NBS

Technical Note No. 180

ANTENNA BEAM ELEVATION ANGLE FOR CONTROL OF TROPOSPHERIC INTERFERENCE BETWEEN SPACE SYSTEM EARTH TERMINALS AND TERRESTRIAL STATIONS

S. G. LUTZ AND W. J. HARTMAN

U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

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ANTENNA BEAM ELEVATION ANGLE FOR CONTROL OF TROPOSPHERIC INTERFERENCE BETWEEN SPACE SYSTEM EARTH TERMINALS AND TERRESTRIAL STATIONS

S. G. Lutz† and W. J. Hartman

High gain antennas, sensitive receivers and high power transmitters which are used at the earth stations of space communications systems complicate the problem of sharing frequencies with other surface services. However, because of the dependence of beyond-the-horizon tropospheric propagation on the scattering angle, it is possible to offset the gain of the terminal antenna by elevating the beam.

Early studies of frequency-sharing assumed that the beam of the earth station was elevated "sufficiently" to increase the transmission loss to that which would be obtained if the actual antenna were replaced by an isotropic antenna. This paper studies the question of what constitutes a "sufficient" elevation angle, as described above, for the particular conditions of a smooth earth, 30-foot antenna heights and several combinations of antenna sizes. Some results are also given when there is an elevated horizon at the earth terminal end of the path.

1. Introduction

It is necessary to predict the transmission loss between two terminals in order to predict whether frequency sharing between two communications systems is possible. When one of the systems is a space communication system, the prediction of the transmission loss is frequently complicated because of possible different orientations of the earth station antenna. Early studies [Lutz, 1961; Firestone, Lutz, and Smith, 1962; EIA-FCC, 1960] of the possible tropospherically propagated interference between the earth station of space communications systems and other surface radio services using the same frequencies assumed that the antenna beam at the earth station would be elevated "sufficiently" to suppress the power propagated via the main beam, and thus justify the assumption of an isotropic earth station antenna. It is clear that the required computation time is greatly reduced if the transmission loss is calculated only once for an omnidirectional antenna rather than the many times required for the different orientations of a high gain antenna. This paper compares the expected value of the tropospheric scatter transmission loss via the elevated main beam of a 60-foot earth terminal antenna to that for an omnidirectional terminal antenna with arbitrary gain relative to isotropic. For 10-foot, 6-foot, and isotropic surface antennas, calculations are given for beam elevation angles to 15°, path lengths to 350 miles, and for frequencies between 1 Gc/s and 10 Gc/s. The results given here are for the particular conditions of a smooth earth and antenna heights of 30 feet at both ends of the path, and have been obtained by consolidating and extending the Hartman and Decker [1961] study.

Certain general features are exhibited, such as the increase with distance of the elevation angle required to increase the transmission loss via the main beam to that for an isotropic antenna, and to values 10 db, and 20 db greater than that expected for an isotropic antenna. Because elevated horizons are frequently advocated for reducing interference, some comparisons are made between paths with one elevated horizon and smooth earth paths.

2. Terminal Beam Elevation and Tropospheric Interference in Satellite Communication

Signals from early solar-powered satellites will be extremely weak; consequently, their earth stations will require high-gain antennas and ultralow-noise receivers. DeGrasse, et al, [1959] have shown that the use of a helium-cooled maser and a horn-reflector antenna

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results in operating noise temperatures of less than 30° K, which corresponds to 20 db less noise than that from most conventional microwave receiving systems. However, such low noise is achieved only when the antenna beam is elevated sufficiently (5° to 10°) above the horizon to reduce the thermal noise from the earth, which enters the antenna's main beam and near side lobes. In addition, elevating the antenna beam shortens the portion of the propagation path through the earth's atmosphere, and thus reduces the atmospheric absorption of the incoming signals and the atmospheric noise. Because of this, early satellite communication systems will probably avoid beam elevations smaller than 5° to 10°. The maximum distance between the earth stations of a satellite communication system will be limited correspondingly.

When satellite repeaters of sufficiently high power can be used, low-noise reception will be less essential. Terminal antenna beams could then be lowered to increase the maximum distance between terminals if it were not for the probability of tropospherically propagated interference with microwave radio relay or other surface radio stations in the vicinity of the terminal [Lutz, 1961; Firestone, Lutz, and Smith, 1962]. Such interference would be greatly increased by the gain of the terminal antenna if its beam were lowered toward such a station. However, tropospheric transmission loss increases as the scattering angle increases, and the effective scattering angle is increased by the beam's elevation angle. When elevated sufficiently, or when the beam is directed sufficiently away from the remote surface station in azimuth, the terminal antenna can be considered to be equivalent to an isotropic antenna with respect to tropospheric scatter propagation of interference; i.e., the path antenna gain is reduced to a value equal to that expected for an isotropic terminal antenna.

3. Antenna Patterns

Few three-dimensional patterns are available for large space communication antennas, although a few azimuth directivity patterns are available, such as that of the horn-reflector antenna used for the ECHO experiments [Crawford, Hogg, and Hunt, 1961]. Even with the smaller microwave antennas, commonly used in line-of-sight relay systems, usually only azimuth directivity patterns are available, though generally for both polarizations. Thus, it is not yet well enough known how rapidly the gain toward the horizon drops off as the beam of an antenna is elevated above the horizon.

Some useful generalizations can be extracted from the available information for parabolic or horn-type reflectors at microwave frequencies, although, as with all generalizations, there will be some exceptions. The patterns for these antennas may be considered to consist of essentially three parts: sector 1, the main lobe; sector 2, the near side lobes, which are 20 db or more below the main lobe, but still exhibiting a definite lobe structure and gain above an isotropic antenna; and sector 3, the remainder of the pattern, which may be described as having no well-defined lobe structure.

For tropospheric scatter calculations, the relatively strong sector 2 sidelobes generally do not contribute significantly to the total power received, since their gain falls off more rapidly with their angle from the beam than transmission loss via the main beam increases as a result of correspondingly increased scattering angle. For example, a 60-foot parabola has its first sidelobes only a half degree from the beam center at 3.8 Gc/s, and their gain would be at least 20 db less than that of the beam. Measurements of tropospheric scatter loss versus beam elevation do not show the sidelobe structure near the main beam, as is observed on line-of-sight or just beyond the horizon diffraction paths.

For sector 3, the scatter transmission loss may be calculated as the loss using an isotropic antenna in place of the directional antenna, minus the gain relative to isotropic of the pertinent part of sector 3.

Because of the foregoing, it is often assumed for interference studies that the three-dimensional pattern envelope is a solid of revolution, generated by an azimuth pattern envelope; or by some usefully simple approximation to such an envelope. One such idealization, used by Electronic Industries Association Technical Committees for Microwave Interference Studies [EIA, 1960], is the three-sector keyhole-shape pattern, whose far-sidelobe sector is considered isotropic. The three-dimensional version of this pattern resembles two cones projecting from a unity-gain sphere. Figure 1 shows two such

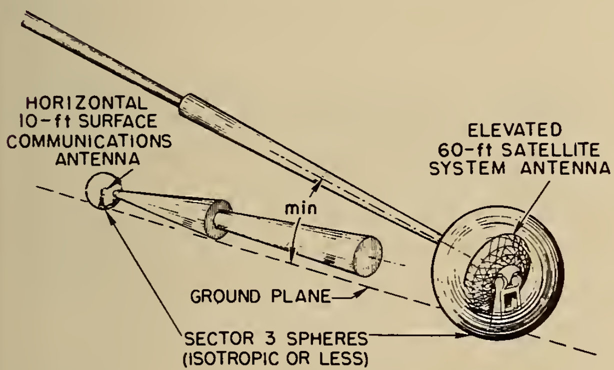

Figure 1: Three-dimensional keyhole-shape antenna pattern envelope

patterns illustrating a surface microwave antenna directed horizontally toward a satellite system's earth antenna [EIA, 1960]. The beam of the latter is directed above the microwave antenna at some minimum elevation angle, which exposes the isotropic sphere horizontally. The geometry of this illustration suggests comparing the tropospheric transmission loss via the elevated beam with that via an isotropic antenna, thereby determining the beam elevation angle for loss equality. Such an analysis and comparison are made in this paper.

4. Methods for Calculating Transmission Loss with Elevated Beams

Both this study and the prior study [Hartman and Decker, 1961] use a modification of the Hartman and Wilkerson [1959] investigation of path antenna gain intended for tropospheric communication paths, where both antennas are directed at the horizon in the great-circle path direction. Only the upper half of each of the beams clears the horizon, and the power from the lower half is assumed to be reflected into the upper half. For the present problem, the entire elevated beam from an earth station antenna clears the horizon, necessitating the modification.

Results of the Hartman and Decker [1961] calculations were presented as a large collection of curve families, most of which showed Time Block II (winter afternoon) transmission loss versus beam elevation of one antenna for 50-mile path length increments between 100 and 350 miles at one of four frequencies (1, 2, 6.5, or 10 Gc/s) and for the antenna combinations, 60-ft. and 10-ft., 6-ft., or isotropic, 30 feet above smooth earth with a surface refractivity value $N_s = 301$. The calculations require the estimation of the smooth-earth basic median transmission loss which was obtained from recent NBS prediction methods [Air Force Technical Order, 1961; Rice, Longley, and Norton, 1959]. In decibels,

$$L = L_b - G_p,$$

where L is the transmission loss, L_b the basic transmission loss between isotropic antennas (the path loss), and G_p is the path antenna gain, given in terms of the free space antenna gains of the transmitter and receiver

$$G_p = G_t + G_r - G_L,$$

and where G_L is the loss of path antenna gain as computed by the modified Hartman and Wilkerson [1959] method. Note that the calculation of

L_{bms} also involves the beam elevation angle ψ in determining the effective scattering angle θ.

For parts of the present paper, the Hartman and Decker [1961] calculations have been extended from $\psi = 9°$ maximum to $\psi = 12°$ and $15°$, also path lengths down to 50 miles are included. The validity of tropospheric scatter predictions for such short paths is questionable because, at distances less than 100 miles, diffraction becomes more important and eventually becomes dominant. No diffraction calculations are included here, however, because if diffraction is dominant when the beam is on the horizon, the beam elevations given are adequate to offset the effects of the gain of the main beam relative to the sidelobes.

5. Variability of Tropospheric Scatter Loss

It is well known that the hourly median values of transmission loss over tropospheric paths are highly variable. The NBS predictions are divided into two parts; predicting the median of the hourly medians for winter afternoon hours when the upper air is well mixed and predicting an empirically derived distribution of the hourly median values about this median. These distributions are presented as curve families depending on the scattering angle θ and a percent of time p during which the signal level will be exceeded by p% of the hourly medians during each of eight time blocks (see table I) and during all hours of the year. Based on extensive measurements, these curves include and allow for some ducting and other propagation abnormalities. For interference control, one is interested in low losses exceeded by, for example, 99.9% of the hourly medians and corresponding to a signal level exceeded for $p = 0.1\%$ of the hours from these curves.

Figure 2 shows a comparison of $p = 0.1\%$ variability curves for several time blocks. All such curves show the greatest variation near $\theta = 10$ mr, which generally corresponds to a distance at which there is the most variable and uncertain combination of diffraction and scatter propagation. In this range, the variability is least for Time Block II and greatest for VII, reaching 56 db. Ducting is most probable in the early morning hours, and especially in summer, when the upper air may be highly stratified and undisturbed. Time Blocks VII and VIII tend to over-weigh the all-year curve, considering that (non-military) communication is lightest during these hours. Except for Blocks VII and VIII, Block IV is the most variable and reaches the same maximum as the all-year curve. Hence, one can use the all-year curve with the assurance that it is typical of the worst of the heavily used Time Blocks.

For further clarification, figure 3 shows some forward scatter path loss versus distance curves. Curve 1 is the basic (Time Block II)

Table I

Time Blocks

	6 AM to 1 PM	1 PM to 6 PM	6 PM to 12 PM	12 PM to 6 AM
November to April	I	II	III	VIII
May to October	IV	V	VI	VII

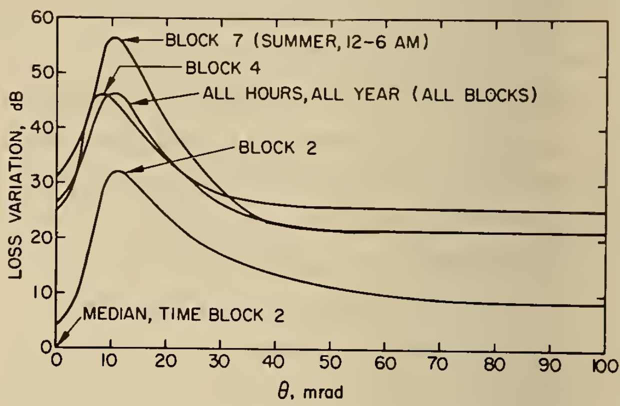

Figure 2: Variability corrections as applied to the Time Block II median to obtain losses exceeded by 99.9% of the hourly medians of the time blocks shown.

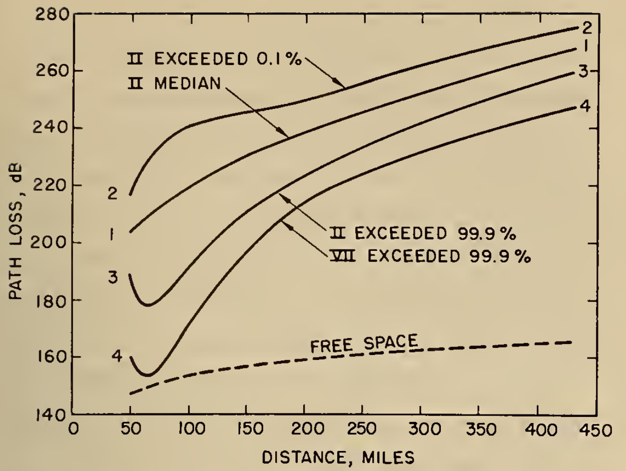

Figure 3: Illustrations of the variability of tropospheric path loss for 30-ft-high isotropic antennas, 6.5 Gc/s, smooth earth, with $N_s = 301$.

median loss which is predicted by NBS methods. Curve 2 was corrected by use of the all-year p = 99.9% curve and shows the maximum probable losses for which one might design tropospheric communication circuits. Curve 3 represents losses exceeded by 99.9% of the hourly medians on winter afternoons. Curve 4 shows corresponding losses during the worst times, Block VII, when losses may fall toward free-space values. An all-year 99.9% curve would lie between curves 3 and 4.

There are several reservations concerning the applicability of these loss-variability corrections to the surface interference coordination problems of satellite communication, most of which reflect the prior research motivation toward tropospheric communication.

1. The CRPL variability curves are supported by long-term measurements over more than two hundred paths, but at relatively low frequencies, predominantly below 1 Gc/s. More adequate experimental confirmation is needed of their applicability at probable satellite communication frequencies in the 3.7- to 8.4-Gc/s range, and particularly for elevated beams.

2. Ducting the similar abnormal propagation which these curves allow for is improbable with the elevated beams of earth-station antennas, except from low sidelobes.

3. The use of θ as the independent variable for loss variability is less applicable at the shorter distances and lower beam angles.

As an example of 3 above, consider two ideal (tight beam, no sidelobe) antennas separated by a path for which θ is only 2 mr. From figure 2, the 99.9%, Time Block II, loss will be 5 db below the median. If one or both beams are elevated, the scatter angle θ will increase, and as a consequence the transmission loss will increase. When θ = 10 mr, the median transmission loss would increase about 20 db, but figure 2 indicates a 32-db loss reduction 0.1% of the time, hence 7 db less than with the beams horizontal. This does not agree with available data.

Despite these observations, the CRPL variability curves seem to be the best thus far available. Consequently, the all-year variability curve will be used in this study.

6. Transmission Loss Requirements for Interference Protection

Except in very specific cases, it is impossible to state the required value of transmission loss which will suppress interference to acceptably low and infrequent levels. Such values depend not only on the transmitter and receiver characteristics, modulation characteristics of both signals, etc., but also on often inadequately defined or agreed upon criteria of acceptability. At least two methods [Firestone, Lutz, and Smith, 1962; Curtis, 1962] have been used to determine transmission loss requirements and consequent smooth-earth separation distances. In general, such losses should exceed, for 99.9% of the hourly medians in a year, values in the 150- to 180-db range, based on presently probable system characteristics. Lower values in this range may be used with microwave relay stations, whereas the higher values may apply between co-channel earth stations. The all-year median losses range from 20 to 40 db higher than the 99.9% values, depending on the variability correction. Note, however, that these transmission losses are the difference between the basic loss (isotropic antennas) and the path antenna gain. With antennas horizontally directed toward each other, the path antenna gain could approach 100 db, thus becoming more important than any probable difference in required loss. For a given basic transmission loss, any path antenna gain increases the required path length correspondingly.

7. Calculated Results

For reference purposes, figure 4 shows

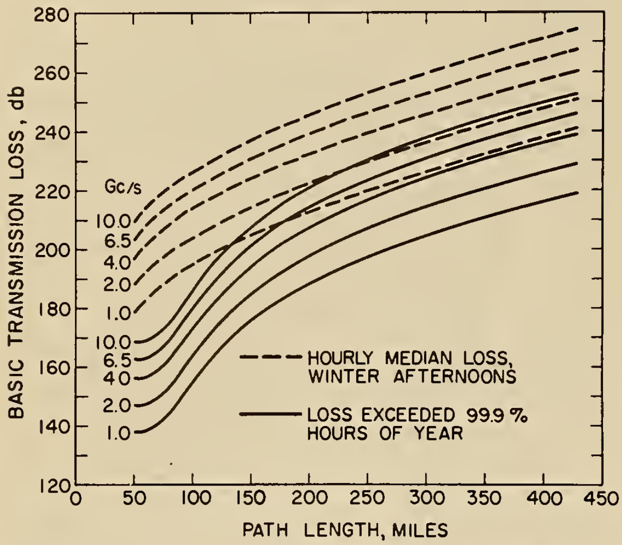

Figure 4: Basic transmission losses; 30-ft-high isotropic antennas, smooth earth, and $N_s = 301$. Comparison of winter afternoon (Block II) medians with losses exceeded by 99.9% of the hourly medians, all year.

basic median transmission losses and 99.9% all-year losses between isotropic antennas, 30 feet above a smooth earth, with $N_s = 301$. One should note that the median loss values below 100 miles assume only forward scatter propagation, neglecting diffraction propagation, which for the stated assumptions may be neglected. However, at the shorter distances, only slight changes in antenna heights or terrain profile are necessary to cause diffraction to dominate. Also, if the primary consideration is to minimize interference, earth stations should not be located on smooth earth and certainly not on hilltops. Such stations should be shielded by surrounding terrain while avoiding obstacle gain.

Figure 4 also shows that, beyond the horizon, tropospheric interference would be a minor problem were it not for its variability or for possible path antenna gain. In fact, Curtis [1962] showed that line-of-sight separations are sometimes adequate in low-sidelobe directions. Figure 4 also shows how increasing the frequency increases the path loss. The importance of keeping the required loss low and the frequency high is indicated. Seventy miles provides 160 db at 4 Gc/s, whereas over 160 miles would be needed for 180 db at 1 Gc/s.

Figure 5, which is a modification of the

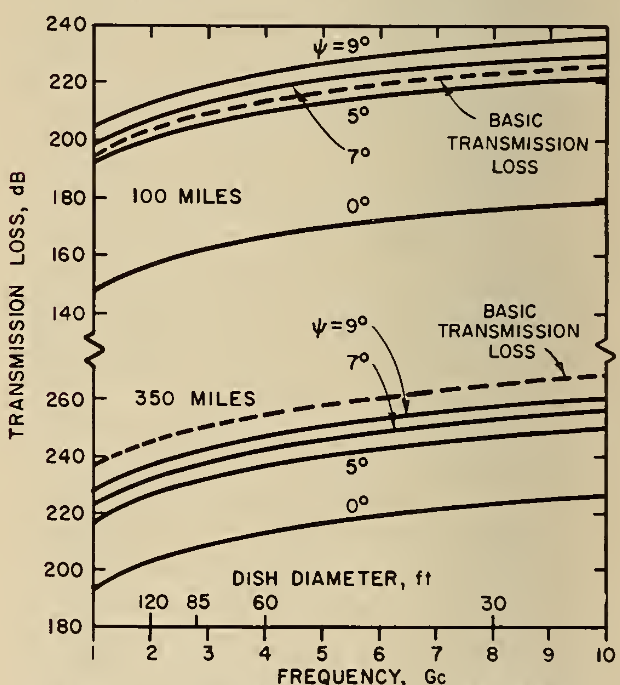

Figure 5: Transmission loss for an elevated 5 mr beam compared with basic transmission loss for winter afternoon medians and remote antenna isotropic.

Hartman and Decker [1961] curves, shows median transmission loss versus frequency and elevation angle ψ of an antenna beam of constant beamwidth (5 mr at 3 db), the second antenna being isotropic. This beamwidth would require a 120-ft antenna aperture at 2 Gc/s, but only 30-ft at 8 Gc/s. The dashed curves have been added to permit comparison with propagation between isotropic antennas. At 100 miles, elevating this beam about 6° cancels the effect of antenna gain. At 350 miles, however, an elevation near 12° would be required. This indicates that the beam elevation required to suppress the gain increases with distance.

Calculations for 1 Gc/s and 10 Gc/s will be used in what follows because these frequencies bound the presently accepted "window" of usefulness for satellite communication. Within this window, the fixed microwave bands from 3.7 Gc/s to 8.5 Gc/s are most apt to be used because of the greater difficulty of sharing frequencies with other services. Relatively complete calculations also have been made at 2.0, 4.0, and 6.5 Gc/s, and the values are consistent with those at 1.0 and 10.0 Gc/s. In all of the remaining calculations, it is assumed that the earth antenna is a 60-foot parabolic dish.

Figure 6 shows the expected median transmission loss as a function of the elevation angle ψ for 50-mile distance increments to 350 miles, at 1 Gc/s with the microwave antenna isotropic. For comparison, the superimposed curve farthest to the left shows the loss between isotropic antennas at these distances. Hence, the intersection values of ψ are the beam elevations at which the increased path loss via the beam reduces the path antenna gain to zero. At this elevation angle, however, the antenna still will have a path antenna gain of some uncertain value because of the additional propagation into its sidelobes. Hence, the additional two superimposed curves intersect the beam-loss curves

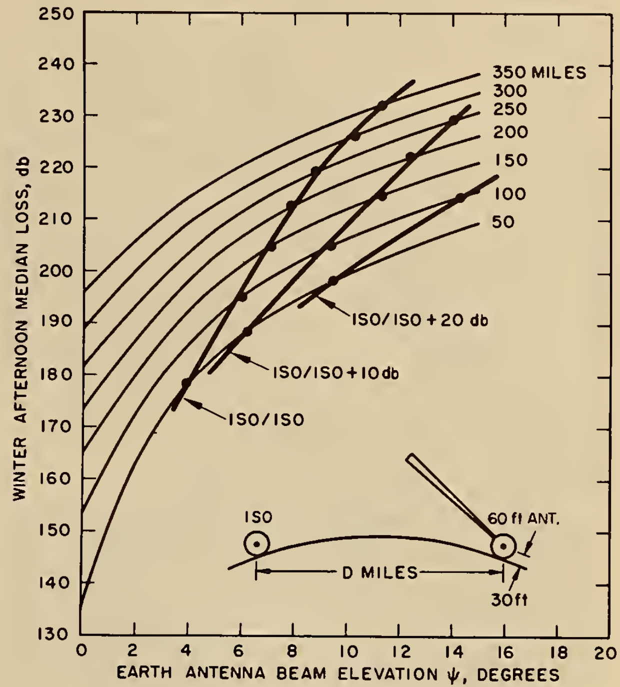

Figure 6: Effect of antenna beam elevation angle ψ on median transmission loss; isotropic remote antenna and 60-ft steerable antenna at 1 Gc/s.

at the angles required for an additional loss of 10 or 20 db.

Figure 7 shows similar curves, applicable when the microwave antenna is directed horizontally at the earth station. The solid curves at 50-mile increments are for a 10-foot aperture, whereas the two dashed curves show the comparison with a 6-foot antenna, at 100 and at 350 miles. The loss difference is approximately the 4.3 db antenna gain difference between a 6-foot and 10-foot antenna. The superimposed curve provides comparison with an isotropic earth antenna, as before. These transmission loss values are reduced from those shown in figure 6 by somewhat less than the gain of the microwave antenna.

Figure 8 shows families of curves at 10 Gc/s, corresponding to figures 6 and 7. The iso-iso locus shows elevation angles ψ, which are approximately the same as in figure 6, but corresponding to larger losses due to the higher

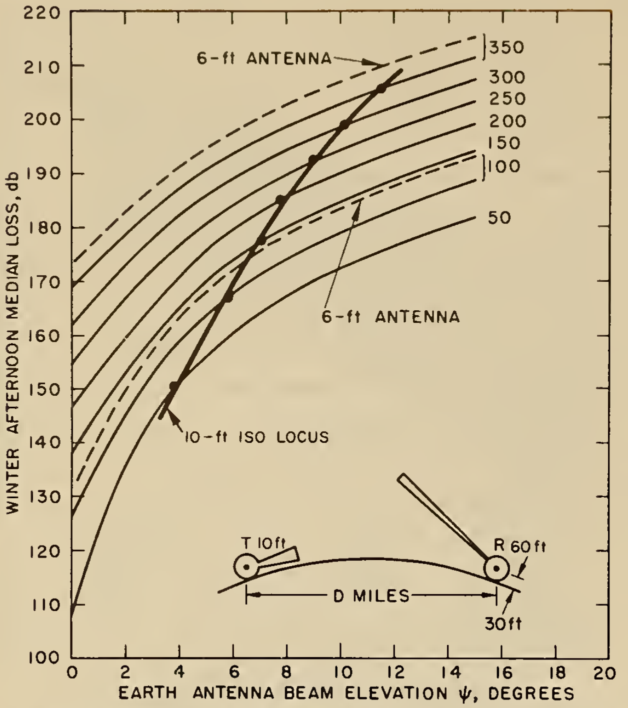

Figure 7: Effect of antenna beam elevation angle ψ on median transmission loss; 10-ft-remote antenna, and 60-ft steerable antenna at 1 Gc/s.

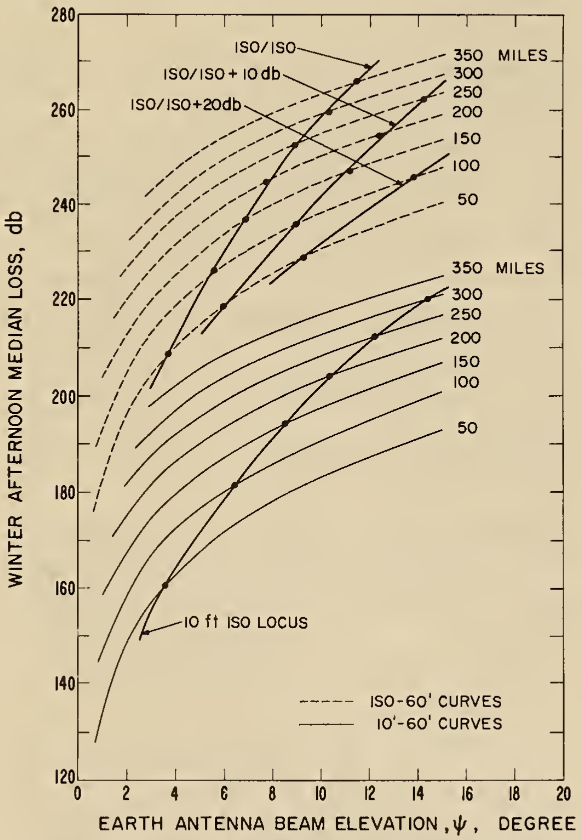

Figure 8: Effect of antenna beam elevation angle ψ on median transmission loss at 10 Gc/s.

frequencies. The 10-foot iso locus, however, exhibits an increase in ψ with distance although with a smaller increase in the loss when compared with the curve in figure 7. This frequency dependence is clarified by using the representations shown in figure 9 and figure 10. Both

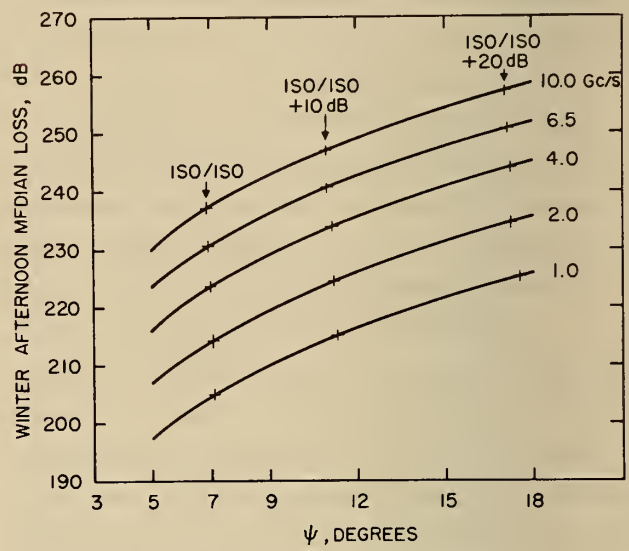

Figure 9: Effect of antenna beam elevation angle on median transmission loss at 150 miles for five frequencies; remote antenna isotropic.

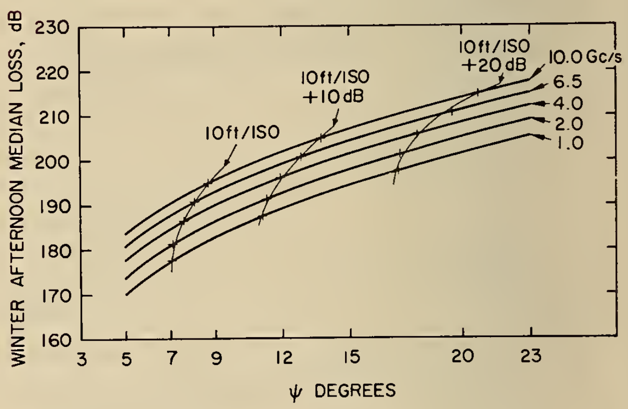

Figure 10: Effect of antenna beam elevation angle on median transmission loss at 150 miles for five frequencies; 10-ft-remote antenna.

figures show transmission loss versus elevation angle for a distance of 150 miles and several frequencies. Figure 9 applies when the microwave antenna is isotropic, and figure 10 when the microwave antenna is a 10-foot dish. The cross marks are plotted at losses equal to 0, 10, and 20 db relative to the transmission loss when an isotropic earth antenna is used. In figure 9, the ψ's are independent of frequency within the limits of computational accuracy (slide rule, curve reading, and plotting). Figure 10 shows that the corresponding equality-ψ's become decidedly frequency-dependent when the 10-foot microwave antenna is directed at the earth station. The reason is that the gain of this second antenna increases with frequency. This gain increase is partly offset by the gain loss term G_L.

Curves such as these two were prepared for distances in 50-mile increments, and the cross mark values of ψ were used to plot figures 11 and 12. Figure 11 shows ψ versus path length, at 1 Gc/s and 10 Gc/s, for beam losses greater by 0, 10, and 20 db than losses to an isotropic earth antenna, from an isotropic microwave antenna. Figure 12 shows the marked frequency-dependence when the microwave antenna is beamed at the earth station. The 1 Gc/s curves are not much different from those in figure 11, but those for 10 Gc/s diverge to much higher ψ's. However, both figures lead to an important conclusion. If the interference path length is relatively short (50 to 100 miles) from a low-power and relatively insensitive microwave station using relatively small antennas, a "reasonable" minimum elevation of the earth-antenna beam will suppress its interference-gain to that if an isotropic earth antenna were used. Such a minimum elevation is reasonable because it is about that (5° to 10°) which will be used, at first, to control atmospheric and earth-noise degradation of maser receiver performance. Interference at greater distances could be caused by (co-frequency) high-power radar, tropospheric communication stations, or other space communication earth stations having large antennas beamed horizontally at the earth station concerned. The beam elevation necessary to suppress such interference to isotropic level could become unreasonably large (ψ > 15°) because such an increase in minimum elevation angle could greatly reduce the satellite's earth-coverage or the maximum distance between earth terminals.

Figures 13 through 16 are the same presentation as figures 6 through 12, except that, instead of median losses, those exceeded by 99.9% of the hourly medians per year are used.

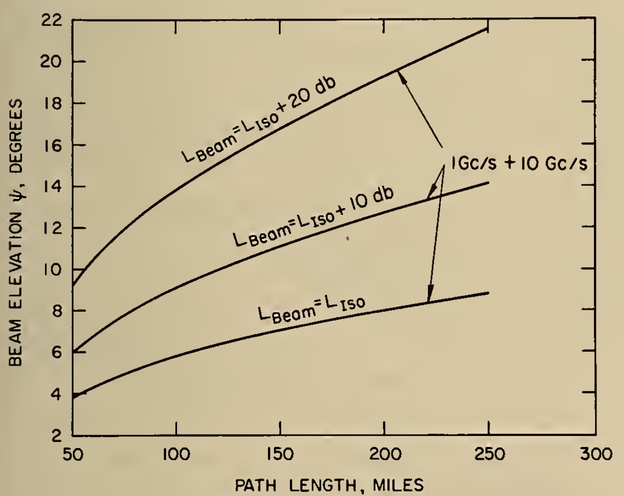

Figure 11: Antenna beam elevation versus distance for median loss equal to or 10 or 20 db greater than that between isotropic antennas; remote antenna isotropic.

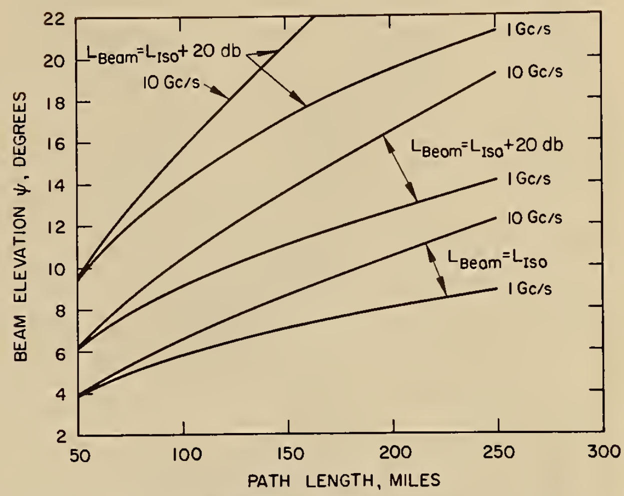

Figure 12: Antenna beam elevation for which the median losses are equal to or 10 or 20 db greater than if the terminal antenna were isotropic for a 10-ft remote antenna beamed toward the terminal.

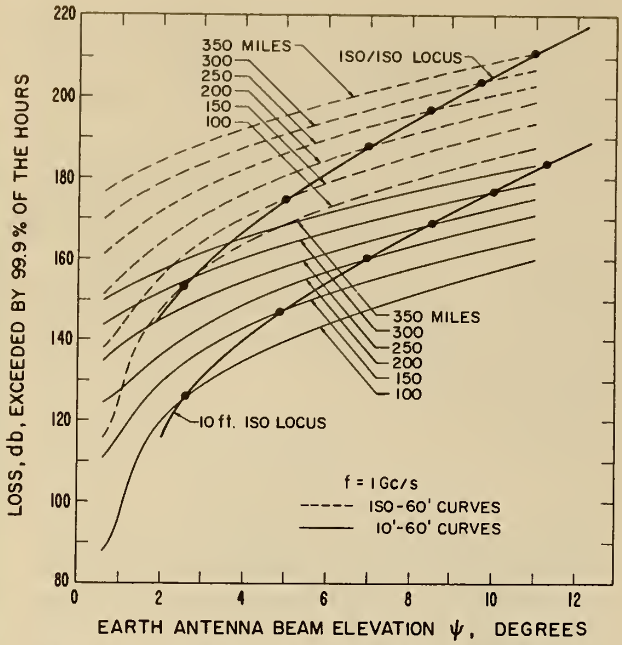

Figure 13: Effect of beam elevation angle on transmission loss exceeded by 99.9% of the hourly medians; 1 Gc/s.

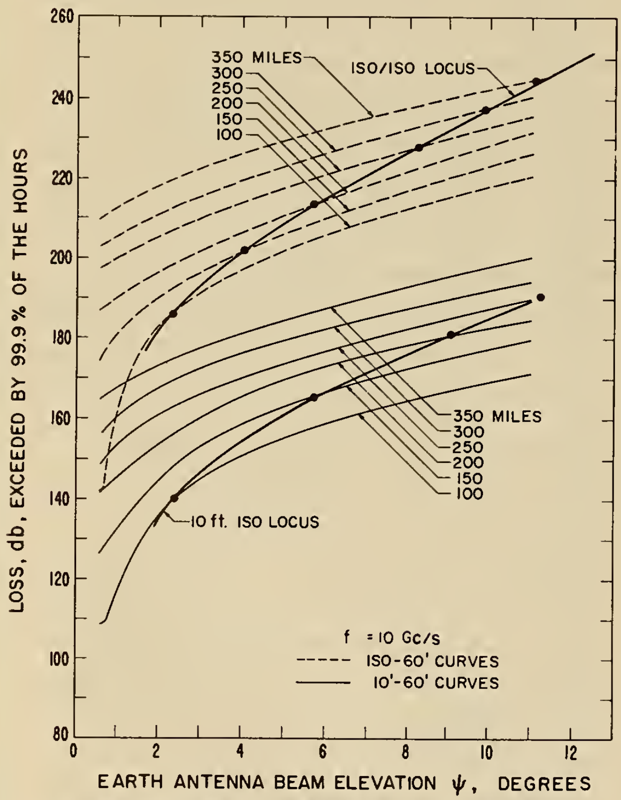

Figure 14: Effect of beam elevation angle on transmission loss exceeded by 99.9% of the hourly medians; 10 Gc/s.

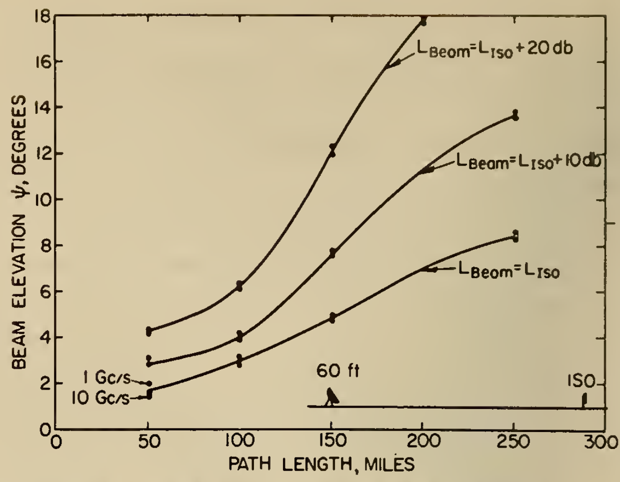

Figure 15: Elevation angle versus distance for the 99.9% level transmission loss equal to or arbitrarily greater than that using an isotropic terminal antenna; remote antenna isotropic.

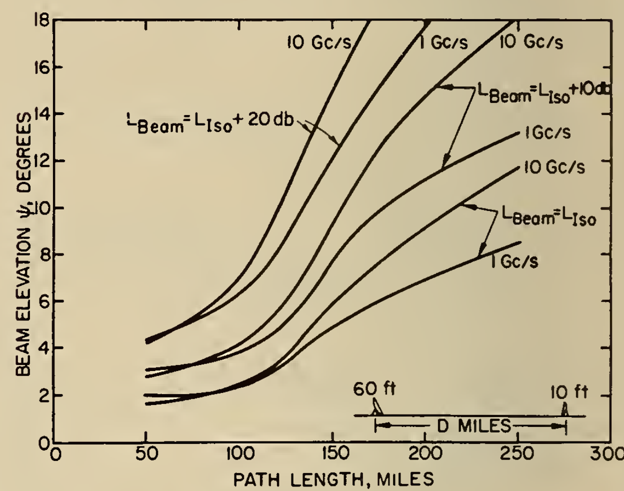

Figure 16: Elevation angle versus distance for the 99.9% level transmission loss equal to or arbitrarily greater than that using an isotropic terminal antenna; 10-ft remote antenna.

These losses are lower by 20 to 40 db, but the shapes are changed only to the extent that the variability correction changes with θ (the scatter angle, or "angular distance") as was shown in figure 5. Hence, the shape-change and loss-reduction is most noticeable for short paths and very low ψ's.

The preceding results have all been based on the assumption of a smooth earth. If terrain is used to shield the earth terminal from interference, the beam elevation required to increase the loss via the main beam to that for an isotropic earth terminal antenna will increase. Figure 17 shows two of the curves from figure 12

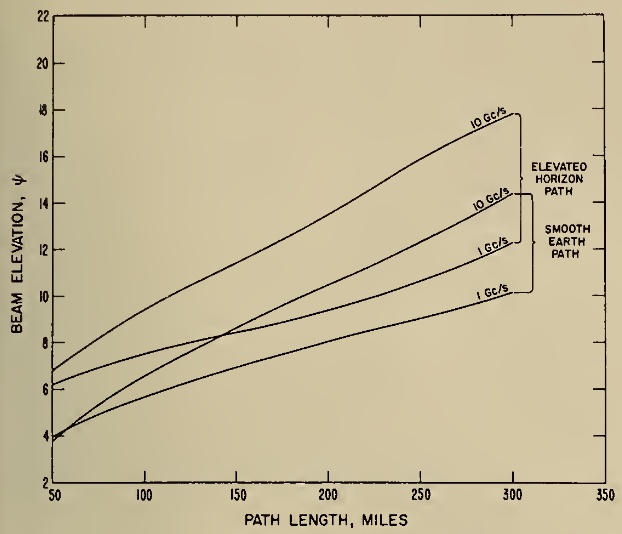

Figure 17: Elevation angle versus distance for the median level transmission loss equal to that using an isotropic terminal antenna, for smooth earth conditions, and for a 200-ft obstacle located 5 miles from the terminal end; remote antenna isotropic, 60-ft terminal antenna.

and the corresponding curves for a path with a smooth 200-foot high obstacle located 5 miles from the earth terminal. It is assumed that this obstacle does not cause obstacle gain, but only introduces path asymmetry and increases the scattering angle by 7.5 mr. These curves show the loss equality angle increasing significantly from the smooth earth to the elevated horizon path with a substantially larger frequency dependence over the latter paths. However, the basic loss is larger over the obstacle path than over the corresponding smooth earth path (~ 13 db at 50 miles and ~ 5 db at 300 miles for both frequencies for the example used here). Thus, the need for caution in assuming a smooth earth for arbitrary paths is illustrated.

8. Recent Results

Thus far, there has not been adequate experimental verification of these predicted effects at high beam angles. The results of one early series of measurements between Boulder and Haswell appeared as figure 3 of the Hartman and Decker paper [1961]. The good agreement with the predicted curve may result from the relatively low frequency, 409.9 Mc/s, for which the loss in path antenna gain corrections were relatively low. Similar experiments near 10 Gc/s would be more critical but would be correspondingly more difficult to make because of the currently available transmitter powers and antennas.

Recently, a program has been prepared for a large digital computer to numerically integrate Hartman and Wilkerson's [1959] equation 3.2 with a Bessel function approximation for the antenna pattern included in the integrand for arbitrary orientations of the antennas. There are several indications that the computer method gives better results even though both methods use the same formulas for evaluation. First, in the Hartman and Wilkerson method, the final form for the calculations was derived empirically from many graphs to facilitate graphical presentation in a report. Because of the intended application of this report [Hartman and Wilkerson, 1959], the calculations were restricted to values of the parameters corresponding to conventional paths. The programmed method is not subject to these restrictions. For conventional paths (i. e., low antenna heights and antennas directed at the horizons) the two methods agree within a few db. Unfortunately, for situations where the two methods give differences of 10 db or more, very few data are available for comparison. These data agree best with the programmed method, although the significance of this agreement is questionable.

At the higher frequencies, these new calculations show higher values of G_L for elevated beams. For example, with 10-foot and 60-foot antennas at 10 Gc/s, the computed value of G_L was about 15 db higher when $\psi = 8^\circ$ at 100 miles.

Such higher values of G_L would reduce the frequency dependence, which was exhibited in figure 10. The new calculations also indicate a smaller difference in loss equality angles between smooth earth and elevated horizon paths than was shown in figure 17.

9. Conclusions

It should be remembered that the beam elevation relations which have been presented were calculated by present path loss prediction methods. These methods are partly empirical and are based on extensive measurements which typified tropo-scatter communication practices: horizon-directed antennas and frequencies predominantly below 1 Gc/s. Additional extensive measurements will be needed to confirm or modify these prediction methods for applicability to the surface interference problems of space communication. Nevertheless, the general propagation behavior dependence on beam elevation angle should not differ greatly from that which has been shown. It is believed that these studies should give the space communication systems engineer a better "feel" for the importance of controlling the minimum elevation angle as a tool for controlling surface interference. More generally, it should be remembered that physical separation is not the only tool and that it is an expensive one. The control of path antenna gain, together with terrain shielding, should become the engineer's best tools for the control of surface interference.

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