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AN ESTIMATE OF HF/VHF SURFACE-WAVE COMMUNICATION LINK REACHES IN THE WEST GERMAN FOREST ENVIRONMENT

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20. ABSTRACT (Continued)

parameters (in particular the antenna design and siting). Since much of Western Europe is forested, we have emphasized the treatment of propagation in a forest environment, a subject that is less well understood and documented than is propagation over open country. The report results indicate that the desired minimum link reach will be substantially exceeded in most cases.

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I. INTRODUCTION

The work described in this report was undertaken to determine the feasibility of using high frequency or very high frequency (HF/VHF) surface-wave communication links to support a nuclear survivable command and control system for NATO forces in Western Europe. HF/VHF surface-wave propagation is considered to be a desirable communications mode because it is not significantly affected by nuclear explosions (as HF skywave would be), and can provide link reaches well beyond line of sight. (The reach is the maximum range at which acceptable communication performance is attained.) These frequencies are also practical for achieving high antenna efficiencies and bandwidths with reasonable antenna sizes, particularly at and above the higher end of the HF band.

In our concept for survivable command and control, the command headquarters are each implemented as several dispersed, highly mobile units or cells. When HF/VHF surface-wave communications are used in such a system, the required communication assets could be completely integral to the cells themselves. Then, the communications would be inherently as survivable as the command and control elements. This is in contrast to alternative systems (which are also of interest) that use airborne or satellite relays that have their own special vulnerability considerations. Note that the HF/VHF surface-wave communications may require relays in many instances, but the notion is that such relaying would be performed by the cells themselves.

HF/VHF surface-wave propagation is not inherently restrictive with regard to the potential range of operating frequencies. (In the case of HF skywave, the ionosphere does introduce such frequency restrictions.) It would be desirable for the cell communications to employ frequency diversity and spread-spectrum techniques to reduce the jamming and signal exploitation (i.e., detection, location, and identification) vulnerabilities

associated with these communications. While the signal processing gains available at HF/VHF are more modest than those achievable at higher frequencies, they are still quite substantial, as has been recognized in a number of recent communication systems developments.

Reach calculations are performed in this report for nominal values of the transmitter power and information data rate. The assumed power is 1 kW, which is consistent with a highly mobile vehicle such as a truck. The assumed data rate of 1 kbps is intended to represent an austere level of intercell connectivity that would be supported by the HF/VHF system in stressful situations in which other communications modes available to the cells had failed. This level corresponds to a few teletype channels per cell (or equivalent computer data transmission) plus a modest relay capability. It will be clear from the development how the reach may be scaled for other values of power or data rate.

Much of Western Europe and in particular Germany is forested. Indeed, we suppose that the command cells might choose at times to locate in or near forested regions. Thus, the effect of forestation on HF/VHF surface-wave propagation is an important consideration in the present study. Although groundwave propagation over different types of open terrain and over the oceans is well understood and documented in the literature, propagation in a forest environment is a less familiar subject and is therefore emphasized in this report.

The desired minimum reach of the HF/VHF link is determined by the expected separation between cells. The cell separation will, of course, vary from case to case. The nominal cell separation may be a function of the distance from the FEBA (forward edge of the battle area). The overall average cell separation will depend on how far down the echelon structure the nuclear-survivable command and control system is conceived

to extend, the necessary number of cells per active command headquarters, and the degree of redundancy provided. In cases of interest, the average separation is typically less than the "nuclear-safe" separation, which is on the order of 10 km. Thus, we suppose that the desired minimum reach be greater than 10 km so that the system is not readily "cut" by nuclear detonations. Of course larger reaches are desirable in order to reduce the degree of relaying required, particularly in regions of the battlefield where the cells are relatively sparse.

Noise levels assumed in our calculations are based on 90 percent reliability and 90 percent confidence levels for atmospheric, galactic and man-made noise. Reach calculations are performed for open country and for two forest-type cases characteristic of West Germany. In the cases with forest we consider a variation in which the transmitting and receiving cells locate themselves in forest clearings in order to increase their reach. We give careful attention to antenna efficiency and bandwidth limitations and discuss an assumed design consisting of a vertical resonant monopole with a circular disc counterpoise (i.e., an artificial ground plane).

The results indicate that the preferred operating frequencies lie in the upper-HF/lower-VHF range. In the cases with forestation, the propagation advantage of lower frequencies is offset by the lower noise levels at higher frequencies. Since we are motivated to avoid the lower HF range for other reasons (including skywave interference, large required antennas, and smaller antenna bandwidth), this is a happy result. As an indication of the calculated reaches, we note that at 30 MHz and with rural man-made noise levels the reach is found to lie between 17 and 52 km, depending on the forest type. These values assume that the cells are in the forest; if instead the cells are assumed to operate from clearings, the

corresponding reaches are 51 and 96 km. The reader is cautioned that in all cases the reaches may be reduced somewhat if there are extensive open country segments along the propagation path, since at 30 MHz the path losses are greater for groundwaves than for surface-waves propagated over the forest. Such mixed path cases are also discussed in the report.

The remainder of this report is organized as follows: Section II presents an overview of those factors that influence the performance of an HF/VHF surface-wave communications link and discusses the choice of the link design parameters, in particular the operating frequency. The third section treats the subject of surface-wave propagation, with emphasis on the effects of a forest environment. Section IV discusses the effects of antenna design and siting on link performance. In Section V we combine the various factors to obtain estimates of the link reach as a function of frequency for various propagation and noise conditions. Conclusions and recommendations for further work are presented in Section VI.

II. LINK DESIGN CONSIDERATIONS AND ASSUMED PARAMETERS

Table 1 lists the nominal link design parameters and constraints that were used in our reach calculations. The 1-kW transmit power at the antenna terminals implies a slightly larger transmitter power decreased by the usual line losses. The 1-kbps data rate was discussed above. Since this rate includes any overhead bits used for error control or other functions (e.g., headers used in network routing), the actual useful information rate will be somewhat lower than this. The bit error rate prior to any error detection and correction is taken to be 10^{-3} , which requires an 11-dB signal-to-noise ratio in Gaussian noise if FSK modulation and noncoherent detection are assumed. Since actual atmospheric and man-made noise is bursty rather than Gaussian, available processing approaches will be required to attain a comparable error rate at this signal-to-noise ratio.

In order to allow for the implementation of some spread spectrum capability, we assumed that a broad-band antenna would be used. The 1-MHz minimum bandwidth corresponds to a 30-dB processing gain relative to a 1-kbps data rate. This processing gain is a nominal measure of the antijamming advantage of the system against a barrage noise jammer that jams the full spread-spectrum bandwidth. The actual antijamming advantage will depend on the jamming technique employed and the robustness of the signal modulation/reception scheme.

The broad antenna bandwidth requires an antenna length comparable to a quarter-wavelength ($\lambda/4$) for a monopole or $\lambda/2$ for a dipole. We assume a resonant vertical monopole is used. Vertical polarizations generally are preferred for forest propagation and invariably are required for groundwave propagation. As discussed at length below, a counterpoise is desirable to avoid the excessive losses that would otherwise

TABLE 1. LINK DESIGN PARAMETERS AND CONSTRAINTS

Parameter	Value	Remarks
Transmit power	1 kW	At antenna terminals
Data rate	1 kbps	Gross rate including any overhead bits
Bit error rate	10^{-3}	Requires $S/N = 11$ dB in Gaussian noise
Antenna bandwidth	> 1 MHz	For spread spectrum
Antenna height	< 50 ft	To enhance mobility
Antenna type	--	Resonant monopole with counterpoise
Frequency	> 5 MHz	Based on antenna constraints
Polarization	Vertical	Generally superior to horizontal

occur in the ground beneath the antenna. If the antenna is mounted on top of a truck, then the counterpoise may be integrated with the truck top. Also the resulting antenna base height itself would tend to decrease the ground losses.

The 50-ft maximum antenna height was assumed to enhance the cell mobility. We recognize that this height is not really mobile in the sense of permitting operation while on the move (particularly in a forest environment). However, a telescoping antenna of this height could be readily obtained and could be erected when the cell is stationary. For operation on the move, a reduced height would be necessary (unless the selected wavelength already permitted a relatively short antenna height), at some sacrifice in performance. For a $\lambda/4$ monopole, this antenna height restriction implies a 5-MHz minimum operating frequency.

We have already alluded to several factors that would affect the choice of operating frequency. Several such factors are summarized in Table 2. Since propagation losses increase rapidly as the frequency is increased, one might expect the lower frequencies to be preferred for system operation. However, ambient noise decreases rapidly with increasing frequency and, for forest propagation, the noise decrease compensates for the loss increase, eliminating any advantages of the lower frequencies. In the case of open country propagation, the loss increases more rapidly and thus dominates the effect of decreasing noise. These variations are treated in detail in the following sections.

From the point of view of antenna requirements, the higher frequencies are best since the required antenna length for a given performance is simply proportional to the wavelength. A resonant monopole, when driven from a matched transmitter power amplifier, provides a 3-dB bandwidth that is as much as 30 percent of its resonant frequency, while operating

TABLE 2. SUMMARY OF FREQUENCY TRADEOFFS

Tradeoff factor	Effect
Propagation losses	Loss increases with frequency as f^4 in forest; faster over open country.
Noise power	Decreases rapidly with increasing frequency; more rapidly for atmospheric noise than for other sources.
Antenna size	Required length decreases with increasing frequency for fixed performance.
Antenna efficiency	Better than 80 percent for resonant monopole; decreases at 6 dB/octave for decreasing frequency or height.
Antenna bandwidth	Approximately 30 percent for resonant monopole; decreases as f^3 below resonance.

with typical efficiencies better than 80 percent. If employed below resonance, a monopole antenna loses bandwidth rapidly unless the antenna is externally loaded to decrease its Q. This approach drastically reduces the antenna efficiency. Also, while electrically short antennas can be tuned to provide reasonable efficiency, only an antenna that approaches the resonant length can simultaneously provide high efficiency and wide bandwidth. Some antenna length decrease is possible with little penalty through end-weighting techniques, but these details need not concern us here.

An additional factor that should be mentioned is electromagnetic compatibility of the contemplated system with other military and civilian systems. At frequencies below about 20 MHz there are many users of HF skywave channels. In the VHF band above 30 MHz we find many battlefield radio systems both existing and planned (e.g., VHF SINCGARS). Thus, the 20- to 30-MHz band would appear attractive from the compatibility point of view. More research needs to be done on this issue, in particular for the European environment of interest.

III. EFFECT OF THE FOREST ENVIRONMENT

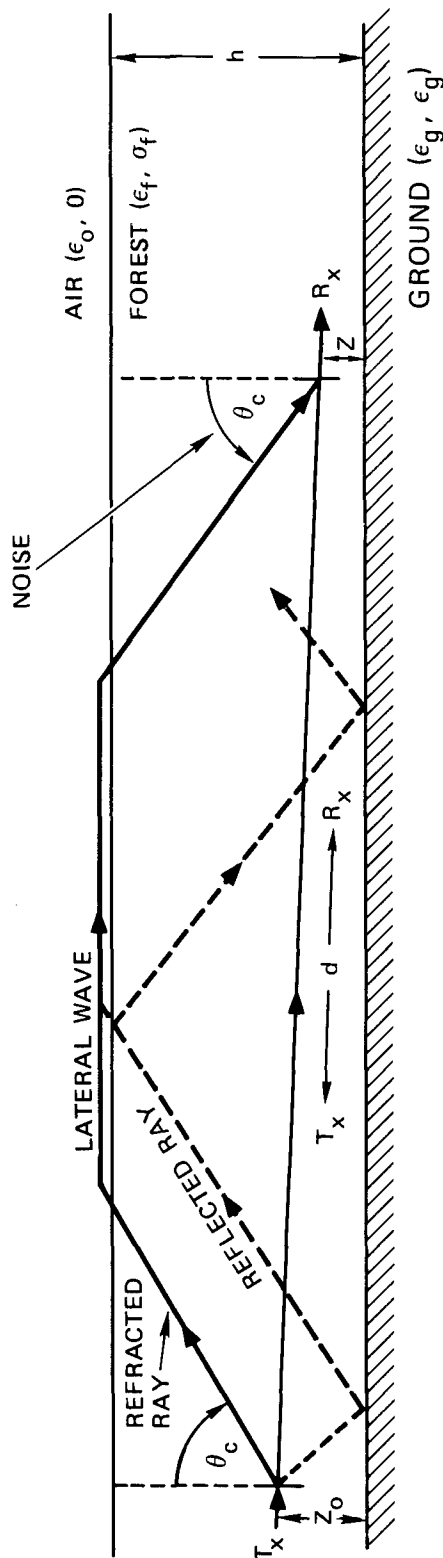
1. SOME HISTORICAL NOTES

During the Vietnam War, it was found that the HF/VHF reach in the heavily forested environment of Vietnam and other Southeast Asia areas was much less than the reach obtained with the same HF/VHF equipment in more open country. In an effort to gain a better understanding of HF/VHF propagation in a forest environment so that reach could be predicted for such environments, the Defense Advanced Research Projects Agency (DARPA) initiated Project SEACORE (Southeast Asia Communications Research) (Ref. 1). The objective of Project SEACORE was to characterize quantitatively the propagation and environmental factors of forested areas that determine the reach of HF and VHF communications links in those areas. As a part of Project SEACORE, Jansky, Bailey and others gathered a large amount of propagation data under well-defined experimental conditions in different types of forest areas in Southeast Asia.

Also under DARPA/SEACORE sponsorship, an effort was initiated to develop a model for estimating HF/VHF propagation loss in a forest environment. Of the several different models attempted, the one developed by Tamir and Dence (Refs. 2 and 3) during 1967 to 1969 has been accepted as the model most accurately characterizing the phenomena involved in such propagation. Propagation losses predicted using the Tamir model agree well with the experimental data taken by Jansky, Bailey and others (Refs. 4 and 5).

2. THE DIELECTRIC SLAB MODEL

The Tamir model characterizing electromagnetic propagation in a forest environment can be described by referring to Figure 1. Tamir views the forest as a lossy dielectric slab



- T_x AND R_x ANTENNAS ARE SHORT VERTICAL DIPOLES
- CRITICAL ANGLE OF REFRACTION, $\theta_c = \sin^{-1} \frac{1}{n_f} \approx \sin^{-1} \frac{1}{\sqrt{\epsilon_f}}$
 $\theta_c = 75^\circ$ FOR AN "AVERAGE" FOREST

- PROPAGATION LOSSES FOR LATERAL PROPAGATION MODE:

$$\text{TOTAL LOSS, } L_T = L_0 + L_s + L_i + L_r$$

L_0 = INITIAL LOSS, L_s = SEPARATION LOSS

L_i = INTERFERENCE LOSS, L_r = ANTENNA LOSS

Figure 1. Tamir's propagation model for a forest environment viewed as a lossy dielectric slab.

characterized by the forest's relative dielectric constant, ϵ_f , and its conductivity, σ_f . These two factors determine the complex index of refraction of the forest dielectric slab, n_f . The dielectric constant of the forest is greater than that of the air above the forest. Thus, Snell's law defines a critical angle θ_c for refraction at the air-forest interface. That is, electromagnetic energy propagating upward from an antenna within the forest medium along a ray path whose angle relative to the vertical is equal to the critical angle, θ_c , will be refracted and follow a ray path parallel to the forest tree tops in the forest-air interface. Tamir defines this tree top propagation as a "lateral-wave" mode. As shown in Figure 1, energy from the lateral wave is also refracted downward into the forest at the same critical angle to a receiving antenna embedded within the forest. The attenuation of electromagnetic energy propagated along the lateral-wave ray path is much less than that experienced by energy propagated along the direct ray path between the transmitting and receiving antennas, which suffers the exponential losses caused by the lossy forest dielectric slab along its entire path. Also, the path followed by the lateral wave suffers much less attenuation than waves which are reflected at the forest-to-ground and/or forest-to-air interfaces. Therefore, the lateral-wave mode is the dominant mode of propagation in the forest environment, at least for paths longer than about 1 km.

Tamir decomposes the total propagation loss for the lateral-wave mode into four components. The first of these results from attenuation within the foliage itself. The distances of the antennas below the forest canopy, in conjunction with the critical angle, determine the path lengths through the foliage that the ray forming the lateral wave must follow to reach the forest canopy and to reach the receiving antenna when refracted downward into the foliage. Tamir defines the combined losses along these two paths as the separation loss, L_s .

The propagation loss experienced by the lateral wave as it propagates along the forest canopy in the forest-air interface is defined by Tamir as the initial loss, L_o . Tamir defines a third type of loss as an interference loss, L_i , which is caused by the reflected ray interfering with the lateral ray as shown in Figure 1. This loss is appreciable only when the antennas are near the ground so that the path-length of the reflected ray through the foliage to the ground and up to the canopy is comparable to the distance along the critical ray path, making the amplitude of the reflected wave at the canopy nearly as large as that of the refracted ray.

The last type of loss necessary to characterize the total propagation loss from the transmitter antenna input to the receiving antenna output is an antenna input resistance loss, L_r , caused by the proximity of the antennas to the imperfect (lossy) ground plane of the forest floor. (Tamir assumes short vertical dipole antennas for his model.) Thus, the total propagation loss, L_t , for the lateral-wave mode is given simply by the sum of the four individual losses described above; that is, $L_t = L_s + L_o + L_i + L_r$.

3. CHARACTERISTIC FOREST PARAMETERS

Table 3 defines three forest types in terms of the parameters that determine the propagation losses. These parameters are the relative dielectric constants and the conductivities of the forest (ϵ_f, σ_f) and the forest ground (ϵ_g, σ_g), and the nominal tree height (h). The three types are referred to, following Tamir, as "thin", "average", and "dense." The parameter values are based on the experimental measurements performed in forests of Southeast Asia as part of Project SEACORE.

The "thin" forest is described qualitatively as a thinly vegetated area with short trees over poorly conducting soil, while the "dense" forest is a thickly vegetated area with

TABLE 3. FOREST CHARACTERISTIC PARAMETERS (PER TAMIR)

	PARAMETER	"THIN"	"AVERAGE"	"DENSE"
FOREST	ϵ_f (RELATIVE DIELECTRIC CONSTANT)	1.03	1.1	1.3
	σ_f (CONDUCTIVITY)	0.03	0.1	0.3 MMHO/METER
	h (TREE HEIGHT)	5	10	20 METERS
GROUND IN FOREST	ϵ_g	5	20	50
	σ_g	1	10	100 MMHO/METER

- THE ABOVE VALUES ARE BASED ON MEASUREMENTS MADE IN TROPICAL ENVIRONMENTS BY JANSKY AND BAILEY, AND PARKER, HAGN AND MAKARABHIROMYA
- "THIN" IS A THINLY VEGETATED AREA WITH SHORT TREES OVER POORLY CONDUCTING SOIL
"DENSE" IS A THICKLY VEGETATED AREA WITH TALL TREES OVER GOOD CONDUCTING EARTH
- WEST GERMAN FORESTS FALL BETWEEN "THIN" AND "AVERAGE" FOR ϵ_f AND σ_f , BUT HAVE AN AVERAGE HEIGHT OF 20 METERS

tall trees over good conducting soil. The "average" forest is an intermediate case for which the parameter values are characteristic of a forest region in which extensive SEACORE measurements were made. Reference 6 states that the forests of West Germany fall between Tamir's "thin" and "average" forests in terms of the parameters ϵ_f , ϵ_g , σ_f , and σ_g . However, the average tree height for the German forests is 20 m, equal to that of Tamir's "dense" forest.

4. THE INITIAL LOSS

Figure 2 shows how the initial loss, L_o , varies with frequency at a distance of 1 km for the three types of forests, as derived from the equation which defines L_o in decibel units:

$$L_o = 20 \log \left[\frac{8}{3} \pi^2 |n_f^2 - 1| (d/\lambda)^2 \right].$$

This equation shows that the power loss (in linear units) varies directly as the 4th power of distance, d , between transmitter and receiver, and also directly as the 4th power of frequency. The dependence on forest type is given by the $(n_f^2 - 1)$ term, where n_f is the complex index of refraction of the forest. This index is in turn defined in terms of the forest electrical parameters, ϵ_f and σ_f , as

$$n_f^2 = \left[\epsilon_f - j \frac{\sigma_f}{\omega \epsilon_o} \right]$$

where ϵ_o = dielectric constant of air,

$\omega = 2\pi f$,

f = frequency of interest.

The 4th power dependence of L_o on distance means that the reach at any given frequency doubles for a 12-dB decrease in total path loss, or for a 12-dB increase in received signal-to-noise ratio, power, and so forth.

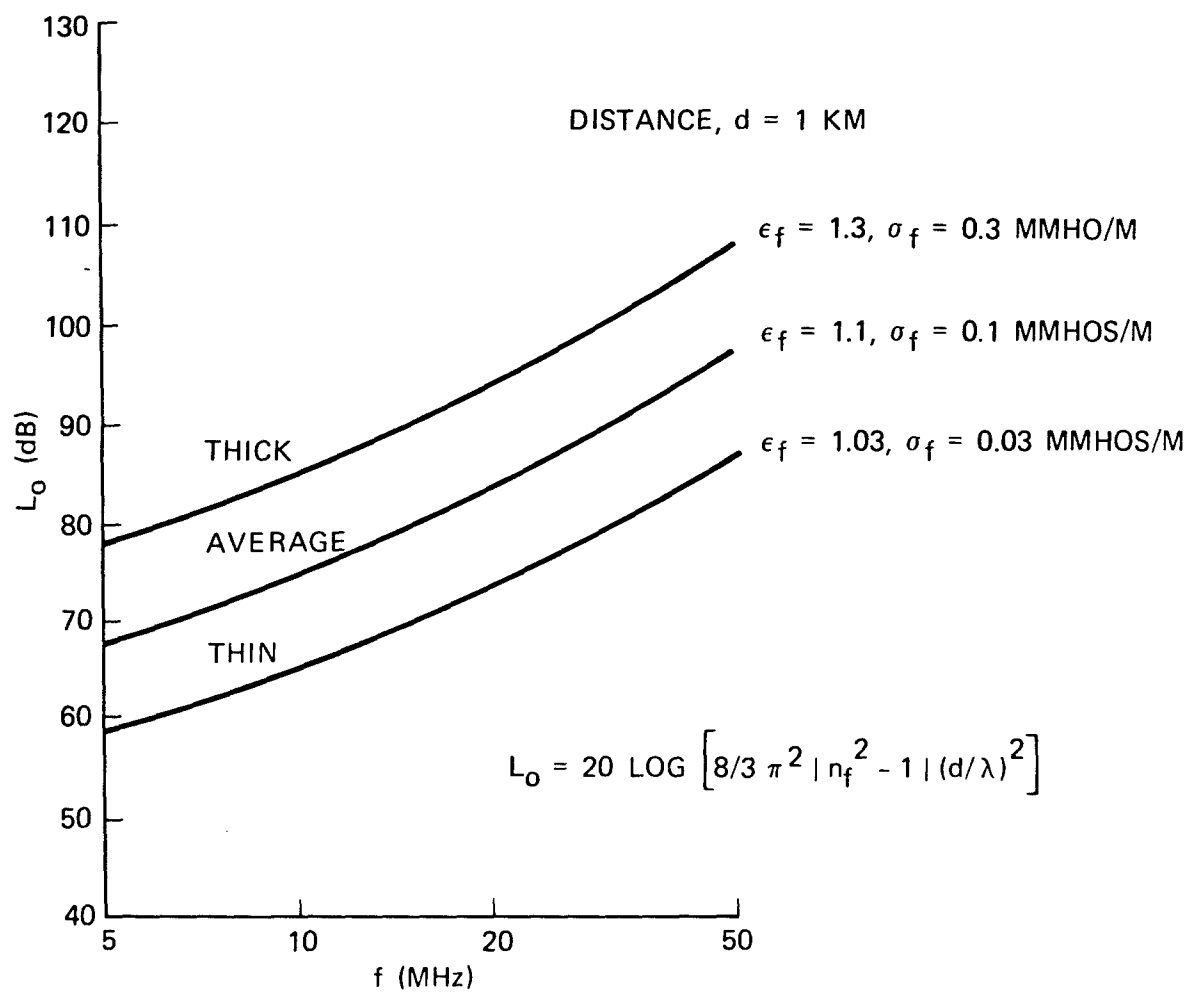


Figure 2. Initial loss vs frequency.

5. THE SEPARATION LOSS

Figure 3 shows how L_s varies with frequency for the three types of forests. Note that the attenuation factor α increases with frequency and also with forest density. Also note that L_s depends only on the heights from the two antennas to the forest canopy ($2h - z - z_o$), and not on the lateral separation between antennas.

As an example of how much L_s may contribute to the total path loss, assume that $f = 10$ MHz and we have a "dense" forest 20 m in height. Then we find that $\alpha = 0.7$ dB/m. With antennas 1 m above the ground ($z = z_o = 1$ m), $S = 2h - z - z_o = 38$ m and $L_s = \alpha S = 26.6$ dB. Since reach decreases by a factor of two for each 12 dB of path loss, in this example L_s would reduce the reach to less than a quarter of what it would be if the antennas were raised to the forest canopy (in which case L_s is zero).

6. THE INTERFERENCE LOSS

Figure 4 shows how this loss varies with frequency for an "average" forest for a short vertical dipole antenna at a height, z , of 1 m above the forest floor. Note that L_i is a negative loss (that is, a gain) over the entire frequency band for this particular case where the antenna is only 1 m above ground. This is because the reflected wave from the ground travels only a slightly longer path in reaching the forest canopy than the refracted wave forming the lateral wave, resulting in constructive interference. For antenna heights greater than a few meters, the additional attenuation suffered by the reflected wave negates the interference effect. Even for a 1-m antenna height, the effect of L_i is negligible for frequencies above 10 MHz.

7. THE ANTENNA RESISTANCE LOSS

Figure 5 shows how L_r varies with frequency for the case of a short vertical dipole 1 m above the forest floor in an "average" forest. This loss is caused by currents induced

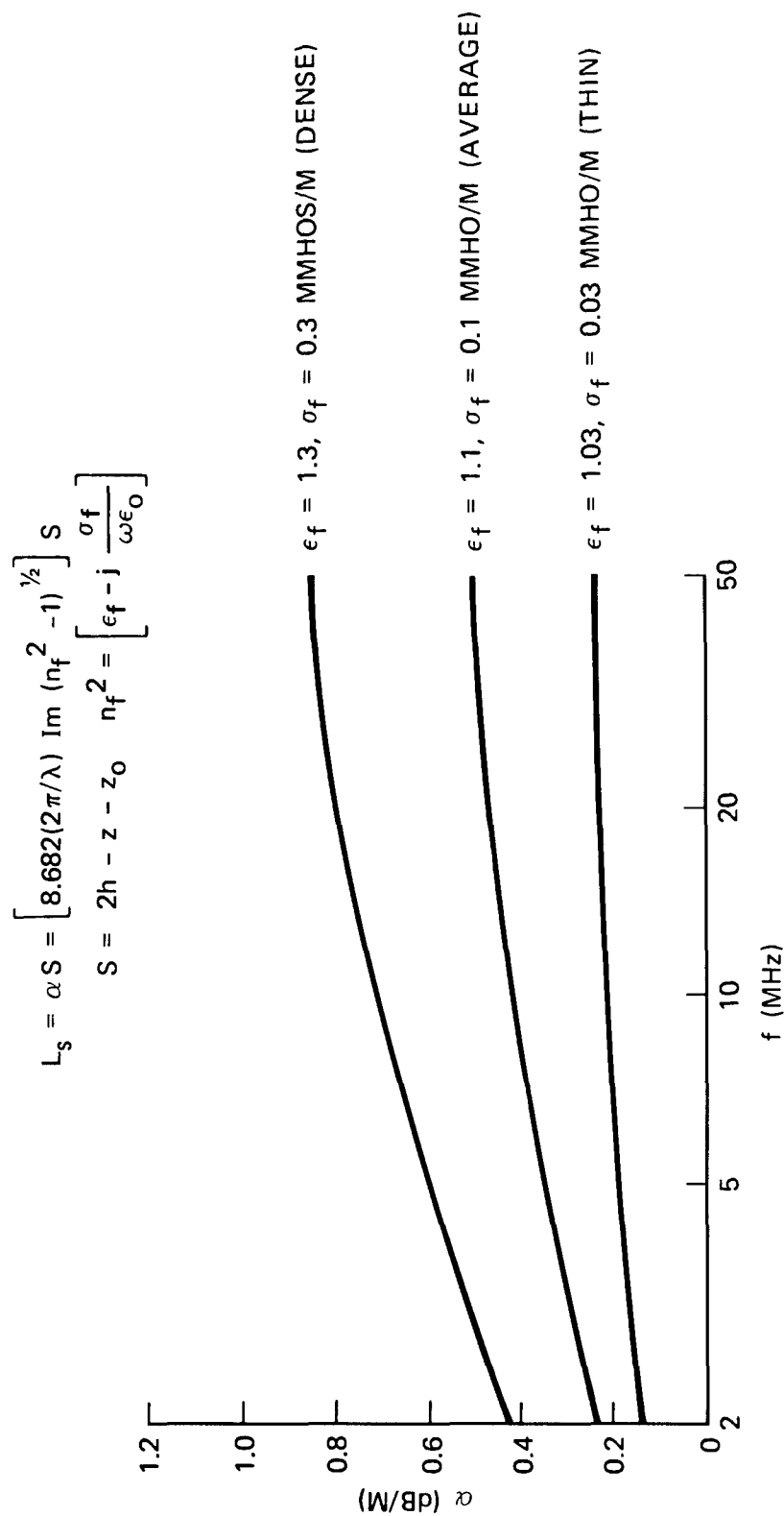


Figure 3. Separation loss vs frequency.

$L_i = 20 \log |F(z)|$
 $F(z)$ IS A FUNCTION OF n_f, n_G, z, h

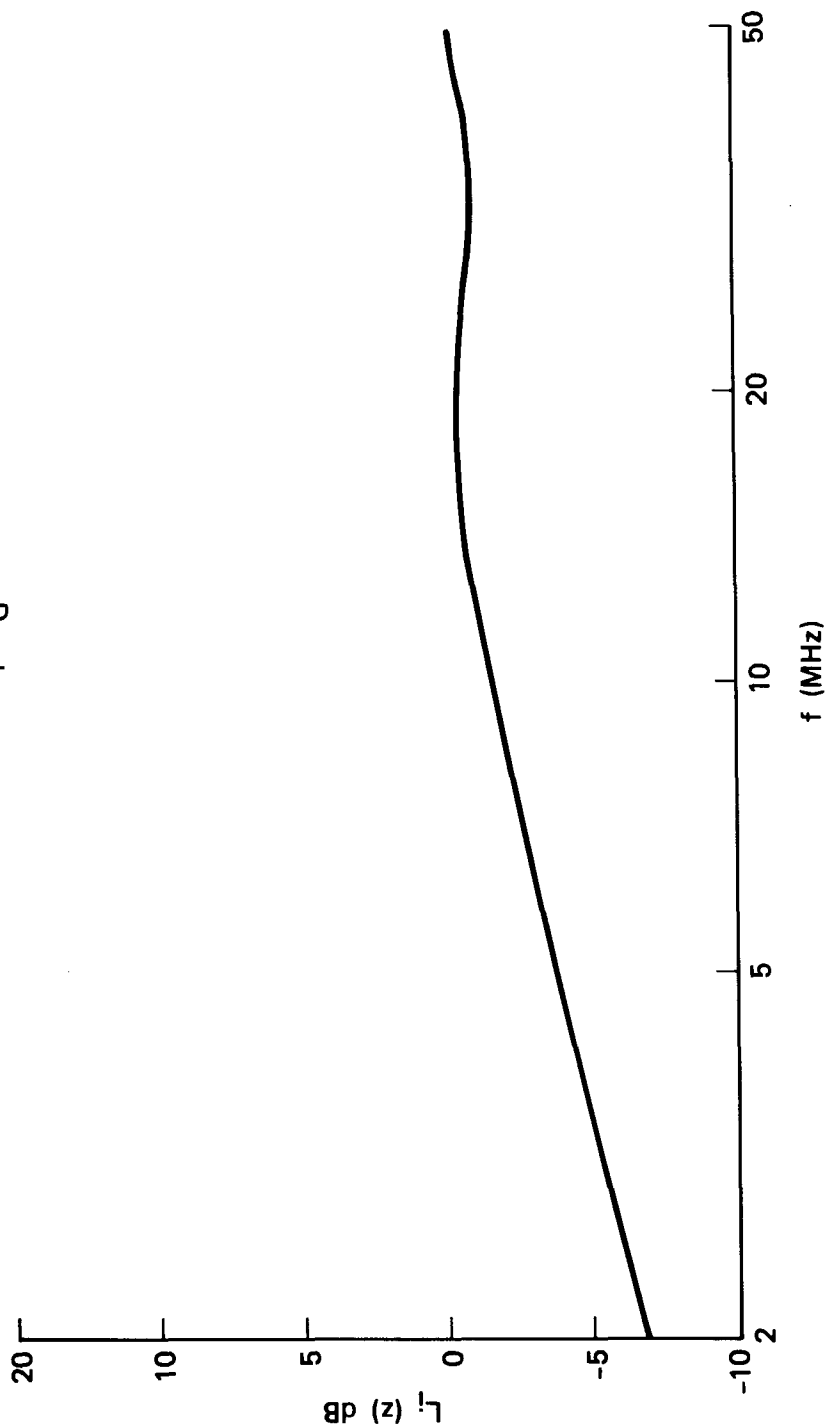


Figure 4. Interference loss vs frequency for one vertical dipole at a height $z = 1$ m above ground in an "average" forest.

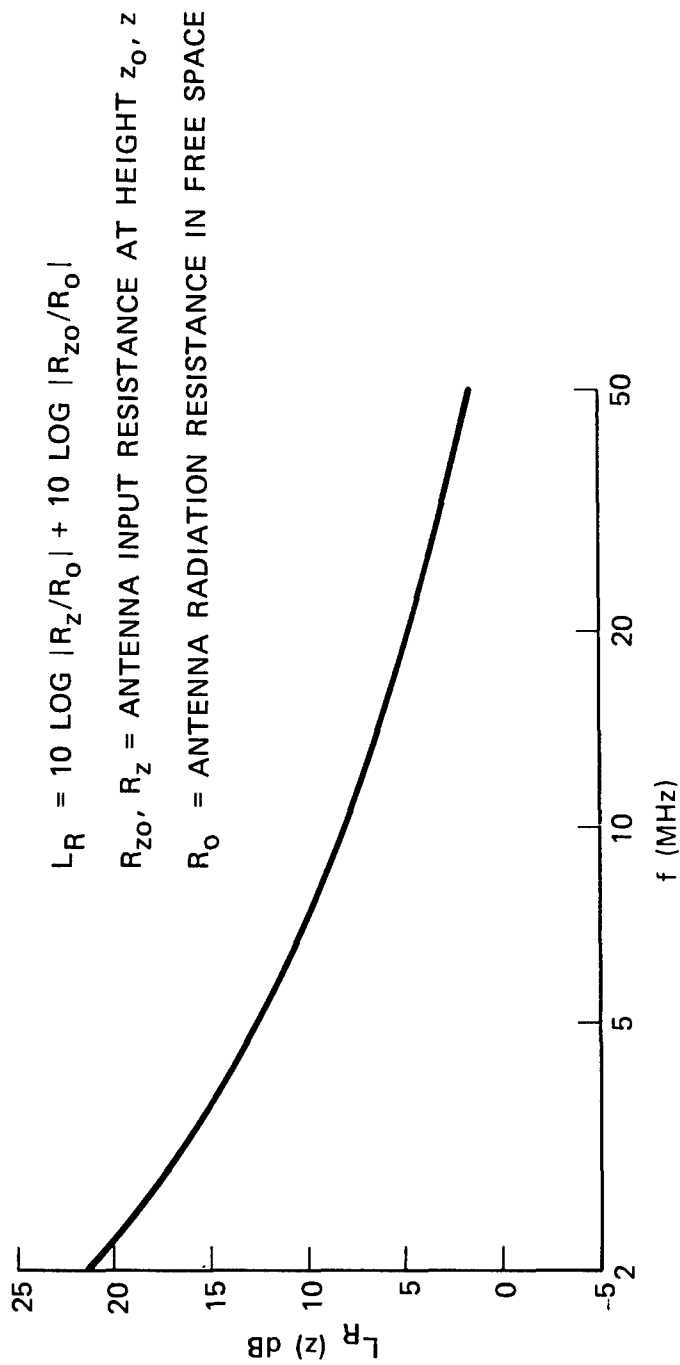


Figure 5. Antenna resistance loss for one short vertical dipole at a height $z = 1$ m above ground in an "average" forest.

in the lossy ground plane of the forest floor by the electromagnetic field of the antenna. This effect introduces an apparent resistance R_z in place of the radiation resistance R_o of the antenna and thereby reduces its efficiency by a factor $10 \log R_z/R_o$. The antenna-to-ground coupling effect is a function of the antenna height above ground, z , and the wavelength of operation. For values of $z/\lambda > 0.1$, the loss L_r is usually less than 5 dB. For a fixed antenna height, L_r decreases with increasing frequency as shown in Figure 5. For the case of both transmit and receive antennas at 1 m above the ground, and for an operating frequency of 10 MHz, $L_r(z) = L_r(z_o) = 8$ dB, and the total antenna resistance loss of 16 dB reduces the reach by a factor of 2.5.

Figure 6 dramatically illustrates how raising the antenna away from the ground can reduce the propagation loss contributions of L_s , L_i , and L_r , especially at the lower frequencies. For the "average" forest example shown at 5-MHz frequency, the losses are reduced by 28 dB by raising the (ideal, short) dipole antenna from $z = 0.1$ m to $z = 1$ m. An additional 7-dB improvement is achieved by raising the antenna another meter, but only another 3 dB results from raising it the final 8 m to the forest canopy. This typical improvement with increased antenna height is called the "height-gain effect" by Tamir. It is significant that the height-dependent losses can be greatly reduced by raising the antenna just a few meters above the forest floor.

8. COMPARISON OF CLEAR GROUND AND FORESTED PATH LOSSES

Values of propagation loss over clear ground or "open country" can be calculated from Norton's formula (Ref. 7) which applies to the loss between two ideal (i.e., lossless) antennas over lossy ground:

$$L_{oc} = 90 - 20 \log \left[\frac{\lambda}{4\pi\sqrt{30}} \right] - 20 \log \left[\frac{186.4A}{d} \right] - 10 \log g_r$$

$L_h(z)$ IS A RESULT OF THE COMBINED
EFFECTS OF L_s , L_i , AND L_r LOSSES

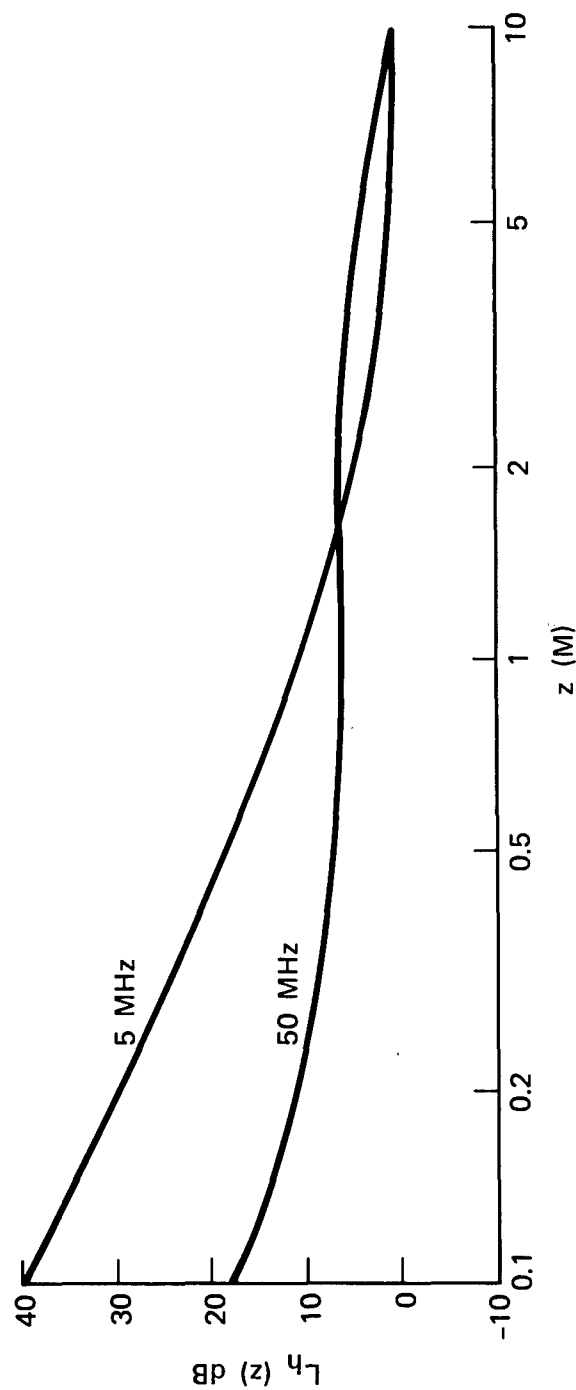


Figure 6. Antenna height-gain effect for one vertical dipole in an "average" forest.

where λ = wavelength (m),
 d = distance (mi) between antennas,
 A = loss parameter defined as a function of f , d , ϵ_g ,
and σ_g ,
 g_r = gain of receive antenna.

The transmit antenna is assumed to be a short vertical monopole.

Figure 7 shows a comparison between L_{oc} as given by the expression and the initial loss L_o shown previously in Figure 2. Since the definition of L_o assumes ideal dipole antennas, we have adjusted L_{oc} to correspond to the same conditions. That is, L_{oc} was decreased by 3 dB to correspond to a dipole rather than a monopole transmit antenna, and $10 \log g_r$ was set to 2 dB for the dipole receive antenna. The losses in both cases are calculated for a 1-km antenna separation.

It is evident from Figure 7 that open-country groundwave propagation loss increases much more rapidly with frequency than does the forest lateral-wave initial loss. As a result, for a given forest type (at least for "average" or "thin" forests) there is a frequency above which the losses for lateral-wave propagation are lower than for groundwave propagation. We see below that this may result in cases where the reach in a forest environment will be greater than the corresponding reach over open country. For given forest and ground parameters there is a crossover frequency above which the forest environment results in increased reach. In effect, what is going on in these cases is that the forest serves to raise the electromagnetic wave off the more lossy ground to the less lossy air-forest interface.

This situation introduces an apparent contradiction that should be discussed. In Figure 7 we see that at the higher frequencies (above about 10 MHz) the loss increases in going from a "thin" forest to open country, even though loss

- NOTE:
 - CURVE (1) SHOWS TOTAL PROPAGATION LOSS, INCLUDING 4 dB OF ANTENNA GAINS ($G_T + G_R$)
 - CURVES (2), (3), (4) SHOW ONLY THE INITIAL LOSS COMPONENT OF FOREST PROPAGATION LOSSES AND ALSO INCLUDES 4 dB OF ANTENNA GAINS
- (1) OPEN COUNTRY ($\sigma_g = 10^{-2}$ MHO/M, $\epsilon_g = 4$)
- (2) "THIN" FOREST ($\sigma_f = 3 \times 10^{-5}$, $\epsilon_f = 1.03$)
- (3) "AVERAGE" FOREST ($\sigma_f = 10^{-4}$, $\epsilon_f = 1.1$)
- (4) "DENSE" FOREST ($\sigma_f = 3 \times 10^{-4}$, $\epsilon_f = 1.3$)

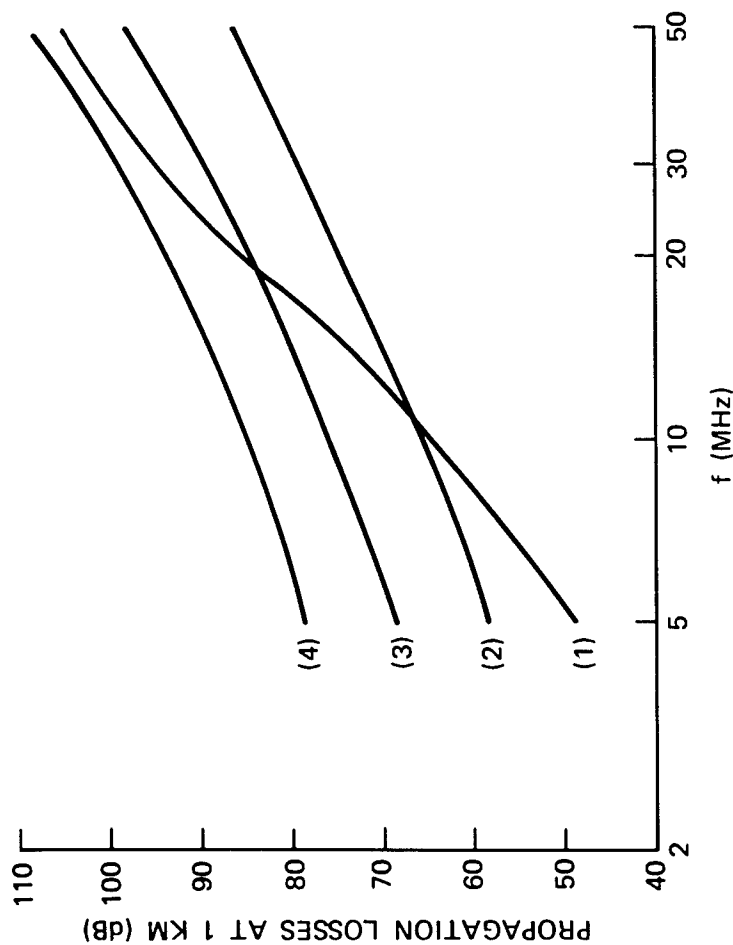


Figure 7. Lateral-wave initial loss and open country propagation loss.

decreases with forest density from "dense" through "average" to "thin" types. One might expect that, in viewing the open country case as the limit of ever-thinner forest types, the open country case would always give the lowest loss. The fallacy in this reasoning is clear when we recognize that there is a minimum forest density for which the Tamir slab model can be applied.

Tamir states that for his slab model to be valid at a given frequency, the open spaces within the foliage must be small (i.e., less than half) compared to the wavelength. While the "thin" forest may be viewed as a slab at frequencies as high as 200 MHz, for sufficiently thin forests the model breaks down at, say, 10 MHz. When the spaces within the foliage become too large compared to the wavelength, the forest fails to support the electromagnetic wave above the ground, and at that point the loss begins to increase, eventually approaching the open country case.

IV. ANTENNA DESIGN AND SITING EFFECTS

1. THE EFFECT OF AN IMPERFECT GROUND PLANE

We saw in Figure 5 that the resistance loss for a short vertical dipole antenna at a height of 1 m above the ground in an "average" forest is very large at low frequencies (e.g., 22 dB at 2 MHz), decreasing to near 0 dB at 50 MHz. We are not surprised that losses for a short vertical dipole in close proximity with the lossy ground of the forest may be large, because the radiation pattern of a vertical dipole directs one-half of its radiated power towards the ground, where it is partially absorbed in the form of ground losses. The remaining power is reflected, causing a distortion of the upper half-plane radiation pattern that may result in additional loss in terms of antenna directivity.

Antenna losses in open country are caused by the same mechanisms as described above for the forest environment. However, the ground conductivity of a forest is characteristically lower than that of open country near the forest, so in general, antenna losses in the forest will be greater than for the same antenna used in the open.

Antenna ground losses have a much greater impact on antenna efficiency for electrically short antennas (short compared to $\lambda/2$ for a dipole, and short compared to $\lambda/4$ for a vertical monopole antenna) than for their self-resonant counterparts. This is because the radiation resistance of an electrically short antenna is very small compared to that of a self-resonant antenna. Therefore, in the short-antenna case a much greater percentage of antenna input power is dissipated in the ground loss resistance (rather than in the radiation resistance) than in the resonant antenna case.

These considerations suggest approaches for reducing ground losses and thus improving the efficiency of a vertical antenna:

- a. Use a vertical monopole antenna with a counterpoise (an artificial conducting ground plane) rather than a dipole. The counterpoise serves to isolate the antenna from the lossy ground. The resulting radiation pattern has the same shape (ideally) as that of a dipole of twice the length in free space. However, because the monopole radiates only in the upper half space, its gain is double that of the dipole.
- b. Raise the monopole with counterpoise above the ground to further isolate the electromagnetic field from the lossy ground plane. For an infinite counterpoise this would of course not be necessary, but for a limited counterpoise there will be a beneficial effect. In our application we imagine the antenna to be mounted on top of a truck at a height of perhaps 3 m, with the counterpoise an integral part of the truck top (perhaps with some extension if necessary).
- c. Use a resonant monopole (rather than a shorter length) to increase the antenna radiation resistance relative to ohmic losses in the antenna, counterpoise, and ground. As mentioned previously, this approach also gives a broad antenna bandwidth.

Note that these measures provide some additional performance benefits. In suppressing the downward directed reflected ray (as shown in Figure 1) the counterpoise eliminates the interference loss discussed above. Also, raising the antenna reduces the separation loss by decreasing the length of the lateral-wave path through the attenuating foliage.

2. ELECTRICAL CHARACTERISTICS OF RESONANT VERTICAL MONOPOLE WITH COUNTERPOISE

Figure 8 depicts a vertical monopole antenna with a circular disc-shaped aluminum counterpoise. The vertical element length and counterpoise radius are both equal to one-quarter of the operating wavelength. We have schematically indicated the radiation resistance of the monopole and the ohmic loss resistances R_E and R_C of the earth and counterpoise, respectively. Since the counterpoise is fabricated from a good conductor, we have $R_C \ll R_E$. In addition, the capacitance, C_C , from the vertical element to the counterpoise is much greater than the capacitance, C_{E1} , of the element to ground. This implies that most of the radial return current flows through the counterpoise, not through the lossy ground, which yields the resulting efficiency improvement.

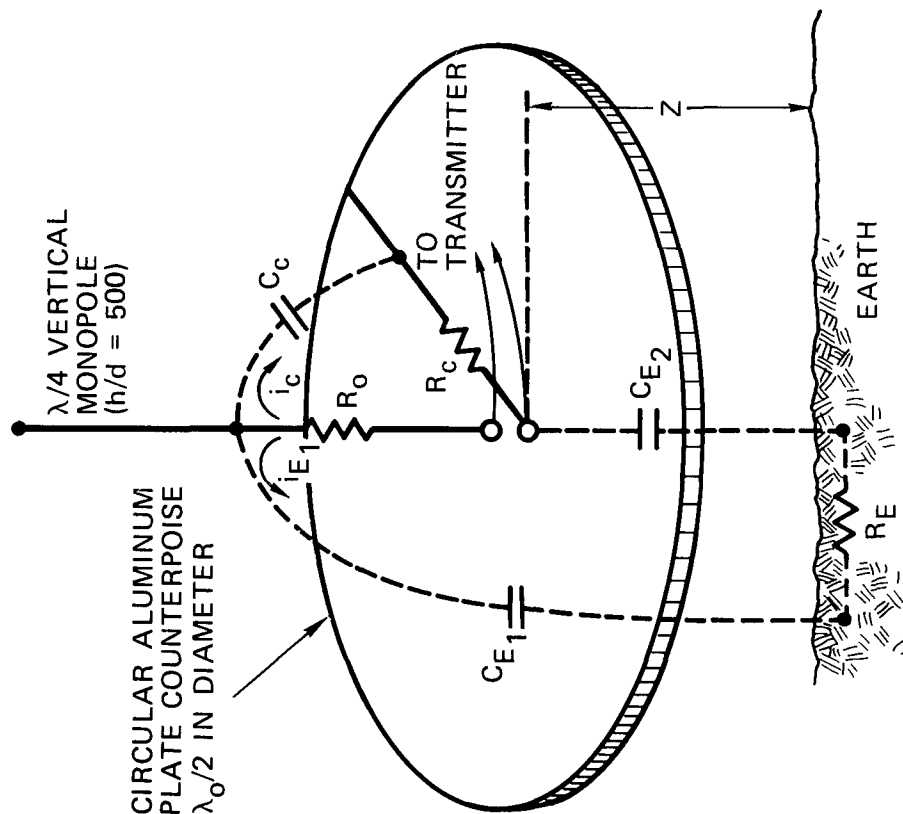
The efficiency, η , can be expressed as

$$\eta = \frac{R_O}{R_O + R_L}$$

where the ohmic loss resistance R_L is, in the present case, dominated by the low ohmic losses of the counterpoise and of the vertical element, and not by that of the earth. The radiation resistance R_O is given by

$$R_O = 1578 (h_e/\lambda)^2 \text{ ohms}$$

where h_e is the effective antenna height. For a resonant monopole, $h_e = 0.636h$, where in turn $h = \lambda/4$ is the actual physical element height. In this case, we find that $R_O = 36.6$ ohms.



- R_o — RADIATION RESISTANCE = 37Ω
 - R_E — OHMIC GROUND LOSSES
 - R_c — RESISTANCE OF COUNTERPOISE GROUND PLANE
 - C_c — CAPACITY FROM MONOPOLE TO COUNTERPOISE
 - C_{E1} — MONOPOLE CAPACITY TO EARTH
 - C_{E2} — COUNTERPOISE CAPACITY TO EARTH
 - Z — HEIGHT OF COUNTERPOISE ABOVE EARTH
- FOR "LOSSY GROUND", $R_E \gg R_c$
 - BY INCREASING HEIGHT Z , C_{E1} AND C_{E2} DECREASE, MINIMIZING THE CURRENTS IN R_E COMPARED TO THOSE IN R_c

Figure 8. Vertical resonant monopole antenna with counterpoise.

It is clear that the efficiency improvement increases as the antenna (element plus counterpoise) height is increased, since this decreases the capacitance C_{E1} still further. It would seem that antenna height may compensate to a degree for the truncation of the counterpoise. Thus, our truck-top mounted antenna may not require the extension of the counterpoise beyond the actual truck dimensions (or as much extension) that might otherwise be necessary at longer wavelengths.

The antenna bandwidth depends on the capacitance C_c , which is given by

$$C_c = \frac{24.16h}{\log(2h/d)}$$

in picofarads where h is in meters. The ratio h/d is the height-to-diameter ratio of the vertical element. The 3-dB bandwidth is then given by

$$B = \frac{0.220 \times 10^{-6} f^4 C_c h_e^2}{\eta}$$

where the operating frequency f and bandwidth B are both in megahertz. Note that this equation holds at and below the resonant frequency of the monopole antenna. For a resonant monopole with $h/d = 500$, we find that $C_c = 2.01 \lambda$ picofarads (with λ in meters) and $B = 0.303 f/\eta$. Thus, if the antenna efficiency is 90 percent, the antenna bandwidth is about one-third of the operating frequency. This bandwidth is depicted in Figure 9.

The above expression for capacitance assumes an infinite, perfectly conducting counterpoise. The results for actual counterpoises of radius $\lambda/4$ are expected to closely approach

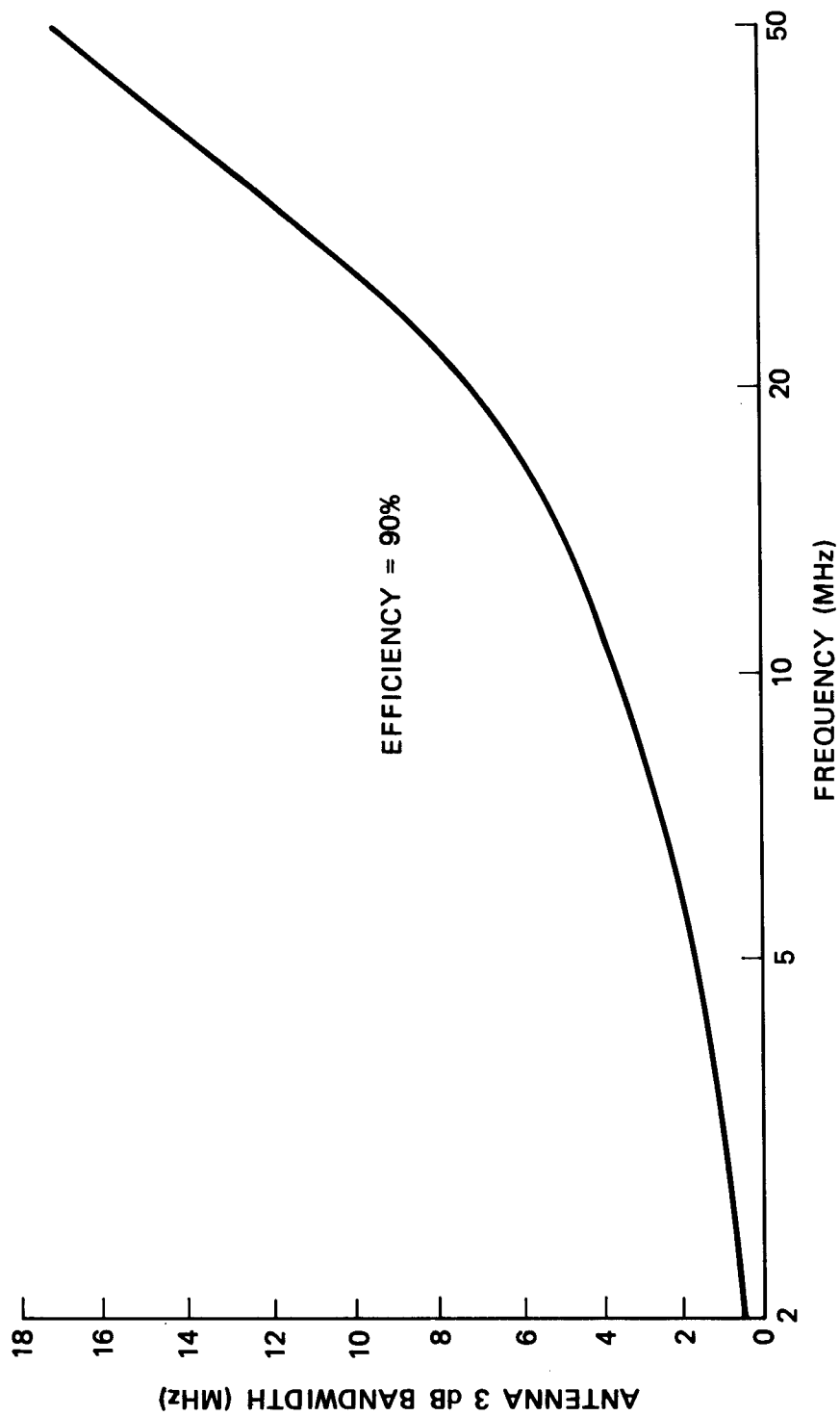


Figure 9. Bandwidth of a resonant monopole with counterpoise.

this value. However, note that we cannot in this application make do with the type of counterpoise frequently used in narrow-band applications such as broadcasting. These counterpoises, consisting of a set of radial conductors meeting at the base of the vertical element, would have a far lower capacitance and would thus not provide the desired wide bandwidth.

We would guess that the efficiency of a vertical resonant antenna with a solid disc counterpoise, as illustrated in Figure 8, should be higher than ~80 percent when the antenna is raised about 3 m above the ground. Expressed as a loss (relative to 100 percent efficiency) this is about 1 dB. In terms of the ohmic loss resistance, R_L , a 1-dB efficiency corresponds to $R_L = 13$ ohms. The ohmic resistance of the antenna and counterpoise will be small compared to this value and, with the counterpoise and antenna height providing isolation from the ground losses, we expect the value of the ground loss resistance coupled into the antenna to be at least as small as this value.

In the reach calculations of the next section we assume a 1-dB efficiency loss for operating frequencies above 20 MHz. For lower frequencies, a 2-dB efficiency loss is assumed, which corresponds to $R_L = 21$ ohms. Some penalty for the lower frequencies seems appropriate since it is less likely that the complete counterpoise would be implemented at the longer wavelengths. Also, it is more likely, in a forest environment, that there will be foliage in the near field of the antenna at longer wavelengths. However, aside from these considerations, the choice of the 1-dB and 2-dB efficiency losses is somewhat arbitrary.

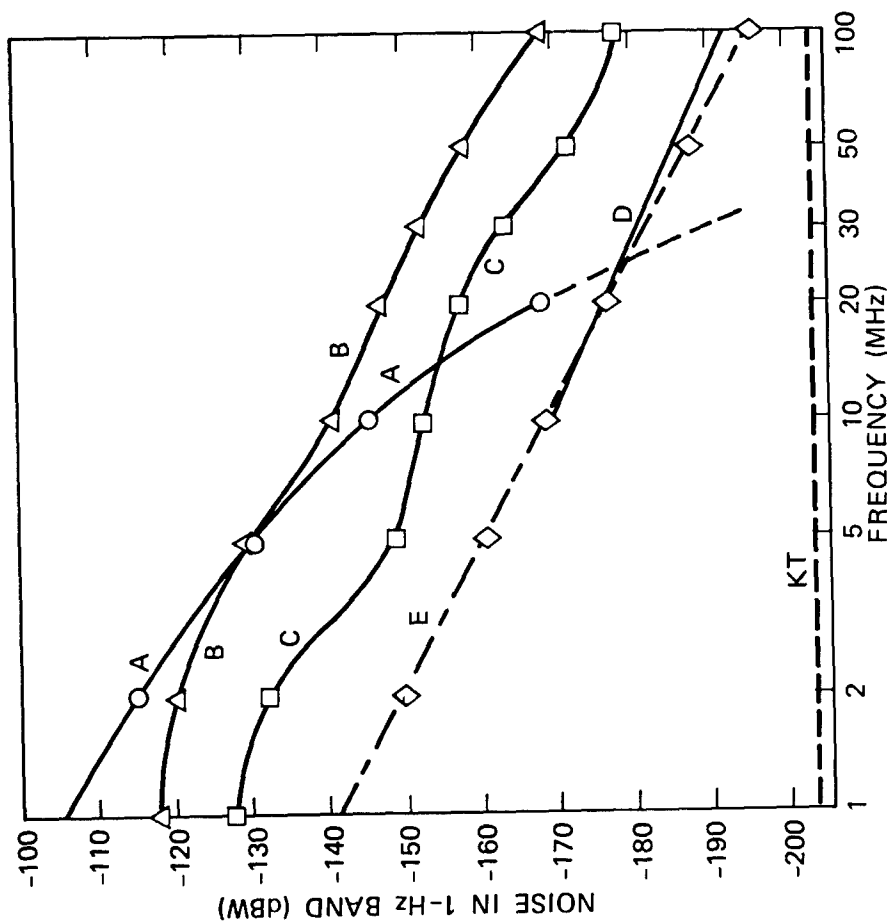
V. CALCULATION OF LINK REACH

1. AMBIENT NOISE

In order to estimate link reach as a function of frequency, it is necessary to make assumptions regarding the noise experienced by the receiver system, as well as to take into account such factors as the transmitter power, the antenna efficiencies and the propagation losses. At the frequencies of interest, there are significant sources of environmental noise which may be expected in general to dominate the noise generated within the receiver itself. The magnitude of these noise sources as a function of frequency is illustrated in Figure 10. Included are atmospheric noise, man-made noise, and galactic noise. In each case the noise shown is that which would be received by an ideal, short, vertical monopole antenna. For comparison, thermal noise at room temperature is also shown.

Curve A in the figure is for worst-case atmospheric noise in West Germany, which occurs during summer nights within the 2000-2400 h time block. During winter months and daylight hours, atmospheric noise below 10 MHz is typically 20-60 dB lower than curve A. Curve A values are statistical values with 90 percent reliability and 90 percent confidence levels that were extrapolated from CCIR Report 322, World Distribution and Characteristics of Atmospheric Radio Noise (Ref. 8).

Curves B and C show estimates, again at 90 percent reliability and 90 percent confidence statistical levels, of man-made noise for business areas and rural areas. These are derived from experimental measurements made by A. D. Spaulding, et al. (Ref. 9) over a five-year period (1966-1971) in six different U.S. states and in Washington, D.C. Spaulding's definition of "business area" includes all areas where the predominant activity is for any type of business; i.e., stores and



NOTES:

1. BELOW 10 MHz THE MAJOR SOURCE OF MAN-MADE NOISE IS POWER LINES; ABOVE 10 MHz THE MAJOR SOURCE IS AUTO-IGNITION

2. BUSINESS AREA NOISE IS VERY LOCALIZED
EX: NOISE FROM A 250 KV POWER LINE AT 500 KHz DECREASES TO AMBIENT BACKGROUND LEVEL AT A DISTANCE OF 300 M FROM THE POWER LINE

- A - WORST-CASE ATMOSPHERIC NOISE FOR WEST GERMANY, SUMMER NIGHT, 2000 - 2400 HRS, VALUES SHOWN FOR 90% RELIABILITY AND 90% CONFIDENCE
 - B - BUSINESS AREA MAN-MADE NOISE FOR 90% RELIABILITY AND 90% CONFIDENCE
 - C - RURAL AREA MAN-MADE NOISE, FOR 90% RELIABILITY AND 90% CONFIDENCE
 - D - GALACTIC NOISE, FOR 90% RELIABILITY AND 90% CONFIDENCE
 - E - QUIET RURAL AREA MAN-MADE NOISE, FOR 90% RELIABILITY AND 90% CONFIDENCE
- KT - THERMAL NOISE = -204 dBW PER HERTZ

Figure 10. Comparison of various noise sources.

offices, industrial parks, large shopping areas, main streets or highways lined with business enterprises. Rural areas are defined as land areas where dwellings are limited to one every five acres.

Spaulding states that the noise levels presented for business or rural areas should apply world-wide. Man-made electromagnetic noise is generated by electrically powered equipment such as motors, generators, and arc welders and by automotive electrical systems and high-voltage power lines. Radiated power levels from individual sources are relatively low so that their effects become negligible very rapidly with distance. For example, at a 0.5-MHz frequency the noise from a 250-kV high-voltage line typically decreases to the ambient atmospheric background noise level at a distance of about 300 m from the power line. At higher frequencies, this distance is even smaller. Among man-made noise sources, the noise from power lines dominates for frequencies below 10 MHz, and noise from automotive ignition systems dominates above 10 MHz. The slopes of both business area and rural area man-made noise as a function of frequency fall off at approximately 30 dB per decade of frequency increase.

Galactic noise is shown as curve D in the figure and again corresponds to 90 percent reliability and confidence levels. This noise source is dominant only for frequencies above about 30 MHz in quiet rural areas.

In the following reach calculations, we assumed that the noise as a function of frequency is determined by curve A of Figure 10 (atmospheric noise) below 13 MHz and by curve C (rural area man-made noise) above 13 MHz. Although curve B (business area man-made noise) exceeds these curves for frequencies above about 5 MHz, we imagine that the receivers of interest (on mobile command headquarter cells) would tend to be located away from business areas, particularly if this were

necessary to attain the desired link reach. In any case, where reach in the forest environment is of interest, we do not imagine that business-area noise would be relevant. It is more likely that man-made noise in this case would be at the rural or quiet rural levels.

It is worth noting that peacetime noise measurements are extrapolated to wartime only with some degree of uncertainty. In wartime, some significant sources of man-made noise may be diminished due to impaired industrial activity. As far as ignition noise is concerned, it is not clear whether the population will be driving their automobiles less (perhaps due to fuel unavailability) or more (e.g., in evacuation attempts). Increased military activity will bring a consequent noise increase. Finally, in nuclear war the effects on weather and on propagation add uncertainty to the atmospheric noise values.

Since we have chosen to use 90 percent reliability and 90 percent confidence noise statistics (that correspond to the worst time of day and season) in our reach calculations, we can expect (aside from the aforementioned uncertainties) the estimated reaches to be met or exceed in almost all instances. In contrast, if we had used median noise values, the estimated reaches would be longer (by about a factor of two) but would not be attained more than half the time. Without specifying the overall communication net architecture and desired performance, any choice of noise statistics is largely a matter of taste. Our choice is intended to be rather conservative without going to extremes.

2. REACH CALCULATION METHOD

The calculation of link reach is somewhat complicated, particularly since different ideal antennas are used in defining the propagation loss and the noise, while at the

same time the actual non-ideal antenna characteristics must be taken into account. In order to make the calculation method clear, we step through a reach calculation in a forest environment at 20-MHz frequency, with reference to Table 4.

The value of the noise power in a 1-Hz bandwidth at 20-MHz frequency is obtained from curve C (rural area man-made noise) of Figure 10. This value is increased by 30 dB to correspond to a 1-kHz bandwidth (or more precisely to the assumed 1-kbps data rate). This noise level includes the gain (about 5 dB) of the ideal vertical monopole antenna assumed for the noise values. To account for the assumed inefficiency of the actual antenna (a raised resonant vertical monopole with counterpoise), the noise value is then decreased by 1 dB (as discussed in Section IV) to obtain the noise power at the receive antenna terminals.

We have assumed that the transmitted power at the transmitter antenna terminals is 1 kW. In using Tamir's results for the lateral-wave propagation loss in a forest environment, we will be implicitly adopting his assumption of ideal dipole antennas. Thus, we add 2 dB to the transmitted power to account for the 3-dB gain of an ideal monopole transmit antenna relative to an ideal dipole, minus the assumed 1-dB loss for the assumed efficiency of the actual transmit antenna.

The propagation loss at a 1-km distance for a "thin" forest is calculated from Tamir's formulas for L_o and L_s , as shown in Figures 2 and 3 above. The forest parameters ϵ_f and σ_f are taken from the values shown in Table 3, while the forest height is taken as 20 m (for West German forests as per Reference 6). The value of L_i is taken to be zero since the counterpoise should prevent the occurrence of the ground reflection path that is the principal cause of the interference loss. A 3-m antenna height is included in the separation loss computation. To get the power at the receive

TABLE 4. SAMPLE CALCULATION OF REACH IN A "THIN" FOREST ENVIRONMENT
USING RESONANT MONOPOLE ANTENNAS WITH COUNTERPOISE

● *NOISE (1 KHz B.W.) AT 20 MHz	- 127 dBW
● INCLUDES + 5 dB GAIN OF A VERTICAL MONOPOLE ANTENNA AND AN ANTENNA EFFICIENCY OF - 1 dB	- 1 dB
● RECEIVED NOISE LEVEL	- 128 dBW
● TRANSMITTER POWER INTO ANTENNA (1 KW)	+ 30 dBW
● TRANSMIT ANTENNA GAIN IN FOREST, RELATIVE TO $G_T = + 2$ dB OF TAMIR'S SHORT VERTICAL DIPOLE	+ 2 dB
● TRANSMIT RADIATED POWER	+ 32 dBW
● PROPAGATION LOSS ($L_o + L_s + L_i$) AT 1 KM	- 82 dB
● RECEIVE ANTENNA EFFICIENCY FOR SIGNAL, RELATIVE TO $G_R = + 2$ dB OF TAMIR'S SHORT VERTICAL DIPOLE	+ 2 dB
● TOTAL PROPAGATION LOSS AT 1 KM	- 80 dB
● RECEIVED SIGNAL LEVEL AT 1 KM	- 48 dBW
● RECEIVED SIGNAL-TO-NOISE RATIO AT 1 KM	+ 80 dB
● REACH FOR A BIT ERROR RATE = 10^{-3} (S/N = + 11 dB)	+ 53 KM

*NOISE IS 90% RELIABILITY, 90% CONFIDENCE VALUE
FOR RURAL AREA MAN-MADE NOISE

antenna terminals, we must again add 3 dB for an ideal monopole receive antenna gain relative to that of the dipole assumed by Tamir, and subtract 1-dB loss for the assumed receiver antenna efficiency. Combining the above factors for the transmitted power, propagation losses, and antenna characteristics gives a received signal power of -48 dBW at the 1-km range.

The received signal-to-noise ratio (SNR) in decibels at 1-km is obtained by subtracting the value of the received noise power from the received signal power at 1 km, giving an SNR of 80 dB. The excess over the required 11-dB SNR (i.e., 69 dB) determines the actual reach relative to the 1-km reference. Since reach in the lateral-wave propagation mode varies at a rate of 10 dB for each 40 dB of SNR excess, the final result is that the reach for an 11-dB SNR is 53 km.

Note that, in our calculation, we have not reduced the received noise power by a "separation loss" corresponding to the effect of foliage attenuation on the noise reaching the receive antenna located in the forest, although the signal power has been so reduced. This treatment is recommended in Reference 4 which states that Project SEACORE measurements showed no significant difference between noise levels at a given site in the forest and a nearby site in the open. We suspect that the adoption of this assumption by us is quite conservative due to likely differences between the SEACORE measurement conditions and our operating conditions.

The SEACORE noise results are explained in terms of two effects. First, atmospheric noise, which propagates largely by skywave, may enter the receive antenna through paths that are steeper than the generally shallow paths corresponding to the critical angle for the lateral-wave mode (e.g., only 15° from the horizontal in an "average" forest). Such steeper

paths pass through less foliage and are attenuated less, so the noise would not be expected to suffer the full component of the separation loss experienced by the signal on the receive end of the path. (For example, at 20 MHz and with a 20-m forest height and a 3-m antenna height, the receive separation loss would be 4.5 dB in a "thin" forest and 8.2 dB in an "average" forest.) Second, an effect of the lossy forest ground is to tilt up the antenna beam pattern toward the vertical, favoring the reception of the noise.

In our application, the principal noise source for frequencies above 13 MHz is assumed to be man-made. Since such noise generally propagates to the receiver by surface-wave paths, the difference in arrival angle for signal and noise would vanish. Also, we expect that with the use of a counterpoise, the beam pattern of our raised antenna would not be tilted upward in such a way as to favor the reception of skywave noise. Consequently, we believe that in neglecting the noise separation loss, we have introduced some performance margin (about 4.5 dB in a "thin" forest and 8.2 dB in an "average" forest).

3. REACH AS A FUNCTION OF FREQUENCY

Using the procedures illustrated above, we calculated the reach as a function of frequency for "thin" and "average" forests and for open country environments. To make these calculations apply to West Germany, the values of ϵ_f and σ_f for "thin" and "average" forests were taken from Reference 6. This reference states that the forests of West Germany are between "thin" and "average" as characterized by Tamir, except that the average tree height is 20 m.

Figure 11 shows the resulting reach versus frequency curves (2) and (3) for "thin" and "average" forests, respectively. The reach for forests in West Germany falls between these two

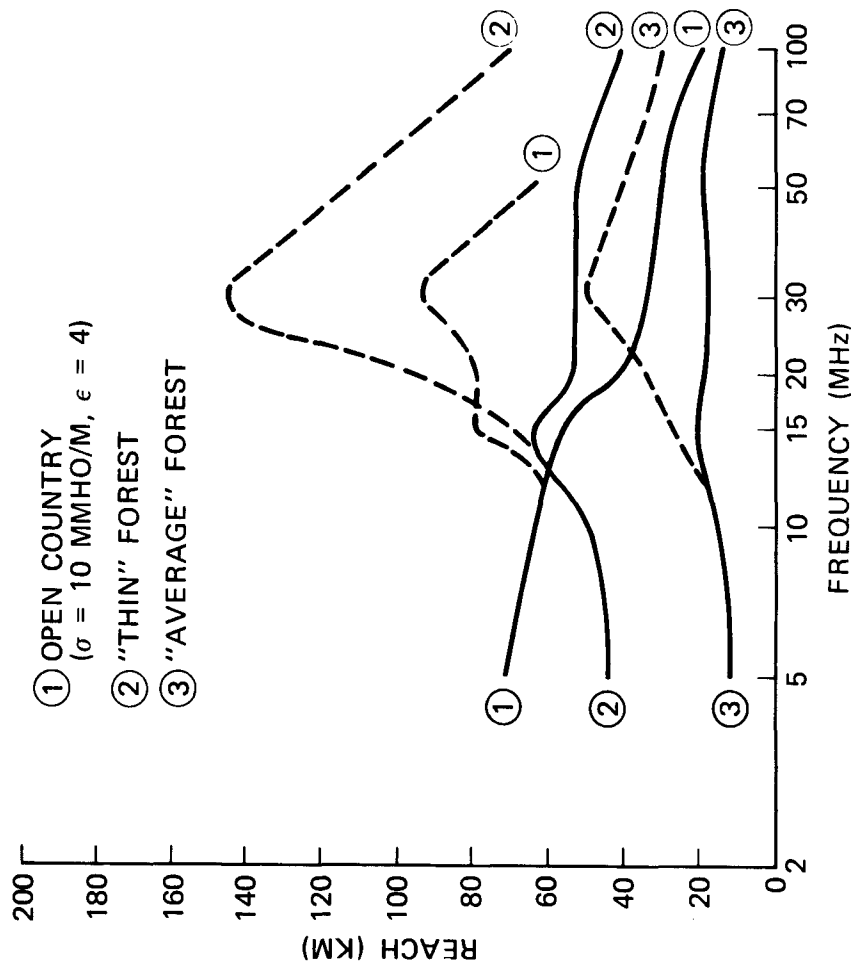


Figure 11. Reach vs frequency in "thin" and "average" forest and in open country environments.

- TRANSMIT POWER INTO ANTENNA = 1 KW

- ANTENNAS: $\lambda/4$ VERTICAL MONOPOLES WITH $\lambda/2$ CIRCULAR DISC COUNTERPOISE, MOUNTED 3 M ABOVE GROUND

- NOISE:

- SOLID REACH CURVES BASED ON 90-90 ATMOSPHERIC NOISE FOR WEST GERMAN SUMMER NIGHT FROM 5-13 MHz, AND ON 90-90 RURAL AREA MAN-MADE NOISE FROM 13-100 MHz
- DOTTED REACH CURVES ARE BASED ON ATMOSPHERIC NOISE BETWEEN 13-23 MHz, AND ON GALACTIC NOISE FROM 23-100 MHz BEING PREVALENT RATHER THAN RURAL MAN-MADE NOISE

- BER = 1×10^{-3} (S/N = 11 dB)

NOTE: WEST GERMAN FOREST PROPAGATION LOSS CHARACTERISTICS FALL BETWEEN "THIN" AND "AVERAGE" CATEGORIES, SO REACH WILL BE BOUNDED BY THE CURVES ② AND ③

extremes. The solid line curves show the estimated reach when it is assumed that rural man-made noise is dominant above 13 MHz. The dashed curves result when we consider a receiver located in a "quiet rural" area where man-made noise above 23 MHz is below the galactic noise level. Recall that all of the noise values used are for the worst case time-of-day and season and that they correspond to 90 percent reliability and 90 percent confidence levels.

Curve 1 in the figure shows the expected reach versus frequency for "open country" in West Germany, assuming the values $\epsilon_g = 4$, and $\sigma_g = 10$ mmho/m obtained from Reference 6. Open country propagation loss values were calculated using Norton's formula (Ref. 7) as described in Section III.8 above. Since Norton's formula already presupposes ideal vertical monopole antennas, we do not have to apply the 3-dB gain factors used when Tamir's lateral-wave propagation equations are employed. However, we do still need to introduce a loss corresponding to the antenna efficiency. We assumed that this loss was the same as that in the forest environment case (i.e., 2 dB for frequencies below 20 MHz and 1 dB above). Otherwise, the computation of reach uses the same procedure illustrated in the last subsection.

As we anticipated earlier in Section III.8, there are cases where the reach in the forest environment exceeds that in open country, which seems rather surprising. Since we have already discussed the reasons for this, we need not repeat them here. The solid reach curves in forest are quite flat as a function of frequency. The increased propagation loss as frequency increases is offset by the decreased noise power. There is a modest advantage to frequencies in the middle range of those shown. When rural area man-made noise is not dominant (i.e., the dashed curves), this advantage of the middle range frequencies is very pronounced.

It is clear that we can exceed our 10-km minimum reach goal and that in most cases the reach will be several times greater than this value. Examination of forestation maps of West Germany indicates that typical paths will be partially forested and partially open country cases. Forested portions will likewise be of various densities between "thin" and "average." Thus, actual reaches will tend to correspond to intermediate values. A more definitive statement would require detailed terrain analysis beyond the scope of this effort.

4. EFFECT OF OPERATING IN FOREST CLEARINGS

Although the link reaches shown in Figure 11 are larger than the required minimum, longer reaches are obviously desirable, particularly in regions of the battlefield where the cells are less dense. When operating in a forest environment, a cell can significantly increase the available reach by locating in a forest clearing, thus eliminating the separation loss caused by the absorption of the signal by the lossy foliage along the propagation path. Recall that at a 20-MHz frequency, the separation loss per antenna (i.e., at the transmitter or receiver end) is about 4.5 dB in a "thin" forest and 8.2 dB in an "average" forest. Thus, substantial reach increases are attainable with this approach.

The necessary diameter of the forest clearing depends on the nominal tree height, the antenna height, and the index of refraction of the forest. Nominally, a ~100-m-diameter clearing is appropriate. An examination of forestation maps of West Germany indicates that clearings of this size are extremely common in forested regions. Thus, as an operational procedure when increased reach is required (e.g., due to unusually high noise conditions or due to cell attrition) during operation within a forested region the cells may move to clearings within the forest. Some compromise in observation vulnerability is of course the penalty for this move.

Figure 12 illustrates the reach attained when both transmitter and receiver operate within forest clearings. Since, for propagation in the lateral-wave mode within a forest environment, a 12-dB decrease in loss results in twice the reach, operation in clearings nearly doubles the reach in a "thin" forest and more than doubles the reach in an "average" forest.

5. EFFECT OF TERRAIN AND FORESTATION VARIATIONS

The case of propagation along mixed paths has also been treated by Tamir (Ref. 10). He considers paths consisting of forest areas separated by clearings or larger open country areas and, in general, the transition across the forest/open country boundary. He concludes that a lateral wave that propagates along the forest canopy can skip over a clearing of either large or small diameter, as long as the path across the clearing has a direct line of sight from the forest edge on one side of the clearing to the edge of the forest on the other side of the clearing. In this case, the strength of the lateral wave is actually enhanced by approximately 5 dB (for $f = 30$ MHz) as it passes over the clearing. This increase occurs because a portion of the lateral wave is reflected from the ground in the clearing and combines with the direct ray between forest edges in such a way as to increase the amplitude of the combined signal.

If the forest clearing is large and the intervening terrain is uneven in its vertical profile so that no line of sight exists between forest edges, then the lateral wave from the forest must make the transition to a groundwave and propagate as such. As discussed in Section III.8, propagation loss for open country can be greater than that of lateral-wave propagation over the forest for frequencies above a value that depends on ground and forest parameters. Therefore, for

this case, the reach over such a mixed path may be less than if the propagation path were over a continuous forest environment. It is clear that the reach may be affected in either way by open country portions of a mixed path. Thus, in general, for specific paths the terrain profile as well as the various electrical parameters must be included if a careful evaluation of link reach is required.

- TRANSMIT POWER INTO ANTENNA = 1 KW
- ANTENNAS: $\lambda/4$ VERTICAL MONOPOLES WITH $\lambda/2$ CIRCULAR DISC COUNTERPOISE, MOUNTED 3 M ABOVE GROUND
- NOISE:
 - SOLID REACH CURVES BASED ON 90-90 ATMOSPHERIC NOISE FOR WEST GERMAN SUMMER NIGHT FROM 5-13 MHz, AND ON 90-90 RURAL AREA MAN-MADE NOISE FROM 13-100 MHz
 - DOTTED REACH CURVES ARE BASED ON ATMOSPHERIC NOISE BETWEEN 13-23 MHz, AND ON GALACTIC NOISE FROM 23-100 MHz BEING PREVALENT RATHER THAN RURAL MAN-MADE NOISE
- BER = 1×10^{-3} (S/N = 11 dB)
- NOTE: WEST GERMAN FOREST PROPAGATION LOSS CHARACTERISTICS FALL BETWEEN "THIN" AND "AVERAGE" CATEGORIES, SO REACH WILL BE BOUNDED BY THE CURVES ② AND ③

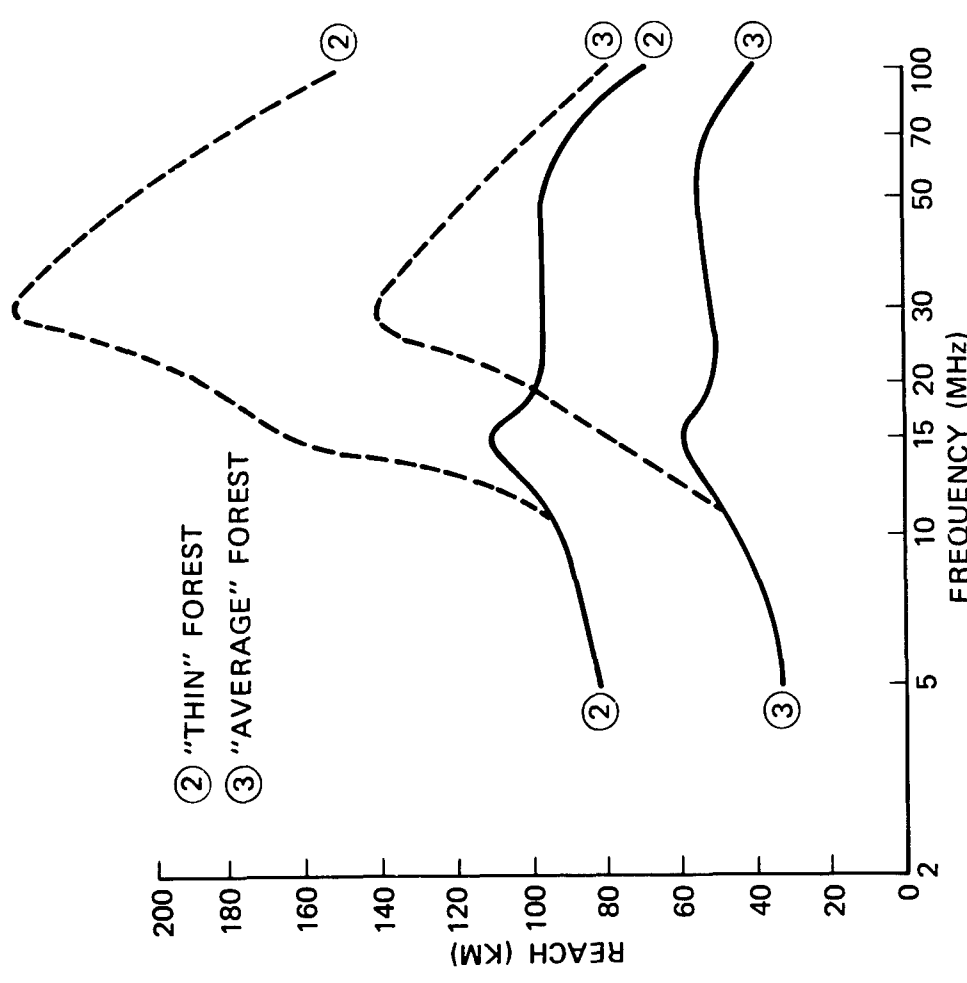


Figure 12. Reach for operation within clearings in "thin" and "average" forested environments.

VI. CONCLUSIONS

It appears that HF/VHF propagation in a surface-wave (i.e., lateral-wave or groundwave) mode can provide the desired minimum link reach to support our concept of dispersed command headquarters cells in the European theater. Our estimates for link reach in the West German forest and open country environments indicate that the 10-km minimum can usually be substantially exceeded and, in a forest environment, can be significantly increased operationally by locating the cells in forest clearings when necessary. Clearings of the necessary size (~ 100 m) are extremely common in West German forests.

The successful operation of the HF/VHF link depends in large part on proper antenna design and siting. A resonant vertical monopole has been suggested so as to provide both a high antenna efficiency and the wide bandwidth desired for spread-spectrum implementation. Some decrease in monopole length is possible without significant performance impact through use of end-weighted designs. A counterpoise is required to isolate the radiated field from the lossy ground. This approach is particularly necessary in a forest environment, where ground losses are generally higher than in open country. The benefits of the counterpoise are enhanced by raising the monopole/counterpoise assembly off the ground. In a forest, raising the antenna also reduces the separation loss. A solid disc counterpoise is required to provide the relatively large monopole-to-counterpoise capacitance (compared to that of a radial-wire counterpoise) needed to maintain a wide antenna bandwidth. In our application, we imagine that the antenna is mounted on top of the truck and that the counterpoise is integrated with the truck top.

The reaches shown above for "thin" and "average" forest and open country paths indicate only approximately the actual reaches that will be attained in practice where, in general, paths will be of mixed character. For particular paths, numerical techniques exist for estimating reach with the actual terrain profile and ground cover, including cultural features (i.e., buildings, industrial structures, etc.). Except at the lower HF range, we may expect to find instances where propagation over open country or mixed paths results in smaller reaches than for forested paths. Cultural features may produce significant effects on reach. Finally, we note that even in apparently homogeneous regions experiments have indicated that significant variations in the propagation loss occur. Thus perhaps we should be satisfied with the sort of nominal reach estimates presented above. Some experimental measurements of propagation in specific regions of interest is of course desirable in order to confirm the reach estimates obtained analytically.

It is not clear that a single optimum operating frequency is implied by the results presented above, unless perhaps if additional specifications of the operational environment are evoked. For example, if the receivers are expected to be located in quiet rural areas, then frequencies near 30 MHz are clearly preferable from the reach standpoint. Also, if receivers are to be in rural (but not necessarily "quiet") areas and the propagation paths are dominated by forested regions, then again frequencies near 30 MHz are best. However, if the receivers are to be in rural areas and the paths consist mostly of open country segments, then lower frequencies would give improved reach.

The higher frequencies are desirable as far as antenna size and bandwidth are concerned. For example, at a 30-MHz frequency the length of a resonant monopole is only 2.5 m

(8.2 ft), and could have a bandwidth of 9 MHz. Such a relatively small antenna could be left deployed while the cell was on the move. At lower frequencies the antenna might need to be partially retracted during vehicle motion, degrading link performance. Also, for a given size vehicle, the vehicle top provides for a more complete counterpoise at the higher frequencies. However, the main impediment to using frequencies as high as 30 MHz is the possible compromise in reach over open country paths.

An additional consideration in choosing the frequency of operation is that of electromagnetic compatibility (EMC) with friendly military and civilian radios, and jamming by enemy countermeasure (ECM) equipment. At frequencies above about 20 MHz, skywave jamming becomes less worrisome, while troposcatter jamming is generally only effective above about 40 MHz. Thus, operating in the 20- to 40-MHz band has some ECM advantages. While radios abound throughout the HF/VHF bands, we suspect that the 20- to 30-MHz band is not used that much because it is less useful for HF skywave and is below the range of military VHF radios.

The ECM and EMC issues are being examined in ongoing work. Also left for future study is the description of the overall architecture of the HF/VHF communication system, including net control, modulation formats, incorporation of security features, and avoidance of self-interference. Voice as well as data communication is of interest. Clearly voice communication will require a higher data rate than the 1 kbps assumed above. Currently, digital voice can be implemented with a 2.4-kbps data rate, not including the necessary overhead for error control, synchronization, etc. If we assume a 3.0-kbps total rate for a voice channel (which does not provide for relaying), the link reach will be reduced

by a factor of about 1.3 from the values presented above. Finally, having defined the netting approach and system parameters we will be able to consider a number of exemplar deployments and to evaluate (using simulation approaches) the net performance. Work in these areas is currently in progress.

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