The sum of the elevation angles is

$$\theta_e = \theta_{e1} + \theta_{e2} \quad \text{or} \quad - d_L/a \ \text{radians}, \tag{6b}$$

whichever is larger algebraically. In (6) all distances are in kilometers and heights are in meters.

For transhorizon paths the path length d is equal to or greater than the sum of the horizon distances d_L. The angular distance for a transhorizon path is always positive and is defined as

$$\theta = \theta_e + d/a \ \text{radians}, \tag{7}$$

where d is the path length and a is the effective earth's radius, both in kilometers.

These additional path parameters, $h_{e1,2}$, $d_{L1,2}$, $\theta_{e1,2}$, and θ, are used in computing reference values of attenuation relative to free space A_{cr}, or transmission loss L_{cr}. When only the basic parameters are supplied, estimates of these additional parameters are calculated using equations (4) through (7). When detailed profiles are available for desired paths, these additional parameters are obtained as described by Rice et al. (1967) and outlined in annex 3.

3. TRANSMISSION LOSS CALCULATIONS

This section describes how the various parameters discussed in section 2 are used to compute transmission loss. Median reference values A_{cr} of attenuation below free space are computed first. The reference values L_{cr} of transmission loss are then the sum of the free space basic transmission loss, L_{bf}, and the reference attenuation relative to free space, A_{cr}:

$$L_{cr} = L_{bf} + A_{cr} \ \text{dB}. \tag{8}$$

The free-space basic transmission loss is

$$L_{bf} = 32.45 + 20 \log_{10} f + 20 \log_{10} d \ \text{dB}, \qquad (9)$$

where the radio frequency f is in megahertz, and the distance d is in kilometers.

The reference attenuation A_{cr} is computed using methods based on different propagation mechanisms for three distance ranges. Well within radio line of sight, the formulas of two-ray optics are used to compute attenuation relative to free space. Just beyond line of sight, diffraction is the dominant mechanism. The prediction method computes a weighted average, A_d, of estimates of diffraction attenuation over a double knife edge, and over irregular terrain. At greater distances, well beyond the radio horizon, the dominant propagation mechanism is usually forward scatter. The prediction method for this distance range is a modification of the scatter computations described by Rice et al. (1967). The reference attenuation A_{cr} for transhorizon paths is either the diffraction attenuation A_d or the scatter attenuation A_s, whichever is smaller. The distance at which diffraction and scatter losses are equal is defined as d_x.

To provide a continuous curve of the computed reference attenuation A_{cr} as a function of distance the following methods are used.

3.1 To Compute A_{cr} Within Radio Line of Sight

When transmitting and receiving antennas are within radio line of sight, the two-ray optics formulas described in annex 3 are used to compute attenuations A_o and A_1 at specified distances d_o and d_1 that are well within the horizon. The distance d_o is chosen to approximate the greatest distance at which the attenuation below free space is zero. The distance d_1 is greater than d_o but well within the range for which two-ray optics formulas are valid. The methods described in the next subsection are used to compute the diffraction attenuation A_{Ls} at the smooth earth horizon distance d_{Ls}. These three values of attenuation, A_o, A_1, and A_{Ls}, computed at the distances d_o, d_1, and d_{Ls}, respectively, are used to determine the slopes k_1 and k_2 of a smooth curve of A_{cr} versus distance for the range $1 \le d \le d_{Ls}$:

$$A_{cr} = A_o + k_1 (d - d_o) + k_2 \log_{10} (d/d_o) \text{ dB} . \tag{10}$$

Note that the smooth-earth horizon distance d_{Ls} may be greater than the actual horizon distance d_L.

Equation (10) may be simplified by defining a term A_e:

$$A_e = A_o - k_1 d_o - k_2 \log_{10} d_o \text{ dB} . \tag{11}$$

Then for all distances greater than one and less than d_{Ls}, reference attenuation is defined as

$$A_{cr} = A_e + k_1 d + k_2 \log_{10} d \text{ dB} . \tag{12}$$

Detailed methods for computing k_1 and k_2 are given in annex 3. Whenever the value of A_{cr} computed from (12) is less than zero, it is assumed that $A_{cr} = 0$. This prediction method does not attempt to describe the lobery within line of sight over irregular terrain.

3.2 To Compute Diffraction Attenuation A_d

The diffraction attenuation is computed by combining estimates of knife-edge diffraction, based on Fresnel-Kirchhoff theory, with a modification of the method for computing diffraction over smooth terrain developed by Vogler (1964). Vogler's method estimates the diffraction attenuation, A_r, over the bulge of the earth in the far diffraction region, and is applicable for smooth terrain. Knife-edge diffraction theory is used to estimate attenuation over an isolated hill or ridge. In this application the knife-edge attenuation, A_k, is computed as though the radio path crossed two sharp, isolated ridges. In general, for irregular terrain, the diffraction attenuation, A_d, is computed as a weighted average of the two estimates A_r and A_k:

$$A_d = (1 - w)\, A_k + w\, A_r \ \ \mathrm{dB}, \tag{13}$$

where the weighting factor, w, is determined empirically as a function of radio frequency and terrain parameters and is defined in annex 3.

The diffraction attenuation A_d is calculated at distances d_3 and d_4 in the far diffraction region using the formulas given in annex 3. A straight line through these points (A_3, d_3) and (A_4, d_4) is then defined by the intercept, A_{ed}, and slope, m_d, as follows:

$$m_d = (A_4 - A_3)/(d_4 - d_3) \ \ \mathrm{dB/km}, \tag{14}$$

and

$$A_{ed} = A_{fo} + A_4 - m_d\, d_4 \ \ \mathrm{dB}, \tag{15}$$

where A_{fo} is a clutter factor defined in annex 3.

The reference attenuation A_{cr} at any distance d greater than the smooth earth horizon distance d_{Ls} and less than the distance d_x where diffraction and scatter attenuation are equal is

$$A_{cr} = A_d = A_{ed} + m_d d \quad \text{dB}, \quad \text{for} \quad d_{Ls} \le d \le d_x . \tag{16}$$

3.3 To Compute Forward Scatter Attenuation A_s

When the path length d or the angular distance θ is large, the forward scatter attenuation A_s may be less than the diffraction attenuation A_d. Therefore, when the product of the distance in kilometers and the angular distance in radians exceeds 0.5 ($\theta d > 0.5$), forward scatter attenuation A_s is computed for comparison with A_d.

For large values of θd, the scatter attenuation A_s is assumed to have a linear dependence on distance; therefore, A_s is computed at two large distances d_5 and d_6. A straight line through the points (A_5, d_5) and (A_6, d_6) is then defined by the intercept A_{es} and the slope m_s as follows:

$$A_{es} = A_5 - m_s d_5 \quad \text{dB}, \tag{17a}$$

and

$$m_s = (A_6 - A_5)/(d_6 - d_5) \quad \text{dB}. \tag{17b}$$

The reference attenuation A_{cr} at any distance d greater than the distance d_x where diffraction and scatter attenuations are equal is given by

$$A_{cr} = A_s = A_{es} + m_s d \quad \text{dB}, \quad \text{for} \quad d \ge d_x . \tag{18}$$

The detailed equations and techniques required to compute the reference attenuation A_{cr} as a function of distance are given in annex 3.

Figures 3 through 8 show computed and measured values of attenuation below free space plotted as a function of distance. The data were obtained in a measurement program described by Johnson et al. (1967). Measurements were made at frequencies of 20, 50, and 100 MHz in three areas. Figures 3 and 4 show data from northeastern Ohio, with corresponding predicted values. Figure 3 shows medians of data recorded at distances of 10, 20, 30, and 50 km from the transmitter, using both vertical and horizontal polarization at 100 MHz, and with receiver heights of 3, 6, and 9 m. The number of measurements at each distance is tabulated, and corresponding medians of point-to-point predictions based on individual profiles for each of the measurement paths are shown. The lines represent computed reference values A_{cr}, based on frequency, antenna heights, and the asymptotic value of terrain irregularity Δh. Figure 4 shows data and predicted values at frequencies of 20 and 50 MHz.

Figures 5 and 6 show measured and predicted values of attenuation below free space for an area in the plains near Boulder, Colorado. Measurements were made at distances of 5 to 80 km from the transmitter. Medians of data and the number of measurements made at each distance are shown, with corresponding point-to-point predictions. The lines represent computed reference values A_{cr}, based on the asymptotic value of terrain irregularity Δh.

Figures 7 and 8 show measured and predicted values of attenuation below free space in the Colorado mountains west of Boulder. The computed values of A_{cr} represented by lines assume $\Delta h = 650$ m. Actually the shorter paths extend only into the foothills. For the 5-km paths the median value of $\Delta h(d)$ is 100 m. The triangles on figures 7 and 8 show values computed using these estimates of Δh.

COMPUTED AND MEASURED VALUES OF ATTENUATION BELOW FREE SPACE
NORTHEASTERN, OHIO
$f = 100$ MHz, $\Delta h = 90$m, $N_s = 312$

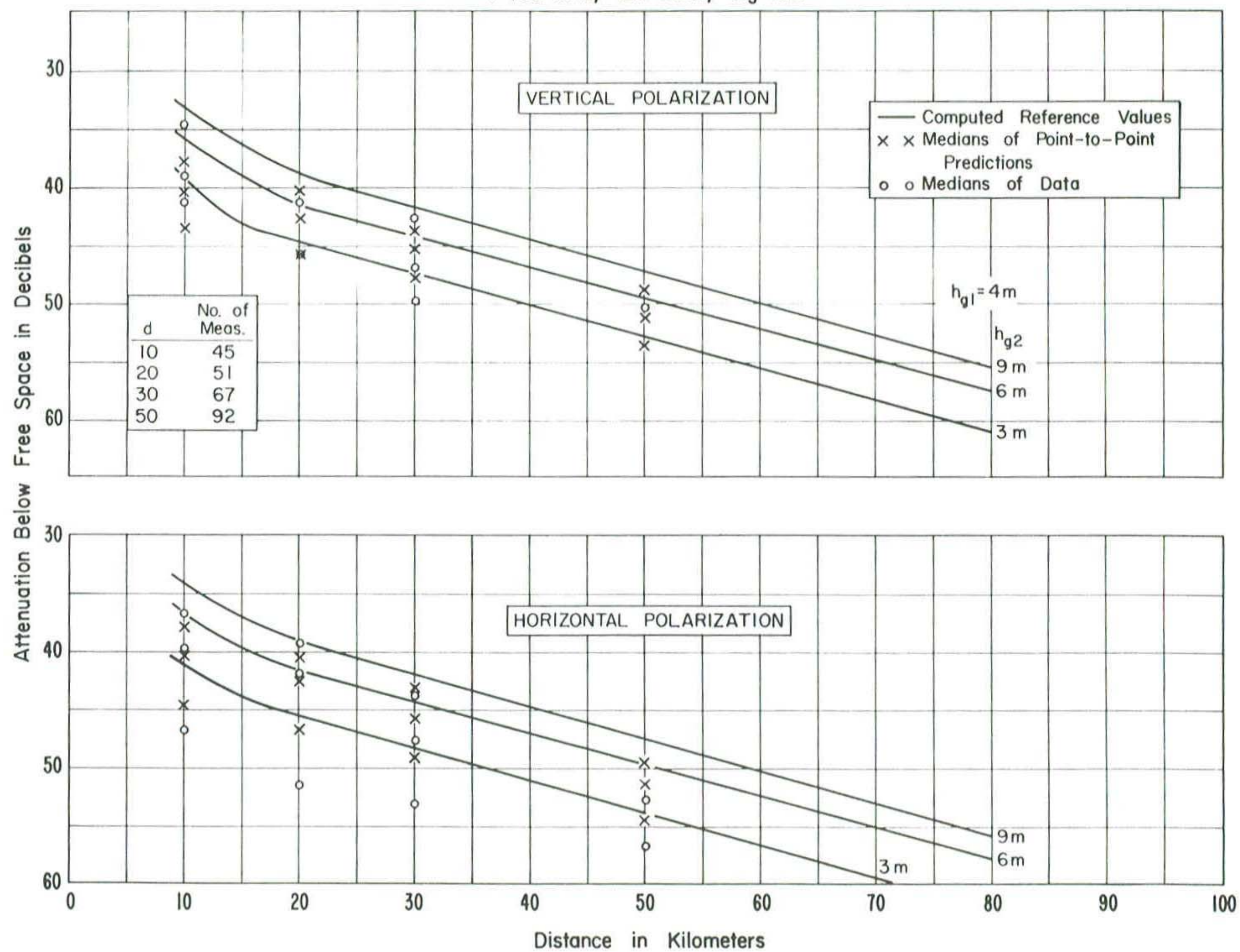

Figure 3

COMPUTED AND MEASURED VALUES OF ATTENUATION BELOW FREE SPACE NORTHEASTERN, OHIO

f =50 and 20 MHz, Δh=90m, N_s=312

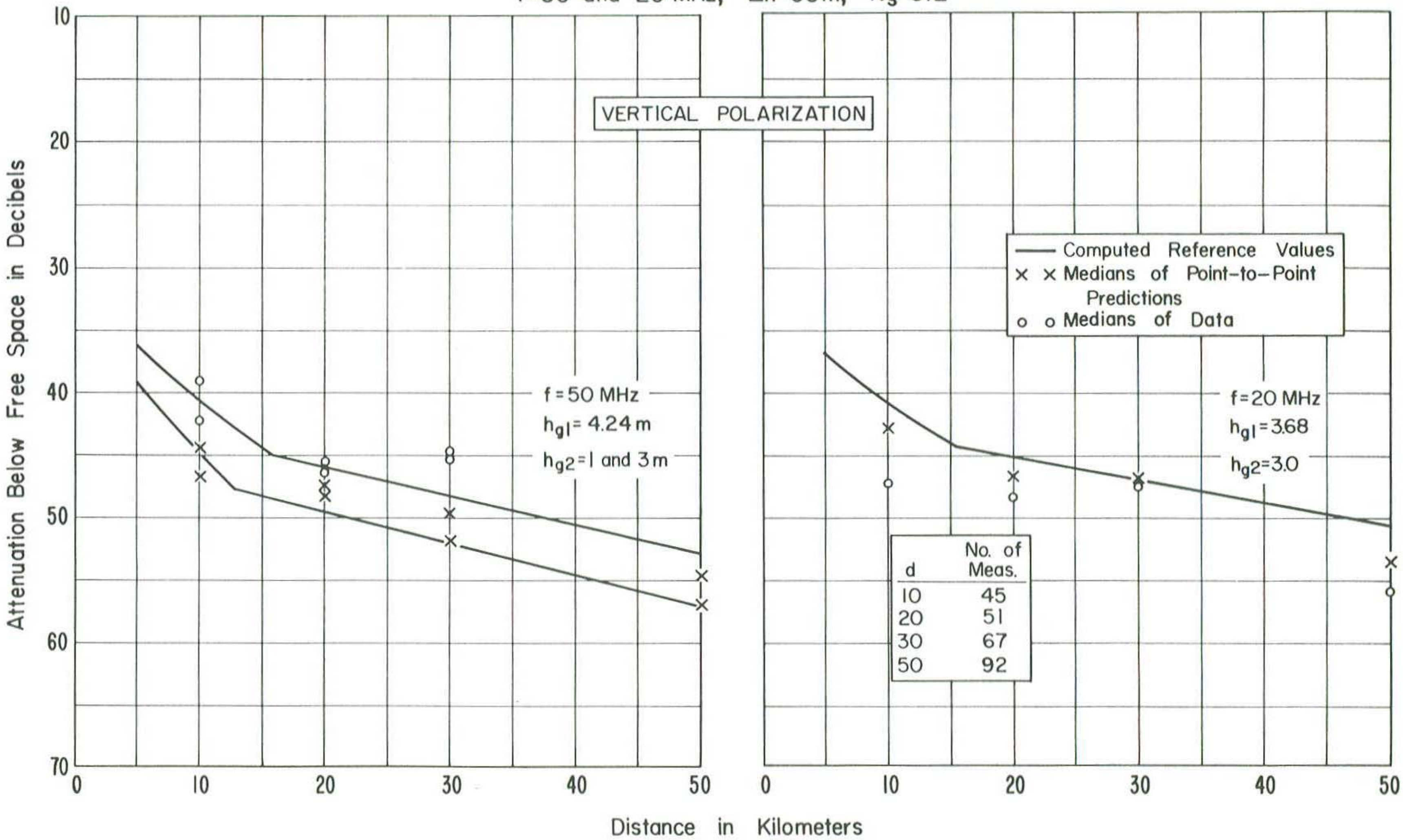

Figure 4

COMPUTED AND MEASURED VALUES OF ATTENUATION BELOW FREE SPACE
COLORADO PLAINS

$f = 100$ MHz, $\Delta h = 90$ m, $N_s = 290$

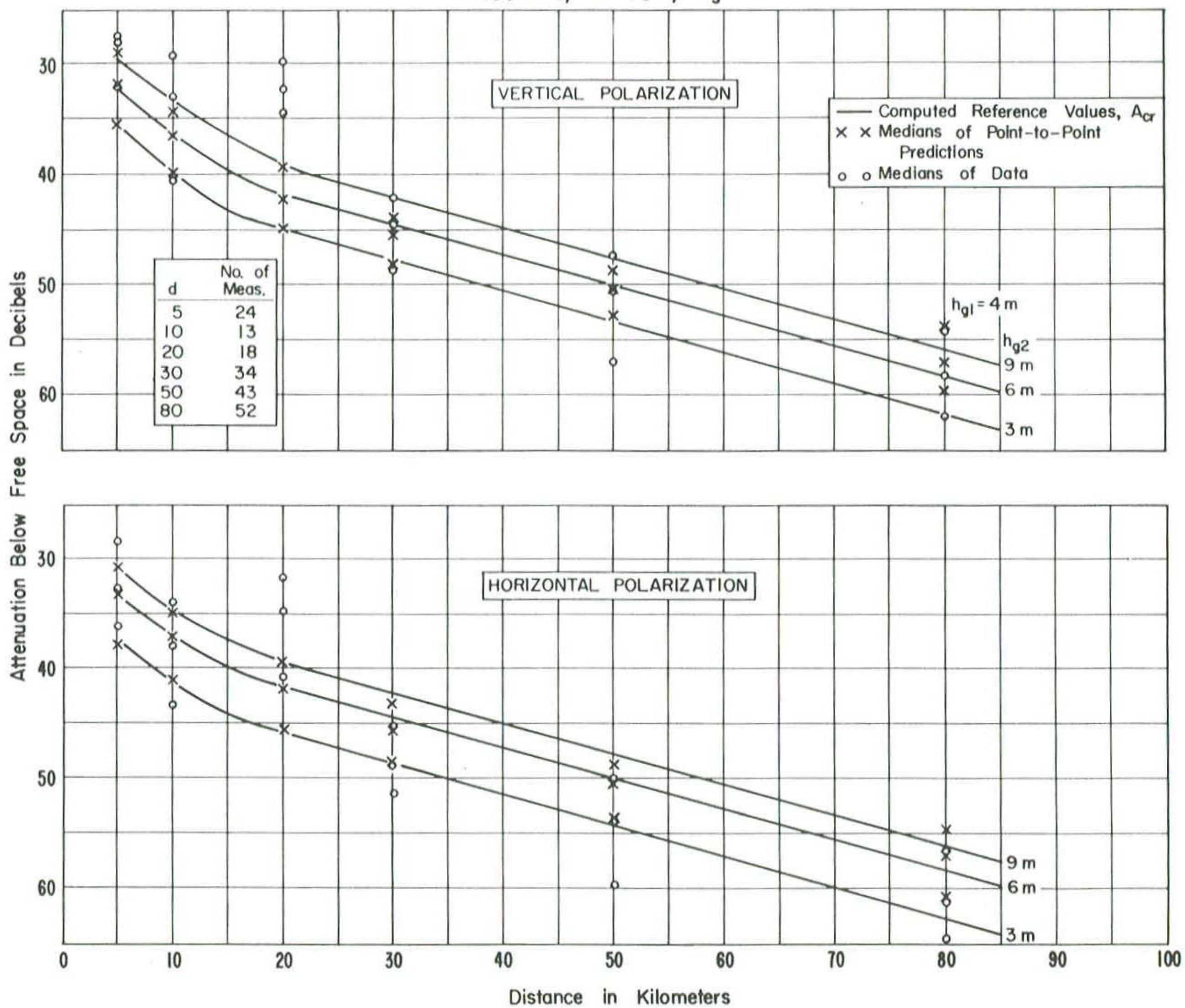

Figure 5

COMPUTED AND MEASURED VALUES OF ATTENUATION BELOW FREE SPACE
COLORADO PLAINS

$f = 50$ and 20 MHz, $\Delta h = 90m$, $N_s = 290$

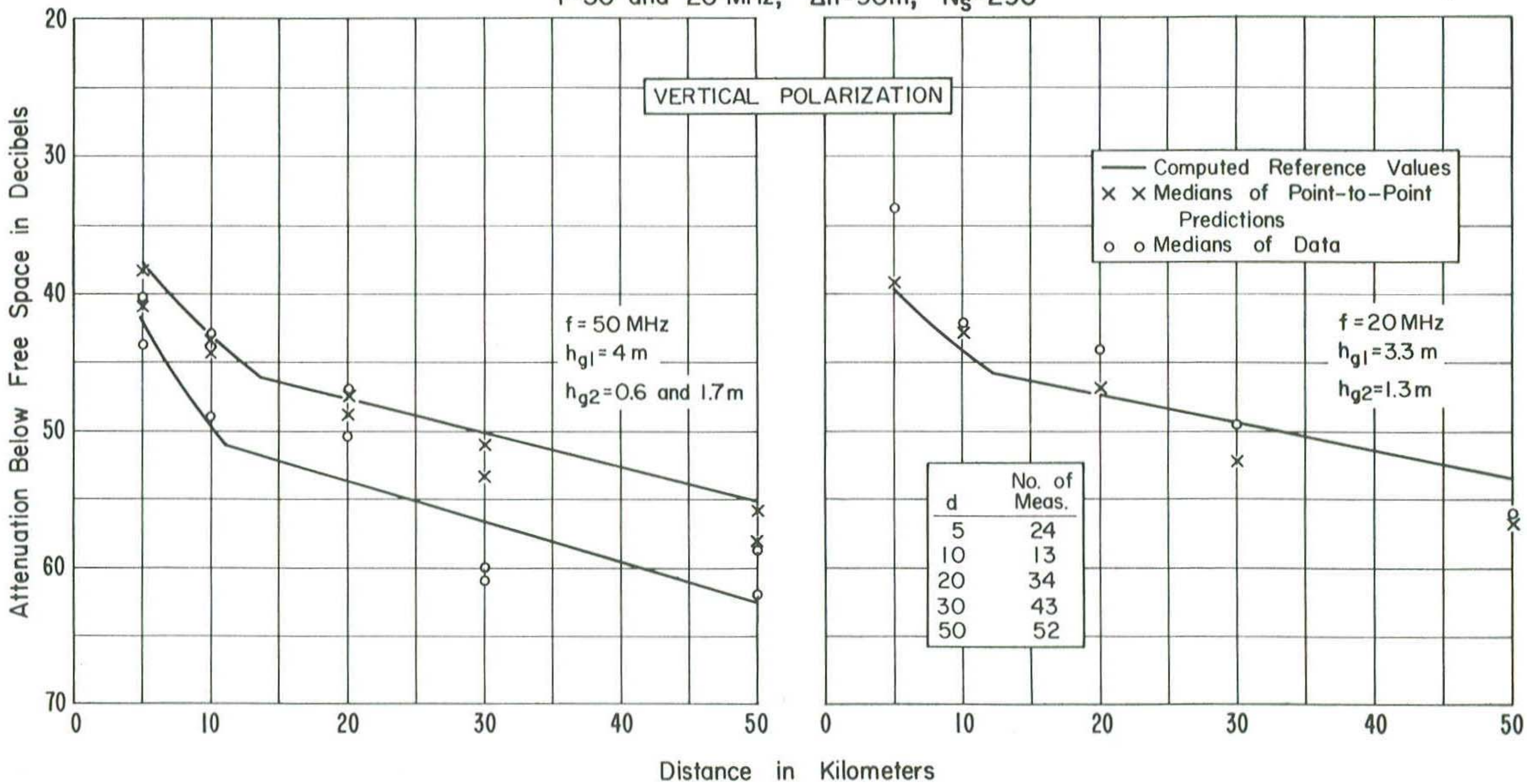

Figure 6

COMPUTED AND MEASURED VALUES OF ATTENUATION BELOW FREE SPACE
COLORADO MOUNTAINS
$f = 100$ MHz, $\Delta h = 650$ m, $N_s = 290$

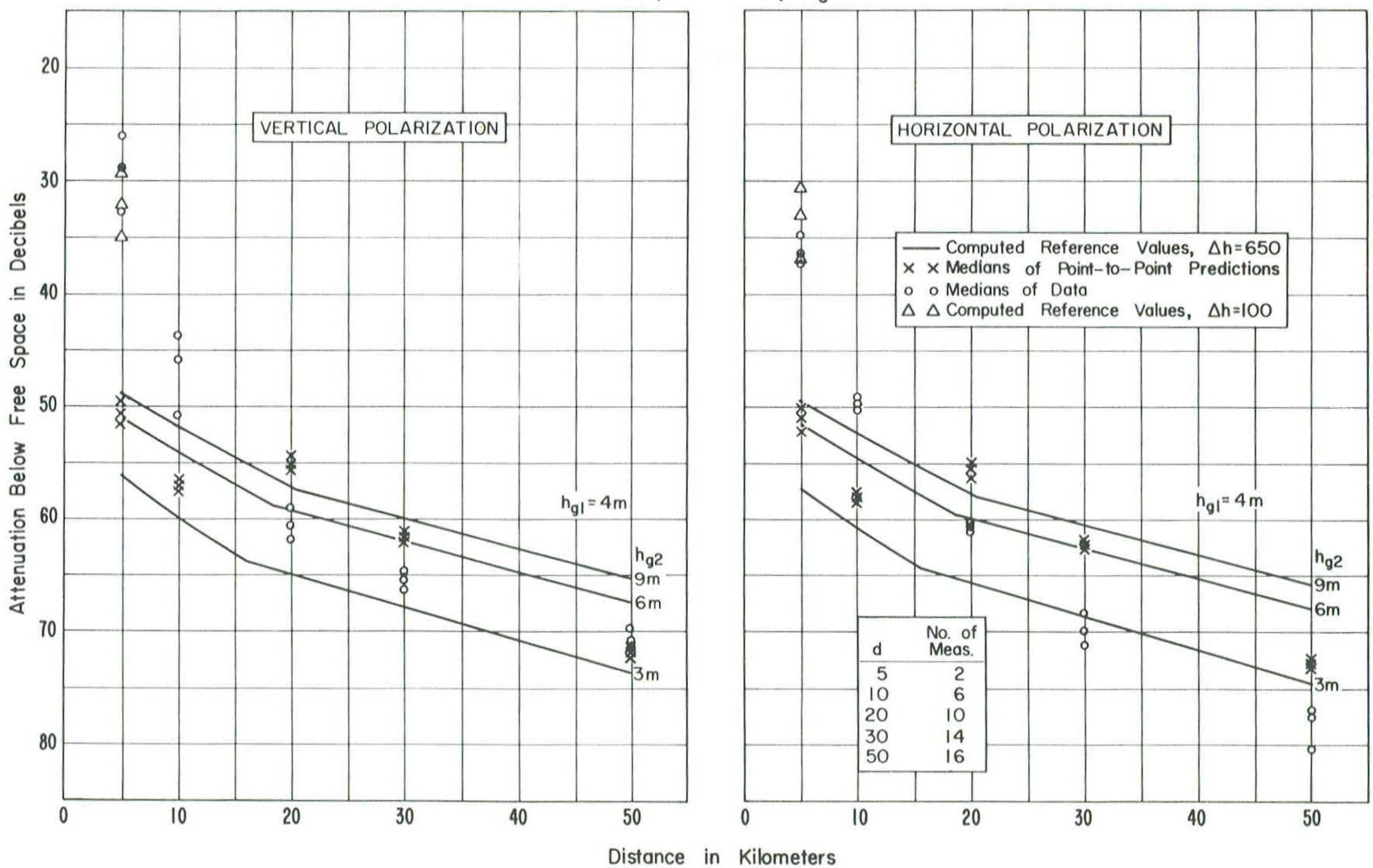

Figure 7

COMPUTED AND MEASURED VALUES OF ATTENUATION BELOW FREE SPACE
COLORADO MOUNTAINS

f=50 and 20 MHz, Δh=650m, N_s=290

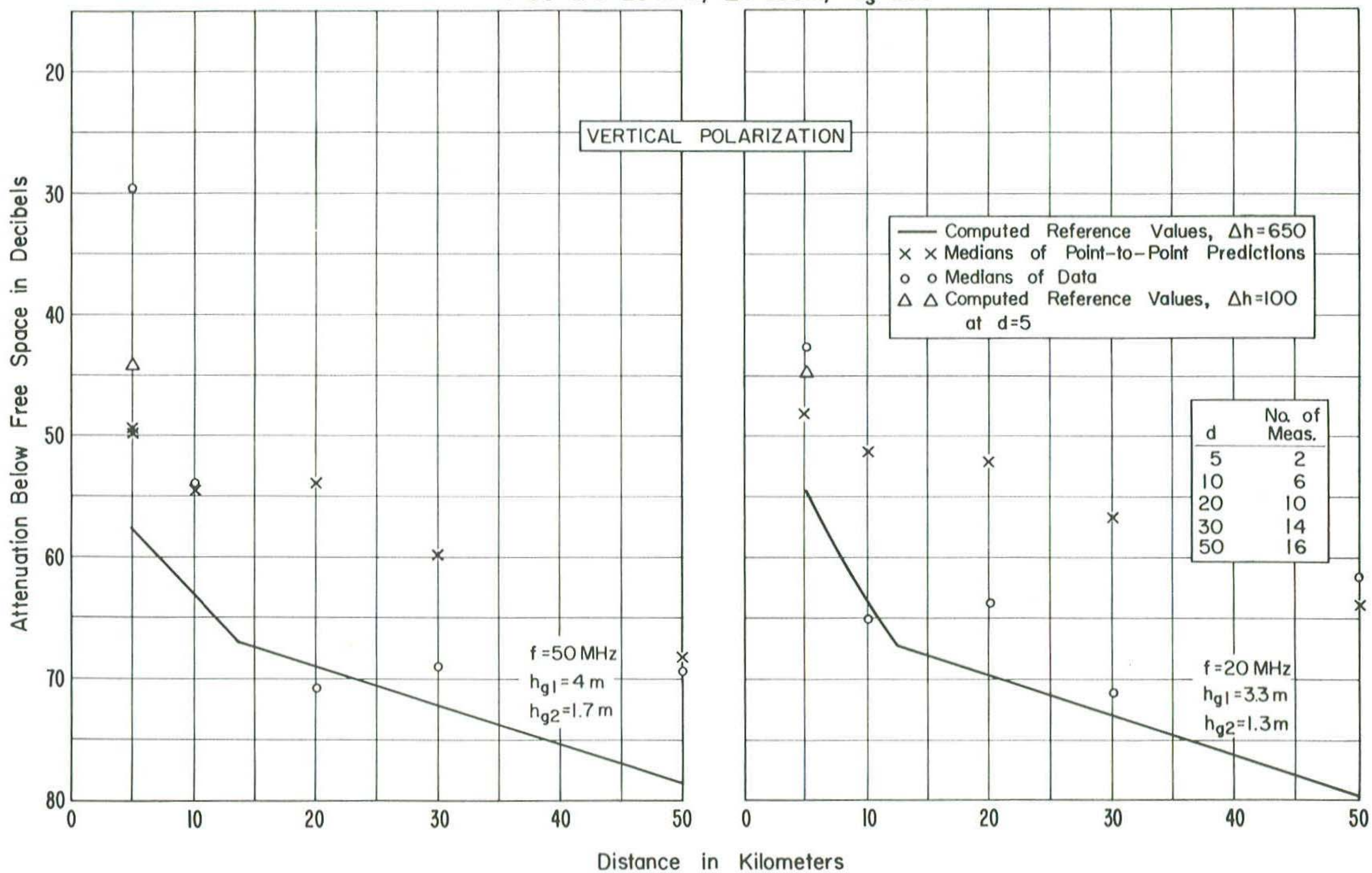

Figure 8