layers.

In addition to the refractive index contour maps of the U.S. and the world, some of these publications show the distribution of atmospheric gradients with time at selected locali-

k, EFFECTIVE EARTH'S RADIUS FACTOR	dN/dh, N UNITS/km	ATMOSPHERIC CONDITION	MICROWAVE PROPAGATION
5/12	+220	HUMIDITY INVERSION (LARGE POSITIVE GRADIENT)	EXTREME EARTH'S BULGE (DIFFRACTION FADE)
1/2	+157	MODERATELY SUBREFRACTIVE	MODERATE EARTH'S BULGE
2/3	+80	SLIGHTLY SUBREFRACTIVE	SLIGHT EARTH'S BULGE
1	0	HOMOGENEOUS	NO REFRACTION
1.25	−30	DRY ATMOSPHERE	STANDARD (MOUNTAINOUS)
4/3	−40	STANDARD ATMOSPHERE	STANDARD
1.6	−58	HUMID ATMOSPHERE	STANDARD (COASTAL)
∞	−157	MODERATE NEGATIVE GRADIENT	FLAT EARTH
−1	−314	STEEP GRADIENT	POSSIBLE BLACKOUT
−0.5	−470	EXTREME GRADIENT	BLACKOUT

Figure 6. Commonly used k factors.

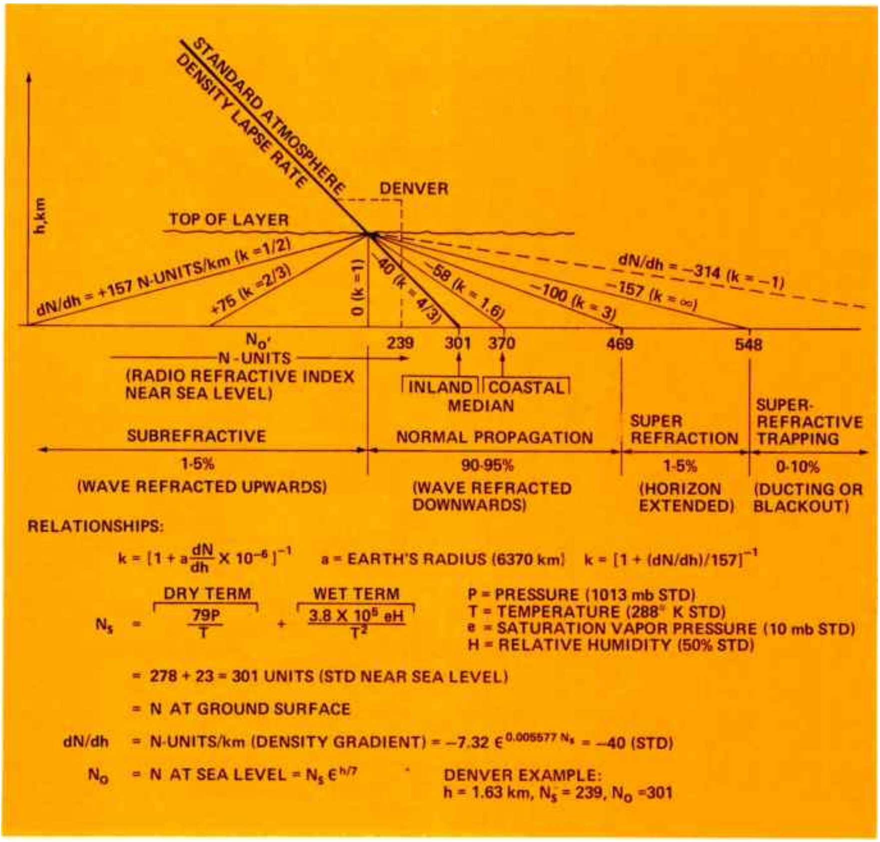


Figure 7. Atmospheric density profiles in subrefractive, standard, and superrefractive layers.

ties. Figure 8, a composite of many charts, shows the major components of a dN/dh (or k) probability distribution chart. In dry, inland areas the annual variation in k is small, with no abrupt changes in the distribution. In humid regions, a low-clearance path over moist ground or warm water is subject to a wide range of refractivity, from inverse bending (5% of the time, as shown on the left) to blackout (0.3 to 3% of the time, on the right). The occurrence of ground-base layering is immediately evident if a sharp bend in the probability curve occurs at the left (subrefraction or earth's bulge) or the right (superrefractive trapping, with possible blackout).

Positive dN/dh gradients (k less than 1) reduce (and possibly obstruct) path clearance, a frequent occurrence in paths traversing an expanse of cool, deep water. A dN/dh gradient of -157 N-units/km equates to $k = \infty$ (flat earth propagation). The range of gradients between -100 and -157, due to superrefractive atmosphere, simply extends the over-the-horizon range of a microwave system (unless obstructed by terrain), and has little effect upon the received signal levels on the established path.

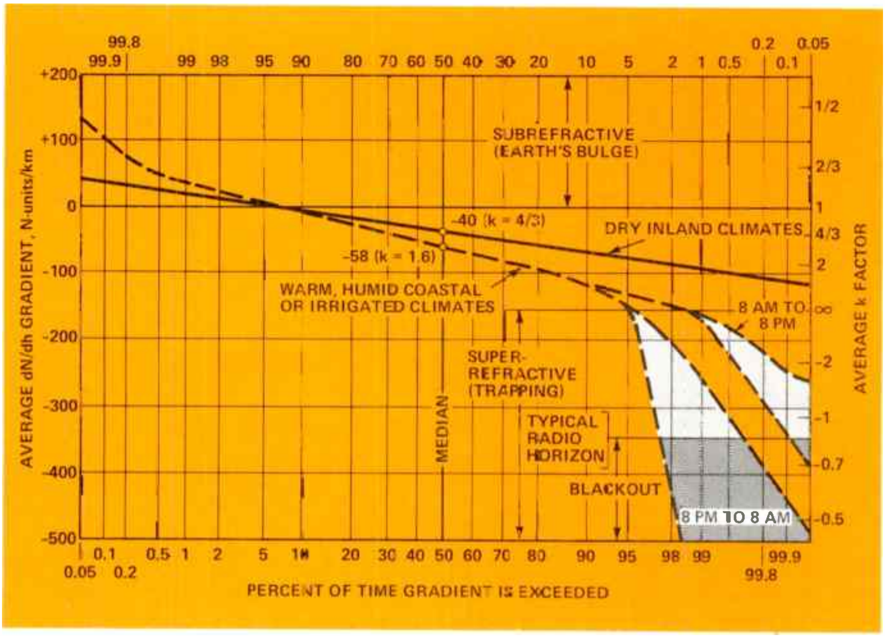


Figure 8. Cumulative probability distribution of dN/dh (or k) for low clearance paths (with layering) in dry and humid climates.

With radio beam curvature smaller than −157 N-units/km (negative k's), however, the microwave beam refracts downward faster than does the curvature of the earth and becomes trapped within the superrefractive duct. A blackout fade occurs if the microwave wavefront is refracted into the surface before it reaches the receive antenna.

Part 2 (the August, 1975, *Demodulator*) of this series will delve deeper into the characteristics and causes of blackout fading, and will suggest several remedies should this phenomenon occur.

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Anomalous Propagation—Part 2

Blackout fading, caused by signal trapping within a ground-based superrefractive layer, can introduce extended outages on low-clearance microwave paths. This rare but catastrophic type of anomalous propagation, which sometimes causes radar equipment to temporarily scan far beyond the normal radio horizon, is often the dominant factor limiting path length in microwave communications systems located in humid regions.

Part 1 of this series on anomalous propagation provided a general discussion of the characteristics of conventional fade types and their remedies, and on the nature of blackout fading. This issue will further investigate the phenomenon of blackout fading, discuss how it affects the microwave path, and what can be done to minimize its effects.

An atmosphere becomes superrefractive, and a low-clearance microwave path through it becomes susceptible to blackout fading, when cooler air passes over or develops above warm, moist soil or a warm body of water. This air mass may be produced by one of two processes: (1) with the passage of a cold front over the warm, moist ground or water at any time of the day or night, or (2) by subsidence.

Subsidence, derived from the word subside (to descend or tend downward), is the slow settling of a high-altitude, dry air mass from a high-pressure system. The air mass is warmed by adiabatic compression, overlaying and entrapping a cooler, moist air mass supported by surface moisture.

Superrefractive layers occur most often during the clear, calm, cool evening and early morning hours, but seldom appear during the afternoon, with its accompanying warmth, low humidity, atmospheric mixing and air turbulence.

Propagation Within the Superrefractive Layer

An analysis of the propagation of a microwave wavefront within a superrefractive layer is simplified if the wavefront is represented as a single line ray, the propagated path is presumed to be bilateral (the transmit and receive rays travel reciprocally on the same route) and it is assumed that the propagated ray will penetrate the layer, rather than being reflected from the boundary surface. Figure 1 shows a ray analysis of several antennas at various locations within a fully developed, ground-based superrefractive layer formed in a cool atmosphere over warm, shallow water.

In the instance where the transmit antenna is located above the layer (Figure 1a), two rays are shown, one above and one within the duct. The upper ray is propagated normally over a k = 1 to k = 3 range, depending upon the non-trapping refractive gradient above the duct. A receive antenna

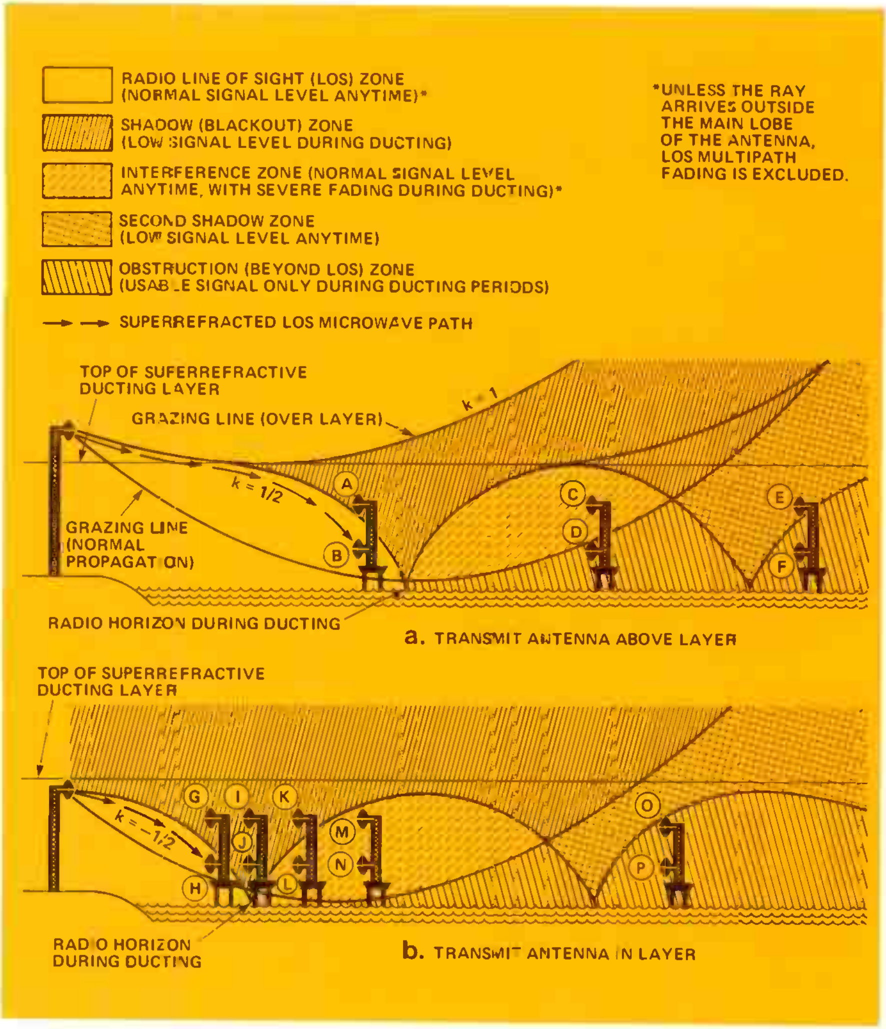

Figure 1. Tracing of a microwave beam within a superrefractive ground-based layer with (a) transmit antenna above layer and (b) transmit antenna in layer.

intercepting this ray would see a normal or perhaps partially obstructed signal level.

Within the duct, antenna B continues to see a high signal level if its radiation pattern is wide enough to avoid discriminating against the superrefracted incoming ray (dashed line), a factor in every superrefracted path. Antenna A, in the first shadow zone, is in blackout.

Antenna C was blacked out as the layer rose from the water, and recovered with a high but perhaps fluctuating signal level as the layer reached its present height. Antenna D, below line-of-sight and therefore obstructed during normal propagation, now has

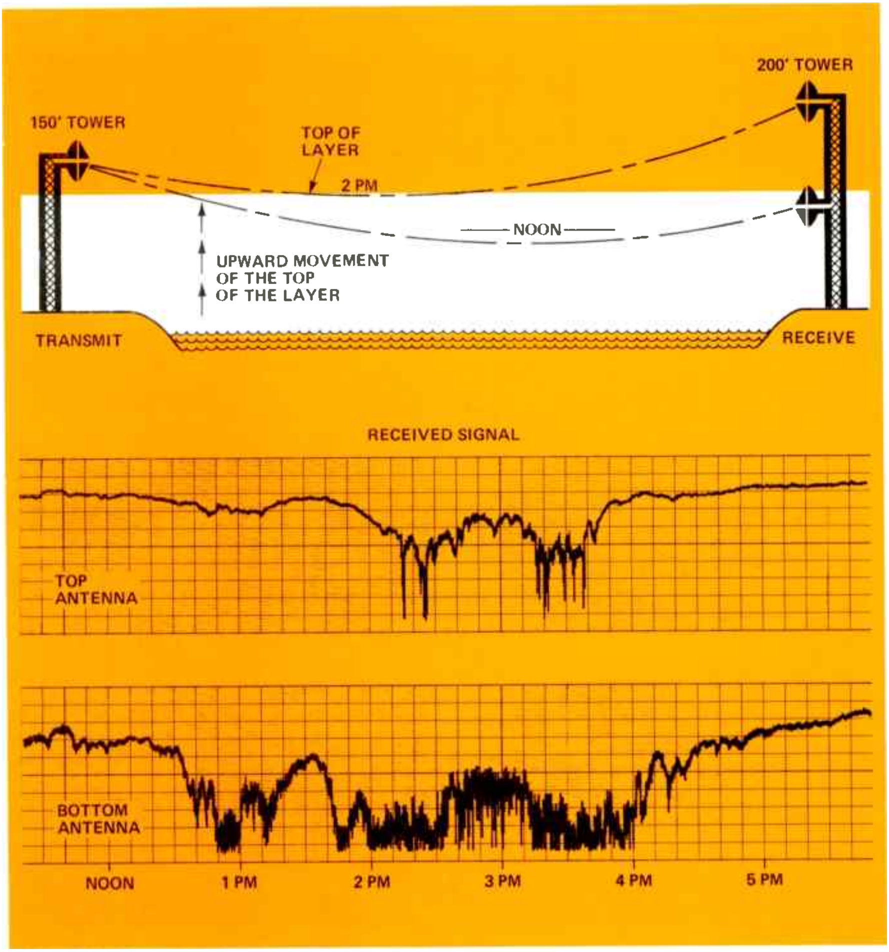

Figure 2. Blackout fading on lower space diversity antenna.

the same high but fluctuating signal level as antenna C.

Antenna E, far below line-of-sight during normal propagation and now in the second shadow zone, is still without input although its rf input fluctuated as the layer rose from the water. The received signal level at antenna F is normal as long as the layer exists.

The higher the transmit antenna, the more distant the radio horizon and range of transmission. If the transmit antenna is low, and within the layer (Figure 1b), the radio horizon range is shortened. Antennas G, I, J and K are blacked out; H has a normal input; L, M, and N have high but fluctuating inputs, and O and P (normally beyond the radio horizon) now also see normal but widely fluctuating signals. Direct superrefracted paths from the transmit antenna to antennas L, M, and N may exist if the layer is very thick.

Signal level recordings of diversity receivers with antennas spaced 100 feet apart are shown in Figures 2 and

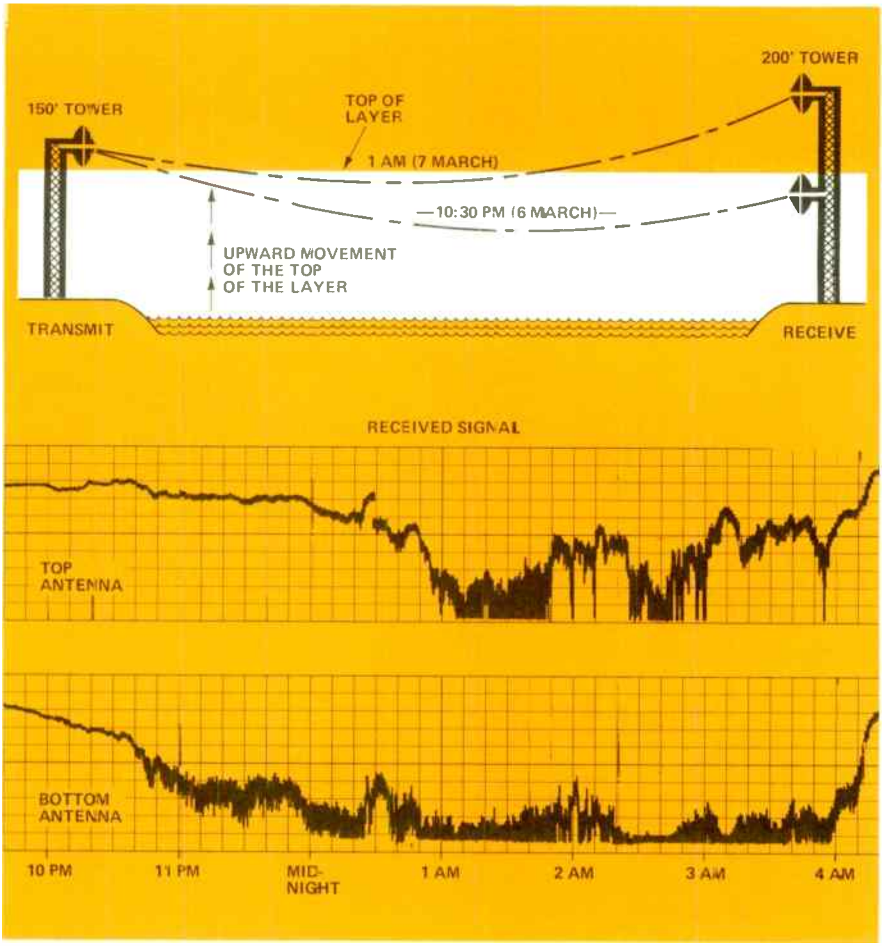

Figure 3. Blackout fading on both space diversity antennas.

3. In Figure 2, the layer moved upward to trap the lower path, which went into blackout (a rare daytime occurrence caused by the movement of a cold front into the area). The layer failed to rise above the path to the upper antenna, which experienced multipath fading, but not blackout fades (the path was reflective) commencing at shortly after 2 p.m.

On another occasion, the layer rose to a higher level and blacked out both paths, as shown in Figure 3. The upper path was out for 3 hours and the lower for more than 5 hours. The slow, strong, sporadic surges in signal level typical of the blackout mechanism are clearly visible in the recording, and are caused by slow changes in the refractive index gradient or thickness of a stabilized superrefractive layer.

Blackout Caused By Antenna Decoupling

Even if the receive antenna is within the radio horizon in the presence of

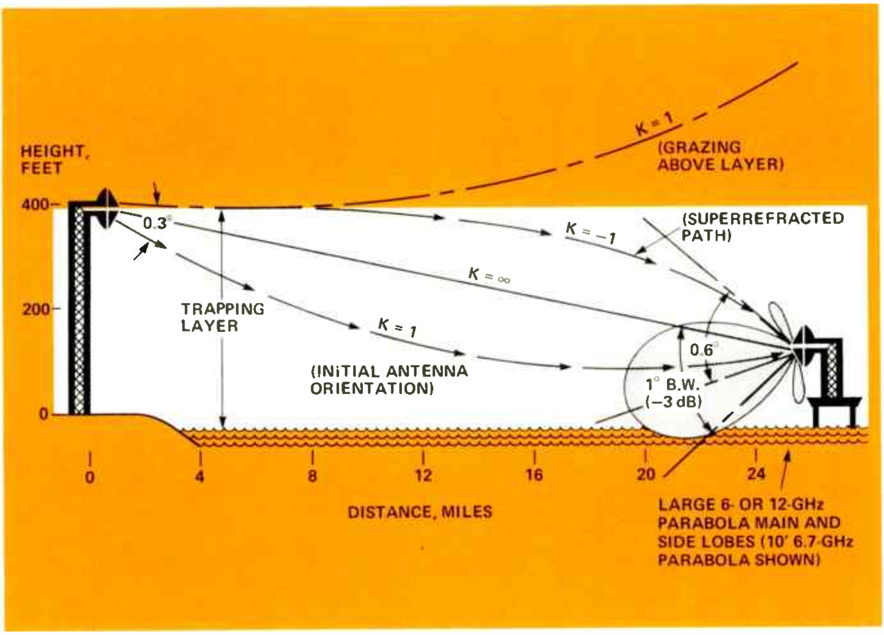

Figure 4. Antenna decoupling in a superrefractive ground-based layer.

a superrefractive layer, the propagated ray will arrive at a greater elevation angle than it normally would. If, during their initial orientation, the transmit and receive antennas were peaked for maximum signal during standard atmospheric conditions, a major upward change in the arrival angle could occur in a superrefractive atmosphere. With the narrow beamwidths common to large antennas or passive reflectors and long paths, a change in arrival angle of up to 0.5° or more may put the path outside the main lobe of the antenna, causing a blackout fade. Figure 4 shows the geometry of such an occurrence.

The characteristic behavior of such an antenna-decoupling blackout fade is identical to a blackout fade resulting from the receive antenna being beyond the radio horizon (see Figures 2 and 3). If antenna decoupling is anticipated (or experienced), the receive antennas may be tilted slightly upward (causing a 1- or 2-dB loss during normal propagation) or the lower antenna in a high-low configuration may be reduced in size. Antenna tilting has the further benefit of providing additional discrimination to a ground or water reflection during normal propagation periods.

Propagation Through a Partial Layer

If the microwave link is perpendicular to a coastline, or only a small part of the path traverses areas suspected of supporting a trapping layer, it is most unlikely that a blackout outage will ever occur. A superrefractive atmosphere capable of supporting steep, negative gradients seldom encompasses an area more than 2-5 km from the moist, warm surface generating such gradients (such as a shoreline). If the layer is close to only the high end of a

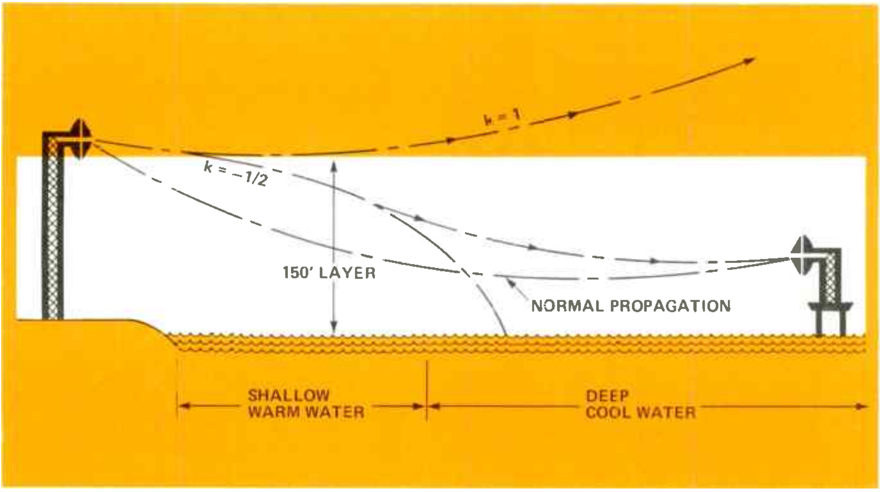

Figure 5. Ray tracing within a superrefractive layer enveloping only a part of the path.

high-low path, the possibility of trapping is greatly reduced as shown in Figure 5.

Low-clearance paths running parallel to a coastline or traversing a swamp or irrigated area at midpath or near the low end of a high/low microwave path would be most vulnerable to the blackout fading mechanism and should be avoided.

The Anatomy of a Blackout Fade

Propagation tests conducted with vertically spaced antennas have revealed that the superrefractive layer precipitating most blackout fades is ground-based (rather then elevated), and has its beginning at the moist ground or water surface and expands upward, rather than moving from a distant location.

A typical blackout fade sequence is illustrated in Figure 6. Six discrete stages or events are shown, any one of which may be more or less pronounced in any giver system. The fade pattern often exhibits a high degree of instability during the blackout process.

The sequence is usually preceded with high ground-base water vapor content or high humidity (dew point very near the ambient temperature), and is triggered with a rapid change in either of these parameters (a 15° rise in wet bulb temperature, or a 10° drop in ambient temperature over a 3-hour period, for example). The superrefractive layer rising from the moist ground has a stable, clearly defined boundary from which a reflected ray could cause a deep interference fade in the system (event 2).

As the layer continues to expand in an upward direction, it becomes a path obstruction, causing a slow diffraction fade (event 3). When the layer actually intercepts the ray, the path is refracted downward away from the receive antenna, effecting a fully developed blackout fade as shown by event 4. The blackout may have a duration of many hours; slight changes in the refractive index gradient or thickness of the layer during blackout may result in slow, rolling increases in signal level (event 5). The layer then

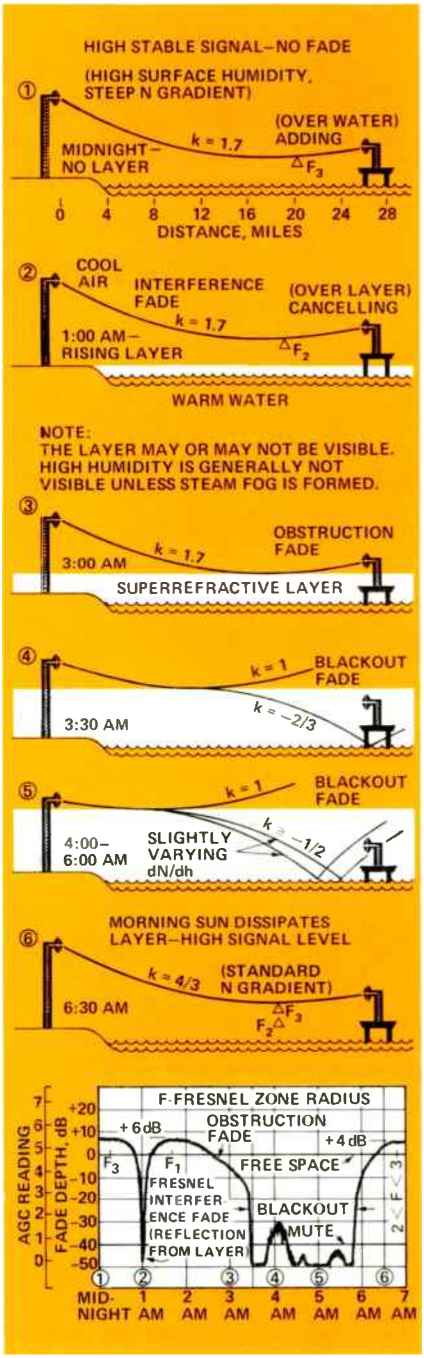

Figure 6. Blackout fade sequence of events.

dissipates with the warmth of the morning sun (event 6).

Outage Time With and Without Blackout

The fading distribution of a typical 22-mile, 6.7-GHz microwave path traversing areas having good, average, and poor propagation characteristics is shown in Figure 7. Any region supporting superrefractive layering of such severity as to cause occasional blackout is probably a poor propagation area whose multipath outages approach a Rayleigh distribution. The cumulative probability distributions with and without blackout are shown. Without trapping, the estimated outage time for the nondiversity system with 40-dB fade margin is about 19 minutes per year.

Blackout fading outage time was found to approach 44 hours per year on this path, the sum of about 11 events. The 11 blackouts, or periods of superrefractive trapping when the link (shown in Figures 2 and 3) exhibited sufficient fade instability as to be unusable, lasted from 20 minutes to 12 hours each.

Propagation studies conducted at many locations around the world in microwave links experiencing the blackout mechanism (or in areas supporting such superrefractive layers) has revealed that if antenna heights establishing at least a k = 1 grazing clearance over an assumed 150-foot layer height are provided, blackout is avoided. This empirically-derived clearance standard has been used in the initial engineering, and subsequent correction, of numerous microwave paths with (thus far) total success. This does not presume that the layer will never rise above 150 feet, but rather that the receive antenna will remain within the radio horizon of the transmit antenna even during layering.

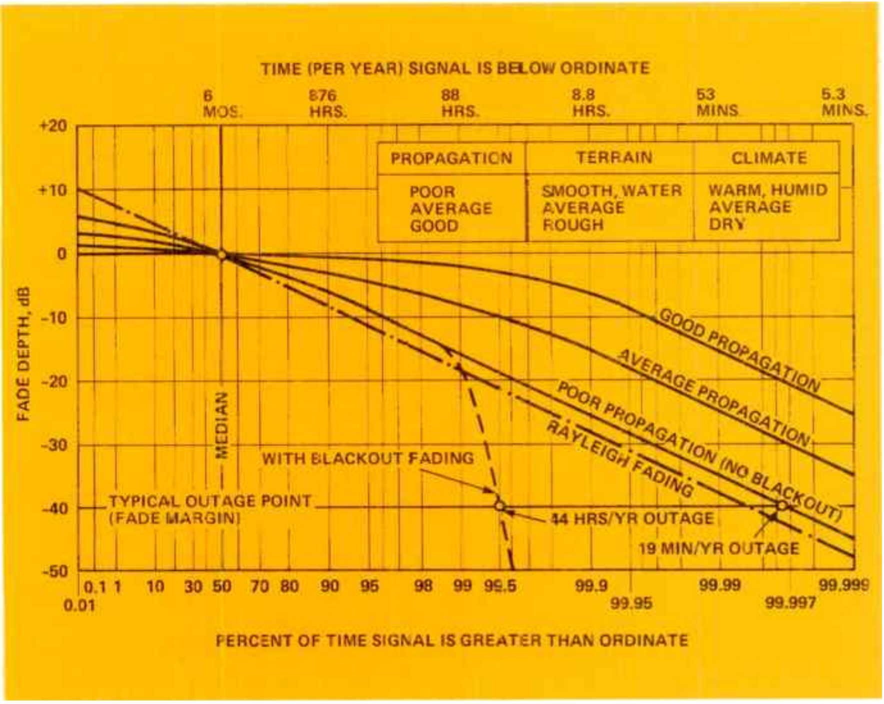

Figure 7. Cumulative probability distribution of fade depth with and without blackout fading on a 22-mile, 6.7-GHz link.

Many microwave paths traversing difficult propagation areas have been engineered with a grazing clearance over the terrain (or water) of k = 5/12. On paths which are longer than 25 miles, and with equal tower heights, this criterion dictates higher path clearance and antenna heights than the k = 1 grazing over a 150-foot atmospheric layer criterion, and is probably overconservative in any area. With path lengths between 15 and 25 miles, the k = 1 grazing over a 150-foot layer appears appropriate.

Blackout fades seldom occur in properly engineered paths shorter than 15 miles in length since the refractive index gradients are seldom so steep that the receive antenna appears beyond the radio horizon of the transmit antenna. But the climatology of any suspected area should be carefully investigated before selecting antenna heights. This is particularly important on paths configured in a high/low antenna arrangement (used to reduce interference fading) where the low antenna is near an area that may support a superrefractive layer.

Clearance Requirements

If a path is found susceptible to blackout fading after installation, the first step is to investigate the possibility of antenna decoupling, particularly if the parabolas or reflectors are large, the path is long, and the higher 6- to 13-GHz bands are used. If one or both antennas are initially oriented slightly down from the normal arrival angle of the path, a superrefractive layer could easily refract the ray enough to miss the main antenna lobe, resulting in a blackout fade. The larger (or lower) of the two antennas could be reoriented vertically during the blackout period in searching for the path. A small 2- or 4-foot search receive test antenna could be used in lieu of reorienting the large path antennas to isolate possible decoupling. A smaller antenna might be eventually required in the path to prevent decoupling.

If the receive antenna is proved to be beyond the radio horizon during blackout, rather than being simply misoriented or decoupled, the second step is to search for the presence of a stable signal of normal level low on the tower, perhaps 10-30 feet AGL (above ground level), or even below normal optical line of sight. If such a path is found to exist during blackout, the receivers could be configured for space diversity, or the diversity antenna placed lower on the tower if already so configured. Special automatic or manual transmitter switching or antenna combining arrangements are required in hot-standby systems since blackout fades occur in both directions simultaneously.

If antenna orientation and signal search with a low antenna are both unsuccessful, the third step is to increase the path clearance to a minimum of k = 1 grazing over a 150-foot layer. An investigation should reveal the location of the layer and the antenna heights adjusted at that end. If the suspected layer is mid-path, both tower heights could be increased. Most towers may be extended somewhat, particularly if the antenna load is less than the original design, although it may be necessary to reduce antenna sizes, and receive signal levels, to permit the extension of a self-supporting tower. Guyed towers are often extended with little structural modification, perhaps by simply increasing guy diameters and incorporating double lacing in overstressed parts of the structure.

A nominal reduction in fade margin to correct a blackout situation, such as reducing antenna sizes or increasing waveguide loss, has little affect on the outage time due to this catastrophic fade. But preventing antenna decoupling or raising the path above the layer could have a significant influence on the path, hopefully eliminating any future occurrence of blackout.

If these steps are unsuccessful or are not economically or technically feasible, other major solutions to a blackout environment are: (1) adding a repeater to shorten the path length, thus bringing the receive antennas to within the radio horizon of the transmitter during blackout; (2) rerouting the path around the blackout area with existing stations, by changing a backbone repeater to a spur terminal, for example; or (3) abandoning one or more repeater or terminal locations and relocating them to areas that support more congenial climates. Complete abandonment of an entire microwave system in favor of cable or other communications media not susceptable to the blackout mechanism is, of course, the least desirable solution.

Climatology

Although ground-based observations of temperature and humidity are useful in revealing atmospheric layering to a knowledgeable observer, a more precise and meaningful method is by radiosonde or refractometry measurements. Radiosonde observations (RAOB) sample upper air temperature and humidity as a function of altitude by airborne instrumentation, and transmit this information to a ground station. Radiosonde measurements are made twice a day at many weather stations; these measurements, however, are usually made in the morning and evening, before and after the critical 10 p.m. to 6 a.m. period when most blackout layers occur. Direct refractive index measurements can be made with a refractometer, a device that may be sent aloft by balloon or suspended under the wing of an aircraft descending into the suspected blackout area.

Radiosonde data, when plotted on adiabatic charts, clearly reveal trapping layers. The U.S. Weather Bureau recently went to code for efficient storage of these data, reducible to chart form by referring to the Manual for Radiosonde Code (WBAN), available from the Government Printing Office, Washington, D.C. The actual radiosonde (and ground-based) data for any domestic area under investigation are available from the National Weather Records Center, Asheville, NC.

Environmental Indicators

There are several environmental indicators which may give a clue to the formation of atmospheric layering conducive to blackout fading. One of these is changes in water temperature with the ambient temperature; this could occur in shallow bodies of water such as swamps, irrigated fields (seasonal), and areas close to shorelines. Layering of smokestack smoke at low altitudes, or the presence of low-lying mist (steam fog), are also indications of possible atmospheric layering.

The formation of a visible haze layer on an otherwise clear day is another indication of possible layering. For example, it is occasionally possible to see, from atop a microwave tower, distant mountains above an atmospheric discontinuity, but to have the mountains disappear if the observer is within or below the layer. An escarpment in New Mexico was named Fade Away Ridge by early settlers since it would occasionally disappear from view; microwave paths in this area, north of Carlsbad, are highly vulnerable to blackout fades severe enough to have required the relocation of several links and the abandonment of at least one microwave station.

The occurrence of blackout fading in some particular geographical locations is seemingly inevitable during times of the year when deciding factors such as atmospheric density and nature of terrain are right for the occasion. However, with an intimate knowledge of the climatic characteristics of a suspected area, the microwave engineer has an excellent chance of avoiding the devastating effects of anomalous propagation.

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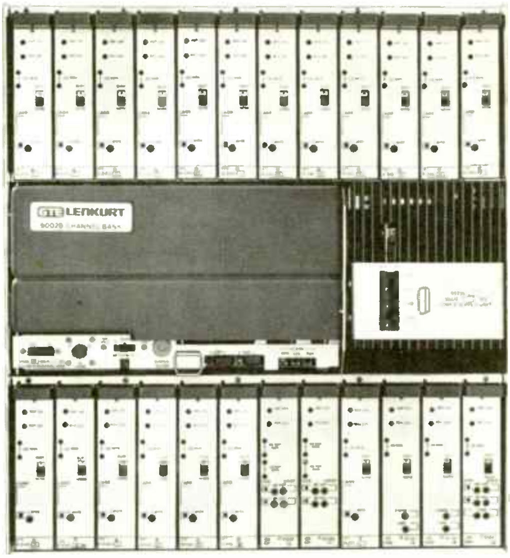

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