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FREQUENCY DEPENDENCE OF RADIO LOSSES FOR RADAR SYSTEMS IN FOREST ENVIRONMENTS

Interim Report

By

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I. INTRODUCTION

The influence of a forest environment on the performance of Doppler radar systems has been examined in an interim report[1], hereinafter referred to as IR. In that report, the net effects of the vegetation were expressed in terms of a terrain loss L_t , which was calculated for a variety of antenna heights, vegetation constants and tree heights. However, the frequency had been assumed to be constant (= 140 MHz.) in all of the calculations that were reported therein. The present report continues the considerations of IR by examining the effect of frequency on the path losses, over the range 100 to 1000 MHz.

In finding the effect of frequency on the operation of a radar system, the first question being asked is how to compare a system operating at a frequency f with another one operating at a reference frequency f_o. In general, any two systems operating at different frequencies will possess different characteristics, especially in their RF stages. Thus, the antenna, the transmission lines, the magnitude of the transmitted power, the signal-to-noise ratio, as well as many other engineering aspects of design and performance, may vary considerably with frequency. When comparing any two systems, which operate at different frequencies, a criterion must therefore be found that would make the comparison valid.

The particular comparison criterion adopted in the present work is as follows. It is assumed that the two systems are placed in exactly the same environment and that they possess identical characteristics, except that they operate at different frequencies. Hence, the signal-to-noise ratio, transmitter power, receiver sensibility, antenna and transmission line losses, etc., are taken to be the same for both systems. However, the antennas must be considered more carefully, because the situation is different if their gains are equal or if their apertures are the same. The former possibility will not be considered, because one main advantage in increasing the operating frequency is the availability of higher-gain antennas. The more realistic situation of antennas with same aperture dimensions will therefore be assumed, which implies that the two radar systems involve antennas that are very closely equal in size. Besides being a reasonable choice from an engineering point of view, the assumption of antennas with equal apertures is therefore a consideration of practical importance. Thus, for a radar system that must be mounted on a vehicle where the antenna size is critical, it makes sense to compare two different systems that operate at different frequencies but possess antennas of same aperture size.

After establishing the above criterion of comparison, it is possible to define a frequency incremental loss ΔL, which yields the difference in decibels between the radio loss $L(f)$ of the system operating at a frequency f and the radio loss $L(f_o)$ of the system operating at a reference frequency f_o. The derivation and calculation of this incremental loss ΔL forms the subject of the present report, the results being given for an environment consisting of a bare ground, as well as for a forest-covered terrain.

II. DERIVATION OF THE INCREMENTAL LOSS

To find the additional radio loss that is produced by increasing the frequency of operation, we consider the expression

$$p(f) = \frac{P_r(f)}{P_t(f)} , \tag{1}$$

where $P_r(f)$ and $P_t(f)$ are the received and transmitted power, respectively, at the antenna of a radar system which is placed in free space. For simplicity, it will be assumed that the receiving and transmitting functions are performed by the same antenna.

In contrast, let

$$p'(f) = \frac{P'_r(f)}{P'_t(f)} \tag{2}$$

denote the same quantities as before, except that now the prime notation indicates that the radar system is placed in a forest environment, as shown in Fig. 1. Likewise, the double-prime notation

$$p''(f) = \frac{P''_r(f)}{P''_t(f)} \tag{3}$$

refers to a radar system located in the presence of bare ground (with no vegetation coverage).

Although the above situations refer to different environments, they refer to the same radar system and geometrical conditions. Thus, the antenna height, the distance ρ between the antenna and the target, the transmitted power, etc., are assumed to remain unchanged. Hence $P_t(f) = P'_t(f) = P''_t(f)$; on the other hand, the received powers $P_r(f)$, $P'_r(f)$ and $P''_r(f)$ are nevertheless unequal because their magnitude may be considerably affected by the different environments. The expression for $p(f)$ is given by the familiar radar equation for free space[2], whereas the expressions for $p'(f)$ and $p''(f)$ may be derived by using the considerations discussed in IR.

If one wishes to compare the performance of a system operating at a frequency f with the performance of another system operating at a reference frequency f_o, it is pertinent to consider the expression

$$\Delta L_2 = 10 \log \frac{p(f_o)}{p(f)} = 10 \log \frac{P_r(f_o)}{P_r(f)} \tag{4}$$

As defined here, ΔL_2 refers to the radio-loss difference (in decibels) between a system operating in free space at a frequency f and that for the same system operating at the frequency f_o. The subscript 2 in ΔL_2 indicates that this is a <u>two-way</u> incremental loss. The equality of $p(f_o)/p(f) = P_r(f_o)/P_r(f)$ follows from the basic assumption that the transmitted powers $P_t(f)$ and $P_t(f_o)$ are equal, as stipulated by the comparison criterion established in Sec. I.

In the case of free space, the radar equation yields[2]

$$p(f) = G_t \, D_t \left(\frac{\bar{\sigma}\lambda^2}{4\pi}\right) D_r \, G_r \tag{5}$$

where: G_t = transmitting antenna gain;

D_t = $1/4\pi\rho_t^2$ = reduction in power due to propagation along a distance ρ_t between transmitter and target;

$\bar{\sigma}$ = radar cross-section of target;

λ = wavelength of operation;

D_r = $1/4\pi\rho_r^2$ = reduction in power due to propagation along a distance ρ_r between target and transmitter;

G_r = receiving antenna gain.

Note that, in contrast to IR, the quantity being used now is $\bar{\sigma}$ rather than the normalized quantity σ that was utilized in IR. However, the two quantities are simply related by means of

$$4\pi\sigma = \bar{\sigma}\lambda^2 . \tag{6}$$

As already assumed before, we take $\rho_r = \rho_t = \rho$, $D_t = D_r = D$ and $G_t = G_r = G$, to obtain

$$p(f) = \frac{\bar{\sigma}}{4\pi}(\lambda G \, D)^2 \tag{7}$$

To compare operation in free space at two different frequencies, Eq. (4) is applied to yield

$$L_2 = 10 \log \left\{ \frac{\bar{\sigma}(f_o)}{\bar{\sigma}(f)} \left[\frac{f}{f_o} \cdot \frac{G(f_o)}{G(f)} \right]^2 \right\} \tag{8}$$

In deriving Eq.(8), f/f_o was taken for λ_o/λ and D does not appear because it is independent of frequency. At this stage, one must assume something about the frequency dependence of $\bar{\sigma}(f)$. For the frequency range considered here (100 to 1000 MHz.), it will be assumed that the scattering cross-section is substantially independent of frequency, so that the ratio $\bar{\sigma}(f_o)/\bar{\sigma}(f)$ is unity in Eq. (8). This assumption imposes a restriction on the generality of the results derived here. However, this restriction does not seem to be too serious because, for targets involving personnel or vehicles, the available information seems to bear out the fact that $\bar{\sigma}(f)$ is essentially constant over the frequency range of interest.

If one considers now the antenna gain G(f) and assumes that the antenna aperture A is kept constant with f, as discussed in Sec. I, one obtains[2]

$$G(f) = \frac{4\pi A}{\lambda^2} \propto f^2. \tag{9}$$

Introducing this into Eq. (8) and recalling that $\bar{\sigma}(f)$ is assumed constant with frequency, one obtains,

$$\Delta L_2 = -20 \log \frac{f}{f_o} . \tag{10}$$

The last result is simple because it refers to a comparison between two systems, both of which are in free space. For a frequency f larger than the reference frequency f_o, ΔL_2 is negative. This means that, if frequency is increased, an incremental gain (rather than loss) is obtained in free space. The appropriate values of ΔL_2 are shown in Fig.2 (right-hand scale). If, on the other hand, the radar systems are located in a forest environment, one uses

$$\Delta L_2' = 10 \log \frac{p'(f_o)}{p'(f)} , \tag{11}$$

where $\Delta L_2'$ has the same meaning as ΔL_2, except that a forest environment is now involved instead of free space. One may then write

$$p'(f) = \bar{\sigma}'(\lambda G' D')^2 , \tag{12}$$

where $\bar{\sigma}'$, G' and D' have the same meaning as $\bar{\sigma}$, G and D, respectively, except that they refer to a forest environment instead of free space. However, it was already argued in IR that

$$\bar{\sigma}' = \bar{\sigma} , \tag{13}$$

i.e., the target cross-section is essentially independent of the vegetation wherein it is located; it is recalled that the basis for this result was largely due to the Doppler-type of operation for the radar systems considered here.

It is then convenient to write:

$$\frac{p'(f_o)}{p'(f)} = \frac{p'(f_o)}{p(f_o)} \cdot \frac{p(f_o)}{p(f)} \cdot \frac{p(f)}{p'(f)} \tag{14}$$

The second factor in the right-hand side of Eq. (14) is related to ΔL_2 via Eqs. (4) and (10), whereas the first and third factors can be phrased, by means of Eqs. (7), (12) and (13), as

$$10 \log \frac{p(f)}{p'(f)} = 10 \log \left(\frac{GD}{G'D'}\right)^2 = 2L_t(f) . \tag{15}$$

Here $L_t = L_t(f)$ is the one-way terrain loss, which was discussed in great detail in IR. As defined, L_t is calculated at any one given frequency. To put things into proper prospective, it is worthwhile re-writing Eq.(7) of IR, namely:

$$L_t = L_t(f) = 10 \log \frac{\text{Incident power on target under free-space conditions}}{\text{Incident power on target under forest-terrain conditions}} \tag{16}$$

Inserting Eqs. (4)(10), (14) and (15) into Eq. (11), one gets

$$\begin{aligned} \Delta L_2' &= -2L_t(f_o) + \Delta L_2 + 2L_t(f) \\ &= 2L_t(f) - 2L_t(f_o) - 20 \log \frac{f}{f_o} \end{aligned} \tag{17}$$

As $L_t(f)$ can be found by the derivations already presented in IR, the incremental two-way loss $\Delta L_2'$ in forest environments may be calculated easily by means of Eq. (17). An analogous derivation may be carried out for the incremental two-way loss $\Delta L_2''$, which occurs over bare ground, namely

$$\Delta L_2'' = 10 \log \frac{p''(f_o)}{p''(f)} \tag{18}$$

In this case, the result is analogous to that of Eq. (17), provided one replaces L_t with the ground loss

$$L_{gr} = L_{gr}(f) = 10 \log \frac{\text{Incident power on target under free-space conditions}}{\text{Incident power on target under bare-ground conditions}}, \quad (19)$$

in which case one gets

$$\Delta L_2'' = 2L_{gr}(f) - 2L_{gr}(f_c) - 20 \log \frac{f}{f_o} . \quad (20)$$

The evaluation of $\Delta L_2''$ and $\Delta L_2'$ is carried out in the following sections.

III. INCREMENTAL LOSS OVER BARE GROUND

In the case of bare ground, the loss L_{gr} is due simply to the ground-lobing effect. If the discussion is restricted to horizontally polarized antennas, as was the case in IR, the loss L_{gr} is rather straightforward. By using Eq. (47) of IR, one then has

$$\begin{aligned} L_{gr}(f) &= - 20 \log \left(2 \sin \frac{k_o z z_o}{\rho}\right) \\ &= - 20 \log \left(2 \sin \frac{2\pi f}{c} \frac{z z_o}{\rho}\right) \end{aligned} \quad (21)$$

Result (21) holds when both the antenna height z_o and the target height z above ground are much smaller than the distance ρ between the antenna and the target. If, furthermore, these distances satisfy the condition $2\pi z z_o/\lambda\rho < 1$, the sine in Eq. (21) may be replaced by its argument, so that

$$L_{gr}(f) \simeq - 20 \log \frac{4\pi f}{c} \cdot \frac{z z_o}{\rho} \quad (22)$$

Introducing this result into Eq. (20) and recalling that, except for f, all of the parameters in Eq. (22) are fixed, one gets:

$$\Delta L_2'' = - 40 \log \frac{f}{f_o} - 20 \log \frac{f}{f_o} = - 60 \log \frac{f}{f_o} \quad (23)$$

Hence, if $f > f_o$, $\Delta L_2''$ is negative and this implies that an incremental gain (rather than loss) is achieved by raising the frequency. This gain may be quite considerable and reaches 18 dB, if frequency is doubled. Other values are given in the plot shown in Fig. 2. However, great caution must be exercised when using result (23) because it is valid only if $2\pi z z_o / \lambda\rho < 1$ <u>at the highest frequency</u>. When this inequality does not hold, the ground lobing effect does not favor the higher frequency so strongly. In fact, Eq. (10) indicates that the incremental gain reduces to 20 log (f/f_o) if the frequency is raised under free-space conditions.

In general, therefore, the incremental loss $\Delta L_2''$ in the presence of bare ground will depend very strongly on the ratio $\zeta = 2\pi z z_o / \lambda\rho$. One expects that the gain will be given by 60 log (f/f_o) for $\zeta < 1$; for $\zeta > 1$, this gain will gradually decrease and, as ζ becomes very large, the gain will be reduced to the value of 20 log (f/f_o), as expected from Eq. (10).

IV. <u>INCREMENTAL LOSSES IN A FOREST ENVIRONMENT</u>

In the case of a forest, the environment can be described in terms of a lossy dielectric slab superposed on a well conducting ground, as shown in Fig. 1. The restrictions and validity of such a model have been discussed at length in the literature[3,4] and the terrain loss $L_t = L_t(f)$ has been derived in IR[1]. The reader is therefore referred to references 1,3 and 4 for further details on these aspects.

An important feature of wave propagation in the presence of a forest is that, at a target embedded in vegetation, the field possesses different properties if the antenna is inside the vegetation or well above the tree tops. In the former case, the signal arrives at the target by means of a lateral wave, whereas, in the latter case, it arrives by means of a refracted line-of-sight. As a result, the expressions for $L_t(f)$ are different in the two cases and they must be examined separately.

(a) <u>Antenna Within Vegetation</u>

If the antenna is at or below the tree tops, the terrain loss for horizontal polarization is given by Eq. (36) in IR, which leads to the result

$$L_t(f) = 20 \log \left| \frac{\pi(\epsilon_1 - 1)\rho}{\lambda} \cdot \frac{\cos^2 k_L h}{\sin k_L z \sin k_L z_o} \right| , \qquad (24)$$

where

$$k_L = k_o \sqrt{\epsilon_1 - 1} = \beta_L - j\alpha_L . \qquad (25)$$

Here $k_o = 2\pi/\lambda$ is the free-space wave-number and ϵ_1 is the relative permittivity of the forest, which is a complex quantity. The value of ϵ_1 is therefore crucial in estimating $L_t(f)$ and a discussion of this quantity is presented in the Appendix. By using Eq. (A7) therein, one notes that $\alpha_L = \alpha_L(f)$ depends on frequency; furthermore, Eqs. (A.10) and (A.12) indicate that Eq. (24) may be well approximated by

$$L_t(f) = 10 \log \left\{ \left| \frac{\pi(\epsilon_1 - 1)\rho}{\lambda} \right|^2 \frac{\cosh^2 [2\alpha_L(f)\, h]}{\cosh [2\alpha_L(f)\, z] \cosh [2\alpha_L(f) z_o]} \right\} \quad (26)$$

In addition, Eq. (A.8) indicates that $|\epsilon_1 - 1|$ is nearly constant with frequency for $f \geq 100$ MHz. Introducing all of these approximations into Eq. (17), and recalling that ρ is fixed, one obtains

$$\Delta L_2' = 20 \log \left\{ \frac{f}{f_o} \cdot \frac{\cosh^2 [2\alpha_L(f)h] \cosh [2\alpha_L(f_o)z] \cosh [2\alpha_L(f_o)\, z_o]}{\cosh^2 [2\alpha_L(f_o)h] \cosh [2\alpha_L(f)z] \cosh [2\alpha_L(f)\, z_o]} \right\} \quad (27)$$

The result in Eq. (27) is relatively simple because it involves only the ratio f/f_o and terms of the form $\cosh u$, where u is determined by $\alpha_L(f)$ of Eq. (A.9) and the geometrical quantities h, z and z_o. Results for $\Delta L_2'$ are therefore plotted in Figs. 3,4 and 5 for three different tree heights h, and for various antenna heights z_o. The reference frequency f_o was arbitrarily chosen to be 100 MHz. In all cases, the height of the target was taken to be $z = 1$ meter, in agreement with the assumptions already discussed in IR. The curves for z_o = high refer to antennas that are located above the tree tops, for which Eq. (27) does not apply. These cases are discussed next.

(b) Antenna Above Tree Tops

For antennas located in the air region above the tre-top contour, the terrain loss for horizontal polarization is given by Eq. (43) in IR, which takes the form

$$L_t(f) = 20 \log \left| \frac{\cos\theta + \sqrt{\epsilon_1 - \sin^2\theta}}{2\cos\theta} \cdot \frac{\cos k_L h}{\sin k_L z} \right| . \quad (28)$$

The angle θ is indicated in Fig. 1, while k_L was already given in Eq. (25).

The term in the square root of Eq. (28) may be written as (see Appendix)

$$\begin{aligned} \epsilon_1 - \sin^2\theta &= \epsilon_1 - 1 + \cos^2\theta \\ &= (\epsilon' - 1)(1 - j \tan \delta_L) + \cos^2\theta \end{aligned} \quad (29)$$

The term $\cos\theta$ in Eq. (29) is a fixed quantity under the present assumptions of fixed ρ and z_o. The remaining term possesses a magnitude equal to $(\epsilon'-1)\cdot\sec\delta_L$, which was already noted above and in the Appendix to be practically unaffected by frequency changes. Hence the entire first fractional term in Eq. (28) may be assumed to be approximately constant with frequency. Introducing this approximation, together with Eqs. (A.10) and (A.12) into Eq.(17), one obtains

$$\Delta L_2' = 20 \log \left\{ \frac{f_o}{f} \cdot \frac{\cosh\left[2\alpha_L(f)h\right] \cosh\left[2\alpha_L(f_o)z\right]}{\cosh\left[2\alpha_L(f_o)h\right] \cosh\left[2\alpha_L(f)z\right]} \right\} \tag{30}$$

This result is similar to Eq. (27) and may be evaluated accordingly. As discussed in IR, Eqs. (28) and (30) do not hold at and close to the forest-air interface ($\theta = 90^o$), where Eqs. (24) and (27) must be used instead. On the other hand, Eq. (30) holds for any antenna height provided that the antenna is at least several wave lengths above the tallest tree tops. Hence, the curves describing $\Delta L_2'$ of Eq. (30) in Figs. 3, 4 and 5 are labeled z_o = high, implying that they apply to antennas located well above the tree tops and satisfying the restriction discussed here.

V. DISCUSSION OF RESULTS

The curve shown in Fig. 2 indicates that there is a clear and definite advantage in operating at higher frequencies over bare ground. As discussed in Sec. III , the incremental gain is given by 60 log (f/f_o) only if strong ground-lobing occurs. At sufficiently high antenna height, the ground-lobing effect is negligible, so that the gain reduces to the free-space result of 20 log (f/f_o), which is still quite appreciable. Hence, by taking advantage of the higher antenna gains available at the higher frequencies (assuming the antenna aperture is fixed) higher operating frequencies are decidedly preferable for radar systems under bare-ground conditions.

The above situation, however, is quite different if a radar system operates in a forest environment. Thus, it is seen from Figs. 3,4 and 5 that losses increase with frequency, except for the case of z_o = high in Fig.3. In general, for targets located in vegetation, it appears that the foliage losses increase with frequency more strongly than the antenna gain. As a result, the result of increasing the frequency is to introduce higher radio losses in the case of antennas located inside the vegetation or close to the tree tops.

For antennas that are more than a few wavelengths above the tree tops (i.e., for z_o = high in Figs. 3,4 and 5), the overall losses are smaller because the propagation path is least affected by the presence of the vegetation. In fact, the incremental loss $\Delta L_2'$ for z_o = high in Fig.3 is negative, which means that actually a gain is achieved if the frequency is increased. Such a gain appears in Fig.3 but not in Figs. 4 and 5, because the first one refers to a situation wherein the signal must traverse a vegetation layer that is determined by a tree height of only 5 meters, whereas the other two refer to tree heights of 10 and 15 meters, respectively. As the tree height decreases, the situation progressively approaches that of a bare-ground terrain, which was seen to yield an incremental gain (rather than loss) if frequency is raised. Hence, the tree height of 5 meters represents a case for which the vegetation losses are slightly smaller than the amount necessary to cancel the gain available under bare-ground conditions. A similar behavior would occur if the tree height h was larger than 5 meters, but the target height z was greater than the nominal value of $z = 1$ meter assumed herein. However, insofar as $\Delta L_2'$ is concerned, increasing h by a certain amount is not equivalent to increasing z by the same amount; although the effect of a larger h is to increase and that of a larger z is to decrease the value of $\Delta L_2'$, the net change is not proportional and must be found accurately by using Eqs. (27) and (30).

To summarize the above discussion, the general trend for $\Delta L_2'$ is that this incremental radio loss increases with frequency if the target is located in vegetation. Exceptions to this result may, however, arise if the antenna is well above the tree tops and if the vegetation layer <u>above</u> the target is not more than 3 or 4 meters thick; when this happens, an incremental gain may occur if the operating frequency is raised. However, this gain is probably not too large and is not expected to exceed a value of 20 log (f/f_o).

At this stage, it is appropriate to emphasize that the results shown in Figs. 3, 4 and 5 refer to only one aspect of radar-system considerations. The quantity $\Delta L_2'$ discussed here describes a radio-propagation loss whose general increase with frequency must be considered together with other determining factors if one desires to arrive at a suitable frequency of operation. Thus, the frequency dependence of clutter, of the signal-to-noise figure, of the available transmitted power, etc. must also be examined. These other factors may, in fact, partially over-ride some of the results obtained here and may therefore favor a frequency that is higher than that recommended by examining only the total radio loss. Nevertheless, for low targets (1-2 meters high) located in a forest with trees of average height of about 10 meters or more, the present results indicate that an operating frequency of 1000 MHz. or higher would require transmitter powers that would be prohibitive. In fact, operation at frequencies closer to the 100 MHz region would then offer considerably smaller losses. For systems operating over bare ground, on the other hand, higher operating frequencies are subject to considerably smaller radio losses; other factors being equal, a higher operating frequency is therefore preferable in a reasonably flat and bare terrain.

Another important factor that needs to be considered when using the curves in Figs. 3,4, and 5 is that they are based on an empirical formula for the complex permittivity ϵ_1 which is discussed in the Appendix. A different choice of formulating ϵ_1 will affect the values of $\Delta L_2'$ to a smaller or larger degree depending on the situation. However, pending further measurements on vegetation constants for thefrequency range 100-1000 MHz., the present results are deemed to represent reasonable projections for average situations. By "average situations" we mean on the one hand, that the losses obtained here are expected to represent an average over many readings under the assumed conditions. On the other hand, the forest environment is assumed to involve an average vegetation, in the sense that the propagation path does not traverse only through either very dense or very sparse foliage, but follows a line along which the vegetation averages out in density.

APPENDIX A: Derivation of an Empiric Formula for the Permittivity of Vegetation.

The particular value that one must ascribe to the vegetation permittivity ϵ_1 poses a problem of primary importance because the complex quantity ϵ_1 enters into all of the calculations for obtaining the radio loss of a radar system located in a forest environment. The problem is especially complicated by the fact that practically no attempts have been made in measuring the value of ϵ_1 for frequencies above 100 MHz. The aim of this Appendix is to briefly review available data and to establish a reasonable estimate for ϵ_1, which has been utilized in preceding sections of the present report.

The quantity that was usually measured in the past (5-9) in the context of vegetation losses is the attenuation factor α. This attenuation corresponds to the loss encountered if a plane wave were to propagate through the vegetation medium. Hence α is derived by assuming that the plane-wave propagation factor k_1 through the forest medium is given by the complex quantity

$$k_1 = k_o \sqrt{\epsilon_1} = \beta - j\alpha \qquad \text{(A.1)}$$

However, in measuring , the assumption is made (5,6,7) that energy propagates from the transmitter to the measuring probe via a line-of-sight path, which is sometimes referred to as "Thru-the-vegetation mode". This implies that the field varies as $\exp(-jk_1 d)$, where d is the distance traversed. In past experimental work α was therefore obtained by measuring the attenuation of the electric field along various paths in forests. A summary of such measurements is presented in Fig. 6.

An inspection of Fig. 6 reveals that the measured attenuation α spreads over a very wide range of values. This large variation, by itself, makes it very difficult to obtain a specific value for ϵ_1. In addition, however, ϵ_1 is complex and it is therefore necessary to know another quantity in addition to the value of α in order to derive ϵ_1. To appreciate this point, it is recalled that the real part ϵ of ϵ_1 is close to unity and that its imaginary part ϵ'' is usually small, so that $\epsilon'' \ll \epsilon' \simeq 1$. One may therefore write:

$$k_1 = k_o \sqrt{\epsilon' - j\epsilon''} \simeq k_o \sqrt{\epsilon'} \left(1 - j \frac{\epsilon''}{2\epsilon'}\right)$$
$$\simeq k_o' \left(1 - j \frac{\epsilon''}{2}\right), \qquad \text{(A.2)}$$

from which it follows that

$$\alpha \simeq \frac{1}{2} k_o \epsilon'' = \frac{\pi \epsilon''}{\lambda}. \qquad \text{(A.3)}$$

Thus α may be utilized to determine ϵ'' to a good approximation. However, in the calculations involved in Eqs. (27) and (30), it is necessary to use $\epsilon' - 1$ rather than just ϵ' ; because ϵ' is close to unity, it is therefore necessary to know its value accurately, otherwise a serious error may be produced in the result.

It is recognized that the above difficulties stem from the fact that, whereas most work in the past[5-7] had assumed a "thru-the-vegetation" path for which the value of α was a sufficient characterization, it is now known[3,4] that the principal propagation mechanism is a lateral wave, whose propagation factor is not k_1 but, instead, is given by

$$k_L = k_o \qquad \text{(A.4)}$$

where it is now evident that the difference $\epsilon_1 - 1$ may be critical if ϵ' is close to unity.

Although one needs to know both β_L and α_L to fully determine k_L , it is more convenient to work with α_L and another quantity δ_L , which is defined by

$$\tan \delta_L = \frac{\epsilon''}{\epsilon' - 1}, \qquad \text{(A.5)}$$

so that one has

$$|\epsilon' - 1| = (\epsilon' - 1) \sec \delta_L \qquad \text{(A.6)}$$

To determine α_L and δ_L from the available data shown in Fig. 6, the following procedure was followed:

(a) The results reported by Stanford Research Institute[8,9] were re-plotted in Figs. 7 and 8, for α_L and sec δ_L, respectively, by using the values of α in Fig. 6 and ϵ' as measured[8,9]. Incidentally, these measurements by Stanford Research Institute are the only ones that were aimed at obtaining the full complex value of ϵ_1. All of the other measurements shown in Fig. 6 obtained α only and did not determine ϵ_1.

(b) The results reported by Jansky and Bailey[7] were re-plotted in Figs. 7 and 8, by using α as shown in Fig. 6, together with an <u>assumed</u> value of $\epsilon' = 1.02$. Although this value of ϵ' is assumed, its magnitude is consistent with the values measured by Stanford Research Institute[9] in the same forest area that the Jansky and Bailey measurements were carried out.

(c) The remaining results were re-plotted in Figs. 7 and 8 by assuming reasonable values for ϵ', which were estimated by taking into account the description of the vegetation as given in the published papers.[8,6] Thus, for the relatively thin vegetation with which Saxton and Lane[6] were concerned, ϵ' was taken to be equal to 1.01, whereas the thick jungle referred to by Krevsky[5] was assumed to possess an ϵ' equal to 1.1.

The resulting curves shown in Figs. 7 and 8 indicate that both α_L and δ_L exhibit a smaller spread than α in Fig. 6. For the purpose of calculations, an intermediate value for α_L was chosen as shown in Fig. 7 by the straight line given by

$$\alpha_L \text{ (dB/m)} = 0.1 \sqrt{f \text{ (MHz)}} . \qquad \text{(A.7)}$$

This turns out to be a very simple empirical formula to characterize lateral-wave losses in a forest environment. However, great caution should be exercised in using it, because this value of α_L represents an intermediate value that may not be adequate for a particular situation.

Referring now to Fig. 8 where sec δ_L is plotted, it is noted that $1 < \sec \delta_L < 1.2$ for $f \geq 100$ MHz. Hence, sec δ_L is not very sensitive to frequency changes. If one then makes the reasonable assumption that ϵ' is also not strongly dependent on frequency, use of Eq. (A.6) yields

$$|\epsilon' - 1| \simeq \text{const. for } f \geq 100 \text{ MHz.} \qquad \text{(A.8)}$$

Two other quantities that are needed for calculating the incremental loss $\Delta L_2'$ are the terms $|\sin k_1 z|$ and $|\cos k_L h|$, which appear in Eqs. (26) and (28) in the text. To evaluate these, consider the first one, namely

$$|\sin^2 k_L z| = \sin^2 \beta_L z + \sinh^2 \alpha_L z \qquad \text{(A.9)}$$

The second term on the right-hand side may be calculated by means of Eq. (A.7), but the first term is, as yet, undetermined. However, $\beta_L z$ represents a phase term for a target height of z meters. As the values for β_L vary strongly as a function of δ_L for $1 < \sec \delta_L < 1.2$, the phase $\beta_L z$ will be strongly dependent on both frequency and the target height z. For moving targets, however, the height z is understood to refer to an average value. Consequently, it is reasonable to take an average value also for $\sin^2 \beta_L z$ in Eq. (A.9). As the average of sine squared is 1/2, we get

$$|\sin^2 k_L z| \approx \frac{1}{2} + \sinh^2 \alpha_L z = \frac{1}{2} \cosh 2\alpha_L z \, . \qquad \text{(A.10)}$$

For the $|\cos k_L h|$ quantity, one obtains

$$|\cos^2 k_L h| = \cos^2 \beta_L h + \sinh^2 \alpha_L h \, . \qquad \text{(A.11)}$$

Applying the same averaging argument that was used in Eq. (A.10), one obtains

$$|\cos^2 k_L h| \simeq \frac{1}{2} + \sinh^2 \alpha_L z = \frac{1}{2} \cosh 2\alpha_L h \, . \qquad \text{(A.12)}$$

The results expressed in Eqs. (A.7), (A.8), (A.10) and (A.12) have been used to derive the curves obtained in this report. However, it should be evident from the present discussion that a large amount of extrapolation was employed, which involved several reasonable but, as yet, non-verified assumptions. If the complex permittivity ϵ_1 will be measured in the future for frequencies above 100 MHz., the results given here may have to be modified substantially.

APPENDIX B: Examples of Radio-Loss Calculations

To illustrate the quantitative aspects of the concepts discussed in this report, several calculations will be presented below. For this purpose, it is assumed that a radar system at the reference frequency f_o operates under the following conditions:

$$f_o = 200 \text{ MHz}$$
$$G = 17 \text{ dB}$$
$$z_o = 10 \text{ m}$$
$$z = 1 \text{ m}$$
$$\rho = 1 \text{ km}$$
$$\bar{\sigma} = 1 \text{ sq.m.}$$

Radio losses will first be calculated at the reference frequency f_o and later at a higher frequency $f = 1000$ MHz. It is important to note that these losses are calculated by neglecting all circuit, polarization or other secondary sources of loss.

1. Free-space radio losses L_{fs}

By definition from Eq. (5), the free-space radio loss L_{fs} is given by:

$$L_{sf}(f) = -10 \log p(f) = -10 \log \frac{\bar{\sigma}}{4\pi} (\lambda GD)^2$$

$$= -10 \log \frac{\bar{\sigma} (\lambda G)^2}{(4\pi)^3 \rho^4}$$

By using all linear dimensions in terms of meters, one obtains the following dB. figures for $f_o = 200$ MHz, i.e., $\lambda = 1.5$ m.:

$\bar{\sigma}$	. . . .	0 dB.
λ^2	. . . .	- 3.5 "
G^2	. . . .	- 34 "
$(4\pi)^3$	. . . .	33 "
ρ^4	. . . .	120 "
$L_{fs}(f_o)$	. . . .	115.5 dB

To find the free-space losses at $f = 1000$ MHz, the graph in Fig. 2 is used to obtain:

$$L_{fs}(f) = L_{fs}(f_o) + \Delta L_2$$

$$= 115.5 - 20 - (-6) = \underline{101.5 \text{ dB}}$$

It is recalled that the last result implies that the antenna gain G was increased by the ratio $(f/f_o)^2$, thus obtaining an increase of 28 dB. for the two-way radar path. However, the net gain at 1000 MHz is only 14 dB. with reference to operation at 200 MHz.

2. Bare-ground losses L_{bg}

It is recalled that, to carry out simplified calculation over bare ground, it is necessary to check whether the ratio $\zeta = 2\pi zz_o/\lambda\rho$ is smaller or larger than unity at the highest frequency. In the present case:

$$\zeta = \frac{2\pi zz_o}{\lambda\rho} = \frac{2\pi \times 1 \times 10}{1.5 \times 1000} = 0.041 \ll 1$$

Hence Fig. 15 in IR and Fig. 2 here may be used. From the former figure one finds that $L_{gr} = 24$ dB. at 140 MHz. As most calculations in IR are for a nominal frequency of 140 MHz., it is necessary to find the free-space loss at that frequency for reference purposes. By denoting this nominal free-space loss as $L_{fs}(140)$ and using Fig. 2, one finds

$$L_{fs}(140) = L_{fs}(f_o) + \Delta L_2$$

$$= 115.5 - (-6) + (-3) = 118.5 \text{ dB.}$$

The bare-ground loss at 140 MHz. is therefore

$$L_{bg}(140) = L_{fs}(140) + L_{gr}$$

$$= 118.5 + 24 = 142.5 \text{ dB.}$$

We may now use Fig. 2 to obtain the losses at the frequencies f_o and f as follows:

$$L_{bg}(f_o) = L_{bg}(140) + \Delta L_2''$$

$$= 142.5 - (-9) + (-18) = 133.5 \text{ dB.}$$

$$L_{bg}(f) = L_{bg}(f_o) + \Delta L_2''$$

$$= 133.5 - (-17.5) + (-60) = 91 \text{ dB.}$$

In the present case, one obtains therefore a gain of 133.5 - 91 = 42.5 dB. if the frequency is raised from 200 to 1000 MHz. over bare ground (provided the antenna aperture is held constant).

3. Forest-environment losses $L_{fe}(f)$, for h = 10 m.

For a forest with moderately high trees such that h = 10 m., one must find first the terrain loss L_t from Fig. 11 of IR. In this context, it is important to observe that the vegetation model derived in Appendix A corresponds to an ϵ_1 which is described by the sparse vegetation at 140 MHz. Hence, only the sparse vegetation curves in IR must be utilized in conjunction with the curves in the present report. In this case, use of Fig. 11 in IR yields L_t = 32.5 dB. At 140 MHz. and ρ = 500 m. one then has:

$$L_{fe}(140) = L_{fs}(140) + L_t$$

$$= 118.5 + 32.5 = 151 \text{ dB} \quad (\text{at } \rho = 500 \text{ m.})$$

However, this result must be modified to obtain the loss at ρ = 1000 instead of 500 m. By using Fig. 6 of IR, it is noted that doubling the range ρ produces an additional loss of 6 dB. Hence, under the present conditions:

$$L_{fe}(140) = 151 + 6 = 157 \text{ dB.} \quad (\text{at } \rho = 1 \text{ km.})$$

To find the radio loss at the present frequencies, we use Fig. 4 to obtain

$$L_{fe}(f_o) = L_{fe}(140) + \Delta L_2'$$

$$= 157-7+13 = 163 \text{ dB.}$$

$$L_{fe}(t) = L_{fe}(f_o) + \Delta L_2'$$

$$= 163-13+61 = 211 \text{ dB.}$$

In the present case, increasing the frequency from 200 to 1000 MHz produces a loss of 211-163 = 48 dB. Of course, this is due to the increased foliage losses at the higher frequencies.

4. <u>Forest-environment losses $L_{fe}(f)$, for $h = 5m$.</u>

For a forest with small trees such that $h = 5$ m., the antenna at $\rho_o = 10$m. will be considered to be "high" because it is more than a few wavelengths above the tree tops. By using considerations similar to the preceding calculations, one finds from Fig. 10 of IR that $L_t = 27.5$ dB. Recalling that 6 dB must be added because of the range being $\rho = 1$ km., one has

$$L_{fe}(140) = L_{fs}(140) + L_t + 6$$

$$= 118.5 + 27.5 + 6 = 152 \text{ dB}.$$

By next using Fig. 3 (with z_o = high), one finds:

$$L_{fe}(f_o) = L_{fe}(140) + \Delta L_2'$$

$$= 152 - (-2) + (-4) = 150 \text{ dB}.$$

$$L_{fe}(f) = L_{fe}(f_o) + \Delta L_2'$$

$$= 150 - (-4) + (1-2) = 152 \text{ dB}.$$

In the present case, a small loss of only 2dB. is obtained if the frequency is raised from 200 to 1000 MHz. The reason for this slight loss was discussed in Sec. V in the text.

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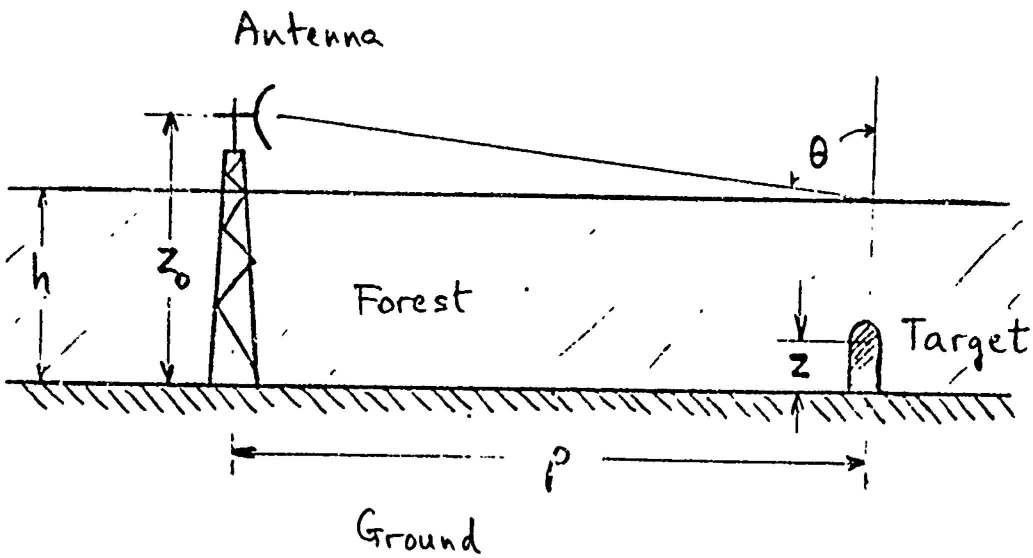

Fig. 1 Geometry of a forest-environment model. Although the antenna is located here above the tree tops, its height z_o may lie anywhere between $0 < z_o < \infty$.

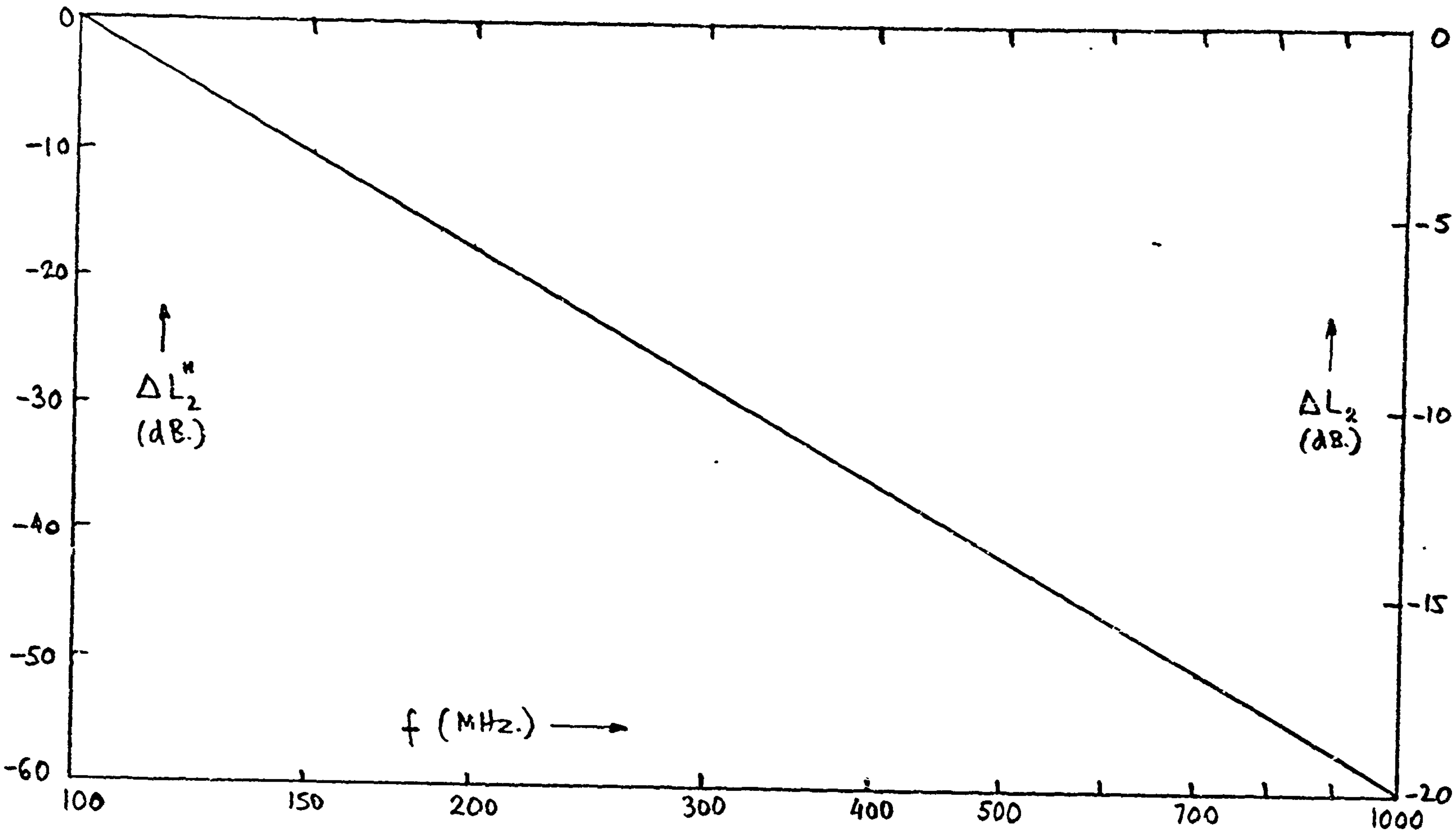

Fig. 2 Free-space incremental loss ΔL_2 and bare-ground incremental loss $\Delta L_2''$ as a function of frequency. The data for $\Delta L_2''$ are accurate only if $\zeta = 2\pi z z_o / \lambda \rho < 1$.

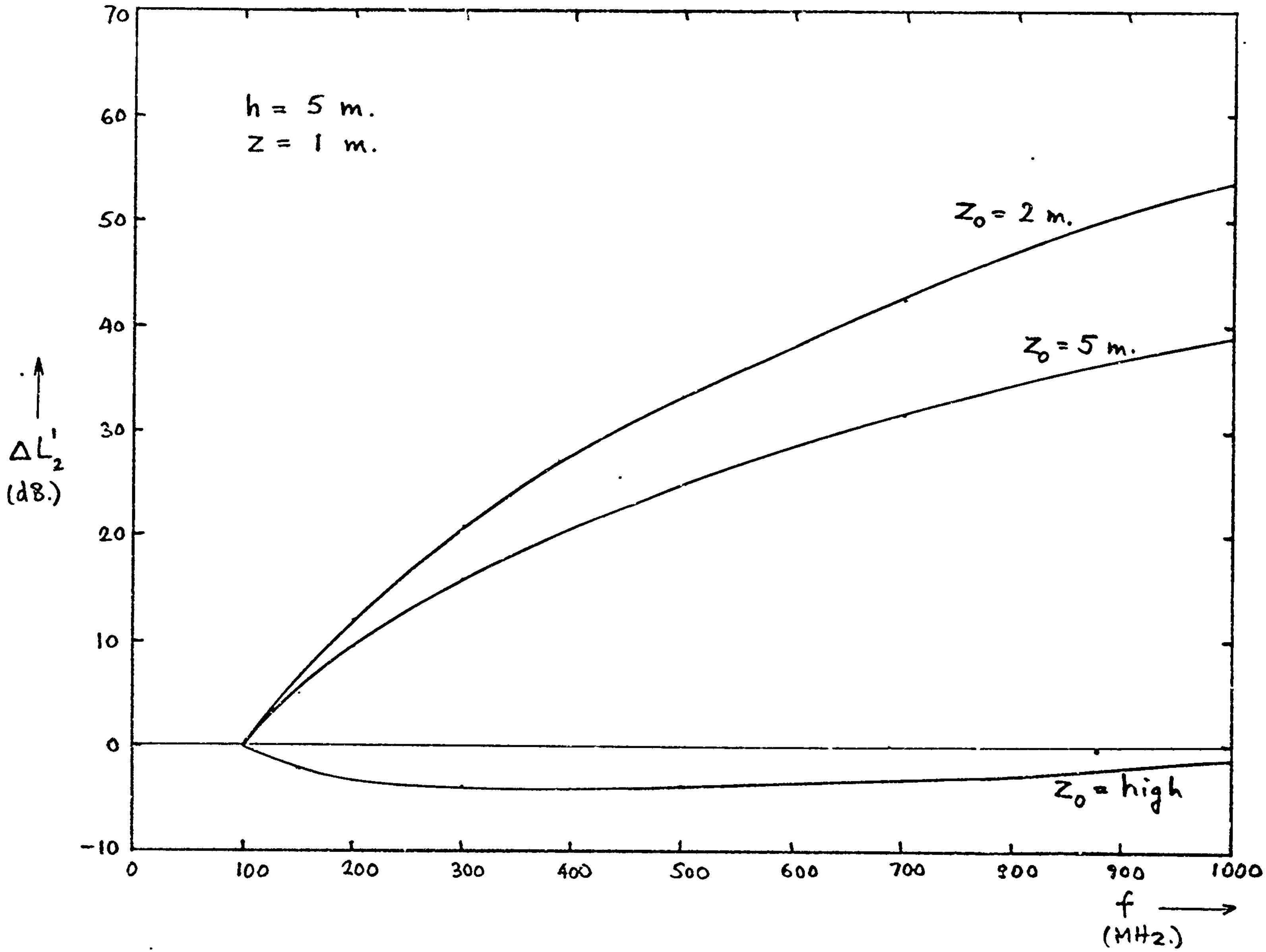

Fig. 3 Incremental loss $\Delta L_2'$ as a function of frequency for a forest with an average tree height h = 5 m. and a target height z = 1 m.

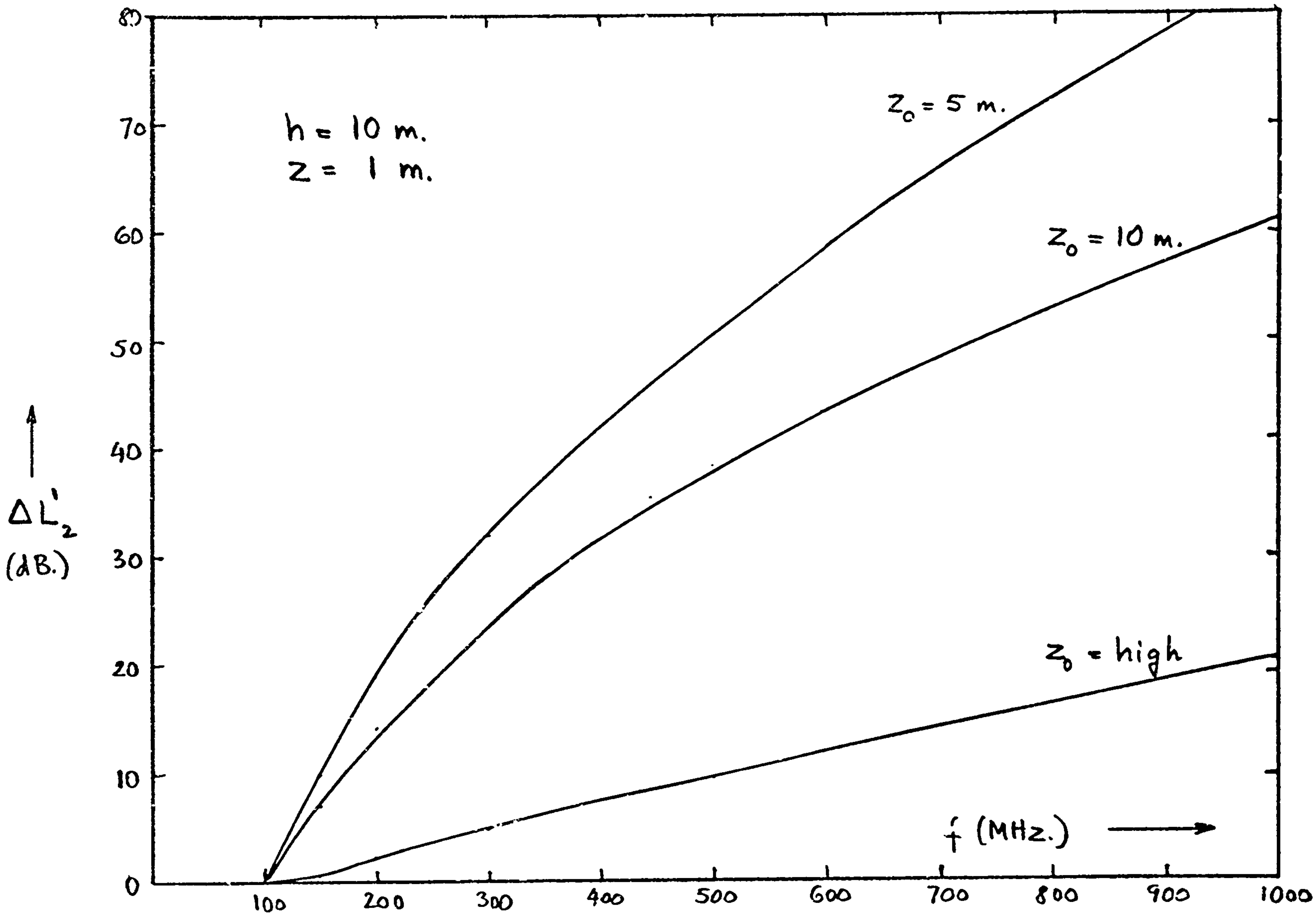

Fig. 4 Incremental loss $\Delta L_2'$ as a function of frequency for a forest with an average tree height h = 10 m. and a target height z = 1 m.

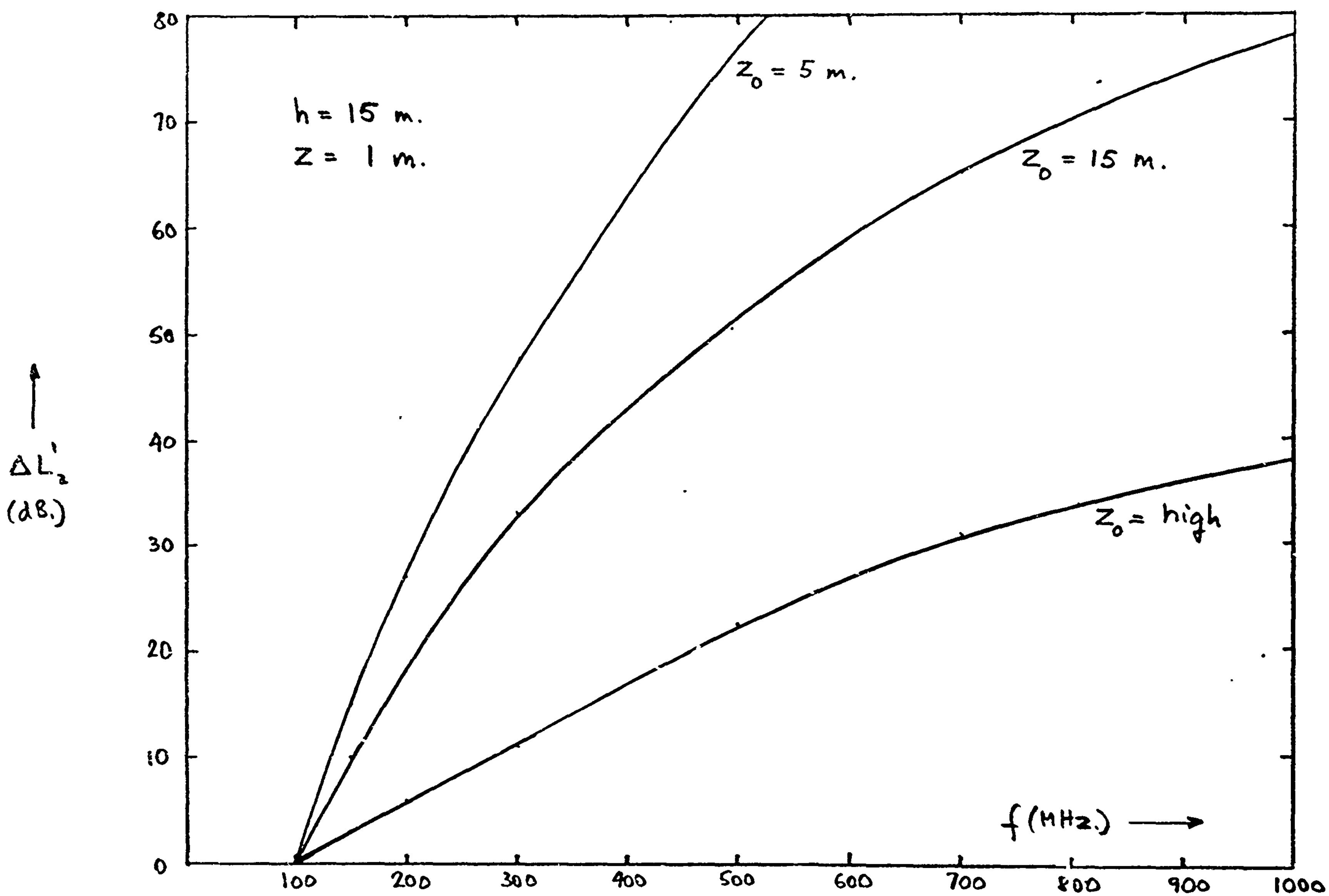

Fig. 5 Incremental loss $\Delta L_2'$ as a function of frequency for a forest with an average tree height h = 15 m. and a target height z = 1 m.

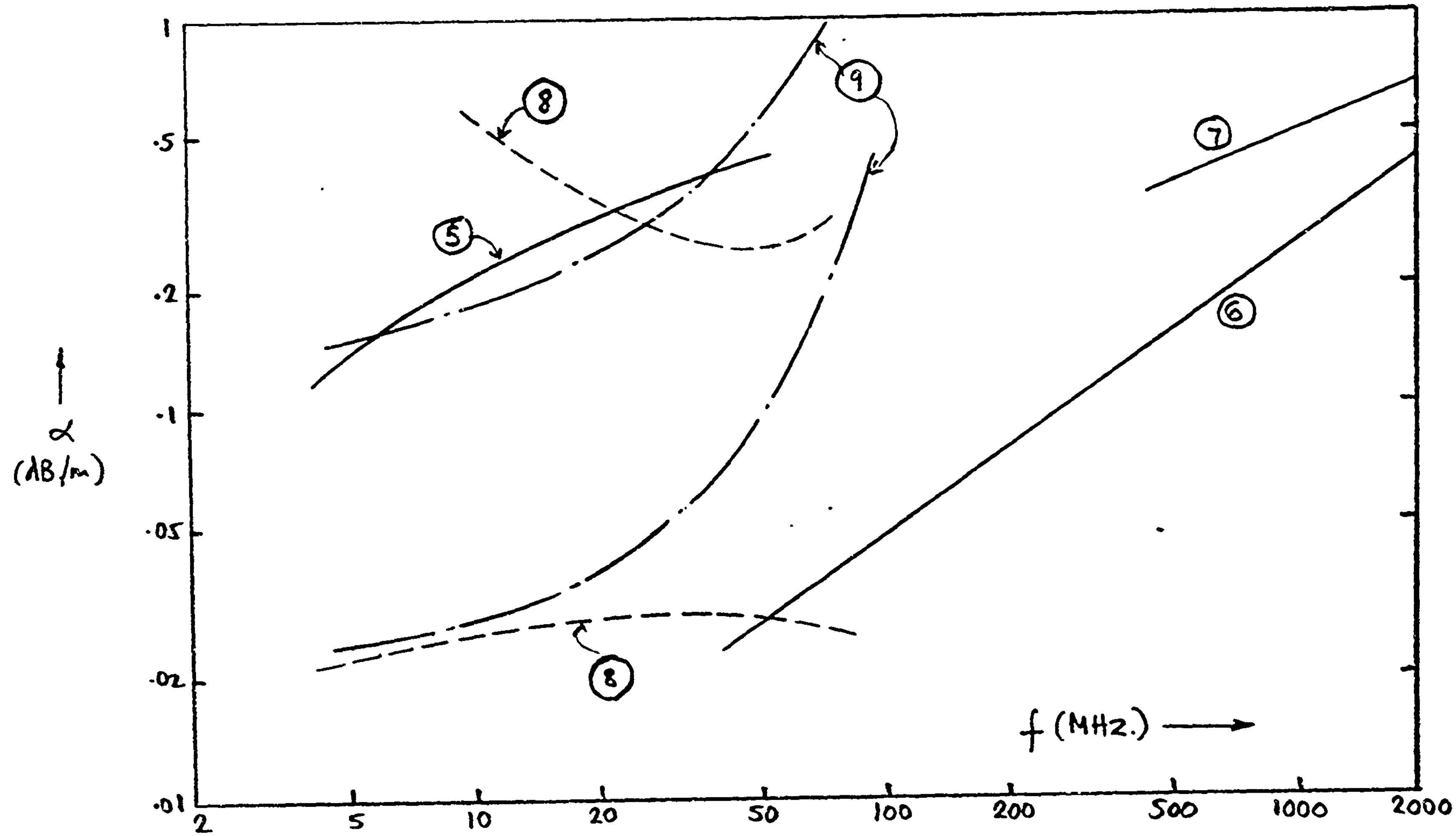

Fig. 6 Measured values for the foliage attentuation α as a function of frequency. Numbers inside circles indicate references from which curves were extracted; when two curves appear for the same reference, they refer to maximum and minimum values measured.

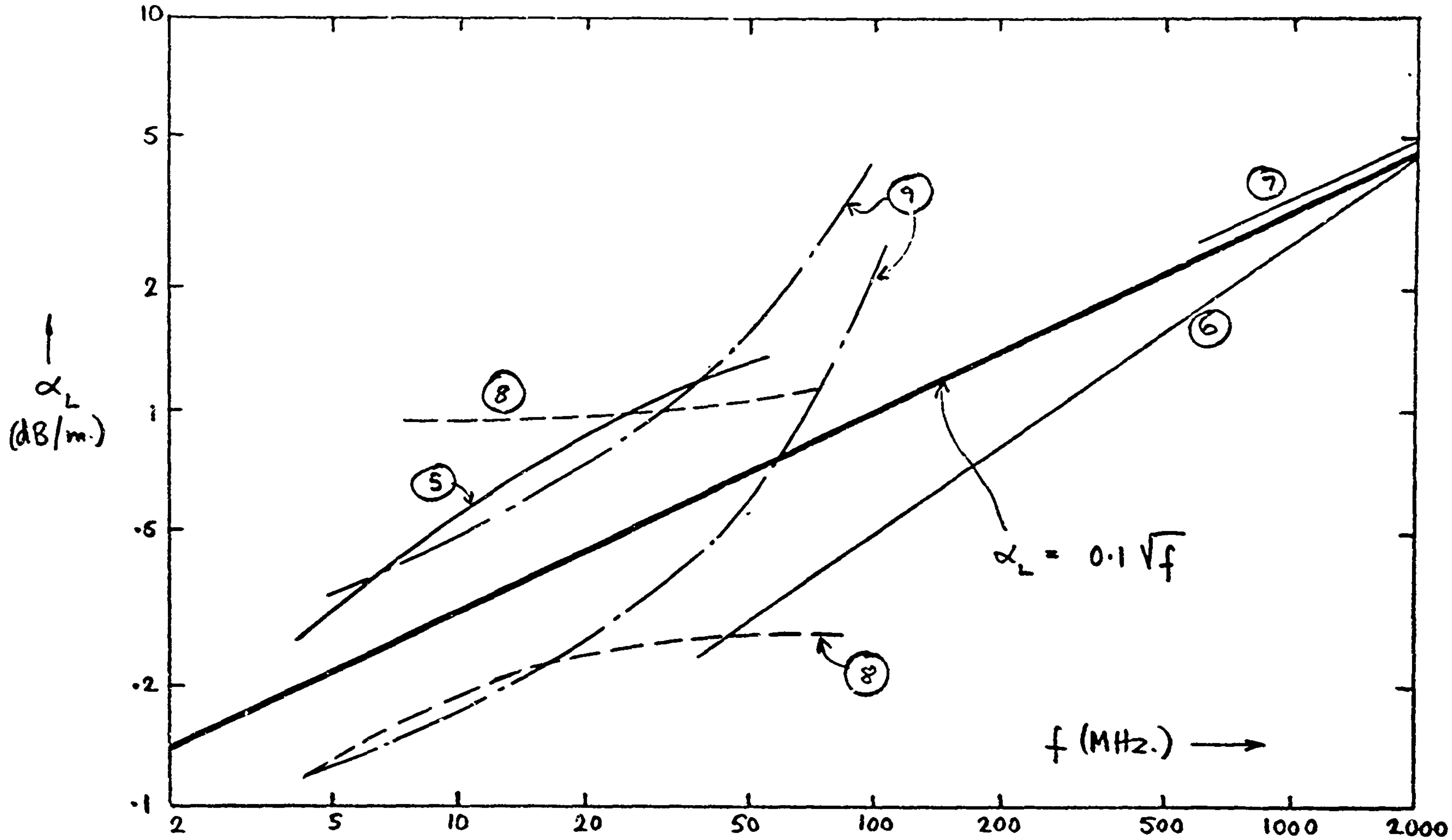

Fig. 7 Calculated values for the lateral-wave attenuation α_L as a function of frequency. Numbers inside circles refer to the curves shown in Fig. 6.

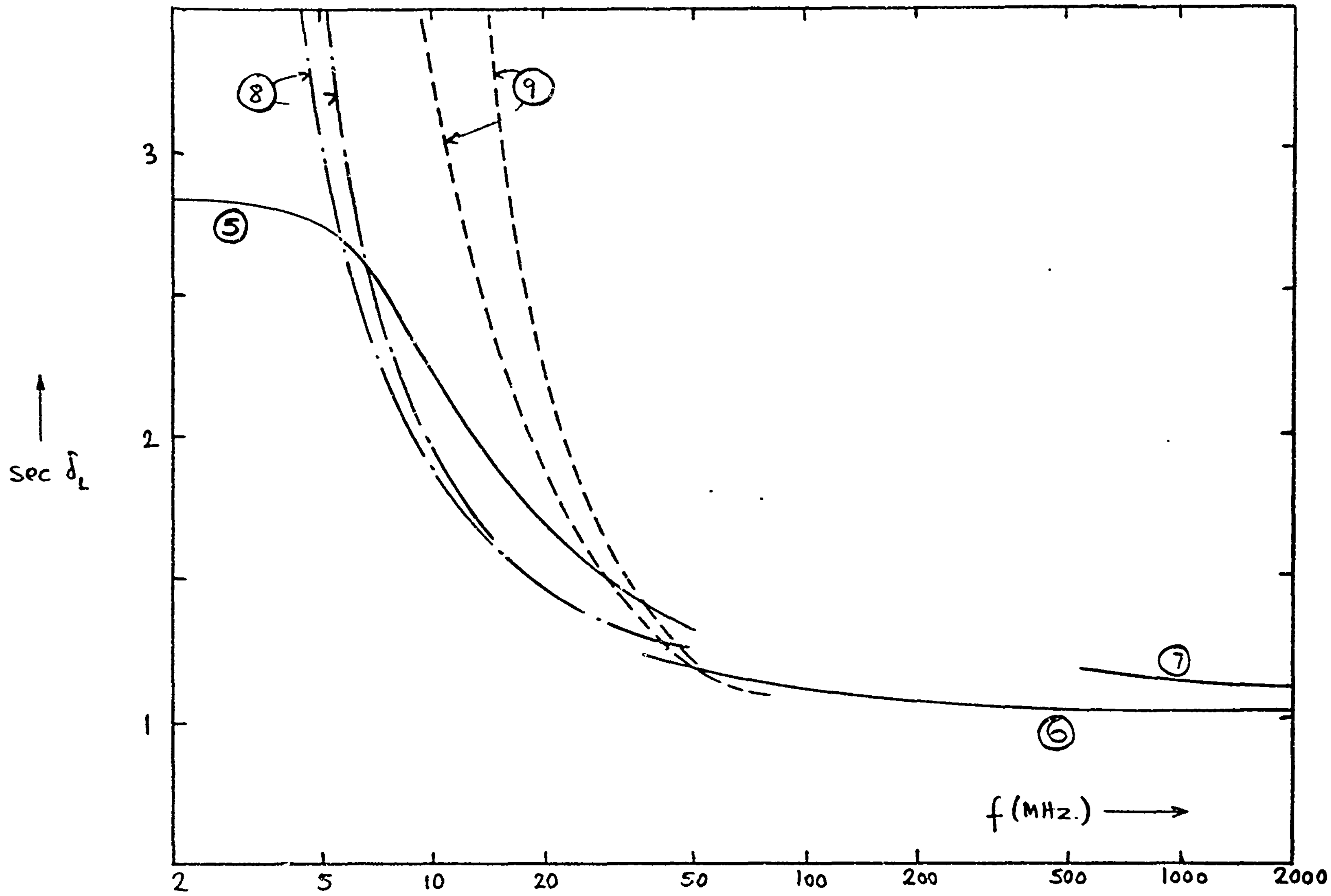

Fig. 8 Calculated values for sec δ_L as a function of frequency. Numbers inside circles refer to the curves shown in Fig. 6.