3.3 Norton Method

As mentioned before, this is a physical model for MF sky-wave propagation and separates the transmission from transmitter to receiver into parts, analogous to a wavehop treatment. The formula for estimating the basic propagation loss in dB for 1 kW of effective radiated power, assuming a short vertical dipole antenna above a perfectly conducting plane earth and corresponding to a field strength of 300 μV/m at 1 km, is given by Rice et al. (1965) as:

$$L_{pb} = 139.37 - L_{rt} + G_t - G_{pt}(\hat{r}_1) + 20 \log_{10} f_M - E_{1(kW)} \quad \text{dB}$$

where

L_{pb} is basic propagation loss, dB,

L_{rt} is the ratio in dB of the transmitting antenna resistance to the radiation resistance of this antenna in free space (3.01 dB),

G_t is the free-space gain of a short vertical dipole transmitting antenna (1.76 dB),

$G_{pt}(\hat{r}_1)$ is the principal polarization directive gain of a short vertical dipole over a half-wave dipole (also 1.76 dB in free space),

r is the resistance of the antenna,

$\hat{r}_1$ is the direction of the most important propagation path from the transmitter to the receiver,

and

f_M is the operating frequency in MHz.

In Norton's method, for hops with one ionospheric reflection,

$$L_{pb} = L_{pbf} + A_t(\psi) + A_r(\psi) + [P + A(\phi,0.5)] - C_1 \quad \text{dB}$$

where $A(\psi)$ represents the antenna radiation loss factors for transmitter and receiver for the angle of elevation, ψ (Norton, 1959, Figures 23 and 24), P is the polarization loss, $A(\phi,0.5)$ is the absorption loss exceeded 50% of the time, C_1 is the additional gain due to the focusing of the energy on reflection of the curved surface of the ionosphere for one hop, and

$$L_{pbf} = 32.45 + 20 \log f + 20 \log d \quad \text{dB}$$

where

L_{pbf} is the basic free-space transmission loss,

f is in MHz, and d = distance in km.

The expression $[P + A(\phi,0.5)]$ has been evaluated empirically from measurements at low frequencies between stations in England, Scandinavia, and Germany, and for standard broadcast frequencies in the United States, and results in an increasing sky-wave field strength with increasing frequencies.

The following formula can be used to calculate the basic propagation loss involving more than one ionospheric reflection, m, and a ray path of length, d:

$$L_{pb} = L_{pbf} + A_t(\psi) + A_r(\psi) + (m-1)A_g(\psi) - C_m(d,0.5) + m[P+A(\phi,0.5)] \text{ dB}$$

where the factor $(m-1)A_g(\psi)$ allows for the ground reflection loss.

For a more detailed discussion of this method, refer to Norton (1959), and Barghausen (1966).

3.4 EBU method

The EBU initiated a measurement campaign in 1952 in response to the IFRB's question concerning the adequacy of the Cairo Curves. Recordings were made of MF field strengths from: Allouis, France, (164 kHz); Rome, Italy, (845 kHz); Horby, Sweden, (1178 kHz); and Monte Carlo, Monaco, (1466 kHz) over approximately 50 transmission paths from October 1952 until December 1960 (Ebert, 1962). From measurements made throughout the night, they were able to establish an empirical formula for the diurnal variation of the nighttime sky-wave field strength relative to local midnight at the path midpoint which was set as the reference hour. Empirical relationships also were derived for including the effects of solar activity, the influence of the magnetic field, the antenna gain as a function of the propagation distance, and a frequency dependence. The final form of the EBU method (CCIR, 1978) for determining the annual median field strength, at the reference time, for a small loop receiving antenna is:

$$F = F_o + P + \Delta_A \quad (\mathrm{dB}\mu\mathrm{V/m})$$

where F_o is the annual median field strength for the reference hour and a specified ground conductivity, in terms of an effective monopole radiated power (e.m.r.p.) of 1 kW or a cymomotive force (c.m.f.) of 300 V; P is the correction for power actually fed to the antenna; and Δ_A is the correction accounting for the gain of the transmitting antenna in the direction of propagation and covers both the horizontal and vertical radiation pattern.

The value of F_o is given by:

$$F_o = 80.2 - 10 \log d - 0.0018 f^{0.26} d + \Delta_I - 0.02R \quad \mathrm{dB}(\mu\mathrm{V/m})$$

where

d is the distance measured along the great circle path (km);

f is the frequency (kHz);

Δ_I is the correction to take account of magnetic dip I;

R is the 12-month smoothed Zurich sunspot number.

This method is considered valid under the following conditions:

1) reflection assumed to be from the E region at a virtual height of 100 km above a spherical earth;

2) distances, d, are between 300 and 3500 km.

As mentioned before, the Federal Republic of Germany derived a formula for calculating F_o for distances under 300 km, and it is included as part of the EBU method. This formula is:

$$F_o = 60.6 - \left[10 \log \; 1 + 1.0175 \left(\frac{d}{200}\right)^2\right] - 0.54f^{0.26} \quad \mathrm{dB}(\mu\mathrm{V/m}).$$

Note that both of these empirical formulas indicate decreasing sky-wave field strengths with increasing frequency.

3.5 Barghausen Method

This prediction technique (Barghausen, 1966) is similar to that of Norton (1959) except that in addition to Norton's semi-empirical formula for polarization and absorption losses, Barghausen included the results of measurements of reflection coefficients as a function of frequency for vertical-incidence soundings in South-West Africa (Elling, 1961). These observations showed a greater frequency dependence than those of Norton and also indicated that the sky-wave field strength may increase with frequency. Median sky-wave transmission curves vs. distance were calculated for only one-hop distances and for E-region reflection at 110 km.

3.6 Revision of EBU Method for the African LF/MF Broadcasting Conference

The CCIR IWP 6/4 developed a set of basic curves for determining the annual median field strength, F_o, for this region. These were based on the EBU formula and extrapolated to 6000 km. Further corrections were made to the EBU curves for distances below 750 km. Also, an antenna correction factor for distances up to 300 km was included.

3.7 Olver Method

This method (Olver et al., 1971) uses a wavehop approach and estimates losses due to all the ionospheric and terrestrial factors that affect a radio wave as it propagates from a transmitter to a receiver. The method requires a model of the electron density profile for a ray trace procedure. As ray tracing is very time consuming and expensive, this method is not considered to be useful for practical applications.

3.8 Knight Method

The Olver et al. method was adopted for manual applications by providing graphs and curves for determining the number of hops, ground loss at transmitter and receiver, polarization coupling loss at transmitter and receiver, ionospheric loss, intermediate reflection loss, and transmitting antenna correction for two or more propagation modes (Knight, 1973). The EBU (CCIR, 1970-1974a, unpublished paper) tested this method for 152 paths. For paths less than 3000 km, 84% of the differences between predicted and measured field strengths are less than 10 dB, and for longer paths, 66% of the differences are in this range. Again, the wavehop method tended to be laborious and time consuming, particularly for long-distance paths. The main source of errors was found to be insufficient knowledge about the variation of ionospheric absorption with latitude and solar activity, and uncertainties about ground conductivity.

3.9 The CCIR Geneva 1974 Methods

3.9.1 U.S.S.R method

Using measured annual median field strengths at local midnight at the path midpoint for 87 paths of different lengths at different latitudes and 14 frequencies between 200 and 1500 kHz, the U.S.S.R. derived an empirical formula which gives the dependence of field strength on distance and frequency as a function of geomagnetic latitude as follows (CCIR, 1970-74b, unpublished paper).

$$F_o = 105.3 - 20 \log d - .0019\, f^{0.15} d$$
$$- 0.0024\, f^{0.4} d\, (\tan^2 \phi - \tan^2 37^o) \quad dB(\mu V/m)$$

where

F_o is the annual median of half-hourly median field strengths (dB above 1 μV/m) at the reference time of six hours after ground sunset at the path midpoint or for paths >2000 km, 750 km from the terminal where the sun sets last;

d is ground distance (km);

f is frequency (kHz);

ϕ is geomagnetic (dipole) latitude at path midpoint.

This formula is considered valid for values of ϕ between 37° and 60°; note that it includes two frequency-dependence terms.

3.9.2 U.K. method

The U.K., recognizing that Knight's method was not sufficiently simple, proposed a semiempirical method based on physical principles, but containing coefficients derived from measured field strengths (CCIR, 1970-74c, unpublished paper). The formula is as follows:

$$F_o = 105 - 20 \log p - 10^{-3} k_R p - L_p \quad \text{dB}(\mu\text{V/m})$$

where

F_o is as defined in Section 3.9.1;

p is slant-propagation distance;

k is a basic loss factor = $3.3[1+2 \sin^4(1.34\phi)]$, where ϕ is the geomagnetic (dipole) latitude at path midpoint(s);

$k_R = k + 10^{-2} bR$, where b = solar activity factor (see Appendix A, Section 2.6) and R is the 12-month smoothed Zurich sunspot number; and

L_p is polarization loss (see Appendix A, Section 2.4).

This method applies to the MF broadcasting bands for paths up to 12000 km worldwide (except auroral zones), but shows no frequency dependence. It includes corrections for terminals located near the sea (sea gain), geomagnetic (dipole) latitude, polarization coupling loss, solar activity, and hourly variation.

3.9.3 Modified U.S.S.R.

The CCIR IWP 6/4, in preparation for the XIIIth Plenary Assembly, Geneva, 1974, considered the above prediction methods and determined that the U.S.S.R. method could be extended to distances less than 300 km and to other regions by making the following modifications:

a. replace ground distance d by slant propagation distance p,
b. add U.K. correction for sea-gain where applicable,
c. apply U.K. correction for polarization-coupling loss in tropical regions,
d. divide paths longer than 3000 km into two equal sections, calculate loss factors separately for each section, and average the two - same as the U.K. method.

This sky-wave field strength prediction method recommended for provisional use by CCIR, Geneva, 1974, but subsequently replaced by CCIR 1978, is presented in Appendix A.

3.10 Wang 1977 Method

This was proposed as an alternative method for the United States of America (Wang, 1977). The basic formula is:

$$F_o = 102.8 - 20 \log p - L_I - L_R \quad dB(\mu V/m)$$

where

F_o is the annual median field strengths (dB above 1 μV/m) for two hours after sunset at path midpoint,

p is slant propagation distance in km,

L_I is ionospheric loss (including other miscellaneous losses),

L_R is ionospheric loss due to solar activity,

and

$$L_R = \left[(\phi_M - 42) - 0.3 \left(\frac{f-500}{100}\right)\right] + 10 \log \left(\frac{p}{1000}\right) 0.01R ,$$

$$L_I = bp \times 10^{-3} ; \qquad b = (\phi_M - 40) - 0.3 \left(\frac{f-500}{100}\right) ,$$

where f is frequency in kHz, R is the 12-month smoothed Zurich sunspot number, b is a solar activity dependence factor, and ϕ_M is the geomagnetic (dipole) latitude at the path midpoint.

Since the North American measurements were made at two hours after sunset, the equivalent formula for F_o for the reference hour of local midnight at the path midpoint is:

$$F = 105.3 - 20 \log - bp \times 10^{-3} - b - 2 + 10 \log \left(\frac{P}{1000}\right) R \quad dB(\mu V/m) .$$

The upper limit for b is 12 units, and the lower limit is such that neither L_I nor L_R can be negative.

3.11 The CCIR Kyoto 1978 Method

The current recommended CCIR (Recommendation 435-3) sky-wave field strength prediction method is:

$$F_o = 106.6 - 2 \sin \phi - 20 \log p - 10^{-3} k_R p - L_p + G_s \quad dB(\mu V/m)$$

where

F_o is the annual median field strength (dB above μV/m) at the reference time defined in Appendix B, Section 2.1;

ϕ is a geomagnetic (dipole) latitude parameter;

p is slant propagation distance in km;

k is a basic loss factor;

K_R is a loss factor dependent on R, the 12-month smoothed Zurich sunspot number;

L_p is the excess polarization-coupling loss (dB); and

G_s is the sea gain correction (dB).

The loss factor, $k_R = k + 10^{-2}bR$, where $k = 3.2 + 0.19f^{0.4} \tan^2(\phi + 3)$, f is frequency in kHz, and b, a solar activity dependence factor, is 4 for North American paths, 1 for Europe and Australia, and 0 elsewhere.

The complete prediction method is presented in Appendix B. Section 6, Appendix B contains a caution on the accuracy of the method when applied to the United States of America.

3.12 The Wang 1979 Method

This is a proposed modification of the recommended CCIR 1978 prediction method given in Section 3.11. Wang suggested that the basic loss factor, k, be changed to

$$k = (0.0667 \ |\phi| + 0.2) + 3 \tan^2(\phi + 3). \qquad (0 \leq \phi \leq 60°)$$

This improves the accuracy in high- and low-latitude areas without affecting the prediction in average-latitude areas and assumes f = 1000 kHz, i.e., no frequency dependence is needed. The other change relates to the solar activity dependence factor, b. The CCIR recommends setting b = 4 for North America and b = 0 for South America. Wang proposed the following formula:

$$b = 0.4 \ |\phi| - 16 \qquad \text{for } |\phi| \geq 45^o$$
$$b = 0.0 \qquad \text{for } |\phi| < 45^o \quad .$$

4. COMPARISON OF PREDICTION METHODS

4.1 General Comparison

A study has been conducted of some of the above sky-wave field strength prediction methods to assess the compatibility and/or variability of the different methods. For this comparison, only the very long paths (>4700 km) for which measured field strengths are available were considered. A total of 46 paths met this criteria, and 36 of these paths were selected for this comparison. In selecting the 36 paths, preference was given to those having at least one terminal in either North, Central, or South America. Twenty-two of the paths are in this category, and the remaining 14 paths are representative of regions other than Region 2. Measurements for 18 of these paths were used