Network Engineering Paper

Digital Microwave Link Engineering – Performance Predictions and Path Calculations

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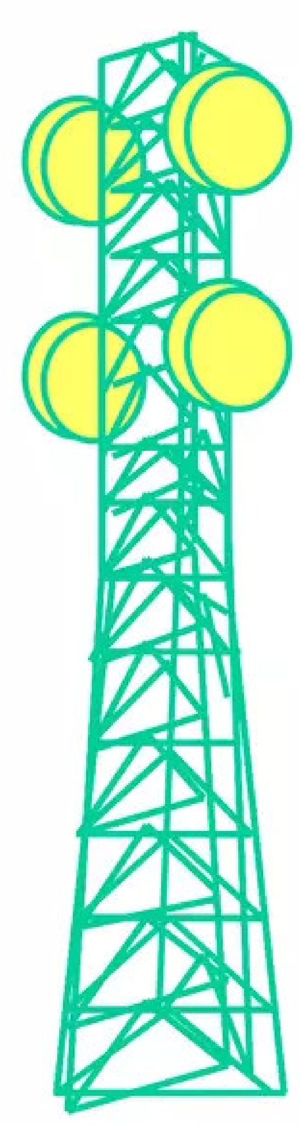

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Abstract

Digital microwave radio link performance is highly dependent upon the matching of path geometry (clearance, diversity configurations, and antenna heights, sizes, and alignments) to the diurnal and seasonal climatic and terrain characteristics and variabilities for the area. This paper describes enhanced transmission engineering models and techniques, compliant to newly standardized performance terms and objectives, now resident in user-friendly calculator and computer programs. With improved field survey, path alignment, and degraded performance troubleshooting procedures added to these engineering tools, compliance to user performance (outage and quality) objectives and other design goals is better assured.

This paper is one of three addressing the subject of Digital Microwave Link Engineering. The companion papers, "Performance Definitions and Objectives" [1] and "Path Alignment, Testing, and Troubleshooting" [2], complete the series.

Introduction

The availability and performance of a digital microwave radio relay link is very often contingent upon the successful marriage of robust radio equipments with optimized path engineering techniques which accommodate multipath and power fading along with the other adverse characteristics of a hostile world such as interference and long-delayed echoes. The full benefits of modern state-of-the-art radios in exceeding user expectations is only attained with the optimum selection of antenna heights, sizes, alignments, or diversity spacings matched to path geometry and atmospheric characteristics. The transmission engineer must consider local and synoptic climatic (atmospheric layering, refractive gradients, rain, weather fronts) and terrestrial (reflectivity, obstruction, moisture content) characteristics and configure the antenna systems appropriately.

Multipath Outage Models

Atmospheric and terrestrial characteristics exhibiting localized diurnal and seasonal variabilities are also influenced by weather fronts and other random occurrences. Mathematical models which take into account climatic conditions, terrain roughness, rain area (in availability computations only), path length, frequency band, fade margin, average annual temperature, and diversity arrangements as variables have evolved which accurately predict the availability and performance of microwave links worldwide.

Amongst the many available, Arvids Vigants' 1975 radio-relay link multipath fade outage model [3], based upon the fade activity on many Bell System microwave paths in the U.S. over an extended period in varied climate and terrain ambients, is the norm for most North American (NA) and international (CCIR, now ITU-R) outage prediction calculations. Diverse models proprietary to some countries are shown in CCIR Rep. 338 [4].

North American Calculations

The most simplistic adaptation of Vigants' North American model for short-term (<10 SES/fade event) non-diversity (ND) fade outage in a digital microwave link, in severely-errored seconds (SES, $BER>10^{-3}$) per year, is (for a 25 mi path):

$$T_{ND} = 0.4\, c\, f\, t\, D^3\, 10^{-CFM/10}$$

where, for example

T_{ND}	=	One-way outage, SES/yr
c	=	NA climate-terrain factor
	=	1 (Fig. 1), or $x(w/50)^{-1.3}$
x	=	NA climate factor, 1 (Fig. 2)
w	=	Terrain roughness, 50 ft
f	=	6.7 GHz
D	=	Path length, 25 mi
CFM	=	Composite Fade Margin, 34 dB
t	=	Average annual temperature, 50°F.

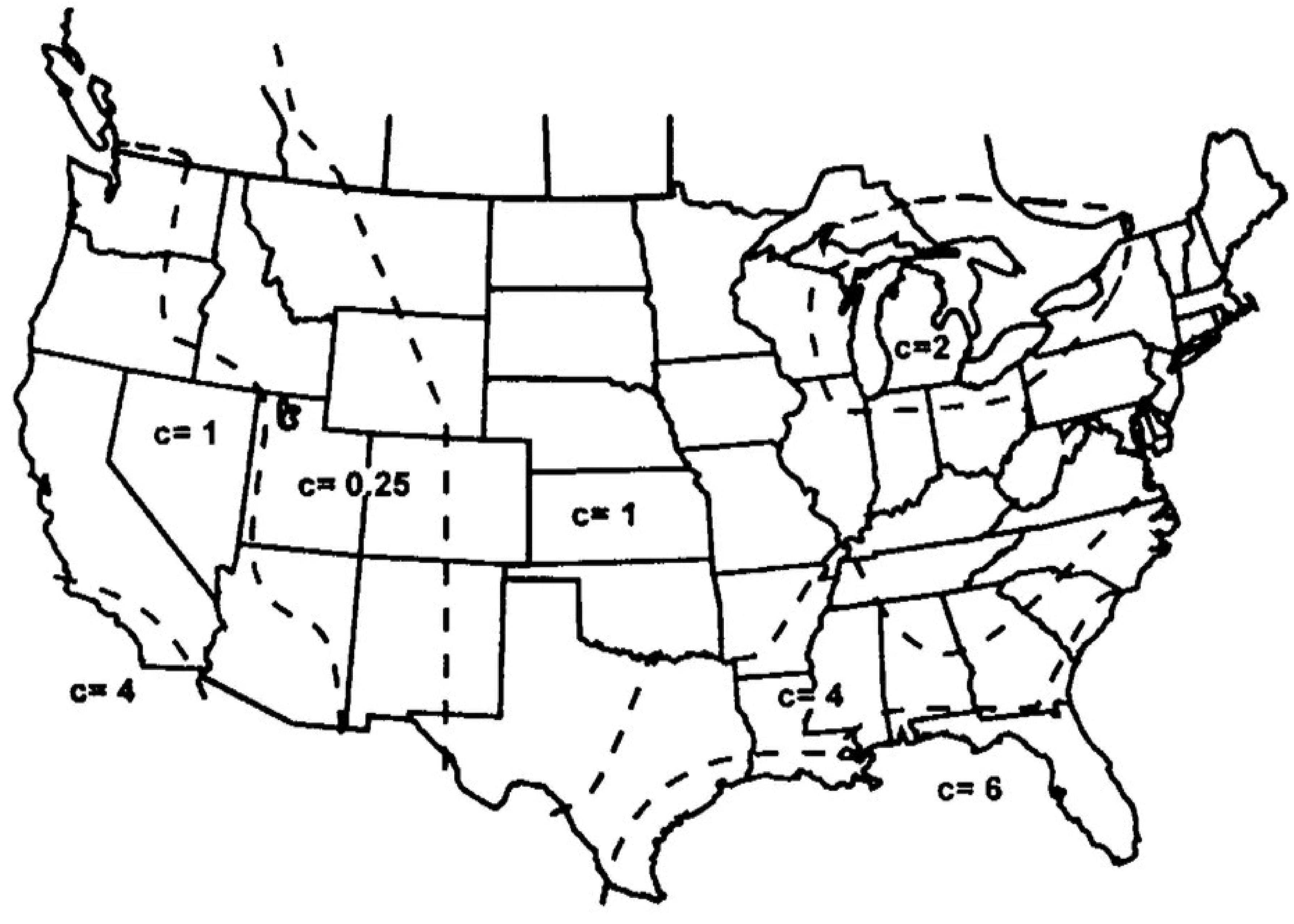


Fig. 1. NA climate-terrain factors, c (U.S.).

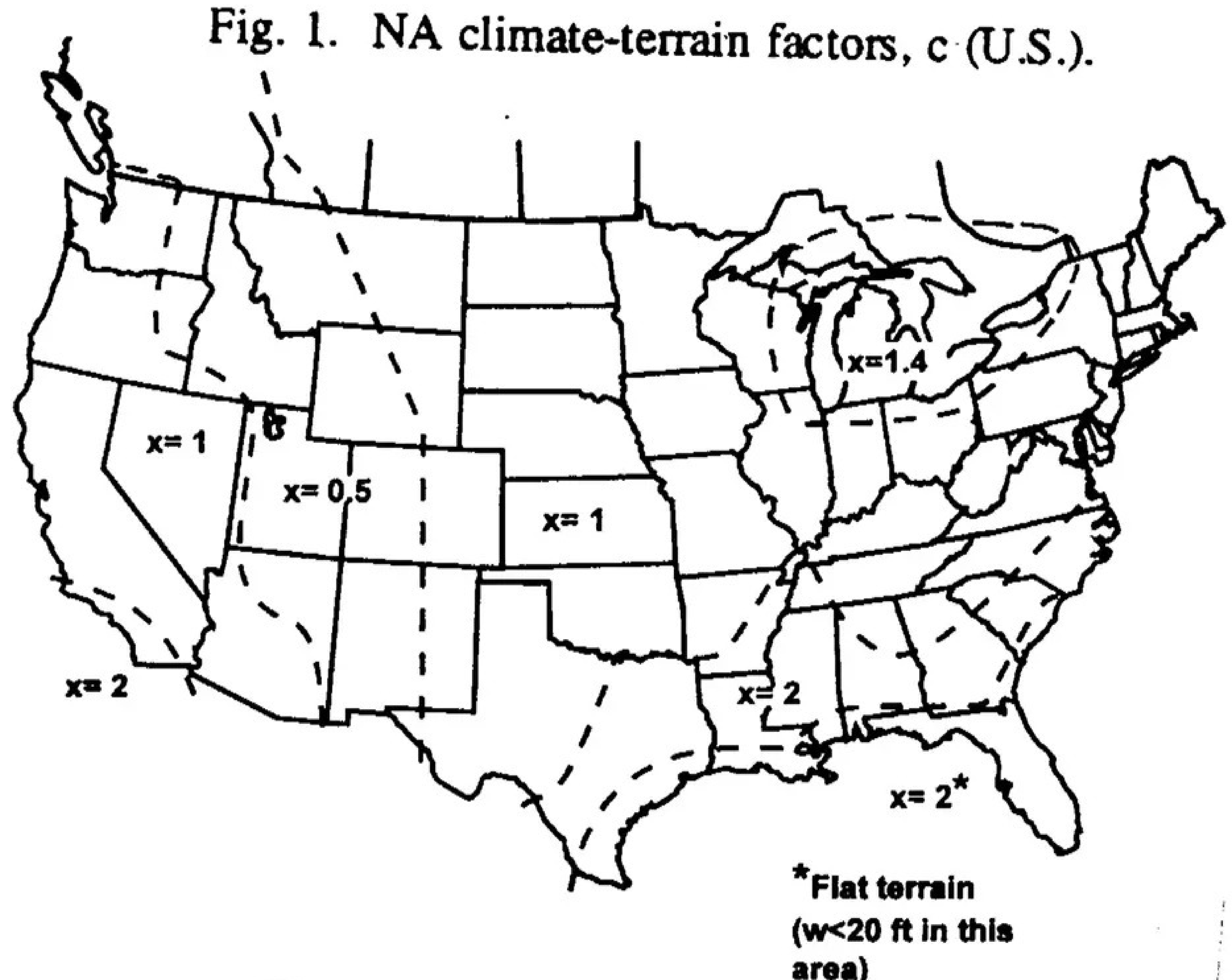


Fig. 2. NA climate factors, x (U.S.).

Therefore

$$T_{ND} = 834 \text{ SES/yr } (99.99735\% \text{ path reliability}).$$

With space diversity (SD), this excessive outage time lowers to 20 SES/yr:

$$T_{SD} = 5.7\text{x}10^3 \text{ c t } D^4\ 10^{-CFM/5}/s^2$$
$$= 5.7\text{x}10^3\ 1\ 50\ 25^4\ 10^{-34/5}/30^2$$
$$= 20 \text{ SES/yr (SD dish separation s = 30 ft).}$$

This SD outage formula may be rearranged to derive the fade margin required to meet a path outage objective (20 SES/yr, in this NA example):

$$CFM = 18.8 - 5 \log (T\ s^2/D^4\ c\ t)$$
$$= 18.8 - 5 \log (20\ 30^2/25^4\ 1\ 50)$$
$$= 34 \text{ db (checks).}$$

CCIR Calculations

In CCIR computations, the fade outage in a digital microwave link, in SES/any month, is (for this same 40 km path):

$$T_{ND} = 2.6\text{x}10^6\ K{\cdot}Q\ f\ D^3\ 10^{-CFM/10}$$

where

T_{ND} = One-way outage, SES/any month
$K{\cdot}Q$ = CCIR climate-terrain factor, $x/S^{1.3}$
x = CCIR climate factor, $2.1\text{x}10^{-5}$ (Table 1)
S = Terrain roughness, 15.2 m
f = 6.7 GHz
D = Path length, 40 km
CFM = Composite Fade Margin, 34 dB.

Therefore

$$T_{ND} = 270 \text{ SES/any month.}$$

Climate Regions	**x (CCIR)**	**x (NA)**
Maritime temperate, coastal or high humidity/temperature	$4.1\text{x}10^{-5}$	2.0
Maritime sub-tropical	$3.1\text{x}10^{-5}$	1.4
Continental temperate or mid-latitude inland	$2.1\text{x}10^{-5}$	1.0
High-dry mountainous	$1.0\text{x}10^{-5}$	0.5
Climate-Terrain Factor (K·Q in CCIR; c in NA)	$x/S^{1.3}$	$x/(w/50)^{1.3}$

Table 1. CCIR climate factors, x, for K·Q computations (and equivalent NA climate factors).

The Model - a Closer Look

If the foregoing NA or CCIR computations meet the user's performance objectives for the link [1], the optimum configuration of the radio equipments and antenna feeder systems is then selected by the transmission engineer. These outage computations are valid only if the fade margin is not degraded by external interference, long-term power fade activity, or antenna misalignment, and that the antenna feeder systems are selected for optimum sizes, heights, diversity spacings, and alignments matched to the path's climatic and terrestrial characteristics. It is the purpose of microwave path engineering to ensure the achievement of this sometimes elusive goal.

Vigants' multipath outage model is universal, with results differing only in the outage period - annual in North American (NA) predictions, and "any month" (usually interpreted as "worst fading month") in CCIR regions (outside of Canada and the U.S.). Whether supporting NA or CCIR, Vigants' outage model yields identical probabilities of outage (U) which, when multiplied times the fade period ($8x10^6$ t/50 sec/fade season in NA or $2.6x10^6$ sec/mo in CCIR), yields the following non-diversity path outage times:

$$U_{ND}\ (NA) = 2.5x10^{-6}\ c\ f\ D^3\ 10^{-CFM/10}$$
$$= 2.5x10^{-6}\ 1\ 6.7\ 25^3\ 10^{-34/10}$$
$$= 0.0001042\ (w = 50\ ft)$$

$$Outage\ (NA) = 0.00010419\ (8x10^6\ t/50)$$
$$= 834\ SES/yr$$

$$U_{ND}\ (CCIR) = K{\cdot}Q\ f\ D^3\ 10^{-CFM/10}$$
$$= 2.1x10^{-5}/15.2^{1.3}\ 6.7\ 40^3\ 10^{-34/10}$$
$$= 0.0001042\ (S = 15.2\ m)$$

$$Outage(CCIR) = 0.0001042\ (2.6x10^6)$$
$$= 270\ SES/any\ month$$

The NA climate-terrain (c) factor is either extracted from the wide area (synoptic) map (Fig. 1) or, preferably, computed from $c = x(w/50)^{-1.3}$ where x is from the wide area climate map (Fig. 2) and w is terrain roughness (limited to a 20-140 ft range) computed from the path profile [3]. In CCIR computations, the Vigants K·Q factor in Table 1 is from the CCIR Rep. 338 table of climate-terrain types ($2.1x10^{-5}$ for "continental temperate climates or mid-latitude inland climatic areas with average rolling terrain", for example) and S (the terrain roughness in m) is (like w, over a 6-43 m range) computed from the path profile [4]. Worldwide K·Q maps are available.

Diversity Improvements

Diversity, usually space but often frequency or hybrid diversity in CCIR regions and some NA electrical utilities, must be added to the microwave link if the non-diversity outage exceeds the user's performance objectives [1]. The reduction in non-diversity outage time is the diversity improvement factor. In North America, the computed SD outage reduction with equal gain ($v^2 = 1$) dishes spaced s = 30 ft is

$$I_{SD} = 7x10^{-5}\ f\ v^2\ s^2\ 10^{CFM/10}/D$$
$$= 7x10^{-5}\ 6.7\ 1\ 30^2\ 10^{34/10}/25$$
$$= 42.$$

The outage time is thus reduced to 834/42 = 20 SES/yr, as previously computed. With frequency diversity (FD), the improvement factor with Δf = 160 MHz (0.16 GHz) is reduced to

$$I_{FD} = 50\ \Delta f\ 10^{CFM/10}/f^2\ D$$
$$= 50\ 0.16\ 10^{34/10}/6.7^2\ 25$$
$$= 18\ (834/18 = 47\ SES/yr\ outage).$$

Similar CCIR improvement factors (and resulting any-month outages) are computed below (s = 9.1 m); hybrid diversity (HD) links use only I_{SD}, ignoring I_{FD}.

$$I_{SD} = 1.2x10^{-3}\ f\ s^2\ 10^{CFM/10}/D$$
$$= 42\ (270/42 = 7\ SES/any\ month\ outage)$$

$$I_{FD} = 80\ \Delta f\ 10^{CFM/10}/f^2\ D$$
$$= 18\ (270/18 = 15\ SES/any\ month\ outage)$$

Outage Model Constraints

It is evident from the foregoing computations that:

- Any loss of fade margin (CFM) due to interference, power fading, antenna misalignment, etc. greatly increases outage time, from x10 (ND) to <u>at least</u> x100 (SD or FD) for a 10 dB loss in CFM.
- Doubling of path length (D) increases multipath outage x8 (ND) to x16 (SD or FD).
- Frequency (f) is irrelevant in SD links; outage time is proportional to f in ND links.
- Outage time (T) is proportional to the annual average temperature (t, NA calculations only) and to the climate-terrain characteristics (c or K·Q).
- Outages due to specular reflections from smooth terrain, exposed bodies of water, etc. are excluded from ND computations and presume optimum dish spacings in SD computations.

The accurate prediction of outage times is thus dependent upon the assignment of path clearances (especially above 3 GHz) adequate to clear atmospheric ducting layers that cause power fading, antenna heights (especially in ND links below 3 GHz) for minimum reflection fading, dish separations for uncorrelative diversity antenna fade activity, and frequency band, dish sizes, and alignments to 1) provide adequate discrimination to multipath and interfering signals and 2) accommodate widely varying incoming ray arrival angles typical of many difficult climatic areas.

Path Clearance Considerations

A half-century accumulation of the fading characteristics of countless analog and digital microwave paths scattered around the world with divergent climatic and terrestrial conditions in all frequency bands and varying path lengths and clearances has established effective top-to-top (main path) clearance rules. These rules apply, of course, to "flat land" microwave links; excessive rather than inadequate clearance is the primary cause of much degraded performance between mountain top sites. The main path in these elevated links is (or should be) between the bottom dishes to maximize CFMs. The diversity paths are then to the top dishes.

The minimum clearances assigned to microwave paths are dependent upon the frequency band, a measure of path sensitivity to ground-based atmospheric boundary layering (ABL), and climate-terrain conditions (c-factor, a measure of the recurrence and severity of the ABLs, as shown in Fig. 1 and Table 1). These criteria are shown below.

Main (Top-to-Top) Path Clearance Rules

Band	Climate-Terrain Factor, c: <2 (good to average)	Climate-Terrain Factor, c: ≥2 (moderate to very difficult)
Above 3 GHz	$0.6F_1$ @ k = 1	F_1 @ k = 4/3 and $0.3F_1$ @ k = 2/3*
Below 3 GHz	$0.6F_1$ @ k = 1	$0.6F_1$ @ k = 1

*If $0.3F_1$ @ k = 2/3 clearance is controlling, diversity protection is usually required.

Diversity (Top-to-Bottom) Path Clearance Rule

All bands	$0.6F_1$ @ k = 4/3	$0.6F_1$ @ k = 4/3

"Blackout" Area Main Path Clearance Rule

Above 3 GHz (>20 mile path)	N/A	k = 1 grazing over a 150 ft ABL

The purpose of these path clearance criteria is the avoidance of long-term fade margin degradations which, at the least, increase short-term multipath fade outage. In some areas, on longer paths above 3 GHz, non-compliance to these clearance rules may even result in the total entrapment, defocusing, or obstruction of the path, thus precipitating a long-term outage [2, 5].

The imminent transfer of some 2 GHz bands from point-to-point service to PCS (PCN), MSS, BAS, and emerging technologies will result in the migration of many private and public (common carrier) links from these stable bands to higher frequencies more vulnerable to performance degradations due to power fading in difficult propagation areas. Many of these displaced links will be upgraded to digital if not SONET or SDH with even more demanding performance objectives imposed by new technologies (LAN, teleconferencing, high speed data transport, ATM, network management including SCADA, and other monitoring and control functions, etc.). Considering this, it is even more essential that the clearances and antenna configurations of these new higher frequency links accommodate the climate-terrain characteristics of the area rather than simply matching that of the more stable existing 2 GHz paths. In difficult areas, clearances on longer paths may have to increase (but could lower in other areas or on short paths), diversity dishes may be added, antennas carefully selected and precisely uptilted and, in very rare cases, path lengths shortened or systems rerouted.

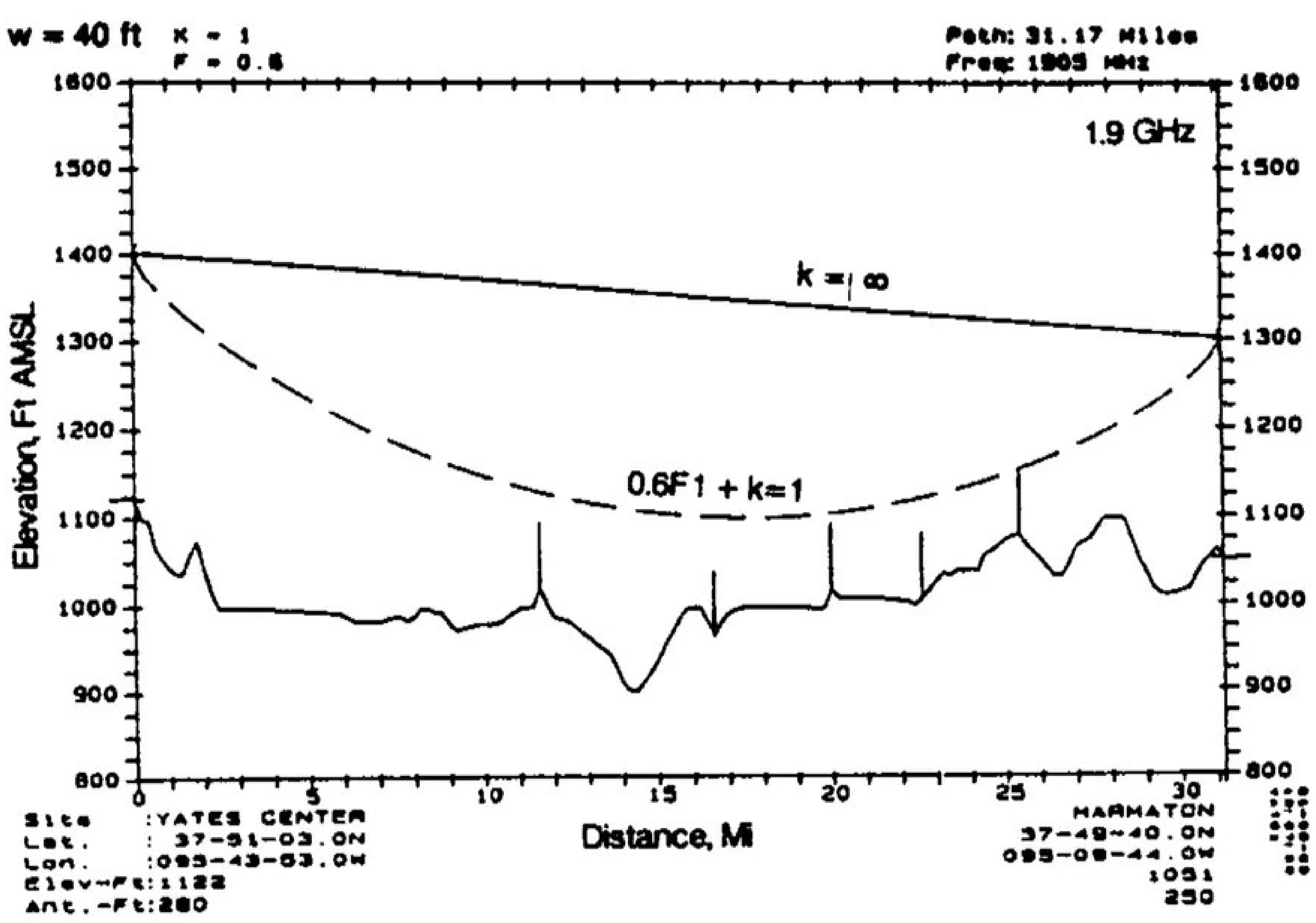
The impact upon the performance of longer (>20 mi) higher frequency (usually 6-8 GHz) paths assigned inadequate clearances in difficult propagation (c≥2) areas cannot be overstated. Substandard (k<1) ABLs often accompany cold fronts, with large temperature drops, over areas with warm surface water. Deep obstruction fades may occur in these areas, causing perhaps hours of severe multipath fade activity and even long-term outages.

In other areas with "microclimates" supporting atmospheric entrapment and defocusing or "blackout" layers, the higher frequency microwave signal is not obstructed, but rather refracted away from the distant antenna or defocused (spread) much like a spot-to-flood beam adjustment on a flashlight. A notorious example of this occurs on a 55 mi microwave link across the English Channel. Even though the main (top-to-top) path met the k = 2/3rds "difficult area" clearance criterion with 800/350 ft main dish heights plus SD dishes 30 ft lower, occasional low-level ABL ducts would obliterate these upper paths. Yet, during this time a normally blocked but now high level stable path existed between a third set of diversity dishes positioned low at their 120/60 ft heights [6].

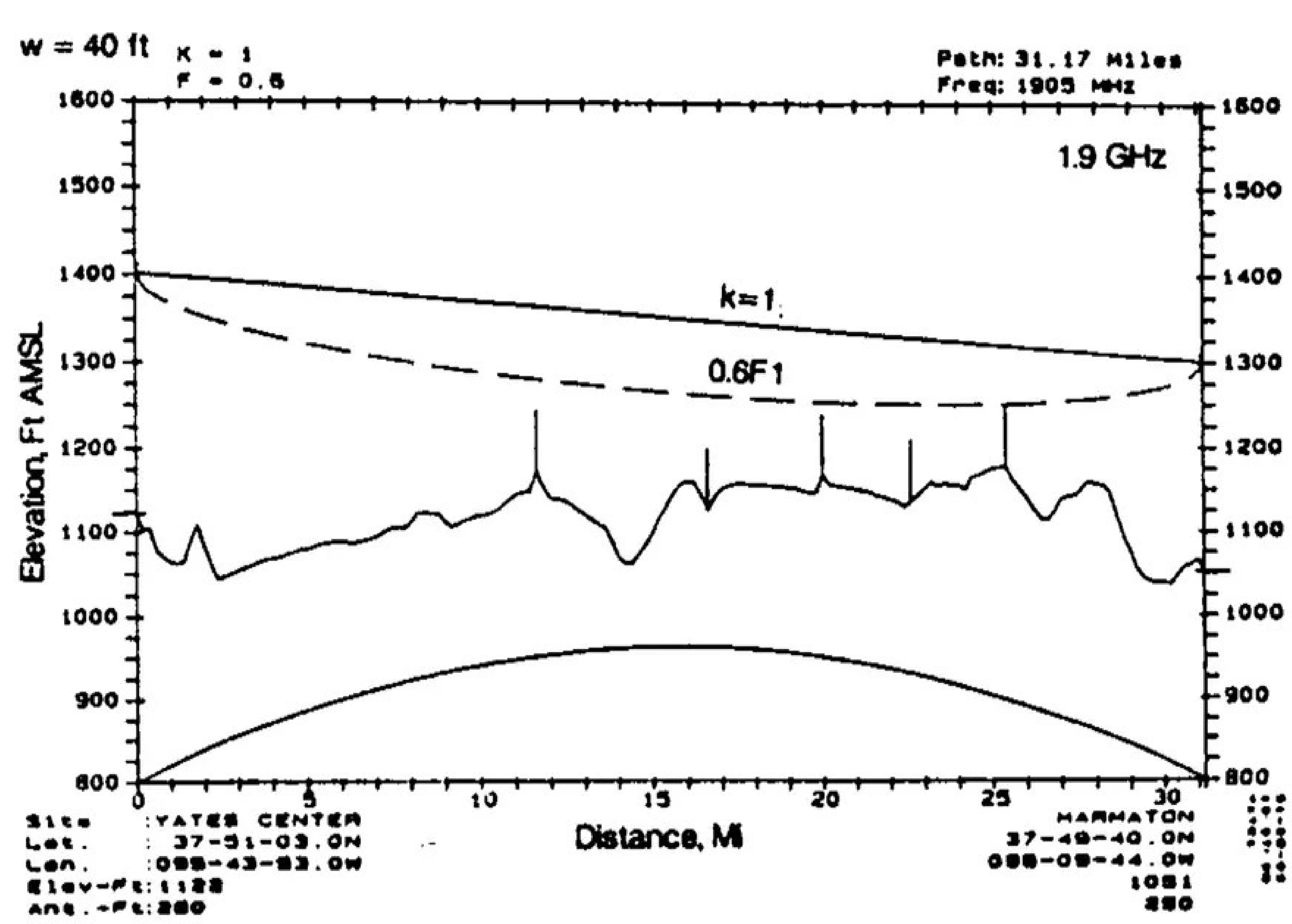
Similar entrapment atmospheres occur, again with a large nighttime temperature drop, over irrigated farmland and swamps, near warm inland lakes, bays, seas and gulfs, and in other areas well known to local microwave link operators. In these areas, some antenna heights have been successfully increased to meet the "blackout" area criterion shown on the clearance rules chart, but only after the incidence of such devastating fade activity was confirmed by operating experience on this or a nearby path similarly configured.

Path Profiles

Antenna heights and diversity dish separations selected to meet the performance objectives are based upon



3a. Flat earth path profile.



3b. True earth path profile.

Fig. 3. Profiles for a $0.6F_1$ @ k = 1 clearance criterion on a 31 mi/50 km path.

accurate, field-verified profles of the microwave path. In many regions, very detailed up-to-date topographic maps show not only swamps, lakes, terrain features, but also buildings, water and oil storage tanks, forested areas, tall "heritage" cottonwood trees grouped around isolated farmhouses, powerlines, and communications towers. With such accurate contour maps, field surveys often focus more on tree heights and densities (with growth), specular reflection zone characteristics, on-path building heights, atmospheric considerations (ducting caused by local ground water - shoreline, lakes, swamps, etc.), existing microwave/VHF sites (for frequencies and zoning), and building codes than on the precise verification of terrain elevations.

Typical field-verified path profiles in Fig. 3a (on "flat earth" $k = \infty$ rectangular paper) and 3b (on "true earth" k = 1 curvature paper) show main antenna heights compliant to a $0.6F_1$ @ k = 1 main path clearance criteria over a 31 mi path. These are plotted from a path profile computer program which, like other available programs, show tree growth, man-made obstructions, Fresnel zone clearances, and earth's curvature (k = 1, k = 4/3, k = 2/3, etc.). One important feature of this and some other profiling programs is the automatic computation of terrain roughness (w, over a 20-140 ft range or S, over a 6-43 m range) that could otherwise be time-consuming. Terrain roughness is an important input to the computation of an exacting climate-terrain factor used in Vigants and other microwave path outage models.

Preliminary path profiles are usually from USGS (or country-equivalent) 7.5 minute (or other) topographic maps; county/province and auto society or other local road maps (often providing urban area details down to street and building names) and aeronautical sectional, local, ONC, etc. charts are important supplements to the topographical maps.

Specular Reflections

Path profiles clearly show those terrain characteristics necessary for assigning antenna heights and diversity spacings. In the absence of flat, exposed, reflective terrain (open farmland, wasteland, swamps) or open water (lakes, shorelines, sea) with no obvious specular (mirror-like) reflection zones, "flat land" (as opposed to mountainous or elevated) paths are assigned diversity spacings adequate to meet the outage objectives (usually about 40, 30, and 20 ft in the 2, 6, and 11 GHz bands, respectively). Vigants' model for flatland path engineering limits diversity spacings to 50 ft as specular reflection fades become increasingly correlated with larger spacings. In the mountains, as on the 60-90 mile (100-150 km) "difficult" inter-island paths in Hawaii, much larger spacings are assigned to accommodate elevated ducting and other atmospheric conditions [5].

Exposed (meaning little terrain blockage or dish discrimination to) specular reflection zones could cause deep multipath fading on each antenna. If the diversity antenna spacing is incorrect, such fading is correlated which increases path outage. Such paths must undergo a geometry analysis, a feature of some newer computer and calculator programs. Harris Farinon's MAGIC and REFL programs are examples.

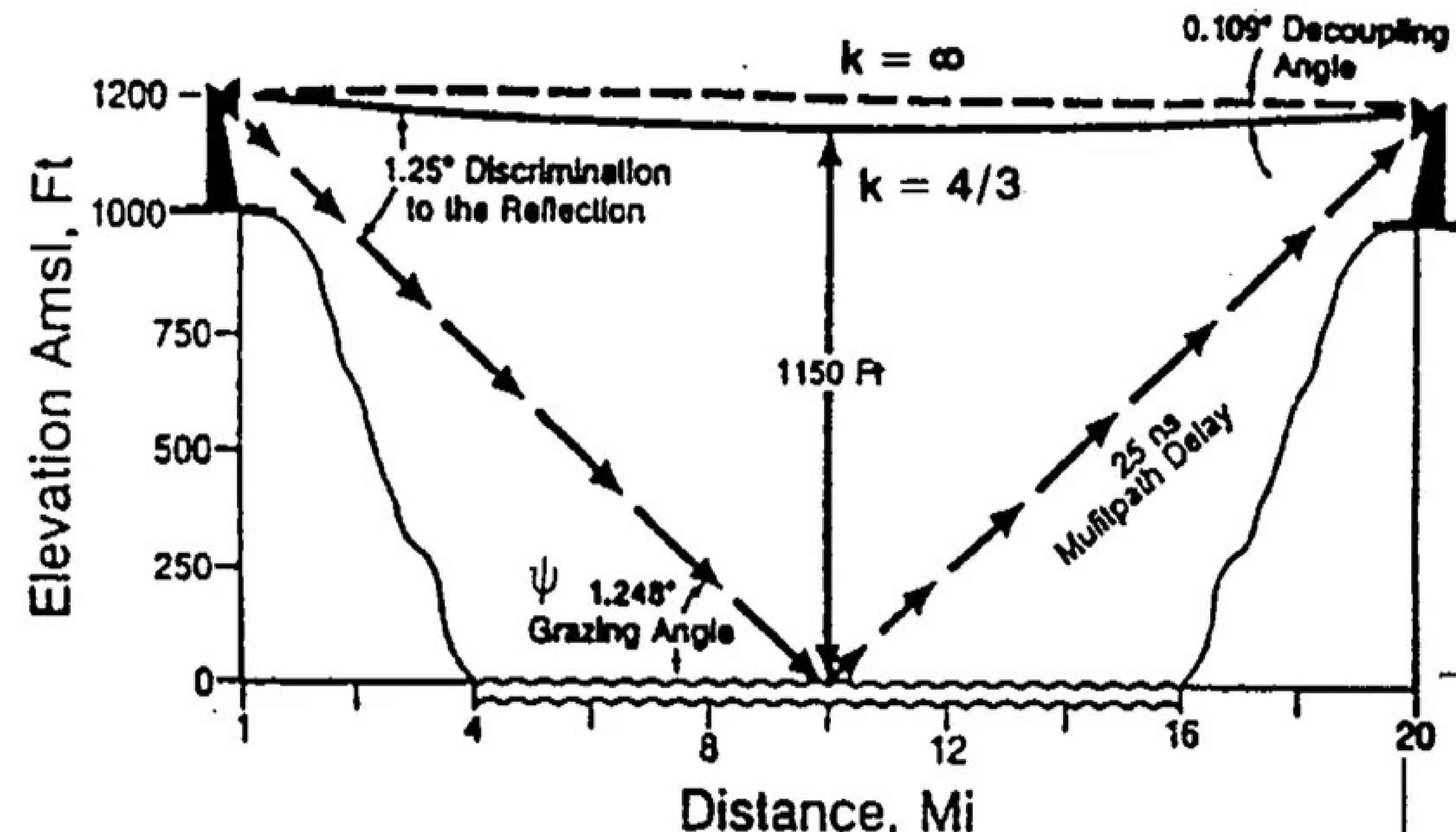
Path Geometry

Very often, path geometry programs are an essential ingredient in the optimum selection of antenna heights, sizes, and diversity arrangements. Harris Farinon's HP41CX/CV (and others, such as the HP48) calculator programs input dish and reflection heights AMSL, path length, frequency, and k-factors (usually k = 4/3 and k = ∞) to derive the following important data (Fig. 4):

- location of the reflection (dish heights?)
- dish discriminations to the reflection (dish sizes?)
- Fresnel zone clearance at the reflection (diversity?)
- reflection grazing angle (V or H pol.?)
- ray height above the reflection zone
- reflected ray delay, nsec (link's DFM?)
- optimum diversity dish separations
- RSL up- or down-fade depth due to the reflection
- arrival angle change with k-factor variations (sizes?)
- obstruction loss vs. terrain ("knife-edge", etc.)

Impressive new computer profile programs now provide not only much of these data, but will "drag" an antenna up and down a tower (with a mouse-controlled cursor) and interactively display a Fresnel interference pattern vs. k-factor (path clearance) below the profile, as seen in Fig. 5.

With these data, precise antenna sizes, heights, uptilt, diversity spacings, frequency band, polarization, adaptive equalization (dispersive fade) countermeasures, and other parameters impacting upon path performance may be optimized. Some of the possible effects upon



English

```
  REFLECTION OR
OBSTRUCTION, K=1.33
  <FT AMSL, MI>

X ELEV=1,200.
R ELEV=0.
  DISTANCE=20.00
Y ELEV=1,200.
  DIST XR=10.00
  DIST RY=10.00
H<R>=1,150.
ANT. DISC. :
  X,DEG=1.248
  Y,DEG=1.248
FREQ=2.000 GHZ
F<N>=101.76

SD DISH SEP:
  SD<X>=18.3
  SD<Y>=18.3
DELAY,NS=25.44
RSL<R=-1>,dB=-11.32
  R,DEG=1.248
```

Metric

```
  REFLECTION OR
OBSTRUCTION, K=1.33
  <M AMSL, KM>

X ELEV=365.
R ELEV=0.
  DISTANCE=32.19
Y ELEV=365.
  DIST XR=16.10
  DIST RY=16.10
H<R>=350.
ANT. DISC. :
  X,DEG=1.246
  Y,DEG=1.246
FREQ=2.000 GHZ
F<N>=101.76

SD DISH SEP:
  SD<X>=5.6
  SD<Y>=5.6
DELAY,NS=25.44
RSL<R=-1>,dB=-11.15
  R,DEG=1.246
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Fig. 4. Geometry sketch and calculator printouts for a short 20 mi/32 km path.

Interactive Computer Path Profile

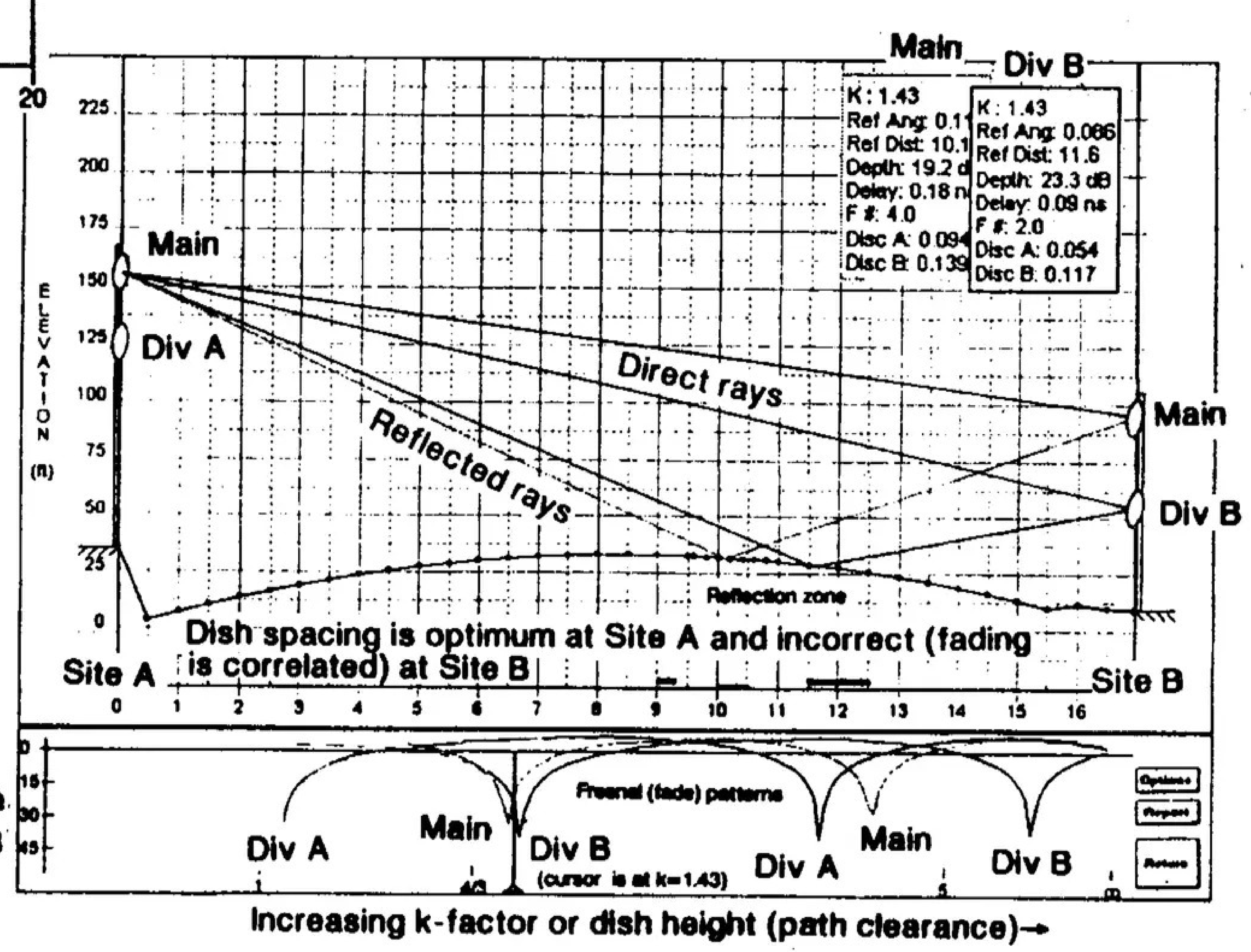


Fig. 5. Computer profile showing the main and diversity antenna Fresnel patterns on a 17 mi/27 km overwater path.

performance if bypassing a geometry study may include the following.

Antenna	Possible Consequence
Too small (for the band)	Inadequate discrimination to the reflection (increased multipath fade outages, degraded DFM)
Too large (and/or not uptilted)	Increased antenna decoupling outages with k-factor variations
Too high	Exposed to the reflection zone
Too low	Possibly obstructed or vulnerable to power fading
Improper diversity dish spacing	Correlated multipath fading and increased outage
Horizontally polarized	Deeper fading compared to V-pol (grazing angle >0.2°)

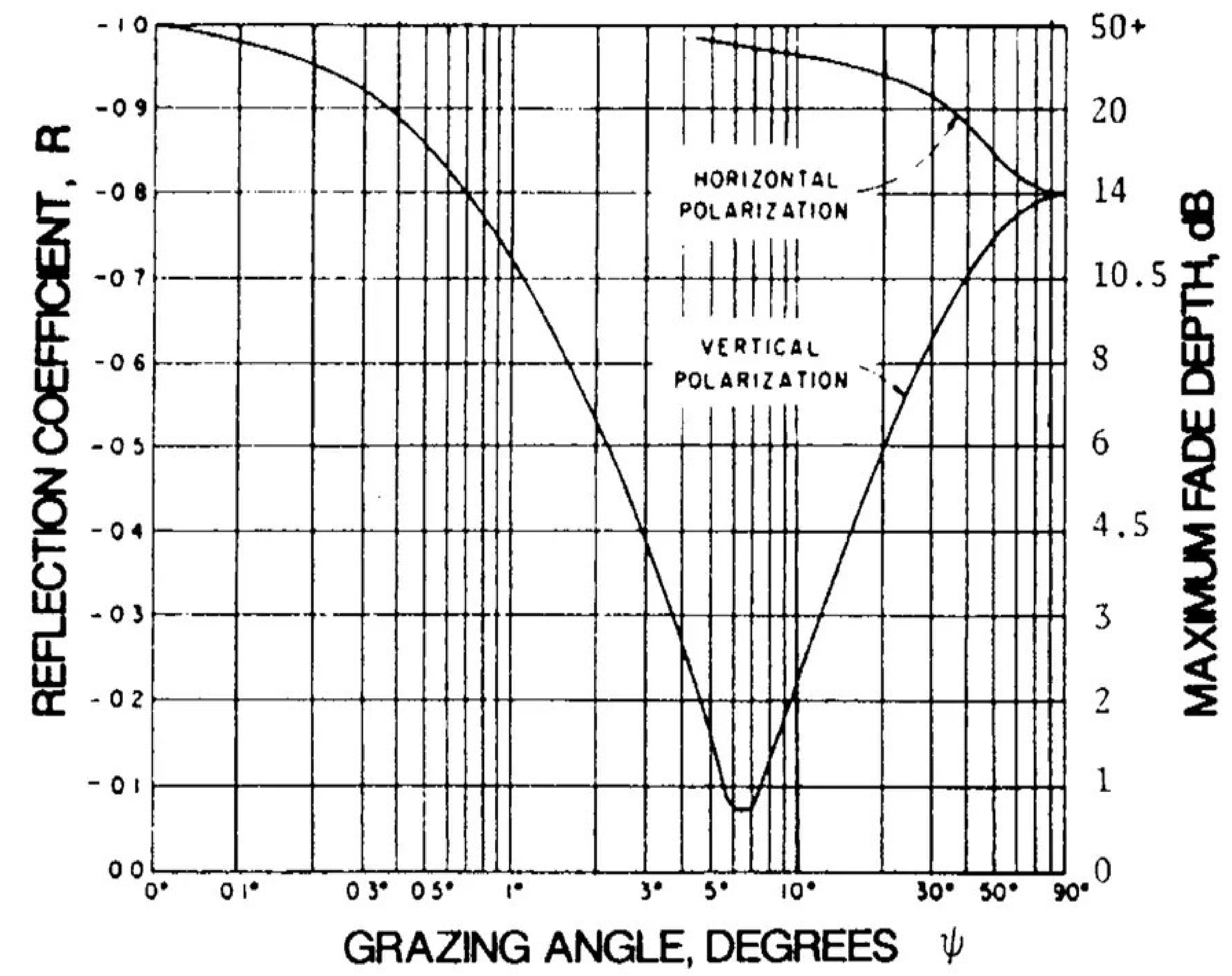
Polarization Selection

While polarization selection (V- or H-pol) is customarily considered a frequency assignment ("prior coordination") function, the performance of certain microwave links is significantly enhanced using V-pol. The two specific configurations for which this is the case is in

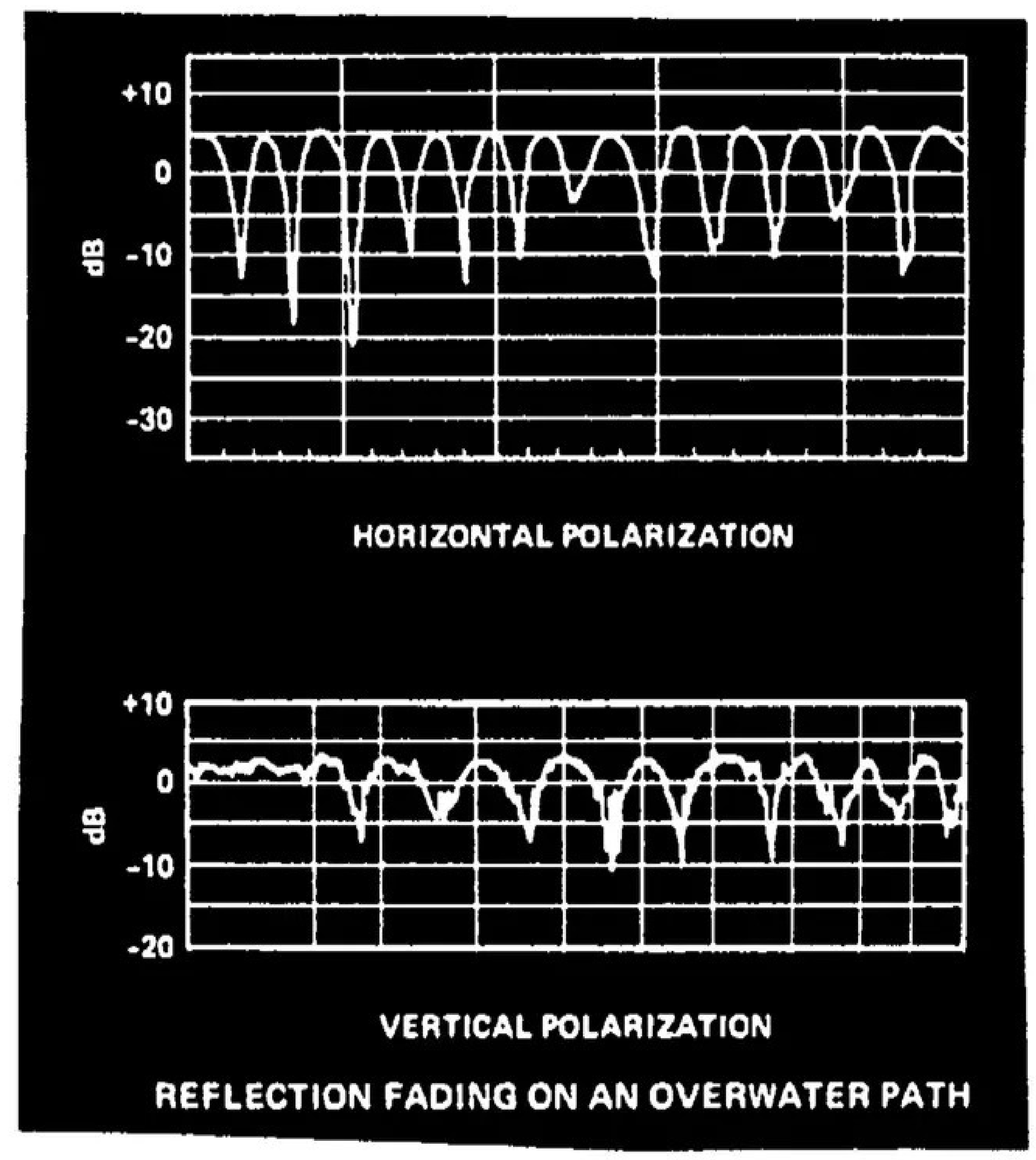
- high frequency (>10 GHz) links, to reduce rain outage ("unavailability") 30-60%, and
- high clearance reflective paths with large (>0.2°) grazing angles, to reduce the reflection coefficient (fade depth).

Intense rain, as often accompanies thundercells, is made up of large drops that are flattened to bean shape (wide horizontal dimension) by air friction. This larger horizontal dimension typically doubles rain outage in high frequency microwave links as compared to vertical. V-pol is thus preferred where rain outage impacts on path availability.

Fig. 6a shows the reduction in the magnitude of the reflection (reflection coefficient, R) as a function of the reflection (grazing) angle at the specular reflection plane. It is not uncommon for the grazing angle on high clearance paths exposed to specular reflections to exceed 0.2°, the threshold of a significant lowering of the reflection coefficient with V-pol. If the path geometry analysis (from REFL or other) computes a 0.4° grazing angle, for example, Fig. 6a shows the -1.0 specular reflection coefficient lowered to -0.9, limiting the fade depth to 20 log $1/(1+R)$ = 20 dB with V-pol compared to >40 dB multipath outage fade depth with H-pol.



6a. Reflection coefficient vs. grazing angle and fade depth, V- and H-pol.



6b. Fade charts, V- and H-pol.

Fig. 6. Reduction of reflection fade depth with V-pol on high clearance paths.

Difficult Digital Microwave Paths

Any microwave path is tagged as "difficult" for digital transmission if it easily supports a high capacity analog link, but severely degrades the performance of a medium to high capacity digital microwave link [5]. Difficult digital microwave links typically have one of the two following characteristics:

- Path is long (perhaps >50 mi/80 km) and supports elevated ducting layers that generate deep, fast multipath fades separated <200 msec between diversity dishes. If the quadrature recovery time of the receiver demodulator is insufficient (e.g. >200 msec), excessive SES path outages may occur.

- Path is short (perhaps <25 mi/40 km) but has high clearance over exposed (little terrain blockage and dish discrimination to) terrain supporting long-delayed (>10 nsec/10 ft) multipath reflections. The resulting narrow amplitude notches may stress the digital microwave spectrum beyond the capability of the adaptive equalizers, causing SES outages and degraded quality (burst ES, high BER, etc.).

Difficult digital microwave path geometry must be identified by the transmission engineer and the path configured appropriately with robust radio equipments and antenna systems optimized for the adverse conditions. As adaptive countermeasures in the receivers improve, so often do the transported bits-per-second payloads, RF bandwidths, and modulation complexities increase to continually challenge the system designer.

Path Calculation Sheets

The more routine transmission engineering function involves the selection of antenna sizes, waveguide types, digital radio system gains, radome types, and other hardware to meet the fade margin and, thus, the path probability of outage (U), annual or any month outage time (T), annual path reliability (%), and path availability (in paths affected by long-term rain outage), objectives for the link. This final configuring of the microwave link is after the frequency band, antenna heights, and diversity spacings have been selected to match climatic and terrestrial characteristics (along with any other constraints on dish sizes and types imposed by interference, tower loading, and mounting space and aesthetics).

All of these data are inputted to a path calculation form, usually interactively with a computer program. As the input data (radio system gain, payload, frequency band, antenna sizes, waveguide types and lengths, polarization, etc.) are modified within the aforementioned constraints, outputted performance and availability results appear on the calculation sheet. With a match of these results to the user objectives, the digital microwave path's transmission design is completed.

Conclusions

Digital microwave path engineering, sometimes described as more of art than a science because of the impact of wide variabilities and uncertainties in nature, has evolved significantly over the years, matching similar achievements in robust medium and high capacity digital microwave radio design. A thorough "proactive" transmission study into the climatic and terrain characteristics of the area, with antenna systems appropriately configured, will eliminate nearly all of the uncertainties involved in meeting user performance objectives.

Acknowledgements

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