layer base elevation and the optimum elevation for launching or receiving energy in the duct) over the lower half of Lake Michigan is h_o = 1250 meters above the surface.

The median M-unit lapse, $|\Delta M(50\%)|$, of all elevated ducts is given by the contour mapping of Figure 13. Over the southern half of Lake Michigan $|\Delta M(50\%)| \simeq 4$ M-units, so that the median critical ducting angle expected at the optimum coupling elevation h_o is, from (3a), $\theta_c(50\%) \simeq \sqrt{8}$ milliradians.

In Figures 14 and 15, contour mappings are presented for the median elevations of the base and top of elevated ducts, respectively, $h_b(50\%)$ and $h_a(50\%)$ in meters above the surface. Over the southern portion of Lake Michigan, for example, the median duct base $h_b(50\%)$ is at about 1200 meters and the median duct top $h_a(50\%)$ is at about 1700 meters above the surface.

Of course, each of the foregoing parameters (h_b, h_o, h_a, f_t) can vary from duct to duct; however, an estimate of the range of their values may be deduced from the 10 and 90 percentile values. These are given by the contour maps of Appendix B.

4. ILLUSTRATIVE EXAMPLES

To illustrate the use of the foregoing material in the estimation of expected interference fields, consider the Great Lakes region of the United States. That region is characterized by warm humid summers and cold cloudy winters; atmospheric layering is somewhat more prevalent in the summers.

From Bean et al. (1966), at Flint, Michigan, between Lakes Huron and Erie (one of the stations in Figure 10), surface ducts occur about 2% of the time both in August and as averaged over the four seasons with a median thickness of $D(50\%) \simeq 100$ m. The corresponding minimum trapping frequency is, from (7),

$$f_t(50\%) = \frac{1572}{(100)^{1.8}} = 0.39 \text{ GHz} . \tag{11a}$$

That is, frequencies above about 400 MHz will be trapped by surface ducts for about p = 0.5(2%) = 1% of the time. This observation of surface ducts is actually the observation of refractivity gradients < -157 N units/km, "over the initial 100 m above the surface (i.e., a change of at least 15.7 N units). From an examination of Figure 7, this refractivity lapse could have been provided by a variety of structures. If we assume it is entirely due to an elevated layer of thickness δh = 10 m, then

$$\frac{dN}{dh} \leq - \frac{15.7}{10} = -1.57 \text{ N units/m} =- 1570 \text{ N units/km}. \tag{11b}$$

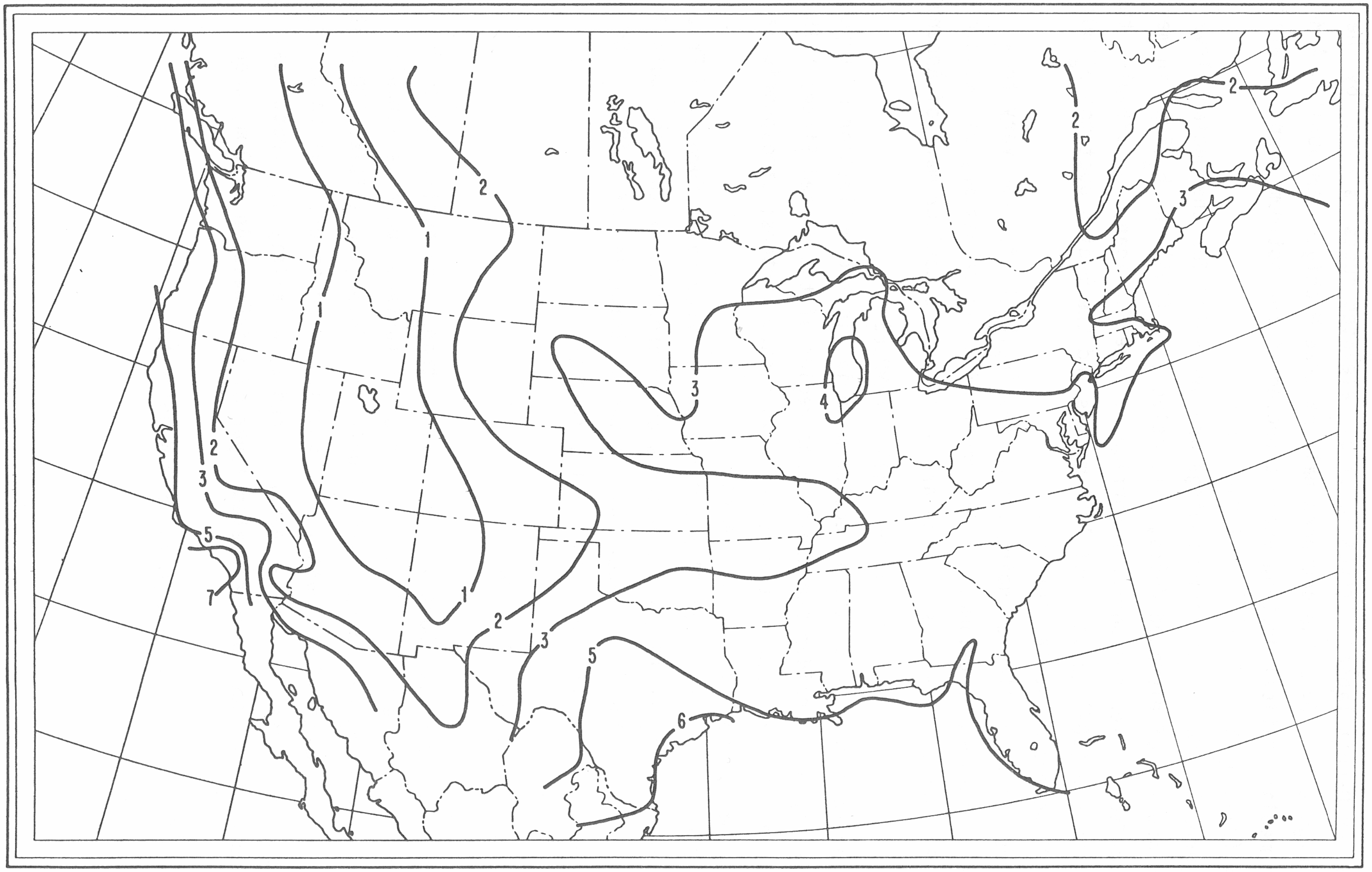

Figure 13. The median M-unit lapse across the observed elevated ducts, $|\Delta M(50\%)|$ in M-units.

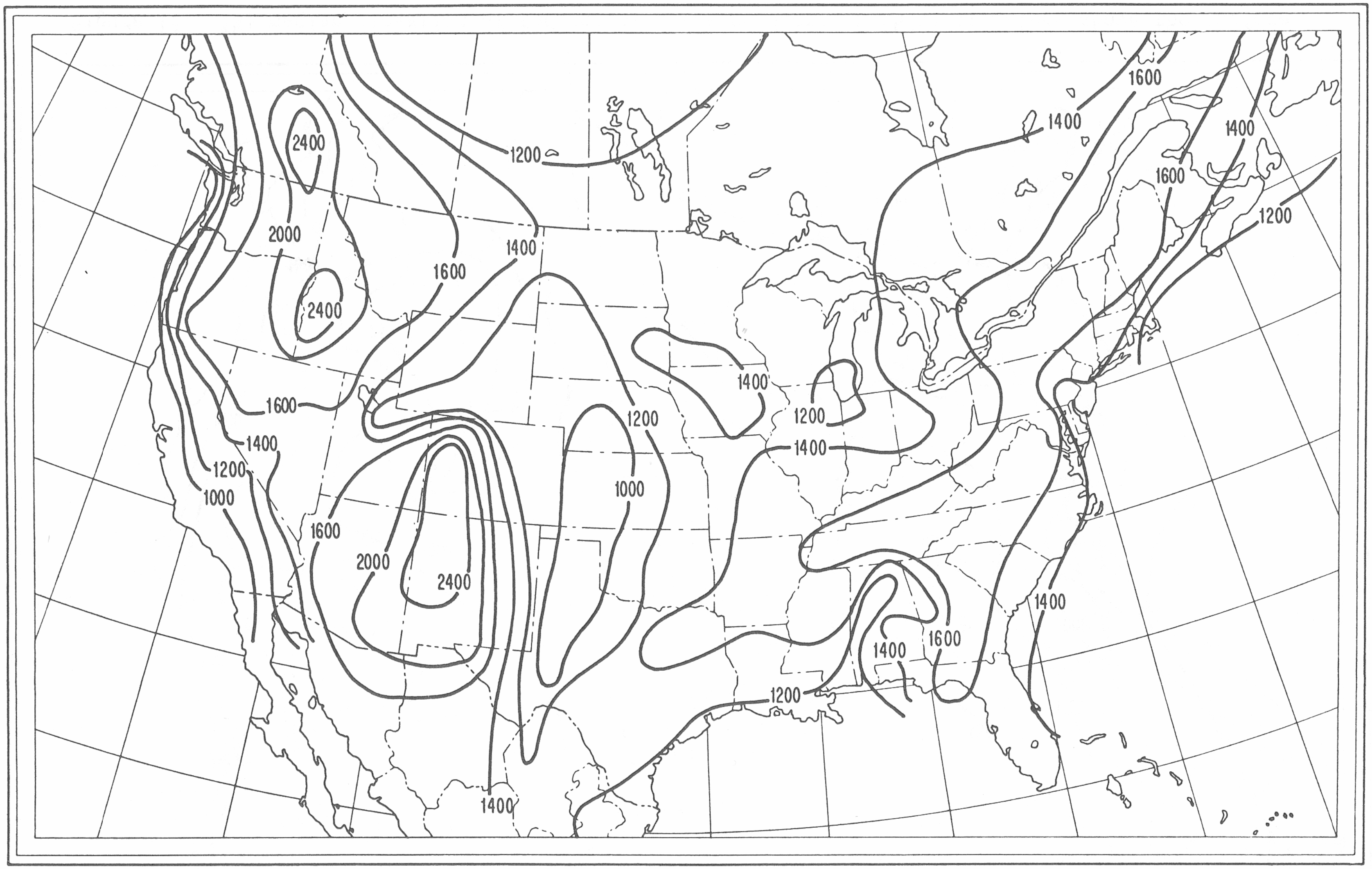

Figure 14. The median base height of elevated ducts, $h_b(50\%)$ in meters above the surface.

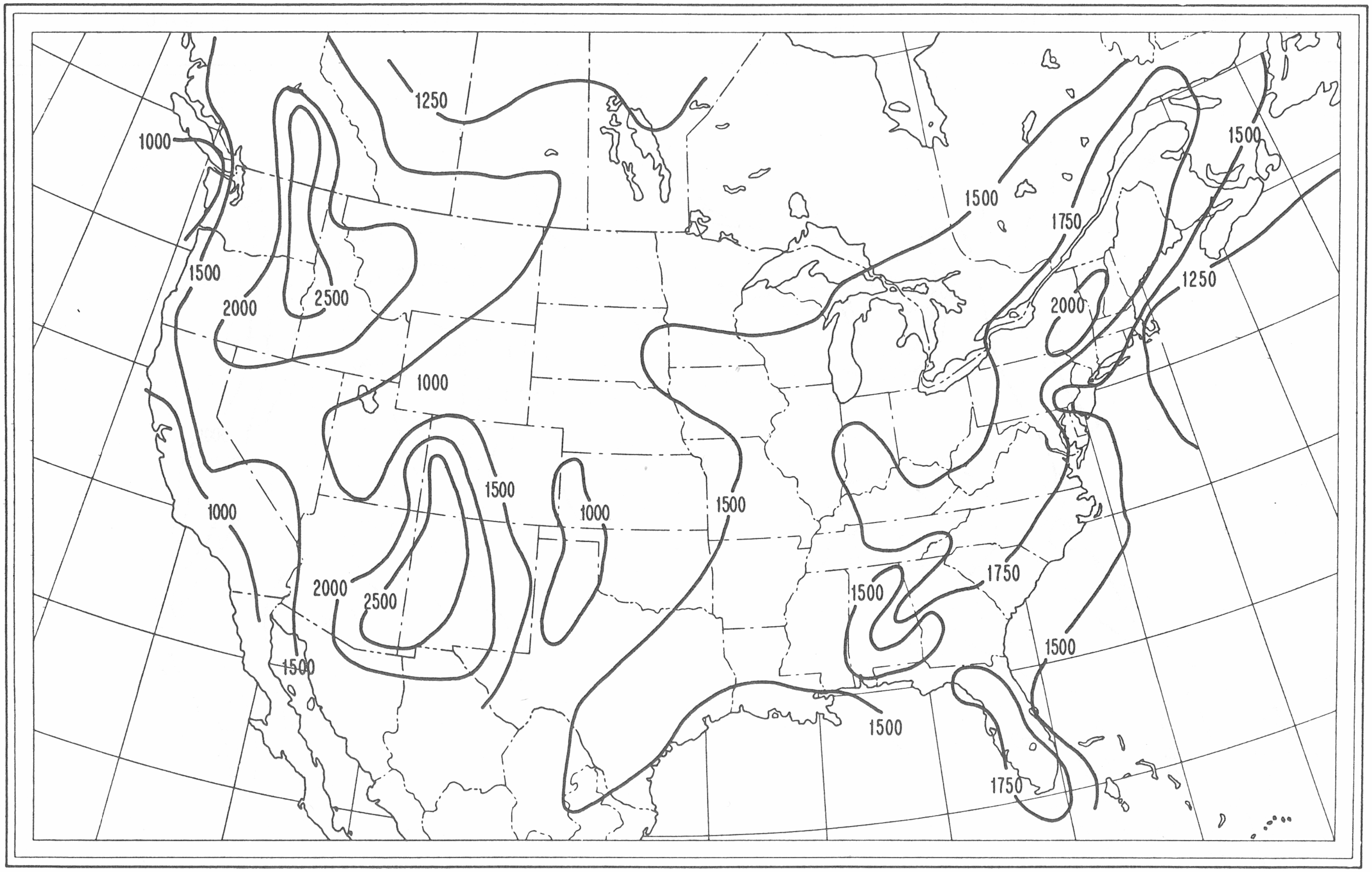

Figure 15. The median elevation of the top of elevated ducts, $h_a(50\%)$ in meters above the surface.

From (2b), for p = 1% of the time

$$\frac{dM}{dh} = -1570 + 157 = -1413 \text{ M units/km} \tag{11c}$$

$$= -1.413 \text{ M units/m.}$$

From (3b),

$$\delta M = -1.413(10) = -14.13M \text{ units.} \tag{11d}$$

From (3a),

$$2\theta_c = 2\sqrt{2(14.13)} = 10.63 \text{ mrad} = 0.61°. \tag{11e}$$

From (10) for $\Omega \geq 10.63$ mrad,

$$A_c = -10 \log (10.63/\Omega)$$
$$= -10.27 + 10 \log \Omega . \tag{11f}$$

For both terminals immersed in the surface duct (h_T, h_R < 100 m at most), the basic transmission loss for a 145 km path at 0.53 GHz is given by (8) for p = 1% of the time as

$$L_b(1\%) \geq 92.45 + 20 \log(0.53) + 10 \log (145) + 0.03 (145)$$
$$- 20.54 + 10 \log \Omega_T + 10 \log \Omega_R$$

or

$$L_b(1\%) \geq 92.36 + 10 \log \Omega_T + 10 \log \Omega_R . \tag{12}$$

Unless the beamwidths exceeds a few degrees, this duct basic transmission loss will be less than the free-space basic transmission loss of (9),

$$L_{bo} = 92.45 + 20 \log (0.53) + 20 \log (145) = 130.16 \text{ dB.} \tag{13}$$

4.1 Application to Broadcasting

Consider a broadcasting station (or the base station of a land-mobile system) operating in the vicinity of Flint, Michigan, in the 0.45 to 1.0 GHz frequency range. From Figures 8 and 9, we note that elevated ducting layers occur in the Flint area for about 18% of the year, but for about 45% of the worst month (August). The median minimum trapping frequency, from Figure 11, is about 0.4 GHz. That is, interference signals at f > 0.4 GHz could be supported via elevated layers for about 0.5(18%) = 9% of the year or about 0.5(45%) = 22% of August.

Let us assume the system parameter values

$$f = 0.53 \text{ GHz}, \ \Delta H = 50 \text{ m},$$
$$h_T = 75 \text{ m}, \quad \Omega_T = 10° \text{ or } 174.5 \text{ mrad}, \tag{14}$$
$$h_R = 10 \text{ m}, \quad \Omega_R = 45° \text{ or } 785.4 \text{ mrad}.$$

where f is the transmission frequency, ΔH is a measure of terrain irregularity (the 10% to 90% range of elevations at 10 to 50 km from the transmitter [CCIR, 1978a]), the h_T and h_R are the heights of the transmitting and receiving antenna centers of radiation in meters above some common reference elevation, and the Ω_T and Ω_R are the transmitting and receiving antennas vertical-plane half-power beamwidths. At a distance of d = 145 km, the basic transmission loss for surface duct propagation is, from (12) and (14),

$$L_b(1\%) \leq 92.36 + 10 \log (174.5) + 10 \log (785.4) = 143.73 \text{ dB}. \tag{15}$$

In the case of elevated ducts, we note from Figure 14 that the median elevated-duct base height is $h_b(50\%) > 1400$ m so that both terminals given by (14) are positioned below the elevated duct. By means of energy coupled into and out of non-uniform elevated ducts, as mentioned in the paragraphs following (10) in job- section 2.5, an upper bound on the basic transmission loss for a field at a distance of 145 km would be given by

$$L_b(9\%) \leq L_{bo} + 10 + 10 = L_{bo} + 20 \text{ dB}. \tag{16}$$

From (13) and (16)

$$L_b(9\%) \leq 130.16 + 20 = 150.16 \text{ dB}. \tag{17}$$

The foregoing values of basic transmission loss may be related to estimates of the corresponding field strengths by

$$20 \log [E_o/E(p)] = L_b(p) = L_{bo} \text{ dB}, \tag{18}$$

for the expected ducted fields expressed in decibels <u>below</u> the free-space field. That is, from (13), (15), (17), and (18),

$$20 \log [E_o/E(1\%)] = 143.73 - 130.16 = 13.57 \text{ dB}(E_o) \tag{19a}$$
$$20 \log [E_o/E(9\%)] = 150.16 - 130.16 = 20 \text{ dB}(E_o). \tag{19b}$$

For the parameter values of (14), the CCIR [1978g] provides predicted broadcast fields for both the standard condition (50% of all locations for 50% of the time) and for selected percentages of the time (50% of all locations for p = 10% and 1% of the time). For paths over either the Mediterranean Sea or overland (at roughly the same North latitudes as the Great Lakes), Table I lists the calculated fields, from (19a) and (19b), and the empirical CCIR predictions. For mixed land/sea paths, the CCIR recommends interpolation on the basis of the proportion of the oversea to total path lengths.

Table 1. Comparison of Broadcast Fields in Decibels Below the Free-Space Level at Flint, Mich., for 50% of Receiver Locations 450 to 1000 MHz.

p	CCIR (overland, ΔH = 50 m)		Calculated
% of the time	20 log [E(p)/E(50%)]	20 log [E_0/E(p)]	20 log [E_0/E(p)]
1	14 dB	45 dB	13.6 dB
10 *	7	52	20.0
50	0	59	--

* approximately, 9 and 10%

The first column of Table 1 is the percent of the year. The second column is the empirically expected service field level relative to the median (50%) field; this indicates modest field enhancements for 10% and 1% of the time. The third column is the same listing of service fields, but expressed in decibels below the free-space level. The third column should be compared with the fourth column values of interference fields to see the effect on overland paths when there are more horizontally extensive elevated ducts present. These fourth column fields exceed those of the third column by the order of 30 dB.

The CCIR predictions of broadcast fields are representative of average climatic conditions throughout the temperate zone [CCIR, 1978g]. As averages of data from broadcast systems of North America, Europe, Japan, etc., they are appropriate for the prediction of service fields. However, for the purpose of protecting against interference, a biased estimate is required [CCIR, 1978h]. One might prefer an estimate from many broadcast systems (of the field exceeded for 1% of the time) based upon the highest observed 1% field, not the average observed 1% field. Table 1 illustrates the inadequacy of estimating interference fields (highest 1% fields), by service-field (average 1% fields) prediction methods.

5. RECOMMENDATIONS

The preceding text, particularly its referenced material, demonstrates the feasibility of predicting interference fields. The next step would be the development of more complete prediction procedures. Advances are required in four aspects of the problem:

(a) additional experimental studies,

(b) further theoretical developments,

(c) formulation of more complete engineering expressions,

and (d) an improved historical data base.

Let us now discuss these four items in further detail:

(a) Additional experimental studies are required to specify further the horizontal periodicity of elevated ducting layers [Crane, 1980] to determine which aspects of that structure contribute to the efficient coupling of energy into and out of the duct from above or below. Is the periodicity simply D, that of a horizontal sinusoidal structure with distance, $h_o(x) = h_o(o) + c \sin (2\pi x/D)$, that has been occasionally observed by the Acoustic or FM-CW Radars [Hall, 1971; Richter, 1969]? Is the periodicity more subtle, such as $\delta M = \delta M_o \sin (2\pi x/D)$ or $\delta h = \delta h_o \sin (2\pi x/D)$? Are there internal variations of structure that would complicate ducting behavior at EHF and higher frequencies?

(b) Further theoretical progress is required. In the case of horizontally uniform layers, some rudimentary but encouraging developments have raised the possibility of associating the various modal (full-wave) solutions with particular wave-trajectories (ray tracing) [Cho et al., 1979; Migliora et al., 1980; Ott, 1980]. Probably, further developments in wave trajectory characteristics will be required (Appendix A) before the mode/ray association will mature and permit extension to nonuniform-duct propagation. Further development of theoretical solutions is required for horizontally non-uniform layers. The non-uniform structures of interest, in addition to the already treated piecewise continuous ducts [Cho and Wait, 1978], are those for horizontally continuously changing layer thicknesses or refractivity gradients and whatever structures are developed under (a) above.

(c) Formulation of more complete engineering expressions would proceed rapidly if a general relationship between the modal (full-wave) solutions and wave-trajectory solutions can be developed. This would permit the accommodation of antenna patterns, polarization, the localized proximity of irregular terrain boundaries, and irregular atmospheric stratification; these are so necessary to the system design engineer.

(d) An improved historical data base would be readily achieved by an expansion of the data base, a refinement of the data base, and the spatial and temporal extrapolation of the data base. Expansion of the data base would involve the incorporation of much more than the present three years of data -- at least 20 to 30 years of data -- to determine the mean (or median), annual or worst-month parameter distribution of characteristics and their year-to-year variation. If the year-to-year temporal distributions are well behaved, their standard deviation about median-year values would probably suffice. Initially, this need not be carried out for all 107 stations in the United States; one would start with the data from a dozen selected representative stations.

A refinement of the data base would require some modification of the successful data-reduction procedures employed to date. The modifications would be to obtain better estimates of the elevated-layer refractivity gradients and their vertical extents. They would attempt estimates of lag coefficients to correct for the time-sequential temperature/humidity recordings for rising sensors with finite response characteristics [Bean and Cahoon, 1961; Bean and Dutton, 1961; Dougherty et al., 1967].

A spatial and temporal extrapolation of the proposed improved data base is implied when data from twice-a-day soundings at fixed locations are used to estimate the occurrence of ducting layers over twenty-four hours and in a region hundreds of miles square. The diurnal variation of surface and elevated layers should be characterized at select locations in the United States. For example, the data from refractometer soundings recorded over U.S. locations such as the Great Lakes [Bean, 1979], should be compared with the same-day radiosonde data from nearby weather stations. Similarly, the data from "adjacent" U. S. weather stations should be compared.

The above four aspects requiring further study are likely to proceed in independently, but not isolated efforts. However, they may not be able to proceed expeditiously. The referenced investigators are likely to be interested in continuing their efforts, but they may require encouragement by financial and other support. Their interest, demonstrated ability, and need for support should be matched to the urgent requirements expressed at the GWARC-79 [ITU, 1979] for data on ducting and interference fields. These requirements also exist for the U. S. National Radio Regulators (the FCC and NTIA).