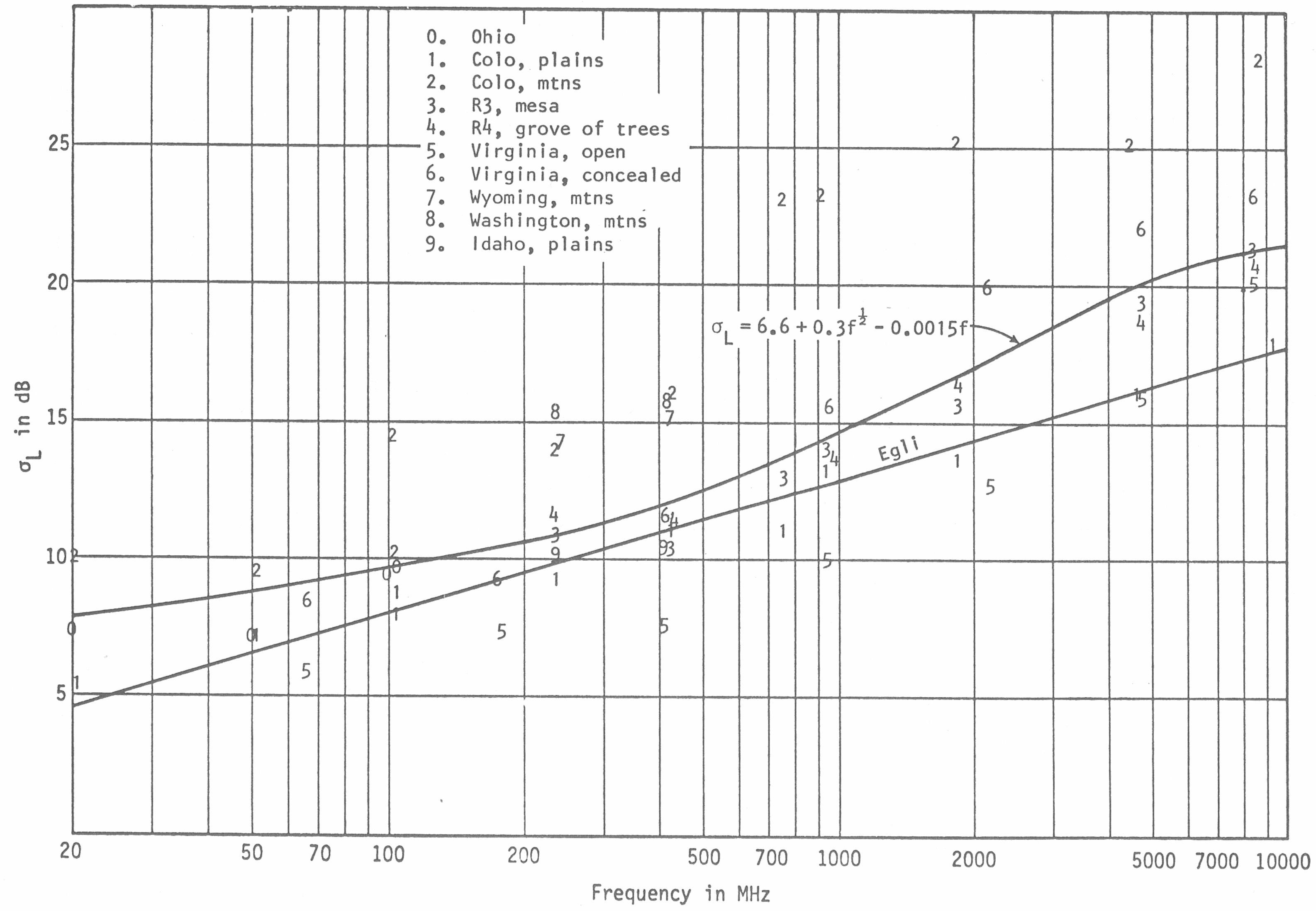

Figure 3. Standard deviation of location variability, σ_L, measured values vs frequency.

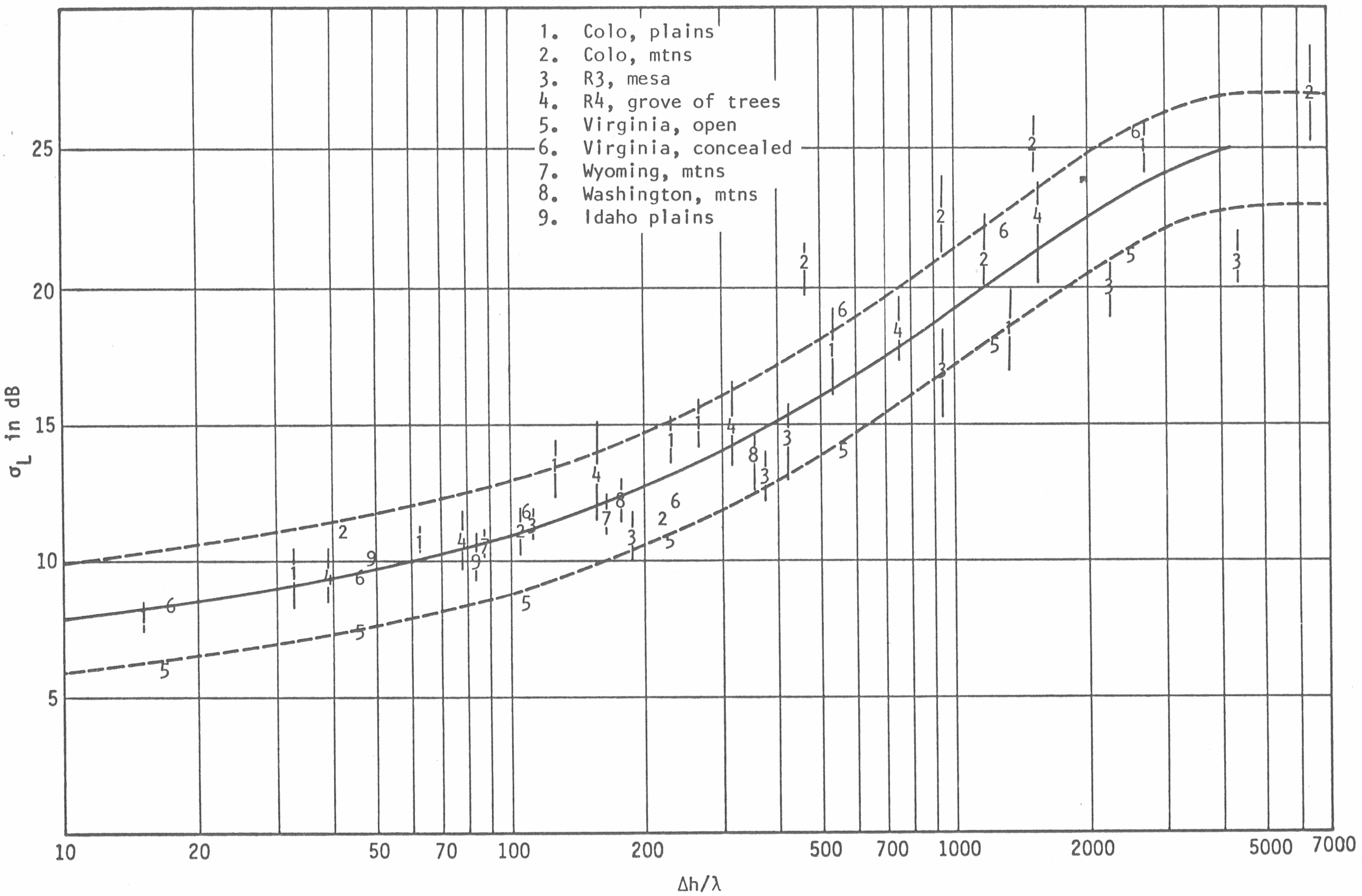

Figure 4. Standard deviation of location variability, σ_L, measured values as a function of the parameter $\Delta h/\lambda$.

in each set of data represents different antenna height combinations. Receiver heights of 1, 3, 7, and 10 m were used for the R1 to R4 data. It is readily seen that there is less spread to the data than in the previous plot, and that σ_L increases gradually with increasing values of $\Delta h/\lambda$.

This relationship could be approximated quite simply in terms of three straight lines:

$$\sigma_L = 5 + 3 \log (\Delta h/\lambda) \text{ dB, for } 10 \le \Delta h/\lambda \le 100 \tag{4a}$$

$$\sigma_L = -6 + 8.7 \log (\Delta h/\lambda) \text{ dB, for } 100 < \Delta h/\lambda \le 4000 \tag{4b}$$

$$\sigma_L = 25 \text{ dB, for } \Delta h/\lambda > 4000. \tag{4c}$$

A somewhat better fit to the data is obtained using the curve shown on figure 4, which is expressed as

$$\sigma_L = 6 + 0.55 (\Delta h/\lambda)^{\frac{1}{2}} - 0.004 (\Delta h/\lambda) \text{ dB, for } \Delta h/\lambda < 4700 \tag{5a}$$

$$\sigma_L = 24.9 \text{ dB, for } \Delta h/\lambda > 4700. \tag{5b}$$

For convenience in using these estimates they are shown in figure 5 as a series of curves of σ_L versus frequency for various values of Δh. Except for the R2 data in the Colorado mountains 90% of all values lie within 2 dB of this calculated curve. The mountain path data at 20, 50, and 100 MHz fall within 2 dB of the predicted values, but at the higher frequencies σ_L is somewhat larger than predicted. There are several possible explanations. One is the small sample size, another that many of these measurements were at the limit of the equipment, and a third that terrain irregularity is so great in comparison to wave length that small errors in estimating the terrain parameter would be magnified. The Colorado R3 data show less than the calculated variability. In this case the receiver is at the top of a mesa so that many of the paths are within line of sight.

To determine whether antenna heights have a uniform effect on location variability, the differences between measured values of σ_L and those calculated using equation (5) are plotted in figure 6 against the sum of the

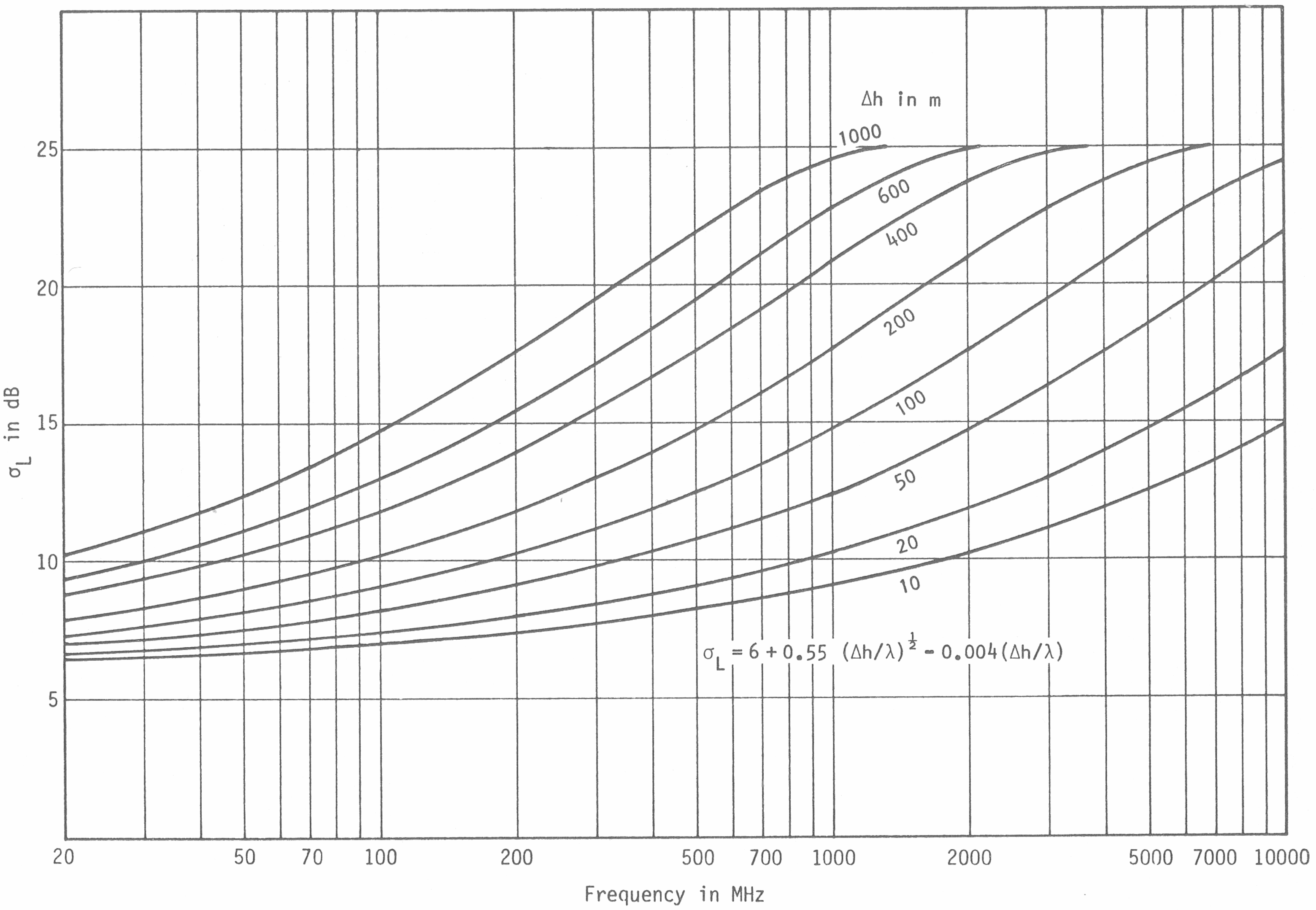

Figure 5. Curves of σ_L versus frequency, for several values of the terrain parameter Δh.

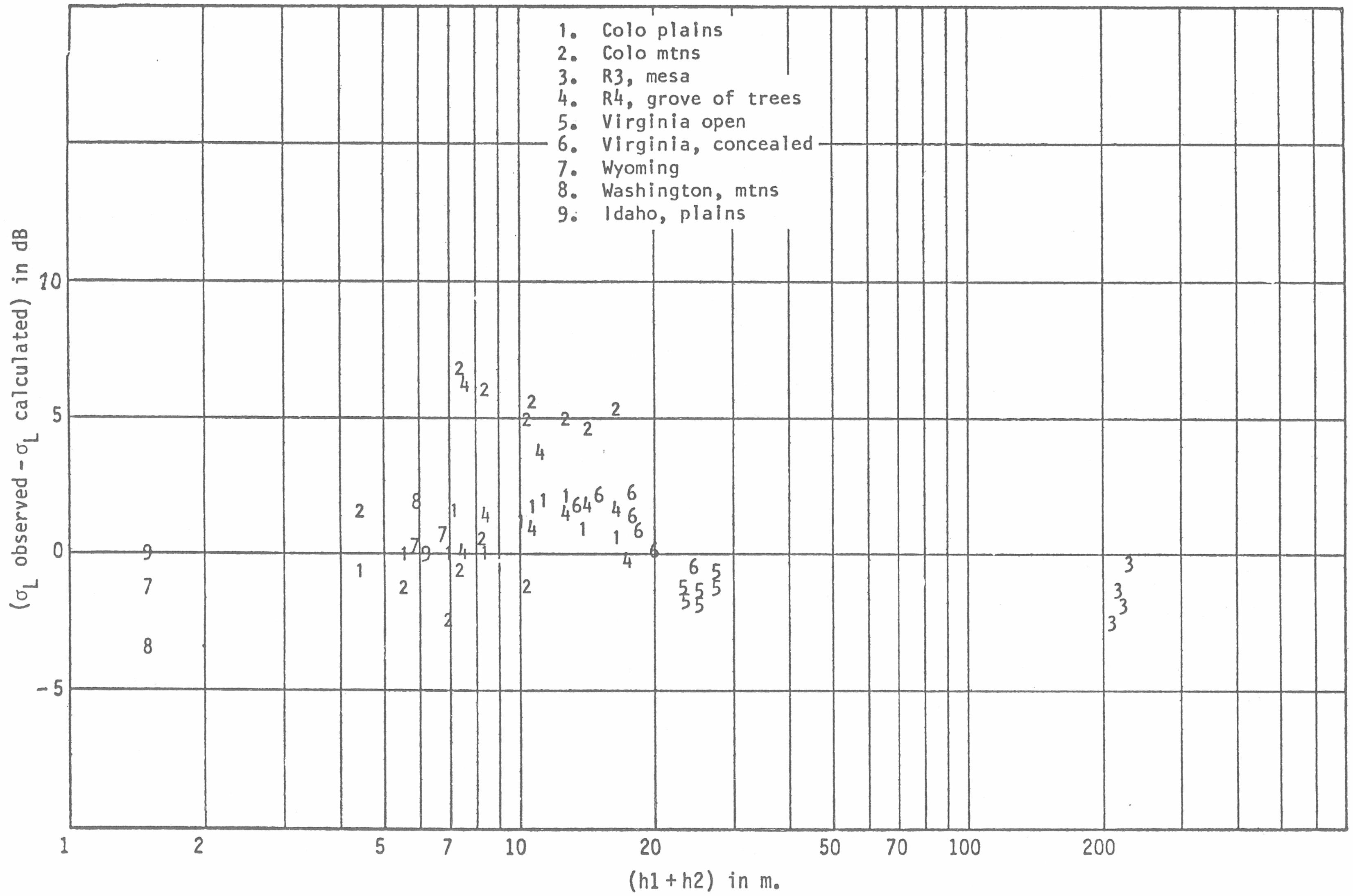

Figure 6. The difference between calculated and measured values of σ_L vs the sum of antenna heights in m.

antenna heights in meters. When the antennas are very low, $(h_1 + h_2) = 1.5$ m, the predicted σ_L is slightly greater than that measured. As the sum of the antenna heights increases to about 15 m the observed values increase until they are somewhat greater than the calculated ones. Excluding the Colorado mountain data this relationship may be expressed as follows:

For $(h_1 + h_2)$ between 1 and 15 m

$$(\sigma_L \text{ observed} - \sigma_L \text{ calculated}) = -1.0 + 2 \log (h_1 + h_2). \qquad (6)$$

For the R3 Colorado data, where the mesa increases the effective height so that $(h_1 + h_2) \simeq 210$ m, the observed variability is some 2.0 dB less than predicted.

As a further check on these conclusions values predicted using the relationship in (5) were compared with a large body of measurements recently analyzed by Longley and Hufford (1975). The measurements were made with very low antennas at frequencies of 172 and 410 MHz over about 130 paths in three quite different types of terrain. These included a flat, heavily forested area in Florida; a hilly, forested area in northern California; and an area in the rugged, arid mountains of Arizona. The path-to-path variability observed in all groups of data agreed well with predicted values. Differences between measured and calculated values of σ_L ranged from -0.5 dB to 1.5 dB, for values of $\Delta h/\lambda$ from 23 to 274. The larger values of σ_L, 1.5 dB more than predicted, were observed in the Arizona mountains where there were large differences in the terrain irregularity among the radio paths. In this area values of Δh ranged from about 50 to more than 900 m, with a median $\Delta h \simeq 180$ m.

4. SUMMARY

The work of many investigators has shown that, in a land mobile or broadcast system, the signal level varies greatly from one path to another for paths of the same length. Such path-to-path variability increases with radio frequency and with terrain irregularity, and is strongly influenced by the presence of buildings and trees near the path terminals.

In urban areas the path-to-path variability depends on the heights, density, and uniformity in size of the buildings. In a highly built-up area, such as Manhattan, the received signal may vary greatly from place to place even at frequencies of 50 to 100 MHz. At higher frequencies the phenomena of channeling along radial streets and improved reception at street intersections are common, so the signal level may change markedly in a very short distance. In suburban areas, with two- and three-storied buildings, the presence and density of trees may have an effect equal to that of the buildings themselves.

In most urban and suburban areas, with rather smooth terrain, it appears reasonable to predict that the standard deviation, σ_L, of path-to-path differences in signal level is about 7 dB at VHF, increasing gradually to 9.5 or 10 dB at 3 GHz. However, much larger values must be assumed for highly built-up urban areas such as Manhattan. Also, greater variability is to be expected when the terrain is quite irregular as, for example, in San Francisco.

The present study of a large amount of data, which was obtained with low antennas in non-urban areas, has led to an expression (5) which defines the standard deviation of location variability in terms of radio frequency and terrain irregularity. Except for data obtained at UHF/SHF in a rugged mountainous area, 90% of all measurements fall within 2 dB of the predicted values. The mountain data show somewhat more variability than predicted, while measurements with very low antennas over level farmlands and signals received at the top of a high mesa show somewhat less than the predicted variability. For the latter set of data the effective receiver height is more than 200 m, and many of the path terminals are within radio line of sight.

Although for most of the measurements in this study the path terminals were placed at open sites, some of them were in cluttered surroundings. At the "open sites" in Virginia the antenna sites were selected with clear foreground areas, while at "concealed sites" they were placed in thickets of trees. Figure 3 shows greater variability at the concealed sites at all frequencies, with differences of 6 to 7 dB between concealed and open sites at the higher frequencies. Similarly at R4, which was located in a grove of trees, the data show greater variability than the R1 data even though the R4 terrain is somewhat smoother. These differences of 2 or 3 dB in σ_L are probably caused by the deciduous trees in the immediate foregound at R4.