Empirical Formula for Propagation Loss in Land Mobile Radio Services

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Abstract—**An empirical formula for propagation loss is derived from Okumura's report in order to put his propagation prediction method to computational use. The propagation loss in an urban area is presented in a simple form: $A + B \log_{10} R$, where A and B are frequency and antenna height functions and R is the distance. The introduced formula is applicable to system designs for UHF and VHF land mobile radio services, with a small formulation error, under the following conditions: frequency range 100–1500 MHz, distance 1–20 km, base station antenna height 30–200 m, and vehicular antenna height 1–10 m.**

I. INTRODUCTION

IN SYSTEM PLANNING for land mobile radio service or service quality evaluation, it is indispensable to determine the propagation characteristics. By using many experimental results and by statistical data processing, many authors have developed nomograms and charts to permit the calculation of expected field strengths from a given transmitter at chosen receiver locations [1]-[7] and made it clear that the propagation loss shows logarithmic behavior to the distance. Of all the studies, Okumura's report [1] is very practical, because it carefully arranges field strength and service area. Not only is the report used as comparison data with other authors' reports [8]-[10], but also the propagation prediction methods in the report have become standard for planning in today's land mobile systems in Japan [11], [12].

In Okumura's prediction method, prediction curves for a basic median field strength were given with these parameters: base station effective antenna height h_b frequency f_c, and vehicular station antenna height h_m. Fig. 1 shows one of these curves. When making a system plan using this method, therefore, it is necessary to select the curves according to f_c, h_b, and h_m. It is more cumbersome to use these curves, represented by 1 kW effective radiated power (ERP) per dipole, since it is necessary to convert the value to the transmitter's power. Under these circumstances, even though the method is practical in the actual work stage such as radio zone estimation, it is awkward to use directly in the system planning stage required to fit the parameters best.

In this report, to make computational use of Okumura's prediction methods in system planning, an empirical formula for propagation loss, which corresponds to free space loss often used in UHF fixed radio communication system planning, is derived from the prediction curves. In order to avoid complication, the following points were considered in its formulation.

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1) Propagation loss between isotropic antennas is treated.
2) Quasi-smooth terrain, not irregular, is treated.
3) The urban area propagation loss is presented as the standard formula. For other areas, a correction equation to the standard is prepared.

II. PROPAGATION LOSS AND EMIPRICAL FORMULA

A. Propagation Loss Between Isotropic Antennas

When the effective radiated power of an isotropic antenna is P_t (dBW: EIRP) and the received field strength of an isotropic antenna is E (dBμV/m), the propagation loss L_p (dB) between these isotropic antennas is obtained as follows.

If A_{eff} is the absorption cross section of an isotropic antenna and P_u is the received power density, the received power P_r is given by

$$P_r\ (\text{dBm}) = P_u\ (\text{dBm/m}^2) + 10 \log_{10} (A_{\text{eff}}) \tag{1}$$

where

$$A_{\text{eff}} = \lambda^2/4\pi, \qquad \lambda\text{: wavelength (m).}$$

$$P_u\ (\text{dBm/m}^2) = E\ (\text{dB}\mu\text{V/m}) - 10 \log_{10} (120\pi) - 90.$$

Since the propagation loss is the difference value between the radiated power and the received power, using (1) we obtain

$$\begin{aligned} L_p\ (\text{dB}) &= P_t - P_r \\ &= P_t\ (\text{dBW}) - E\ (\text{dB}\mu\text{V/m}) - 10 \log_{10} (\lambda^2/4\pi) \\ &\quad + 145.8. \end{aligned} \tag{2}$$

B. Okumura's Prediction Curves and Propagation Loss

As Okumura's prediction curves give the received field strength at 1 kW ERP/dipole, it is necessary to transform the unit from ERP/dipole to EIRP. This transformation is accomplished by adding the difference value for power gain between the isotropic antenna and the dipole antenna. Since the absolute power gain of the dipole antenna is 2.2 dB, then

$$P_t\ (\text{dBW EIRP}) = P_t'\ (\text{dBW ERP/dipole}) + 2.2\ (\text{dB}). \tag{3}$$

When P_t' is 1 kW (ERP/dipole), therefore, P_t (dBW EIRP) is 32.2 dB.

Using (2) and (3), the progapation loss L_p (dB) between the isotropic antennas is given by the prediction curves and the following equation:

$$L_p\ (\text{dB}) = 178 - 10 \log_{10} (\lambda^2/4\pi) - E\ (\text{dB}\mu\text{V/m}). \tag{4}$$

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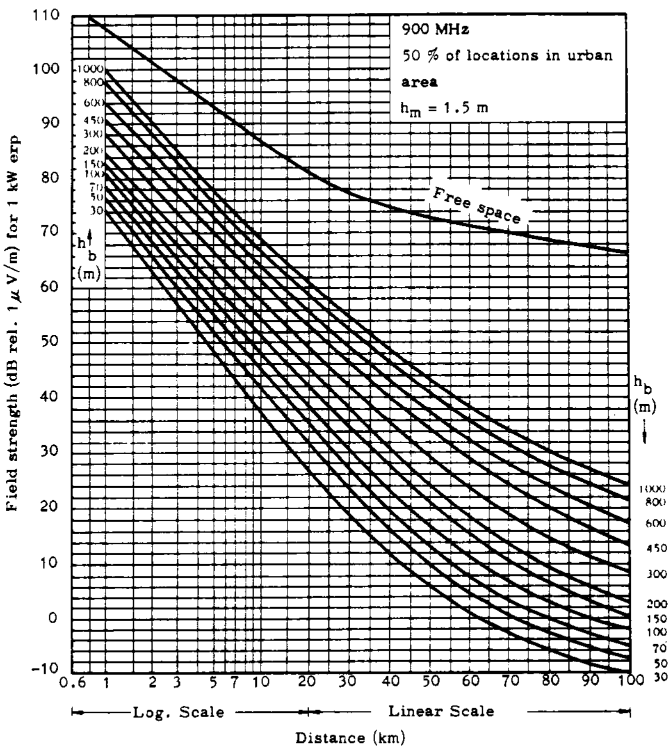

Fig. 1. Basic median field strength curve in the 900-MHz band.

TABLE I
VALUE OF *A*

h_b (m)	f_c (MHz) 150	450	900	1500
30	105.5	117.0	124.5	132.0
50	103.0	114.0	122.5	129.5
70	101.0	112.0	120.5	127.0
100	98.5	110.0	118.0	125.0
150	96.5	108.0	116.5	123.0
200	94.5	106.0	114.5	121.0

TABLE II
VALUE OF *B*

h_b (m)	f_c (MHz) 150	450	900	1500
30	35.0	35.0	35.7	35.7
50	33.4	34.1	33.8	34.1
70	33.2	32.5	32.2	33.4
100	31.5	31.3	32.5	32.2
150	30.4	30.4	31.1	30.9
200	29.9	29.4	29.9	29.9

C. Empirical Formula for Propagation Loss

As a standard formula, the propagation loss in an urban area over quasi-smooth terrain is introduced by using the basic median field strength curves. By the examination of these curves, for example from Fig. 1, the characteristic is found wherein the field strength E (dB μV/M) can be prescribed as a function of distance R(km) as

$$E\,(\mathrm{dB}\mu\mathrm{V/m}) = \gamma + \beta \log_{10} R \tag{5}$$

where γ and β are constants determined by h_b (m) and f_c (MHz). Therefore, the standard of propagation loss can also be prescribed by substituting (5) into (4),

$$L_p\,(\mathrm{dB}) = A + B \log_{10} R \tag{6}$$

$$A = 178 - 10 \log_{10} (\lambda^2/4\pi) - \gamma + a(h_m) \tag{7}$$

$$B = -\beta \tag{8}$$

where $a(h_m)$ is the correction factor for the vehicular station antenna height h_m (m). In the basic curves, h_m is 1.5 m, and correction curves for the other heights are provided. Therefore, it is convenient to take $a = 0$ dB for $h_m = 1.5$ m and to introduce the correction equation for the other heights.

1) Introduction of the Empirical Formula: Using (5) and (6), A is given by the value of the field strength E (dB μV/m) at $R = 1$ (km), and B is determined by the slope of the field strength curve. Tables I and II show values for A and B taken from the basic median field strength curves. Table I contains two regulations: 1) at each frequency f_c (MHz), A decreases two by two against logarithmically increasing h_b (m), and 2) when f_c becomes n times as large for fixed h_b, A increases in proportion to log n. Considering these points, A can be shown as in Fig. 2. From this figure, A can be presented by

$$A = \alpha - 13.82 \log_{10} h_b - a(h_m)$$
$$\alpha = 69.55 + 26.16 \log_{10} f_c. \tag{9}$$

Table II also shows two regulations: 1) B is almost independent of f_c, and 2) decreases constantly against logarithmically increasing h_b. B can also be shown as in Fig. 3. Connecting the mean value at each h_b, it becomes an almost straight line, as shown in the figure. When this line is represented by

$$B = 44.9 - 6.55 \log_{10} h_b, \tag{10}$$

the maximum fluctuation width is about ±0.5, and it becomes the linear approximation error about B. Substituting (9) and (10) into (6), the standard formula for propagation loss is obtained by

$$L_p\,(\mathrm{dB}) = 69.55 + 26.16 \log_{10} f_c - 13.82 \log_{10} h_b - a(h_m) + (44.9 - 6.55 \log_{10} h_b) \log_{10} R \tag{11}$$

where

f_c: 150-1500 MHz,

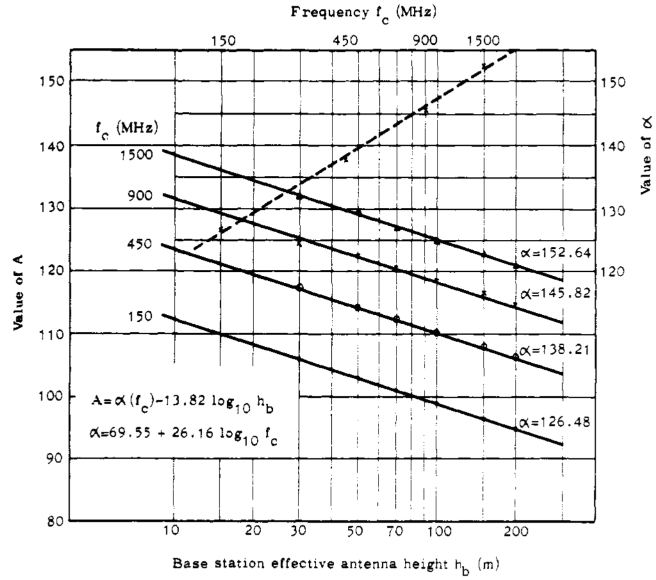

Fig. 2. Introduction of factor A.

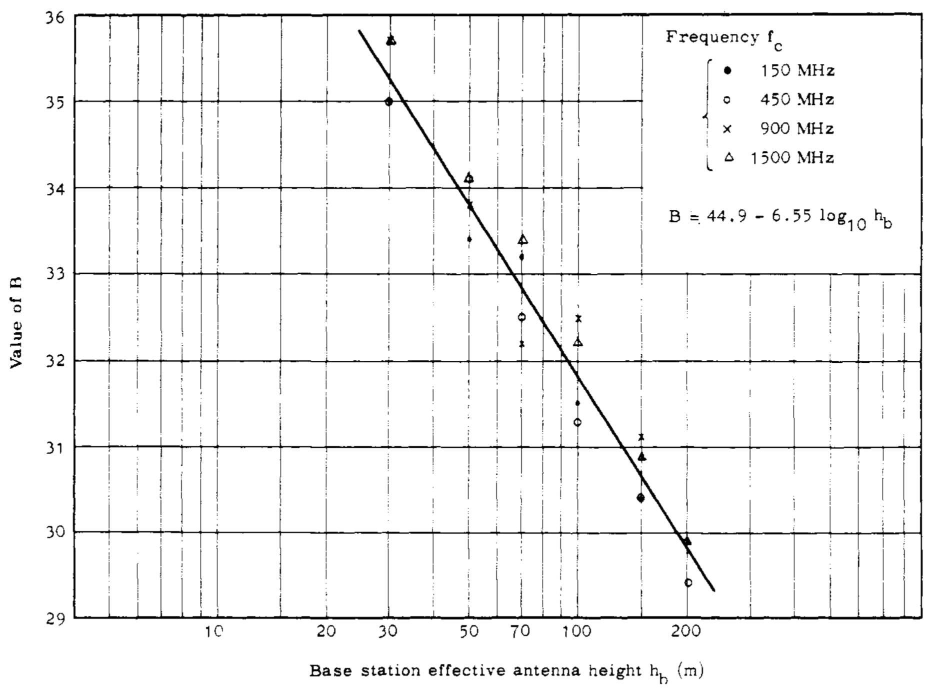

Fig. 3. Introduction of factor B.

h_b: 30-200 m,
R: 1-20 km,

and $a(h_m)$ is the correction factor for h_m, and $a = 0$ dB for $h_m = 1.5$ m.

2) Determination of Correction Factor $a(h_m)$: In the prediction method, correciton curves for h_m are given by Fig. 4. Namely, the correction is presented as relative height gain to a standard of $h_m = 3$ m in an urban area over quasi-smooth terrain.

1) Correction factors in a medium-small city: In the correction curves for a medium-small city, if the horizontal axis is translated into linear scale, it can be expected that these curves will be shown by straight lines.

From this viewpoint correction curves are rewritten as shown by the plotted points in Fig. 5. Since the empirical formula should be as simple and accurate as possible for usability, the approximate lines in this figure are used.

As the propagation loss L_p of (11) has taken $h_m = 1.5$ m into standard, the correction factor $a(h_m)$ satisfies the condition that $a = 0$ dB for $h_m = 1.5$ m. If it is assumed that the correction curves which satisfy this condition can be presented by

$$a_{1.5} = \xi(f_c) \cdot h_m - \eta(f_c), \tag{12}$$

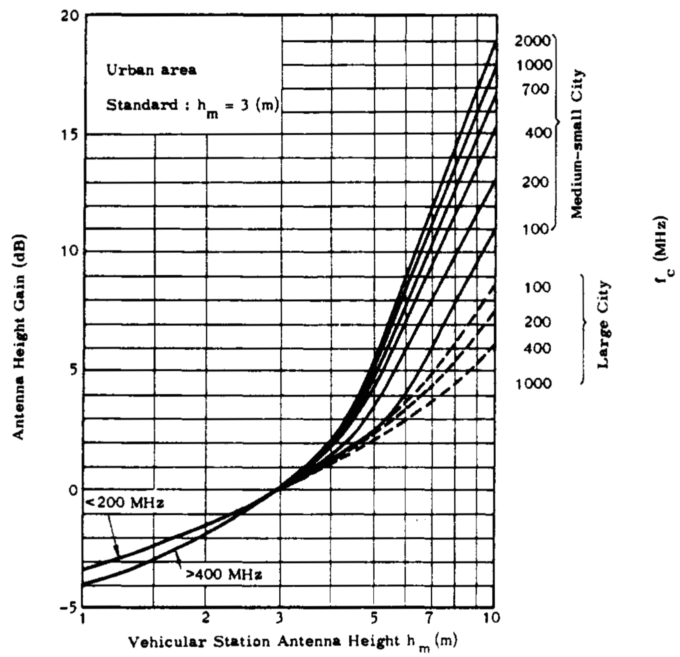

Fig. 4. Prediction curves for vehicular antenna height gain in an urban area.

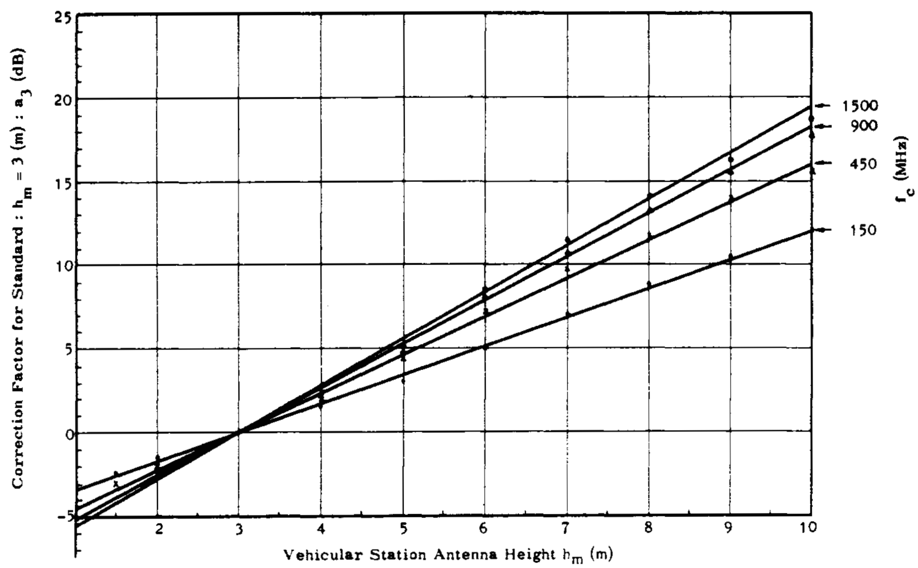

Fig. 5. Correction factors in a medium-small city (1).

the coefficients $\xi(f_c)$ and $\eta(f_c)$ are given as follows by using Fig. 6:

$$\xi(f_c) = 1.1 \cdot \log_{10}(f_c) - 0.7$$

$$\eta(f_c) = 1.56 \cdot \log_{10}(f_c) - 0.8. \tag{13}$$

Substituting (13) into (12), the correction factor $a(h_m)$ is obtained for vehicular antenna heights in a medium-small city:

$$a(h_m) = (1.1 \cdot \log_{10} f_c - 0.7) \cdot h_m - (1.56 \log_{10} f_c - 0.8) \tag{14}$$

where

h_m: 1-10 m,

f_c: 150-1500 MHz.

The error to the linear approximation in Fig. 5 is in proportion to the frequency, and is about 1.0 dB when f_c = 1500 MHz. As the correction curves in Fig. 4 have irregular characteristics in h_m = 4~5 m, the approximation error of this part in Fig. 5 becomes larger than the other part. Therefore, it can be estimated that the maximum error will arise in f_c = 1500 MHz and h_m = 4~5 m.

2) Correction factors in a large city: The correction curves are given by dashed lines in Fig. 4. These curves can be

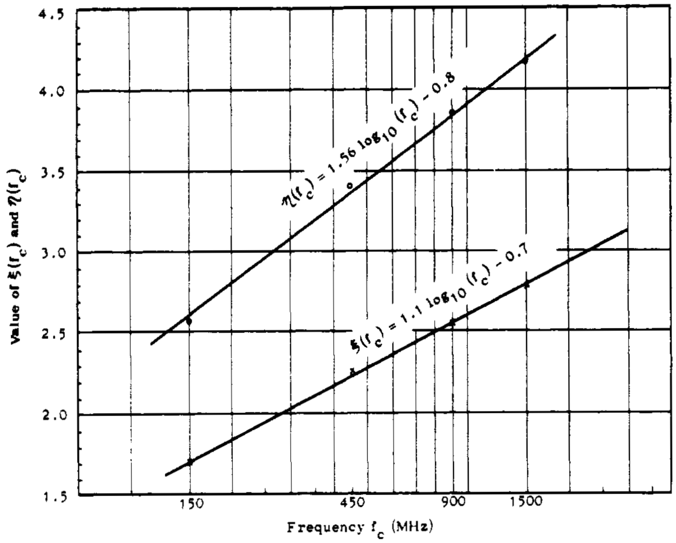

Fig. 6. Determination of coefficients $\xi(f_c)$ and $\eta(f_c)$.

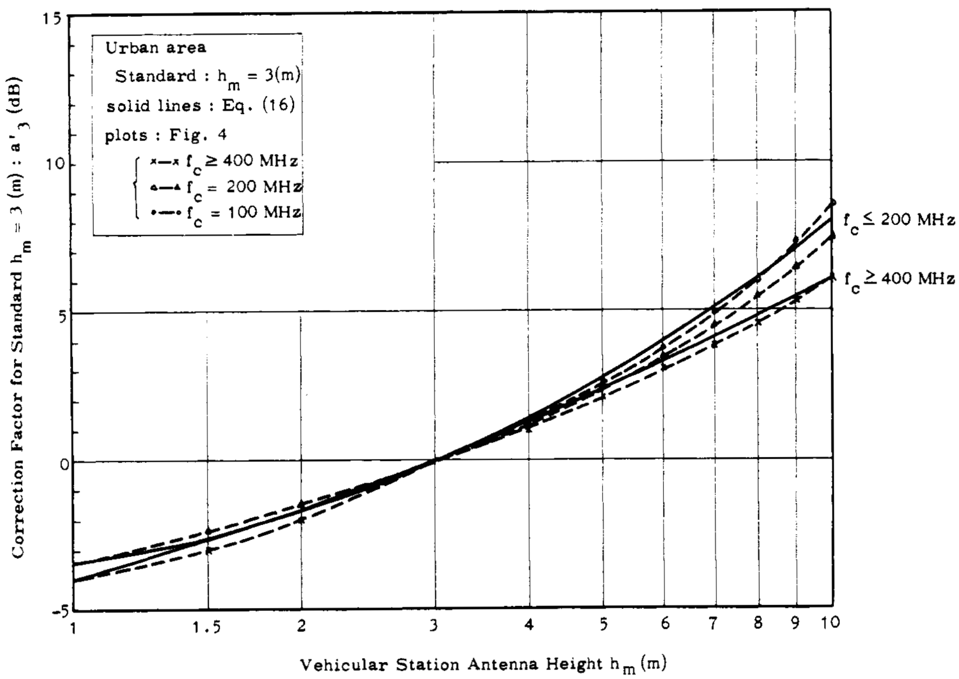

Fig. 7. Correction factors in a large city (1).

considered as parabolas. The following equations are approximate expressions of these curves:

$$a_3' = 8.29 \cdot (\log_{10} 1.54\, h_m)^2 - 3.69 \text{ (dB)}, \quad f_c \leqslant 200 \text{ MHz}$$

$$= 3.2 \cdot (\log_{10} 11.75\, h_m)^2 - 7.63 \text{ (dB)}, \quad f_c \geqslant 400 \text{ MHz}. \tag{15}$$

Although the curves for $f_c = 200$ MHz and 100 MHz are presented by one equation in (16), the error of this expression is only about 0.5 dB, as shown in Fig. 7. It is also necessary to transform (15) to an equation which satisfies the condition that $a = 0$ dB for $h_m = 1.5$ m, then the correction factor $a(h_m)$ for vehicular antenna heights becomes

$$a(h_m) = 8.29 \cdot (\log_{10} 1.54\, h_m)^2 - 1.10 \text{ (dB)}, \quad f_c \leqslant 200 \text{ MHz}$$

$$= 3.2 \cdot (\log_{10} 11.75\, h_m)^2 - 4.97 \text{ (dB)}, \quad f_c \geqslant 400 \text{ MHz}. \tag{16}$$

As shown in Fig. 8, values given by (16) and values given by Fig. 4 agree well in $f_c \geqslant 400$ MHz. Their maximum difference

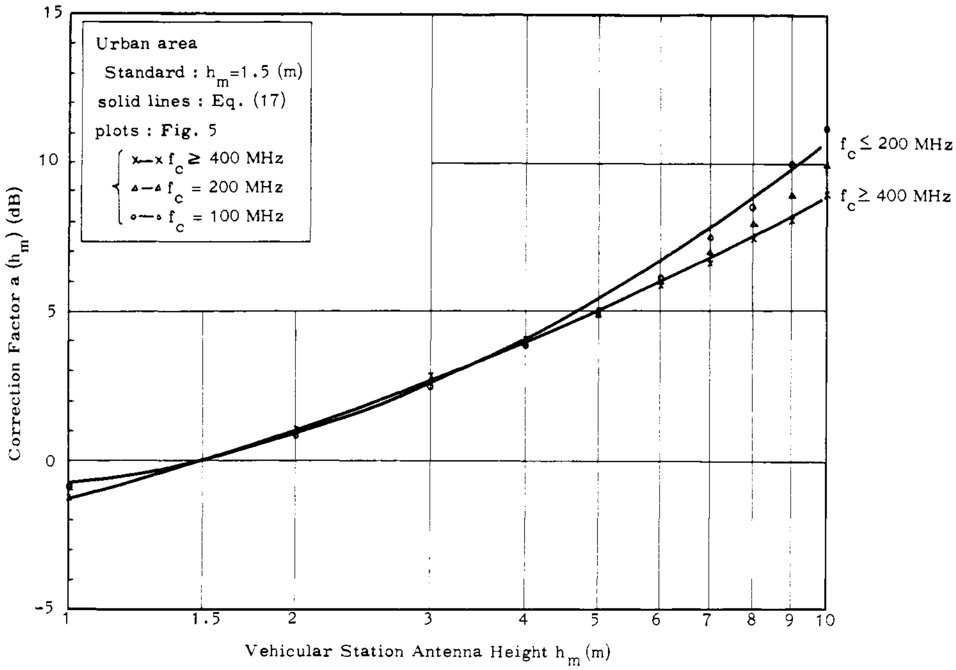

Fig. 8. Correction factors in a large city (2).

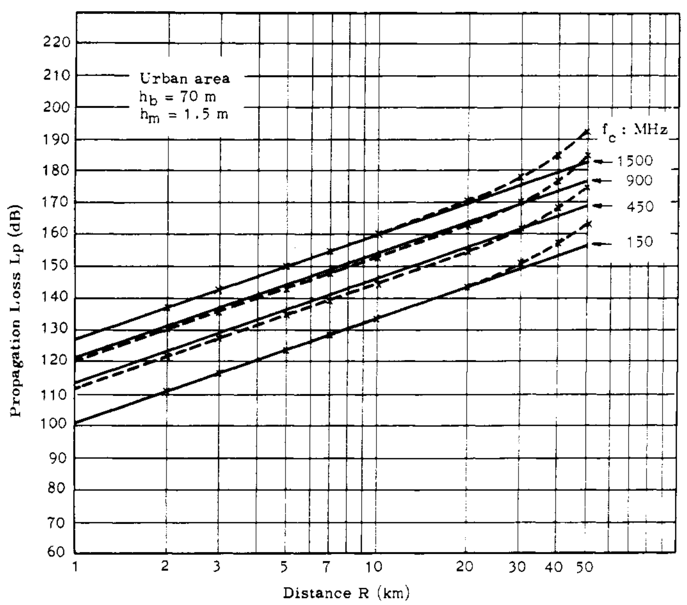

Fig. 9. Propagation loss in an urban area (1).

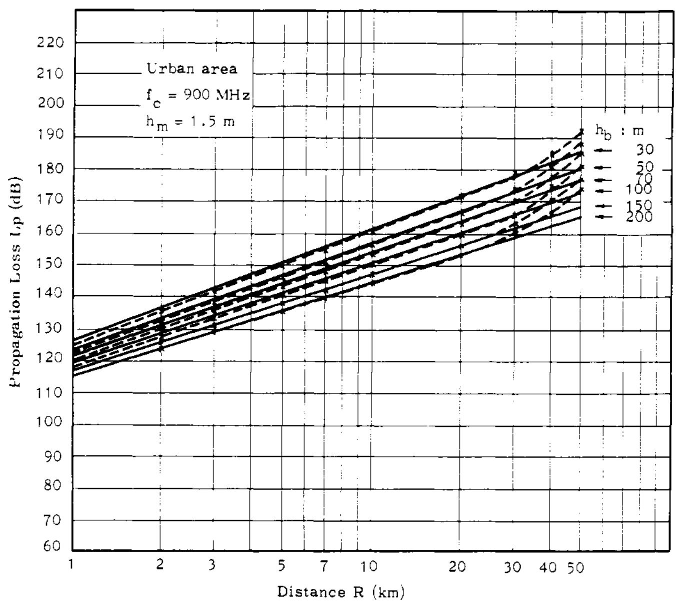

Fig. 10. Propagation loss in an urban area (2).

occurs in $f_c \leqslant 200$ MHz and $h_m \geqslant 5$ m, and is about 1 dB. Therefore, (16) is used as the correction factor $a(h_m)$ for vehicular antenna heights in a large city, where the building height average is more than 15 m.

III. ESTIMATION OF THE APPROXIMATION ERROR

In this section we investigate how accurately the empirical formulas express the prediction curves. Figs. 9 and 10 show the propagation loss in an urban area with parameters f_c and h_b, respectively. The solid lines are the values given by the formula and the dashed lines are the values given by the prediction curves. Fig. 9 shows that the error at both ends of the frequency range is very small, and the maximum error, which occurs in the middle frequency range, is only about 1 dB. Furthermore, it shows that the error is independent of the distance (1~20 km) and is constant for each frequency. This is the reason that only term A in (7) depends on frequency. Therefore, the error in Fig. 9 mainly indicates the approximation error in (19) which gives term A. Fig. 10 shows that the error fluctuates about h_b, and its maximum value is about 1 dB. This is due to the

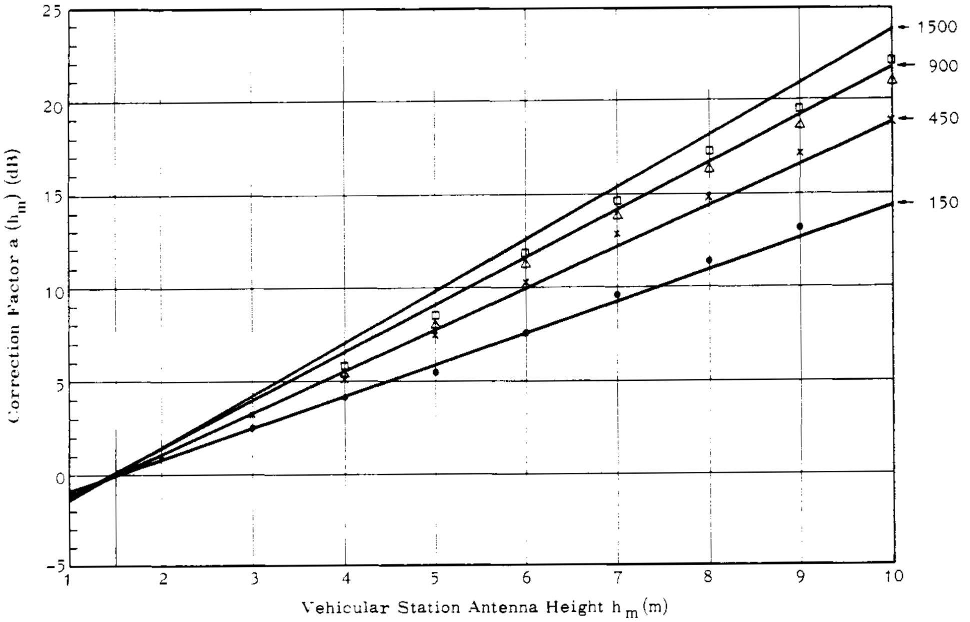

Fig. 11. Correction factors in a medium-small city (2).

linear approximation in Fig. 3. From Fig. 10, it can be said that (10), which gives term B, is a fairly accurate equation. Fig. 11 shows the correction factor $a(h_m)$ for vehicular heights in a medium-small city. The solid lines are values calculated by using (14) and the plotted points are the correction values given by Fig. 4. As mentioned in Section II-C, the linear approximation error is porportional to the frequency and the antenna height. The maximum error arises in f_c = 1500 MHz and h_m = 4~5 m, and its value is about 1.5 dB. Below f_c = 900 MHz, the error is only 0.5 dB (except when h_m = 4~5 m), or 1 dB (in h_m = 4~5 m). Considering equation simplicity, therefore, it can be said that (14) is a simple and well-approximated equation. The correction factor $a(h_m)$ in a large city is mentioned in the previous section. When using (16), there is little error in $f_c \geqslant 400$ MHz, and the maximum error is about 1 dB in $f_c \leqslant 200$ MHz and $h_m \geqslant 5$ m. In practice, there are few cases in which the vehicular antenna height is above 5 m. Therefore, it can be considered that (16) is very practicable.

IV. CORRECTIONS FOR SUBURBAN AND OPEN AREAS

According to Okumura's prediction method, the suburban correction factor K_r (dB), which is the difference between the median field strength in the urban area and that in the suburban area, is given by the dashed line in Fig. 12. In this figure the solid line is the approximated curve given by

$$K_r\,(\mathrm{dB}) = 2\,\{\log_{10}(f_c/28)\}^2 + 5.4, \qquad (17)$$

$$f_c\text{: MHz.}$$

As Fig. 12 shows that (17) gives a good approximated value, the propagation loss in suburban area L_{ps} (dB) will be calculated by

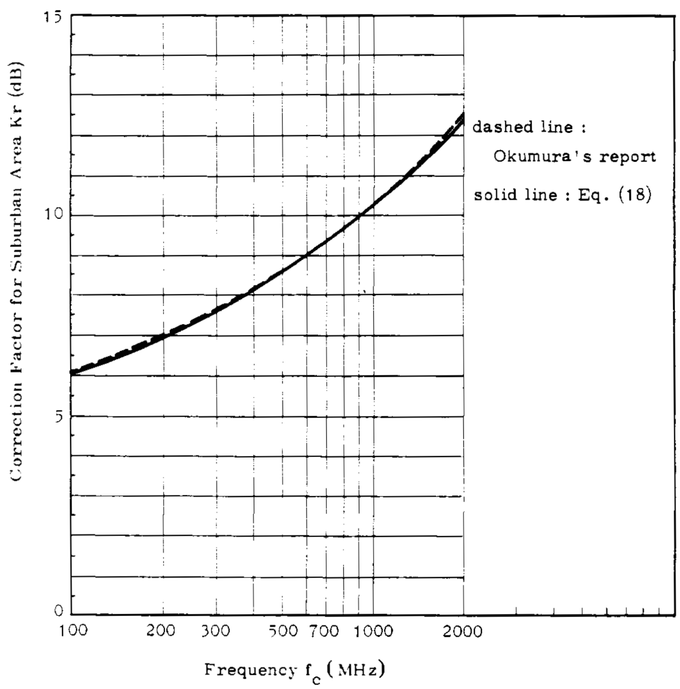

Fig. 12. Correction factor for suburban area.

$$L_{ps}\,(\mathrm{dB}) = L_p\,\{\mathrm{eq}\,(11)\} - K_r. \qquad (18)$$

On the other hand, the open area correction factor Q_r (dB) is given by the dashed line in Fig. 13. In this figure the solid line is the approximated curve given by

$$Q_r\,(\mathrm{dB}) = 4.78\,(\log_{10} f_c)^2 - 18.33\,\log_{10} f_c + 40.94,$$

$$f_c\text{: MHz.} \qquad (19)$$

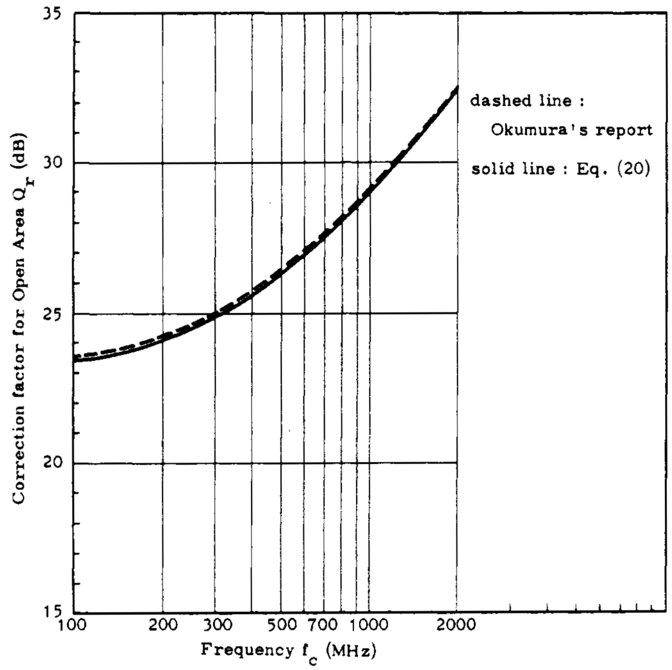

Fig. 13. Correction factor for open area.

TABLE III
EXPERIMENTAL FORMULA FOR PROPAGATION LOSS

Urban Area	$L_p = 69.55 + 26.16 \cdot \log_{10} f_c - 13.82 \cdot \log_{10} h_b - a(h_m)^{*}$ $+ (44.9 - 6.55 \cdot \log_{10} h_b) \cdot \log_{10} R$ (dB) * correction factor for vehicular station antenna height medium-small city $a(h_m) = (1.1 \cdot \log_{10} f_c - 0.7) \cdot h_m - (1.56 \cdot \log_{10} f_c - 0.8)$ large city $a(h_m) = 8.29 \cdot (\log_{10} 1.54\, h_m)^2 - 1.1$; $f_c \le 200$ MHz $= 3.2 \cdot (\log_{10} 11.75\, h_m)^2 - 4.97$; $f_c \ge 400$ MHz
Suburban Area	$L_{ps} = Lp\,\{\text{Urban area}\} - 2\,\{\log_{10}(f_c/28)\}^2 - 5.4$ (dB)
Open Area	$L_{po} = Lp\{\text{Urban area}\} - 4.78 \cdot (\log_{10} f_c)^2 + 18.33 \cdot \log_{10} f_c - 40.94$ (dB)

where

f_c : frequency (MHz) ---------- 150 ~ 1500 (MHz)

h_b : base station effective antenna height (m) ------ 30 ~ 200 (m)

h_m : vehicular station antenna height (m) --------- 1 ~ 10 (m)

R : distance (km) ------------- 1 ~ 20 (km)

Fig. 13 shows that (19) gives a good approximated value, and therefore, the propagation loss in open area L_{po} (dB) will be calculated by

$$L_{po}\,(\text{dB}) = L_p\,\{\text{eq}\,(11)\} - Q_r. \tag{20}$$

In (17) and (19), if the coefficients are taken down to three places of decimals, the error becomes slightly smaller, but the equation becomes more complicated. If the coefficients are taken down to one decimal place, the error becomes very large. Therefore, coefficients are fixed down to two decimal places.

V. SUMMARY

In order to put Okumura's prediction methods to computational use in system planning, prediction curves are formularized as propagation loss. These results are arranged in Table III. Since the propagation loss can be treated as a formula, it becomes possible to put the formula into various calculations about system planning. However, since the formula can only be applied in restricted ranges, it is necessary to take notice of its applicable ranges and units.

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