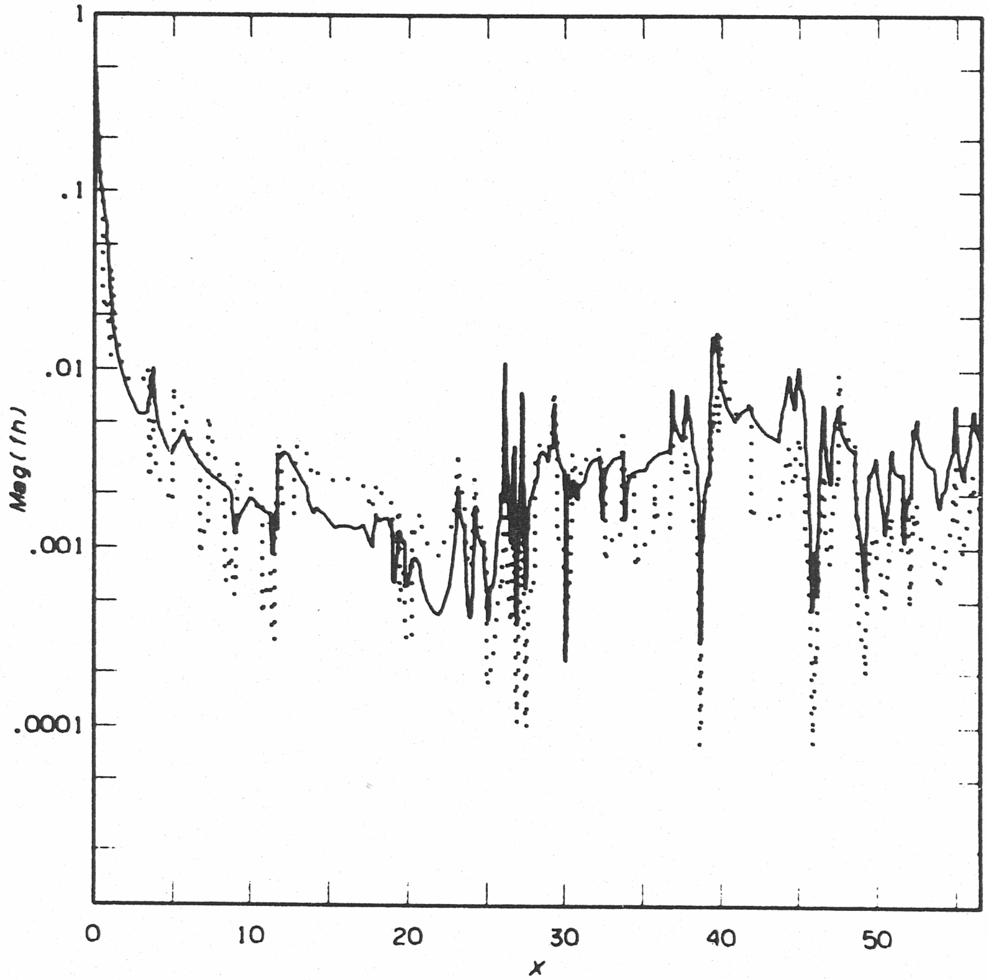

Figure 17. Propagation from Inneringen to Boblingen at 20 MHz. The solid curve is for bare ground, and the dotted curve includes the forest and urban slabs.

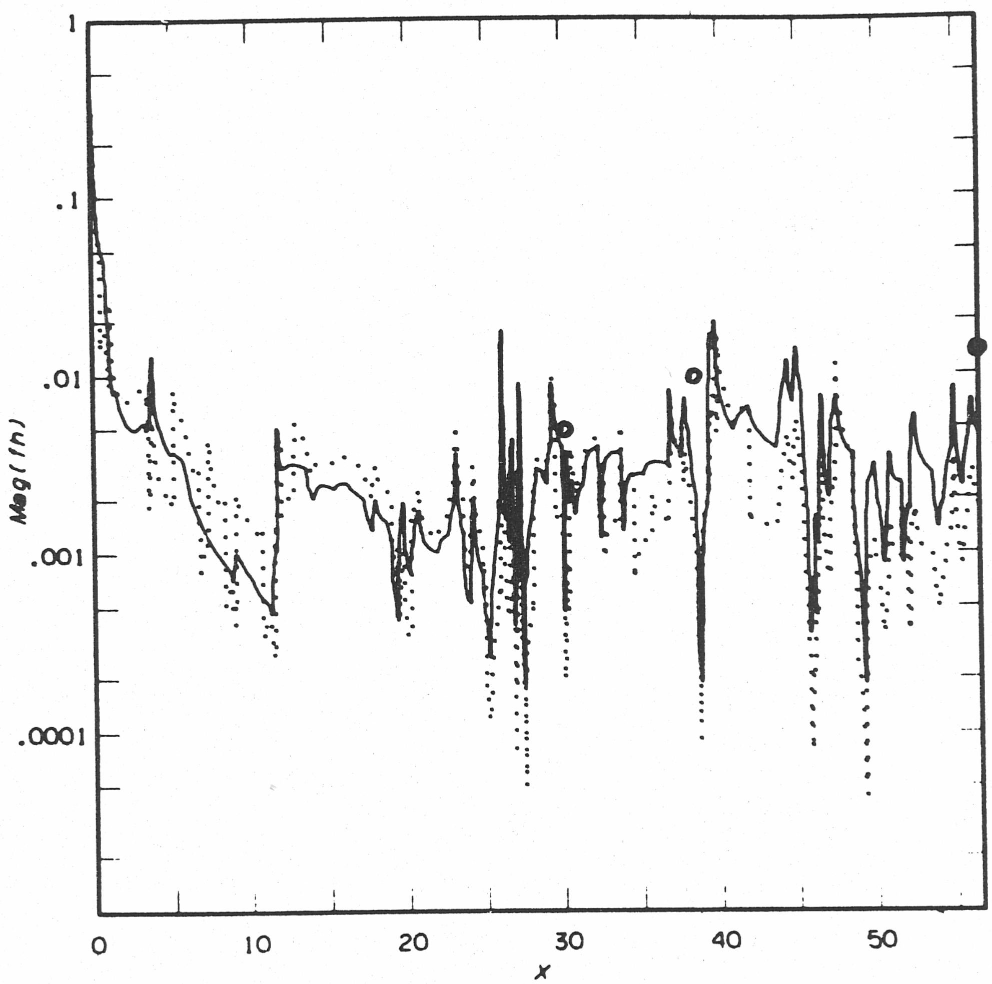

Figure 18. Propagation from Inneringen to Boblingen at 30 MHz. The solid curve is for bare ground, and the dotted curve includes the forest and urban slabs. The circles are obtained from multiple knife-edge diffraction theory.

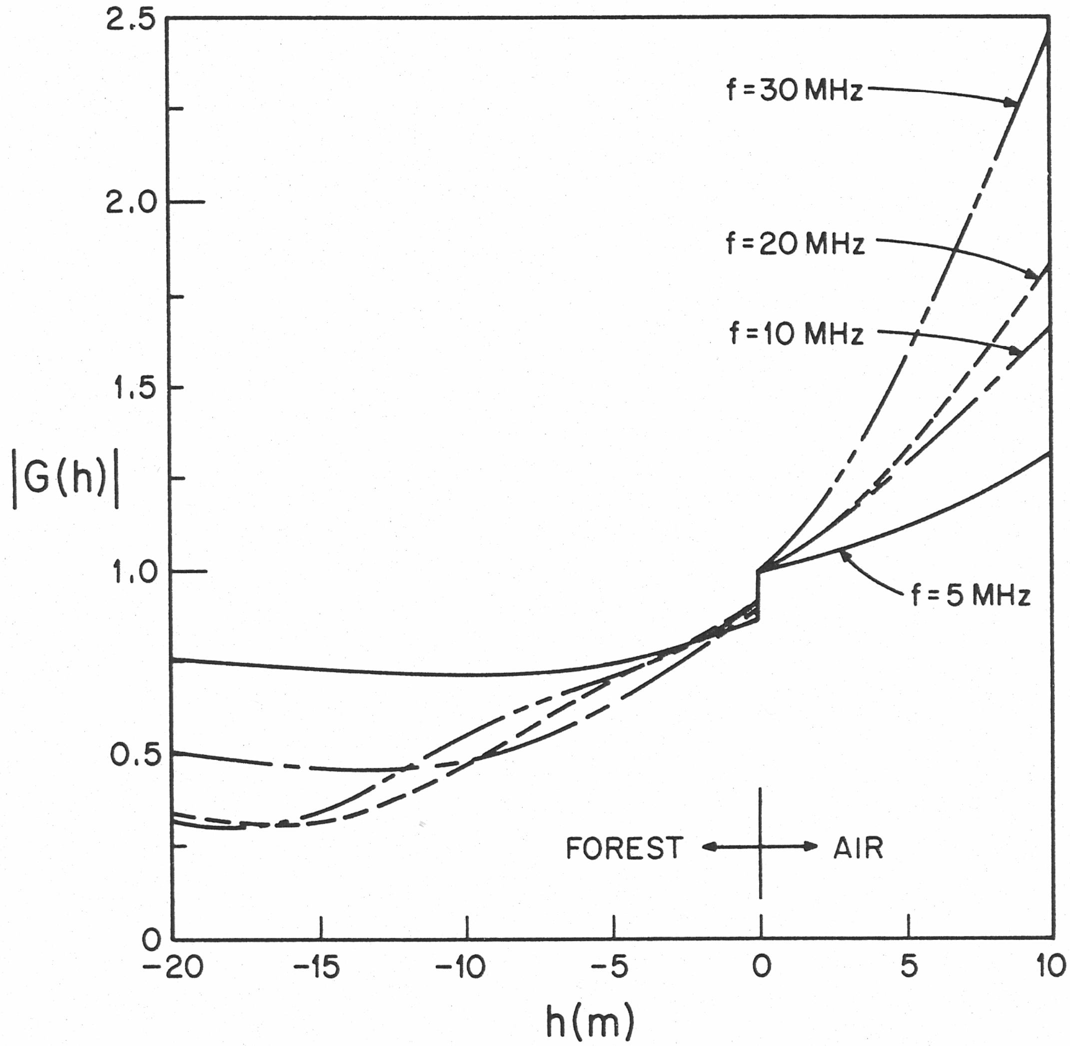

Figure 19. Magnitude of height-gain function in forest slab and in air. Parameters: D = 20 m, $\varepsilon_v = \varepsilon_h = 1.1$, $\sigma_v = \sigma_h = 10^{-4}$ S/m, $\varepsilon_g = 10$, and $\sigma_g = 10^{-2}$ S/m.

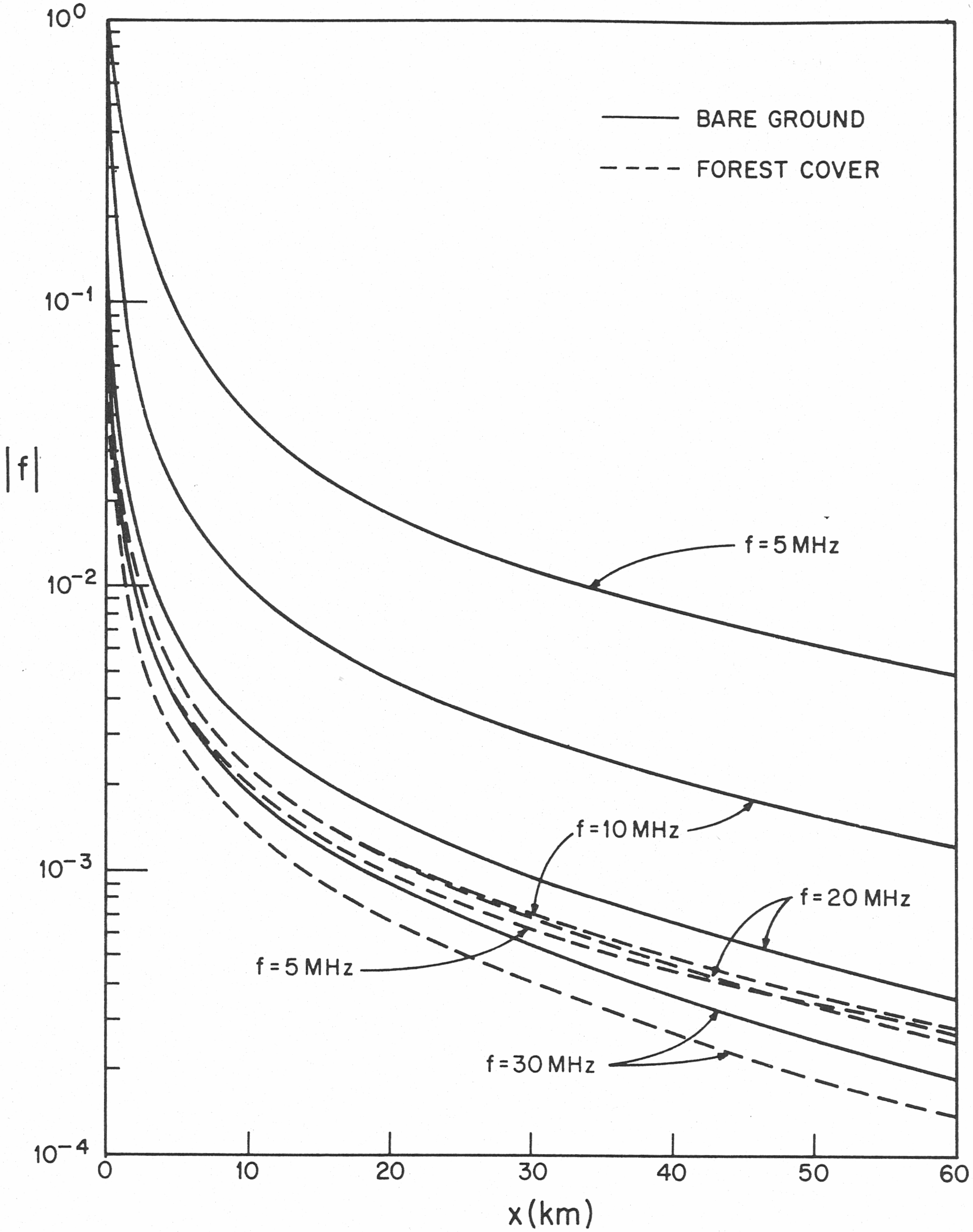

Figure 20. Spherical earth attenuation function for bare ground and with forest cover. Parameters: D = 20 m, $\varepsilon_v = \varepsilon_h = 1.1$, $\sigma_v = \sigma_h = 10^{-4}$ S/m, $\varepsilon_g = 10$, and $\sigma_g = 10^{-2}$ S/m.

also precision loss occurs for long rough paths. It is generally difficult to predict the precise limitations of the integral equation approach (Ott, 1971b), but generally the results start to appear noisy with large oscillations when the integral equation approach starts to fail. This behavior is difficult to identify because the actual field variation for rough paths at high frequencies contains oscillations due to multipath. A good example is the change in character of the Inneringen to Bollingen results as the frequency is increased in Figures 14-18. The 30 MHz curve is much noisier than the 2 MHz curve. Also the average signal level does not continue to drop for large distances. To check the behavior, we compared the integral equation result with Vogler's (1981) multiple knife edge calculation for the same path. Vogler's results are shown at 5 MHz in Figure 15 and at 30 MHz in Figure 18, and each point was obtained by fitting the terrain profile with ten equivalent knife edges. The agreement is slightly better at 30 MHz, but is fairly good even at 5 MHz. Vogler's results at 30 MHz actually predict a higher field strength at 56.6 km than at 30 km because of the shadowing which occurs from the steep terrain slope between 25 km and 30 km.

A second check for the integral equation solution is reciprocity. If we reverse the transmitting and receiving points (Monteath, 1973), the results should be unchanged. In Figures 21-23 we show the integral equation result for propagation in both directions over the Inningen to Boblingen path. If reciprocity is satisfied, then the two results at the end of the path (x=56.6 km) should be identical. Because of the way the terrain profile is handled, we would actually expect some small differences. It is clear that reciprocity is very well satisfied at 2 MHz and 5 MHz, but that some difference occurs at 20 MHz. We can conclude that some accuracy is lost at 20 MHz. Perhaps agreement could be improved by increasing the number of sample points, but we did not attempt this. The good agreement with the multiple knife edge results at 30 MHz in Figure 18 indicates that the integral equation solution can produce useful results at the upper end of the HF band even if some accuracy is lost.

A second terrain profile which runs from Inneringen to Lechfeld is shown in Figure 24. This path is longer (116.5 km), but much smoother than the Inneringen to Boblingen path in Figure 13. Also this path is less heavily forested than the Inneringen to Boblingen path and runs through a great deal of farm and pasture land. Consequently, we did not consider any forest or building effects and used ε_g=10 and σ_g=10^{-2} S/M for the ground parameters over the entire path. Again we set both antenna heights h_a and h_r equal to zero.

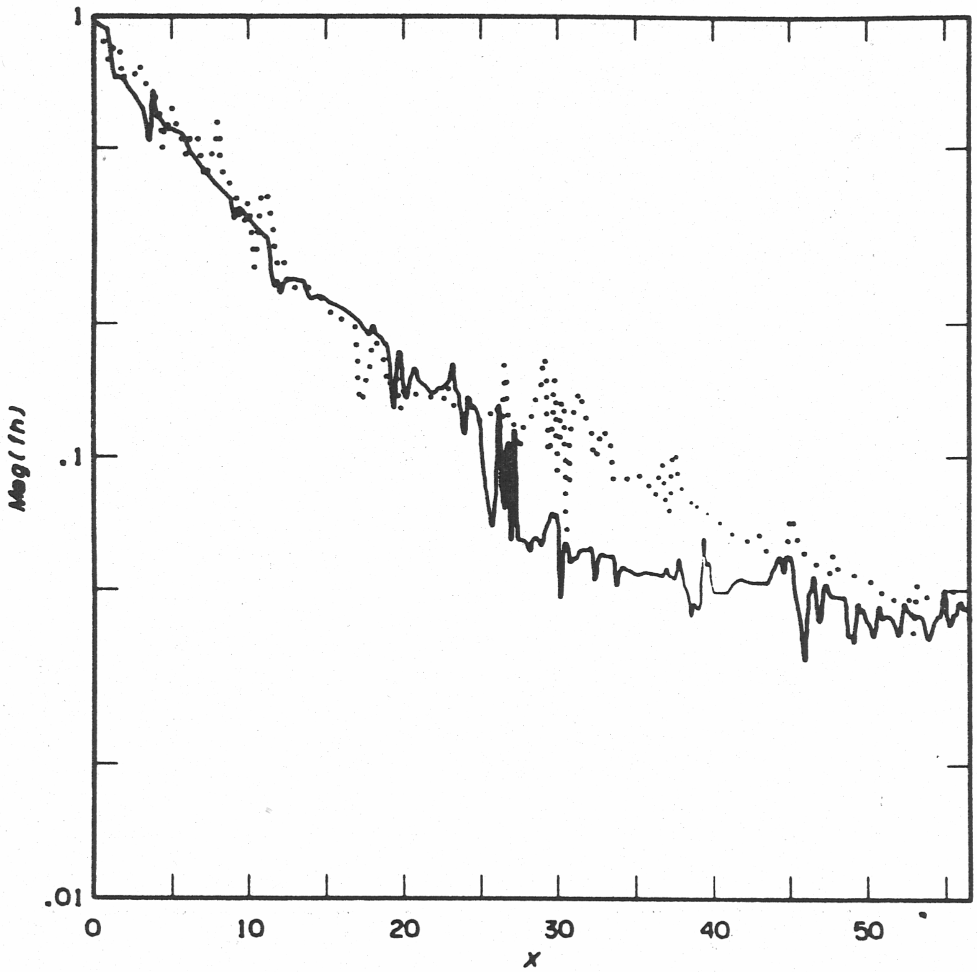

Figure 21. Propagation from Inneringen to Boblingen (solid curve) and in the reverse direction (dotted curve). Both cases are for bare ground, and the frequency is 2 MHz.

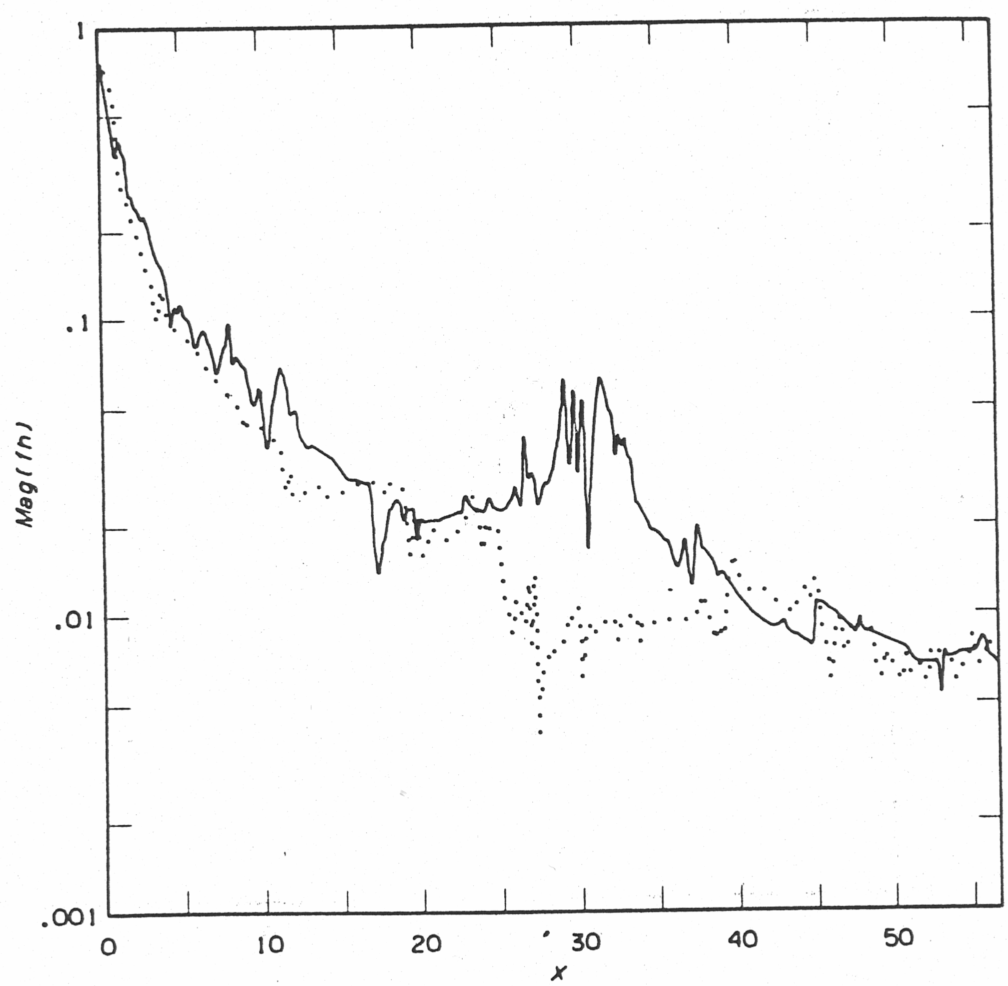

Figure 22. Propagation from Boblingen to Inneringen (solid curve) and in the reverse direction (dotted curve). Both cases are for bare ground, and the frequency is 5 MHz.

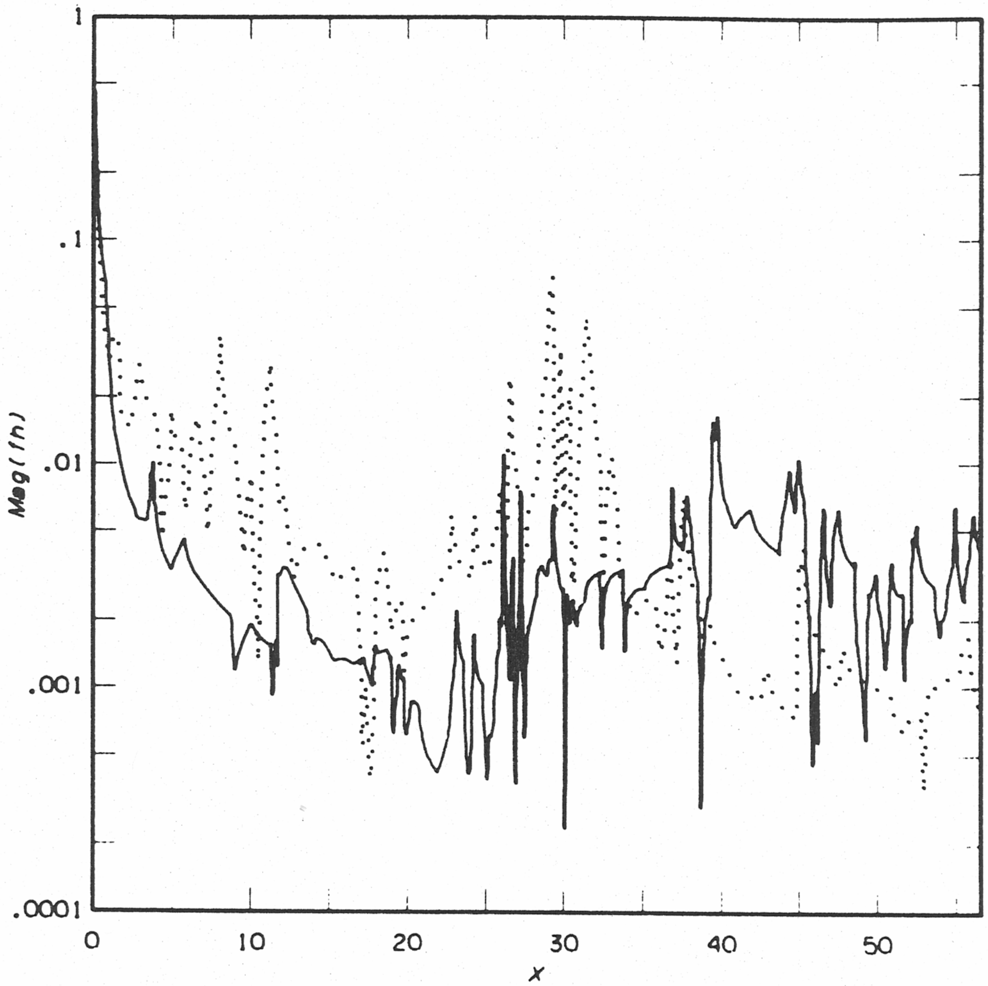

Figure 23. Propagation from Inneringen to Boblingen (solid curve) and in the reverse direction (dotted curve). Both cases are for bare ground, and the frequency is 20 MHz.

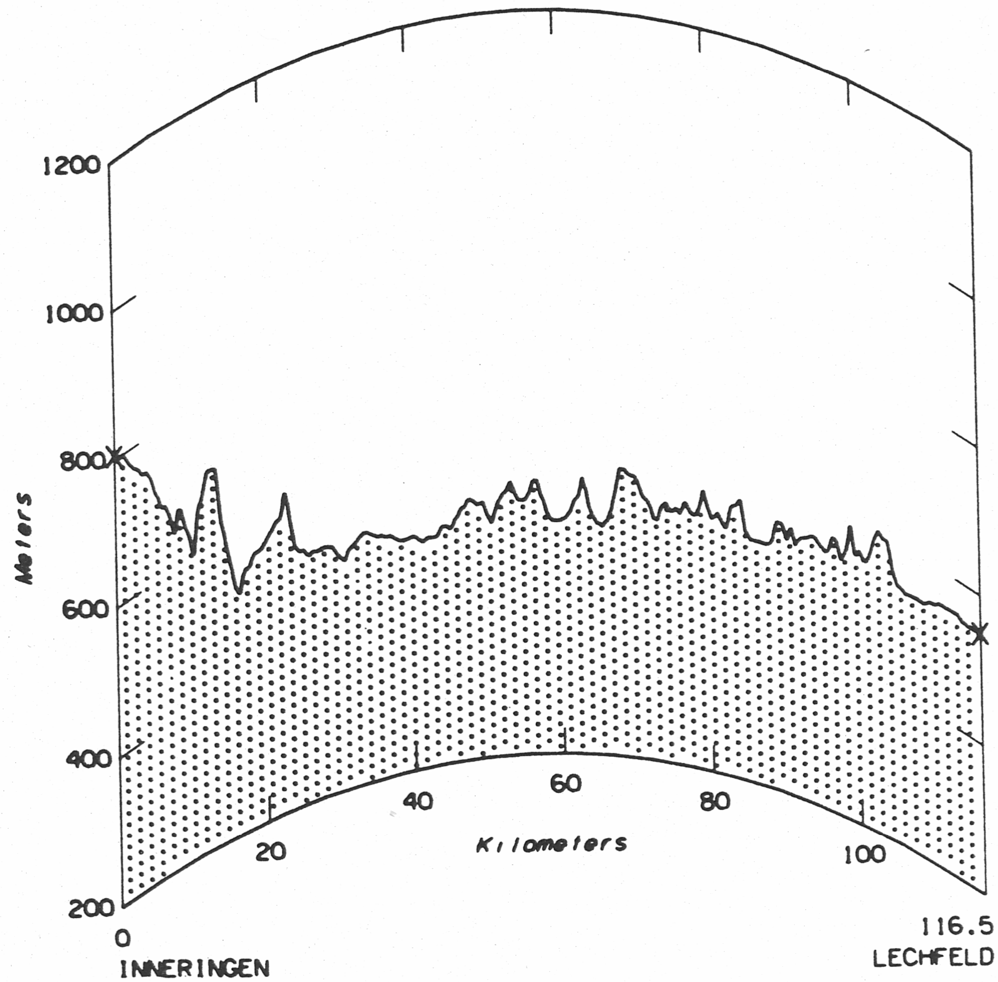

Figure 24. Terrain profile for the path from Inneringen to Lechfeld.

In Figures 25 and 26, we show propagation in both directions at frequencies of 2 MHz and 5 MHz. Since the results are in close agreement at the ends of the paths, reciprocity is well satisfied and the accuracy is probably quite good. We did not run WAGSLAB for higher frequencies over such a long path because of the large computer time which would have been required.

7. CONCLUSIONS AND RECOMMENDATIONS

The main purpose of this report is to describe a theoretical method for predicting HF ground wave propagation over irregular terrain with forest, building, or snow cover. The only method that appears to be general enough for detailed predictions over arbitrary paths is the integral equation method (Ott, 1971a). The approach which was adopted and described in Section 3 was to generalize Ott's program WAGNER (Ott et al., 1979) to allow for the effect of a lossy, anisotropic slab over the earth. The slab parameters can be chosen to match those of forest, snow, or buildings as discussed in Section 5. Although the approach was applied to the HF band (3 MHz - 30 MHz), it actually becomes more efficient as the frequency is decreased. For frequencies above HF, it is probably only useful for short, relatively smooth paths. The new computer code is called WAGSLAB and a user's guide, listing, and sample output are given in Appendix C.

Numerous special cases were considered in this report because they are good checks for WAGSLAB and because they are amenable to analytical solution. For uniform paths which are short enough to neglect earth curvature, the uniform slab model (Tamir, 1967; Wait, 1967a) is adequate. This model is described in Section 2, and the results are cast into a form convenient for ground wave propagation. When the path has two sections as in a forest-to-clearing case, an approximate analytical solution can be derived. This solution is derived and compared with the integral equation solution in Section 4. When the path is uniform, but is long enough for curvature to be important, then spherical earth theory (Hill and Wait, 1981b) can be used. It is compared with the integral equation solution in Section 6.1.

Two long, rough paths were analyzed by program WAGSLAB in Section 6.2. No experimental results were available, but some comparisons were made with multiple knife edge diffraction (Vogler, 1981). Also, reciprocity was checked by running the terrain profiles in each direction. This appears to provide an excellent check for asymmetric paths.

This report represents only a first attempt at ground wave prediction over irregular, forested, and built-up terrain. Numerous improvements and extensions are probably possible, but we recommend the following: (1) detailed comparisons