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Radio System Parameters

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1. INTRODUCTION

This set of lectures introduces a number of topics which should be useful for subsequent lectures. Antenna gain, radiated power and transmission loss are commonly used terms when describing systems, but the precision given by the internationally agreed definitions of these terms is necessary if ambiguity is to be avoided. System performance and design is governed not only by the transmission loss, under some stated conditions, but also by the variability of the signal in time or space, which can then be described in statistical terms, and by the level of background signals - either broadband noise or interfering transmissions. The statistical probability distributions in common use are introduced, and the benefits of diversity reception are outlined. The types of radio noise are described together with the ways in which noise power from a number of sources may be combined for use in performance prediction. These lectures finish with a review of the rediowave propagation across the spectrum, identifying the main services in use.

2. PROPAGATION IN FREE SPACE

A transmitter with power, p_t, in free space which radiates isotropically in all directions gives a power flux density, s, at distance d of

$$s = \frac{p_t}{4\pi d^2} \qquad (1)$$

Using logarithmic ratios:

$$S = -71 + P_t - 20\log d \qquad (2)$$

where S is the power flux density in decibels relative to 1 $w.m^{-2}$
P_t is the power in decibels relative to 1 kw
and d is in km.

The corresponding field strength, e , is given by:

$$e = \sqrt{120\ \pi s} = \frac{\sqrt{30 p_t}}{d} \qquad (3)$$

This relationship applies when the power is radiated isotropically.

A $\lambda/2$ dipole has a gain in its equatorial plane of 1.64 times (see section 3) and in this case the field strength is:

$$e \approx \frac{7\sqrt{p_t}}{d} \qquad (4)$$

The power available, p_r, in a load which is conjugately matched to the impedance of a receiving antenna, is:

$$p_r = s a_e \qquad (5)$$

where a_e is the effective aperture of the antenna which is given by $\lambda^2 / 4\pi$ for an isotropic radiator.

Thus, again for an isotropic radiator in free space,

$$p_r = \frac{p_t}{4\pi d^2} \cdot \frac{\lambda^2}{4\pi} = p_t \left[\frac{\lambda}{4\pi d} \right]^2 \tag{6}$$

and the free space basic transmission loss is the ratio p_r / p_t , but see section 6.

3. ANTENNA GAIN

The ITU Radio Regulations formally define the gain of an antenna as "The ratio, usually expressed in decibels, of the power required at the input of a loss-free reference antenna to the power supplied to the input of the given antenna to produce, in a given direction, the same field strength or the same power flux density at the same distance." When not specified otherwise, the gain refers to the direction of maximum radiation. The gain may be considered for a specified polarisation. Gain greater than unity (positive in terms of decibels) will increase the power radiated in a given direction and will also increase the effective aperture of a receiving antenna.

Depending on the choice of the reference antenna a distinction is made between:

a) absolute or isotropic gain (G_i), when the reference antenna is an isotropic antenna isolated in space; [It should be noted that isotropic radiation relates to an equal intensity in all directions. The term "omnidirectional radiation" is often used for an antenna which radiates equally at all azimuths in the horizontal plane; such an antenna will radiate with a different intensity for other elevation angles.]

b) gain relative to a half-wave dipole (G_d), when the reference antenna is a half-wave dipole isolated in space whose equatorial plane contains the given direction;

c) gain relative to a short vertical antenna conductor (G_v) much shorter than one quarter of the wavelength, normal to the surface of a perfectly conducting plane which contains the given direction.

An isotropic radiator is often adopted as the reference at microwaves and at HF, whilst a half-wave dipole is often adopted at VHF and UHF, where this type of antenna is convenient for practical implementation. A short vertical antenna over a conducting ground is an appropriate reference at MF and lower frequencies where ground-wave propagation is involved and this usage extends to sky-wave propagation at MF and, in older texts, at HF.

The comparative gains of these reference antennas, and of some other antenna types, are given in Table 1.

4. EFFECTIVE RADIATED POWER

The Radio Regulations also provide definitions for effective or equivalent radiated power, again in relation to the three reference antennas:

Equivalent isotropically radiated power (e.i.r.p): the product of the power supplied to the antenna and the antenna gain in a given direction relative to an isotropic antenna (absolute or isotropic gain). Specification of an e.i.r.p. in decibels may be made using the symbol - dBi.

Effective Radiated Power (e.r.p.) (in a given direction): the product of the power supplied to the antenna and its gain relative to a half-wave dipole in a given direction.

Effective Monopole Radiated Power (e.m.r.p) (in a given direction): the product of the power supplied to the antenna and its gain relative to a short vertical antenna in a given direction.

Note that e.r.p, which is often used as a general term for radiated power, strictly only applies when the reference antenna is a half-wave dipole.

TABLE 1 The Gain of Typical Reference Antennas

Reference antenna	g_i	G_i (1) dB	Cymomotive force (for a radiated power of 1 kW)
isotropic in free space	1	0	173 V
Hertzian dipole in free space	1.5	1.75	212
Half wave dipole in free space	1.65	2.15	222
Hertzian dipole, or short vertical mono-pole, on a perfectly conducting ground (2)	3	4.8	300
Quarter-wave monopole on a perfectly conducting ground	3.3	5.2	314

(1) $G_i = 10 \log g_i$;
(2) In the case of the Hertzian dipole, it is assumed that the antenna is just above a perfectly conducting ground.

An alternative way of indicating the intensity of radiation, which is sometimes used at the lower frequencies, is in terms of the 'cymomotive force', expressed in volts. The cymomotive force is given by the product of the field strength and the distance, assuming loss-free radiation. The values of cymomotive force when 1 kw is radiated from the reference antennas are also given in Table 1.

5. THE EFFECT OF THE GROUND

The proximity of the imperfectly conducting ground will affect the performance of an antenna. In some cases, where the antenna is located several wavelengths above the ground, it may be convenient to consider signals directly from (or to) the antenna and those which are reflected from the ground, as separate signal ray-paths. When the antenna is close to, or on, the ground it is no longer appropriate to consider separate rays and then the effect may be taken into account by assuming a modified directivity pattern for the antenna, including the ground reflection; by modifying the effective aperture of the antenna; or by taking account of the change in radiation resistance; etc. A discussion of this for the ground-wave case, where the problem is most difficult, is contained in Annex II of ITU-R Recommendation P.341.

Information concerning the electrical characteristics of the surface of the earth are contained in further ITU-R texts: Recommendations P.527 and P.832.

6. TRANSMISSION LOSS

The concept of free-space basic transmission loss was introduced in equation 6 as the ratio p_r / p_t. However, transmission losses are almost always expressed in logarithmic terms, in decibels, and as a positive value of attenuation:

$$i.e. \quad L_{bf} = 10 \log \left[\frac{p_t}{p_r}\right] = P_t - P_r = 20 \log \left[\frac{4 \pi d}{\lambda}\right] \tag{7}$$

$$or \quad L_{bf} = 32.44 + 20 \log f + 20 \log d \tag{8}$$

where f is in MHz and d is in km.

The concept of transmission loss may be extended to include the effects of the propagation medium, and of the antennas and the radio system actually in use.

Free-space basic transmission loss, L_{bf} ,relates to isotropic antennas and loss-free propagation;

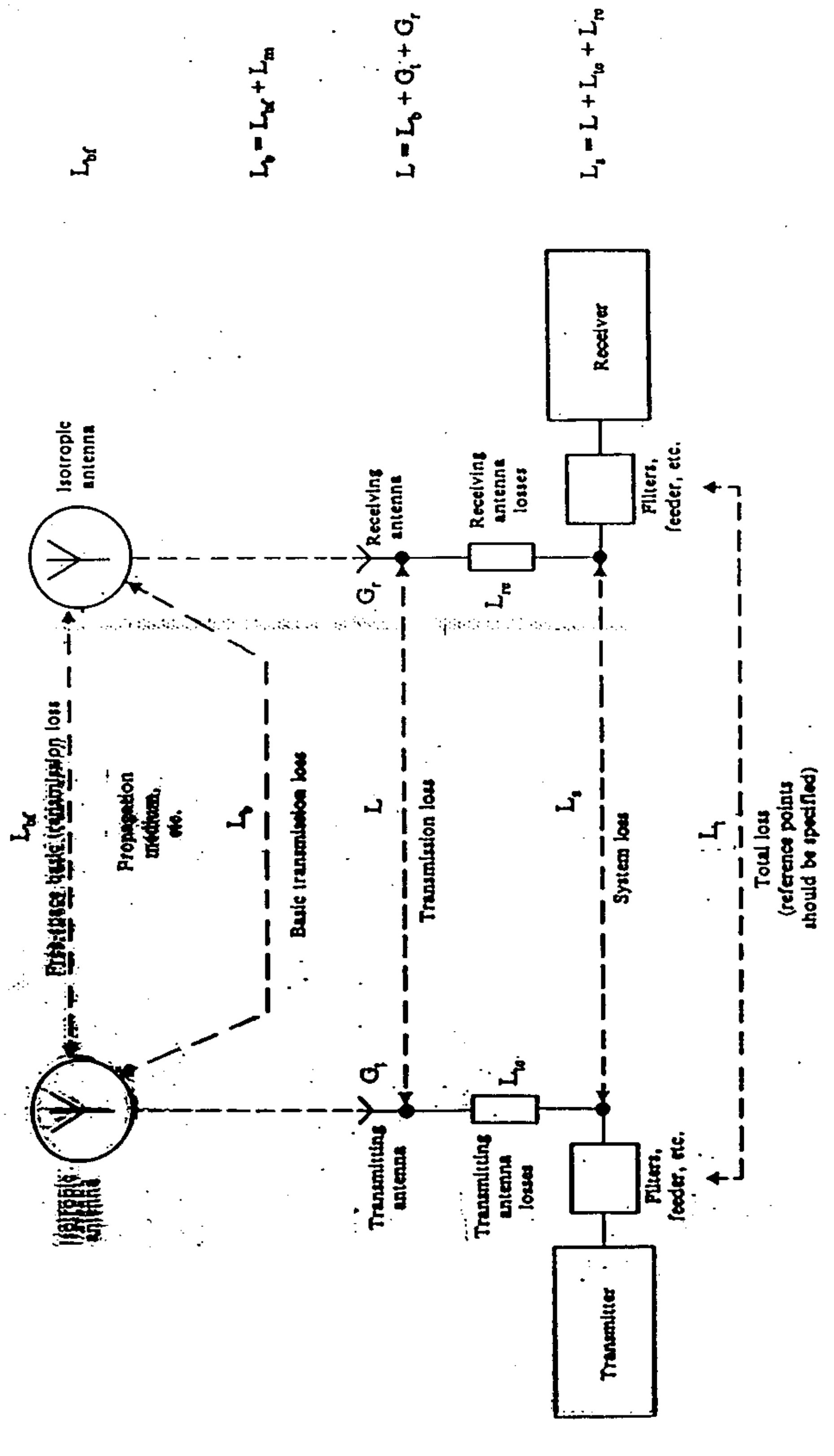
Basic transmission loss, L_b , includes the effect of the propagation medium:
e.g. - absorption loss (ionospheric, atmospheric gases or precipitation);
- diffraction loss
- effective reflection or scattering loss, in the ionospheric case including the results of any focusing or defocusing due to curvature of a reflecting layer;
- polarisation coupling loss; this can arise from any polarisation mismatch between the antennas for the particular ray path considered;
- aperture-to-medium coupling loss or antenna gain degradation, which may be due to the presence of substantial scatter phenomena on the path;
- effect of wave interference between the direct ray and rays reflected from the ground, other obstacles or atmospheric layers.

Transmission loss, L, includes the directivity of the actual transmitting antennas, disregarding antenna circuit losses;

System loss, L_s , is obtained from the powers at the antenna terminals; and

Total loss, L_t , is the ratio determined at convenient, specified, points within the transmitter and receiver systems.

The relationships between these loss ratios are illustrated in Figure 1. It is important to be quite precise when using the terms, and the full definitions are given in ITU-R Recommendation P.341.



– *Graphical depiction of terms used in the transmission loss concept*

Fig. 1.

7. RADIO NOISE

There is a number of types of radio noise that must be considered in any design; though, in general, one type will pre-dominate in particular circumstances and that should be taken into account in the system design. Broadly, the noise can be divided into two types: - noise internal to the receiving system and noise external to the receiving antenna.

The internal noise is due to losses in the antenna circuits or in the transmission line, or is generated in the receiver itself. It has the characteristics of thermal noise (i.e white Gaussian noise). External noise arriving at the receiving antenna may be due to:

- atmospheric noise generated by lightning discharges, or resulting from absorption by atmospheric gases (sky noise);

- the cosmic background, primarily from the Galaxy, or from the sun;

- or to the broadband man-made noise generated by machinery, power systems, etc.

In some cases, e.g. noise emanating from computer systems, such noise may have considerable frequency variability.

Narrow-band emissions due to interfering transmissions, spurious outputs, etc are also important in determining the background level but should be considered specifically as dictated by circumstances.

7.1 Internal noise

The thermal motion of atoms or molecules in a resistive material gives rise to random noise currents. Although the mean noise current in any direction is zero, the mean-square values are not zero and give rise to a thermal noise power of

$$p_n = 4ktbr$$

where t is the temperature in Kelvin
k is Boltzmann's constant, 1.38×10^{-23} J/K
b is the bandwidth of the measurement, in Hz
and r is the resistance in ohms

When this power is delivered to a matched load resistor at zero Kelvin, the available noise power is ktb.

7.2 noise factor

The noise factor, f, of an amplifier, under matched input conditions is:

$$f = \frac{(\textit{signal-to-noise ratio at the input})}{(\textit{signal-to-noise ratio at the output})}$$

Taking a refence temperature of the source resistor as T_0, usually taken as 290K, and describing the noise contribution of the amplifier in terms of an effective noise temperature at the amplifier input, T_a, the noise factor becomes:

$$f = 1 + \frac{T_a}{T_o}$$

Note that here the lower case, f , is used for the numerical noise factor and the upper case, F, is used for the noise figure in logarithmic terms.

For a sucession of amplifier, or attenuator, stages with gains $a_1, a_2, a_3, etc.$ with noise factors $n_1, n_2, n_3, etc.$, then the overall noise factor referred to the system input is :

$$f_r = f_1 + \frac{f_2 - 1}{a_1} + \frac{f_3 - 1}{a_2} + etc.$$ with an equivalent noise temperature $T_r = T_o(f_r - 1)$

In some cases the effective noise temperature of the input, for example where this is an antenna, will not be at the reference temperature. Then the available input noise power to an equivalent noise-free receiver may be expressed as:

$$n_i = kt_o b\left(\frac{t_a + t_r}{t_o}\right) = f_s kt_o b$$ where f_s is the system noise factor, and t_a, t_r are the noise temperatures due to the antenna and the receiver.

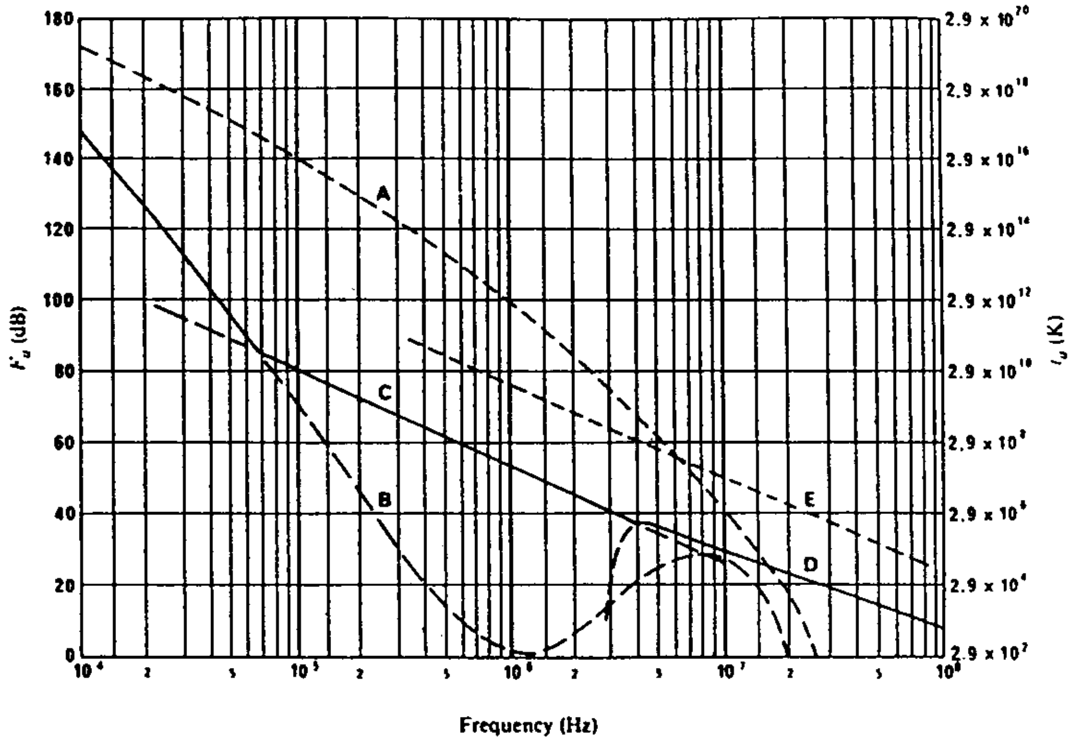
In logarithmic terms the noise power is:

$$N_i = F_s - 204 + B \qquad \text{dBW, where} \quad B = 10 \log b$$

7.3 external noise

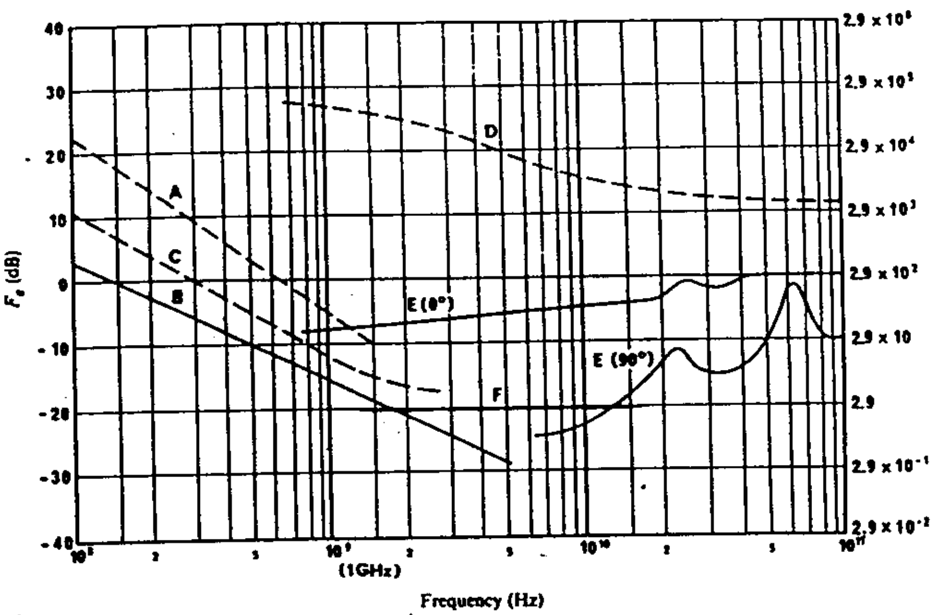
Minimum, and some maximum, values for the external noise figures are shown in Figs. 2 and 3 (taken from Recommendation ITU-R PI. 372-6). Generally one type of noise will predominate, but where the contributions of more than one type of noise are comparable, the noise temperatures (not the figures in decibels) should be added. Atmospheric noise due to lightning varies with location on the earth, season, time of day and frequency. Maps and frequency correction charts are given in Recommendation 372-6. Man-made noise varies with the extent of man-made activity and on the use of machinery, electrical equipment, etc. The relationship for a range of environments is also given in the Recommendation. It should be noted that some care may be needed to ensure that an appropriate curve is selected since the noise generated, for example in a 'business' area, may differ from country to country.

Both atmospheric and man-made noise are impulsive in character and an assessment based wholly on the noise power is likely to be inadequate. In some cases the dominant feature which determines system performance will be a parameter derived from the amplitude probability distribution of the noise. The Recommendation includes this information together with examples of the prediction of system performance. However in other cases, such as for digital systems, the characteristic duration and repetition rate of noise impulses may be important.



— *F_a versus frequency (10^4 to 10^8 Hz)*

A: atmospheric noise, value exceeded 0.5% of time
B: atmospheric noise, value exceeded 99.5% of time
C: man-made noise, quiet receiving site
D: galactic noise
E: median business area man-made noise
——— minimum noise level expected



— *F_a versus frequency (10^8 to 10^{11} Hz)*

A: estimated median business area man-made noise
B: galactic noise
C: galactic noise (toward galactic centre with infinitely narrow beamwidth)
D: quiet Sun (½° beamwidth directed at Sun)
E: sky noise due to oxygen and water vapour (very narrow beam antenna); upper curve, 0° elevation angle; lower curve, 90° elevation angle
F: black body (cosmic background), 2.7 K
——— minimum noise level expected

Figs 2 & 3

8. FADING AND VARIABILITY

Both signals and noise are subject to variations in time and with location. These changes in intensity arise from the nature of a random process, from multi-path propagation, from movements of the system terminals or the reflecting medium, from changes in transmission loss, etc. A knowledge of the statistical characteristics of a received signal may be required in the assessing of the performance of modulation systems, etc.

Statistics of the signal variability are also required for spectrum planning and for predicting the performance of systems. For these purposes it is important to know, for example:

- the signal level exceeded for large percentages of time or location (e.g. for the determination of quality of the wanted service or of the service area);

- the signal level exceeded for small percentages of time (e.g. to determine the significance of potential interference or feasibility of frequency reuse).

In some cases signals are subject to rapid or closely spaced variations, superimposed on a slower variability. In such cases it may be possible to treat the phenomena separately, say by using a long receiver integration time or by 'averaging ' the level of the signal (e.g. with AGC) so that the time interval adopted encompasses many individual short term or closely spaced fluctuations.

8.1 The normal (Gaussian) distribution

When the value of a parameter results from the cumulative effect of many processes, each of which has the same central tendency, the probability density, p(x), has a bell shaped distribution peaking, at a central, mean, value, $\bar{x}$. For n discrete values of a variable x, measured at regular intervals of time or location, etc:

$$\bar{x} = \frac{\sum x_n}{n}$$

Where the distribution is symmetrical, the values of the mean, $\bar{x}$; the mode, m, which is the most frequently recurring value; and the median, x_{50}, the middle value when the individual values are listed in order, are all identical.

The shape of such a symmetrical, centrally-peaking distribution is often that of the normal, Gaussian, distribution:

$$p(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left[\frac{x-\bar{x}}{\sigma}\right]^2\right]$$

where σ is a normalising parameter, the standard deviation;
σ^2 is also called the variance.

$$\sigma = \sqrt{\frac{\sum(x_n-\bar{x})^2}{n}}$$

The cumulative probability function, F(x), for this distribution is given by:

$$F(x) = \frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^{x} \exp\left[-\frac{1}{2}\left(\frac{t-\bar{x}}{\sigma}\right)^2\right] dt$$

Statistical tables giving values for both p(x) and F(x) are readily available, as is graph paper with a graticule such that the normal cumulative probability function appears as a straight line.

An approximation for the half of the distribution where $X < \bar{X}$ is given by:

$$F(x) = \frac{\exp[-(y^2)/2]}{\sqrt{2\pi}\left[0.661y + 0.339\sqrt{y^2+5.51}\right]} \quad \text{and} \quad y = \frac{\bar{x}-x}{\sigma}$$

The upper half of the distribution may be obtained by using the above equation with $y = (X - \bar{X})/\sigma$, in this case giving *1-F(x)*.

Table 2 gives some examples taken from the distribution.

TABLE 2 The normal distribution

occurrence	
68% 95.5%	within 1σ within 2σ
90% 99% 99.9%	less than $+1.28\sigma$ less than $+2.33\sigma$ less than $+3.09\sigma$

In fact, in radiowave propagation, a normal distribution of signal power, etc, only occurs when there are small fluctuations about a mean level, as might be the case when studying scintillation. Predominantly, it is the normal distribution of the logarithms of the variable which gives useful information: the log-normal disribution discussed below.

8.2. The Log-Normal Distribution

In the case of a log-normal distribution, each parameter (the values of the variable itself, the 'mean', the standard deviation, etc.) is expressed in decibels and the equations above then apply. The log-normal distribution is appropriate for very many of the time series encountered in propagation studies, and also for the variations with location, for example within a small area of the coverage of a mobile system.

Note that when a function is log-normally distributed the mean and median of the function itself are not equal: the centre of the distribution, when F(x) = 0.5, is still the median. whereas the mean of the numerical values is given by $\bar{x} + \sigma^2/2$

Normal probability graph paper is available, for which a normal distribution is plotted as a straight line with a slope dependent on the standard deviation: see Fig 4.

8.3 The Rayleigh distribution

The combination of a number (say, more than three) of component signal vectors with arbitrary phase and comparable amplitude leads to the Rayleigh distribution. Thus, this is appropriate for situations where the signal results from multi-path or scatter.

In this case

$$p(x) = \tfrac{2x}{b^2}\exp\left[-\tfrac{x^2}{b^2}\right]$$

and

$$F(x) = 1 - \exp\left[-\tfrac{x^2}{b^2}\right]$$

where b is the root mean square value. [Note that x and b are numerical amplitude values, not decibels]

For this distribution the mean is 0.886b, the median is 0.833b, the mode is 0.707b and the standard deviation is 0.463b.

It is useful to note that for small values of F(x),

$$F(x) \approx \tfrac{x^2}{b^2}$$

so that when x is a voltage amplitude, then its power decreases by 10dB for each decade of probability. However this is not a sufficient test to determine whether a variable is Rayleigh distributed, since some other distributions have the same characteristic.

TABLE 3 Rayleigh distribution

F(x)	20 log(x)
0.999	+10 dB
0.99	+8.2
0.9	+5.2
0.5	0
0.1	-8.2
0.01	-18.4
0.001	-28.4
0.0001	-38.4

This characteristic is shown in Table 3 which gives some examples from the Rayleigh distribution. Special graph paper is also available on which this distribution is plotted as a straight line, note however that such a presentation greatly overemphasises the appearance of small time percentages and care should be taken that this does not mislead in the interpretation of plotted results.

8.4. Combined log-normal and Rayleigh distribution

In a number of cases there will be a composite variation in the signal, in which rapid or closely spaced fluctuations, which may be due to multipath or scatter, follow a Rayleigh distribution but the mean of these, measured over a longer period of time or a longer distance, is itself subject to log-normal distribution.

This distribution is given by Boithias:

$$1 - F(x) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{+\infty} \exp\left[-x^2 e^{-0.23\sigma u} - \frac{u^2}{2}\right] du$$

where σ is the standard deviation (in decibels) of the log-normal distribution. This combined distribution is given in Figure 5 An alternative representation, normalised at the 50% probability, is given by Picquenard and reproduced in ITU-R Report 266. This combination of distributions has also been studied by Suzuki, and his proposed formulation has been evaluated by Lorenz.

8.5. The Rice distribution

The Rice distribution (also described as the Nakagami-n distribution) applies to the case where there is a steady, non-fading, component together with a random variable component with a Rayleigh distribution. This may occur where there is a direct signal together with a signal reflected from a rough surface; at LF and MF where there is a steady groundwave signal and a signal reflected from the ionosphere; or where there is a steady signal together with multi-path signals.

The probability density for the Rice distribution is given by:

$$p(r) = \frac{2r}{b^2} \exp\left[-\frac{r^2+a^2}{b^2}\right] I_o\left(\frac{ra}{\sigma^2}\right)$$

where the rms values of the steady and the Rayleigh components are a and b respectively. A parameter $K = a^2/b^2$, the ratio of the powers of the steady and Rayleigh components is often used to describe the specific distribution. K is sometimes expressed in decibels. (Boithias (and the ITU-R Recommendation) use 1/K). The distribution, parametric in probability, is shown in Figure 6

In most cases the power in the fading component will add to the power of the steady signal, where, for example, the multipath brings additional signal modes to the receiver. In some other cases the total power will be constant where the random component originates from the steady signal.

8.6. Other distributions

Many further assymetrical distributions have been studied and utilised in propagation studies. Griffiths and McGeehan (1982), have compared some of these such as the exponential, Gamma, Wiebull, Chi-squared, Stacy and Nakagami-m distributions. It may be appropriate to include such distributions in models of particular propagation behaviour. For example, Lorenz (1980) has suggested that the Suzuki distribution is appropriate for VHF and UHF mobile communication in built-up areas and forests, while the Wiebull distribution is appropriate for area coverage statistics where line of sight paths occur frequently.

However, before embarking upon the use of an unfamiliar and complicated distribution, the user should be sure that the uncertainty and spread in the observations is small enough that the use of the distribution will result in a significant improvement in the accuracy of the model. The difference between various distributions for values between, say, 10% and 90% occurrence will often be small, and it is only in the tails of the distribution, where observations may be sparse, that a distinction could be made.

For applications concerned with the quality and performance of a wanted signal, or with the interference effects of an unwanted signal, it is seldom necessary to consider both tails of a distribution at the same time. In some cases half-log-normal distributions, applying a different value of the standard deviation on each side of the median, will be quite adequate. The mathematical elegance of a complete distribution should be weighed against the practical convenience of using the appropriate half of a more common distribution for the occurrence percentages of interest.

9 FADING ALLOWANCES

For service planning, the specified signal to noise ratio for the required grade of service, will probably include an allowance for the rapid fading which will affect the intelligibility or the bit error ratio of the system. It may still be necessary to allow for other variations (hour to hour, day to day, location to location) of both signal to noise, which are likely to be log-normally distributed, but uncorrelated. It is appropriate to do this by first determining the overall median signal to noise ratio expected and then to apply a log-normal distribution to this where the variance,σ^2, is obtained by adding the variances of each contributing distribution.

An example of this procedure is given in ITU-R Report 266. The procedure may, if necessary, be extended still further to include the probable error of the prediction, due to the sampling involved in establishing the method, etc. Where no allowance for this is included, the prediction has a confidence level of 50%, since one half of the specific cases calculated are likely in practice to be below the predicted level. An assessment may be made of the probable error and, by applying a normal distribution an allowance may be made for any other desired confidence level.

10 DIVERSITY

The fading allowance necessary to achieve a good grade of service may demand economically prohibitive transmitter powers and antenna gains. In any case the use of excessive radiated power conflicts with the need for good spectrum utilisation. Techniques for overcoming this problem include coding and diversity. Particularly for circuits with rapid fading, such as those where Rayleigh or Rician fading dominates, copies of the signal with the same characteristics are available displaced in time, position, frequency, or, for some types of propagation, with angle or orthogonal polarisation. For example, a signal message may be repeated later in time i f, when first transmitted, a fade had reduced the signal to noise ratio. For digital systems this process may be automated by the use of an error detecting code and using a method of automatic repeat requests (ARQ) if errors are detected in the received signal. More modern techniques use sophisticated error correction and detection codes, to combat the effects of fading and these may take account of the expected patterns of error occurrence. Spread spectrum signals, both direct sequence and frequency hopping, employ techniques to take advantage of the frequency selective nature of fading and this is discussed in later chapters.

Diversity techniques utilise two or more samples of the signal obtained from separated antennas, or sometimes from duplicated transmissions on several frequencies. These signals are then combined in the receiver to produce an output with a smaller fading variability. Signals may be combined by techniques such as:

- selection of the stronger or strongest:
- combining the output of channels with equal gain;

- weighting the combination according to the signal to noise ratio of the channel (maximal ratio combining).

Fig. 7 shows the distributions for two element diversity where the signals are uncorrelated and each have a Rayleigh distribution, for various methods of combination. The correponding distribution for four channel diversity (as might be employed for tropospheric scatter systems) is shown in Fig. 8. In fact, a substantial advantage is still obtained if the signals are partially correlated. Fig. 9 shows, for two element selection diversity, the effect of varying the correlation coefficient.

The advantage given to system performance by the application of diversity may be expressed in two ways:

- either as diversity improvement - the ratio of the time percentages, with and without diversity, for which the signal fade depth exceeds a specified level,

- or as diversity gain - the increase in the signal level exceeded when using diversity for a specified time percentage.

10.1 correlation coefficient

The correlation coefficient is obtained as:

$$r = \frac{\sum[(x-\bar{x})(y-\bar{y})]}{[\sum(x-\bar{x})^2 \bullet \sum(y-\bar{y})^2]^{1/2}} = \frac{\sum(xy)-n\bar{x}\bar{y}}{n\sigma_x\sigma_y}$$

where x and y refer to simultaneous, or appropriately time-shifted, pairs of values from the two distributions and n is the number of pairs.

11. RELIABILITY

Using the techniques above, the reliability of a system may be specified. Although precise definitions have not, so far, been universally adopted, the set of terms given in Recommendation ITU-R P. 842 has been applied for example to the assessment of HF broadcasting. The Recommendation includes:

Reliability - Probability that a specified performance is achieved.

Circuit reliability - Probability for a circuit that a specified performance is achieved at a single frequency.

Reception reliability - Probability for a circuit that a specified performance is achieved by taking into account all transmitted frequencies associated with the desired signal.

Service reliability - Probability that a specified performance will be achieved at a specified percentage of the service area by taking into account all transmitted frequencies.

These definitions distinguish between `basic' and `overall' reliability where the limiting background is respectively noise, or the combination of noise and interference. For a given radio service the definitions may need to be adapted to the requirements of that service. For example, for broadcasting applications, the term service reliability is replaced by the term broadcast reliability, and is calculated for a specified number of test points within the nominal service area.

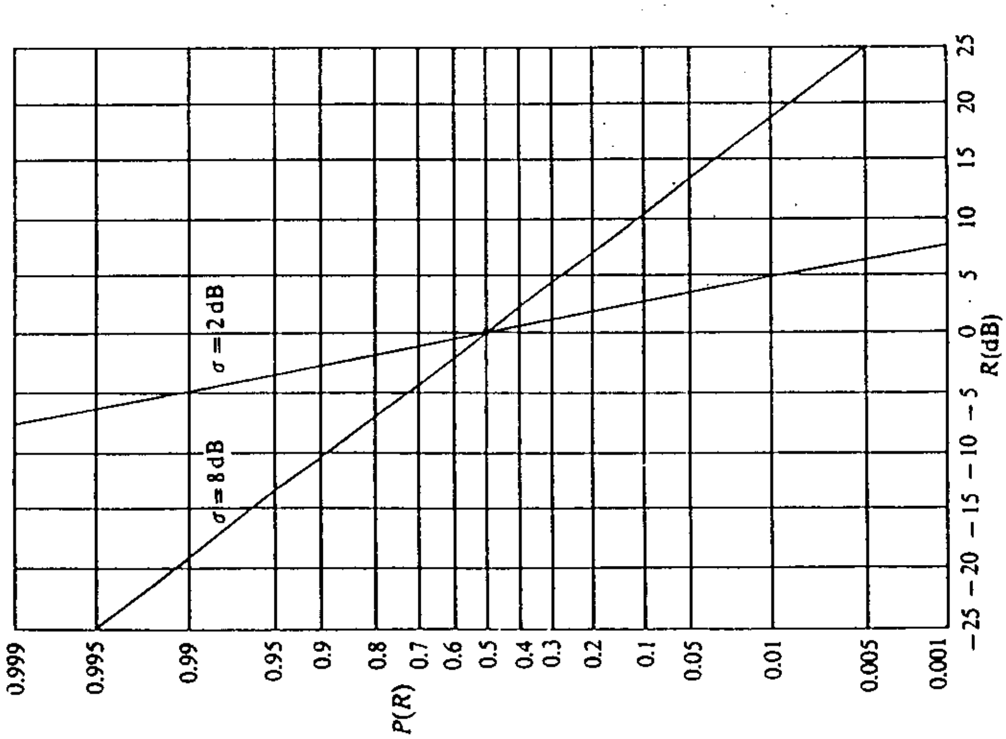
12. ISDN PERFORMANCE REQUIREMENTS

The discussion above relates to analogue systems and to digital systems where the requirement is for a specified average bit error ratio. For high integrity circuits to be used in the public telephone network, ITU-T performance objectives are used.

Such criteria make great demands on the propagation information and are likely to require specialised measurement programmes.

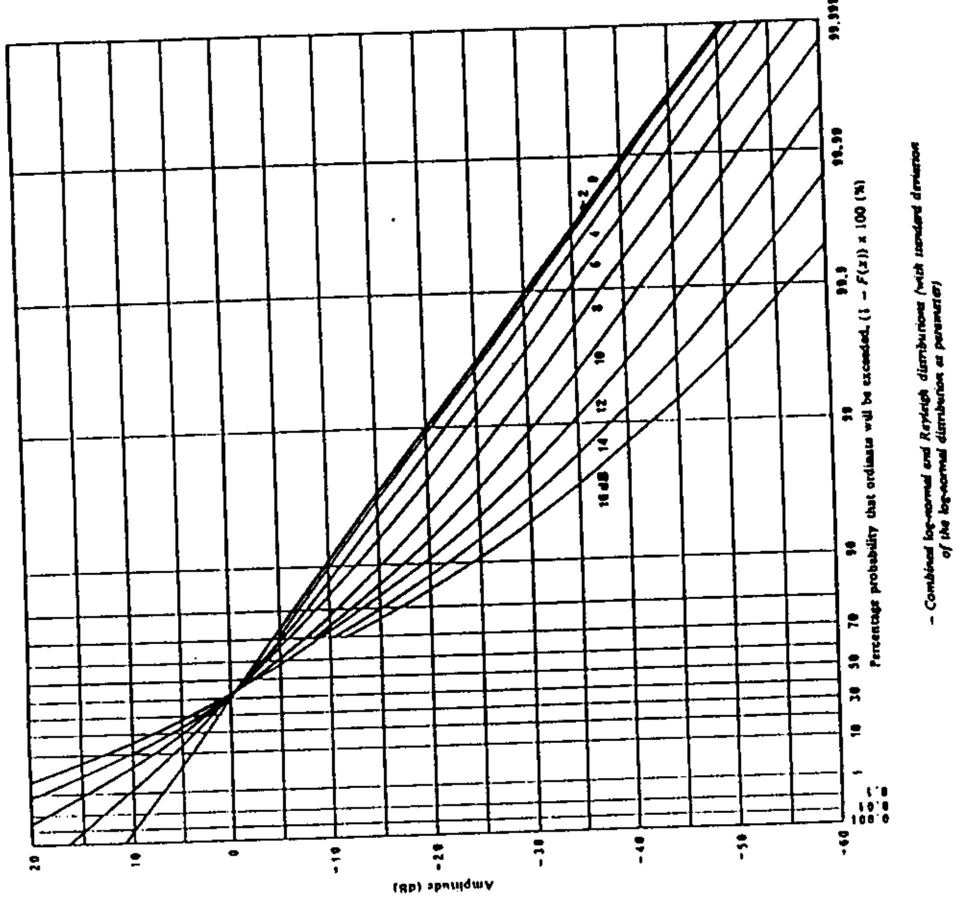
13. WORST CONDITIONS

For system planning it is often appropriate to consider a worst case. At MF and HF, where ionospheric modes are involved it may, for example, be useful to make predictions for sunspot minimum conditions and perhaps for the season which has the highest noise level, or the lowest MUF, etc. At UHF and higher frequencies where climatic effects are very important, it is valuable to know the expected performance in terms of a specified parameter in the worst month in a period of 12 consecutive months. The fraction of time during which a preselected threshold is exceeded in the worst month of a year is referred to as "the annual worst-month time fraction of excess", and the appropriate statistic would be the long term average of that fraction. The average annual worst-month time fraction of excess, p_w, is calculated from the annual value, p, by use of a conversion factor Q, the ratio of two fractions. Typical values of Q are given in ITU-R Recommendation P.841. Definitions are in Recommendation P.581, and the topic is further discussed in the old ITU Report 723.



Normal or log-normal probability paper with two lines representing σ = 2 dB and 8 dB as examples.

Fig 4



– Combined log-normal and Rayleigh distributions (with standard deviation of the log-normal distribution as parameter)

Fig 5

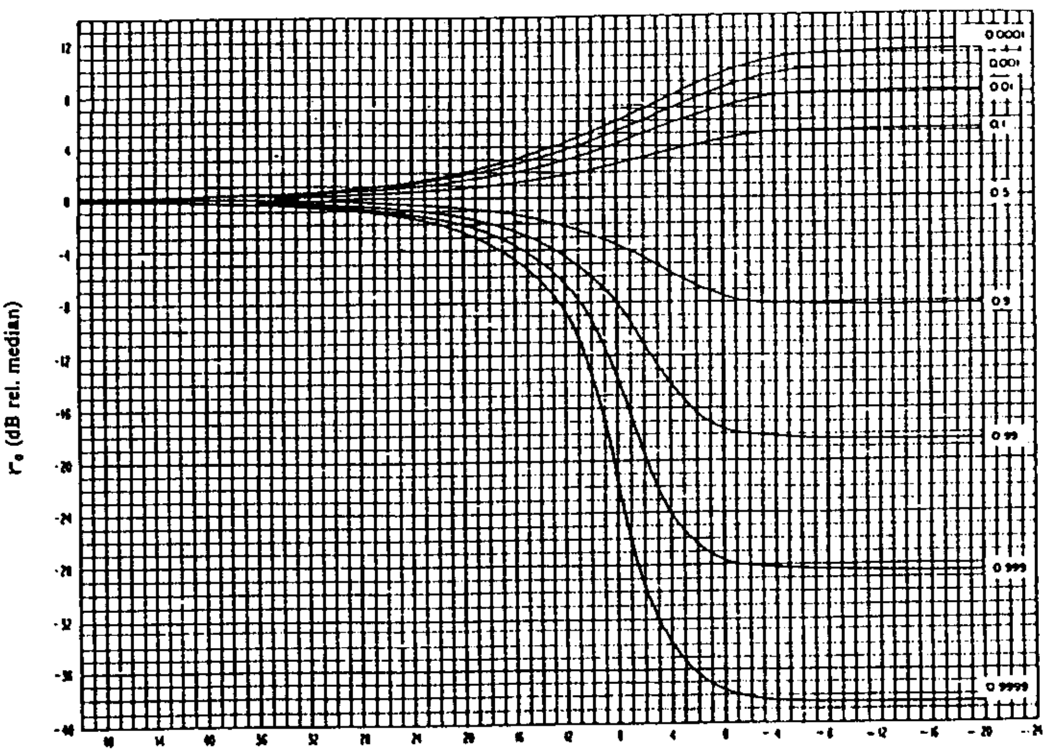


Fig 6

. Distribution function F(r) for the Nakagami-Rice distribution
(The values of F(r) are shown on the curves)

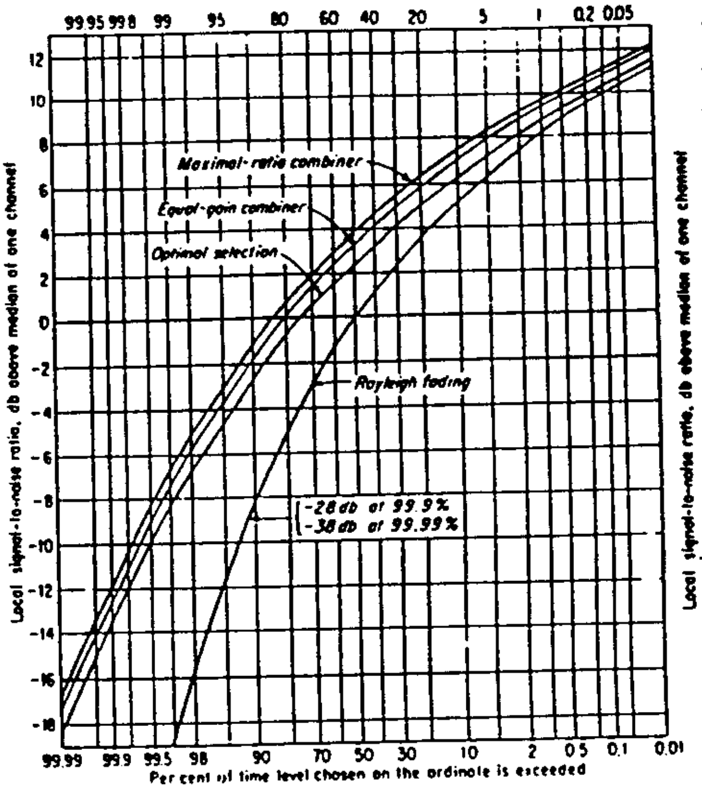


Fig. 7. Two element diversity, uncorrelated Rayleigh fading.

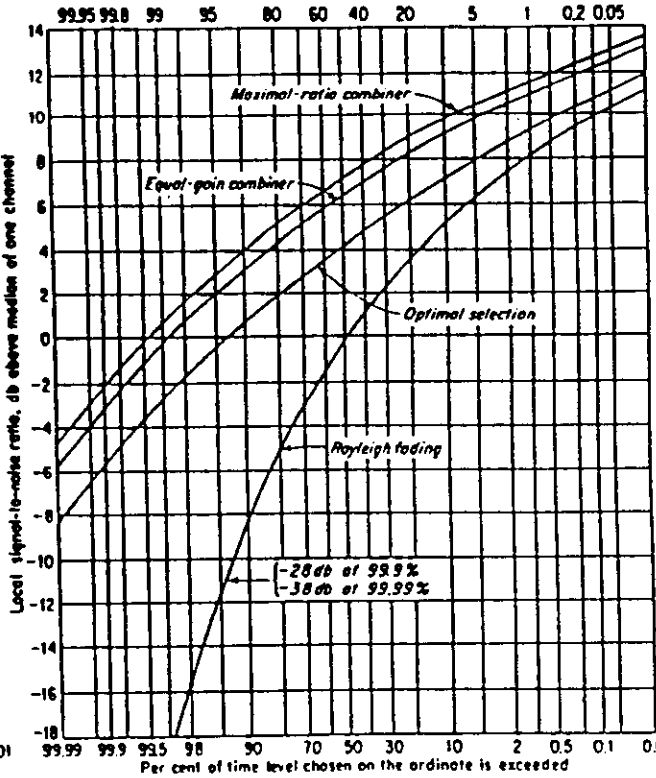
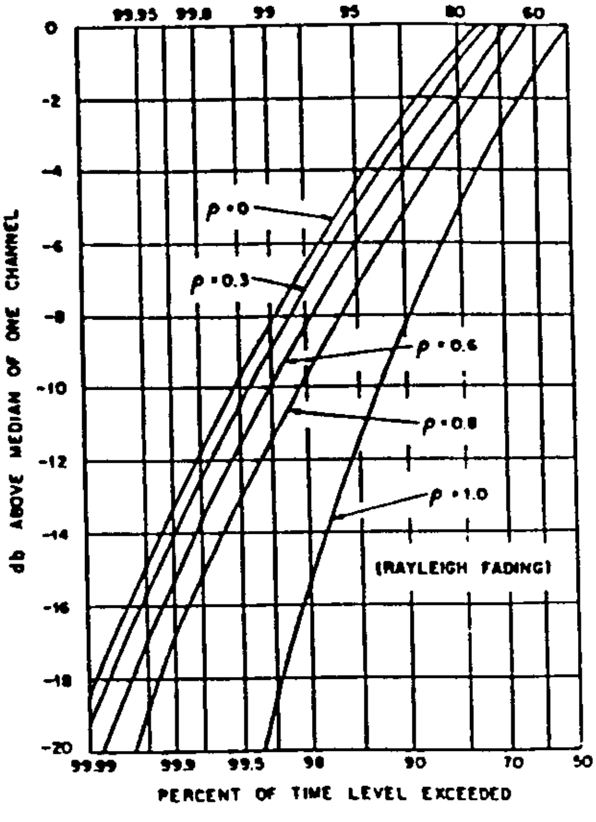


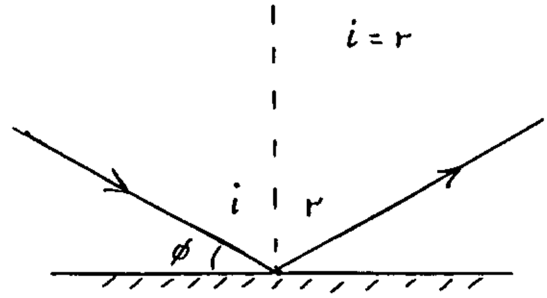
Fig. 8. Four element diversity, uncorrelated Rayleigh fading.



Dual selection diversity distributions, Rayleigh fading, for various degrees of correlation.

Fig 9.

14 REFLECTION



At long distances from a transmitting source adjacent rays are almost parallel and the wave front may be considered to be plane. Parallel rays reflected from a plane surface obey the usual law that the angles of incidence and reflection are equal. For propagation studies it is more convenient to use the "grazing angle", ϕ, - the angle between the ray direction and the surface, rather than the complementary incidence angle.

The reflection coefficient of a surface depends on the complex relative permittivity of the surface:

$$\varepsilon_r^* = \varepsilon_r - j\frac{\sigma}{\omega\varepsilon_0} = \varepsilon_r - j60\sigma\lambda$$

where ε_r is the relative permittivity, σ is the conductivity (Seimens/metre) and ε_0 is the permittivity of free space.

Information concerning the electrical characteristics of the surface of the earth are contained in ITU-R Recommendations 527 and 832.

The reflection coefficient is:

for horizontal polarisation:

$$R_H = \frac{\sin\phi - \left(\varepsilon_r^* - \cos^2\phi\right)^{0.5}}{\sin\phi + \left(\varepsilon_r^* - \cos^2\phi\right)^{0.5}}$$

and for vertical propagation:

$$R_V = \frac{\varepsilon_r^*\sin\phi - \left(\varepsilon_r^* - \cos^2\phi\right)^{0.5}}{\varepsilon_r^*\sin\phi + \left(\varepsilon_r^* - \cos^2\phi\right)^{0.5}}$$

Thus for grazing rays, where ϕ is nearly zero, the reflection coefficient for both polarisations is nearly unity, with a phase reversal, and this is the most usual case. Fot vertical polarisation there is an amplitude minimum at a particular value of ϕ , depending upon ε_r^*, this is the pseudo Brewster angle. At greater grazing angles, the phase change for vertical polarisation on reflection is small.

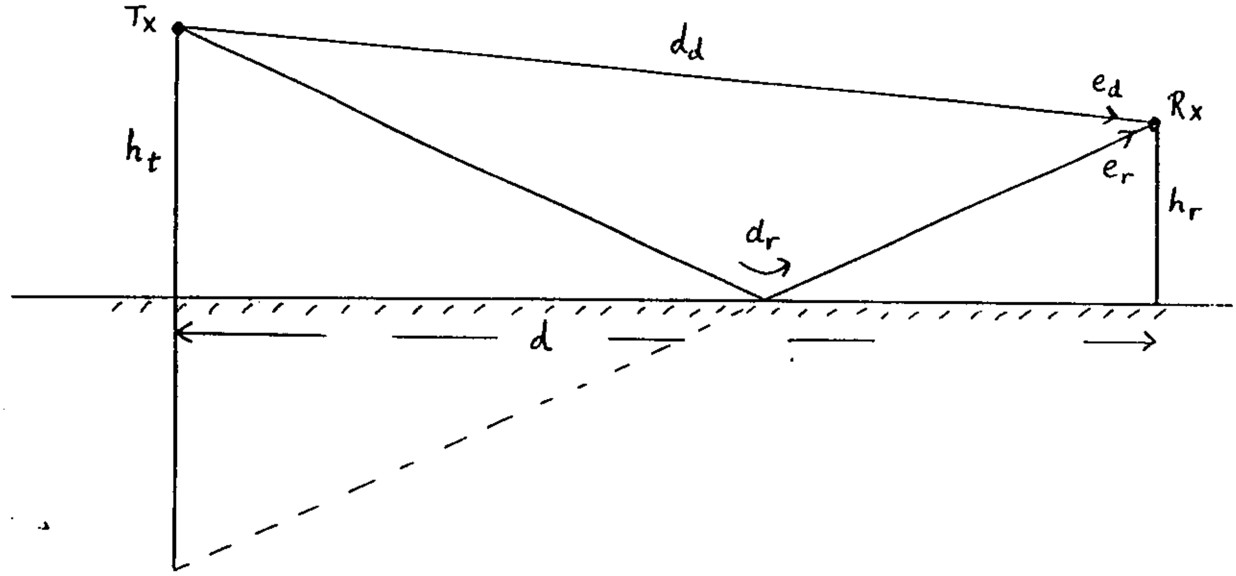
Consider two elevated antennas above a smooth plane earth.

$$d_d = \left[d^2 + (h_t - h_r)^2\right]^{\frac{1}{2}} \approx d\left[1 + \left(\frac{h_t - h_r}{d}\right)^2\right]$$

$$d_r = \left[d^2 + (h_t + h_r)^2\right]^{\frac{1}{2}} \approx d\left[1 + \left(\frac{h_t + h_r}{d}\right)^2\right]$$

Thus $d_r - d_d = \frac{2h_t h_r}{d}$. This path difference gives a phase difference:

$$\phi = \frac{2\pi}{\lambda} \bullet \frac{2h_t h_r}{d} = \frac{4\pi h_t h_r}{\lambda d} \text{ radians.}$$



When $e_d = -e_r$, i.e. when the reflection coefficient is minus one and the path lengths are almost identical, the resultant field is:

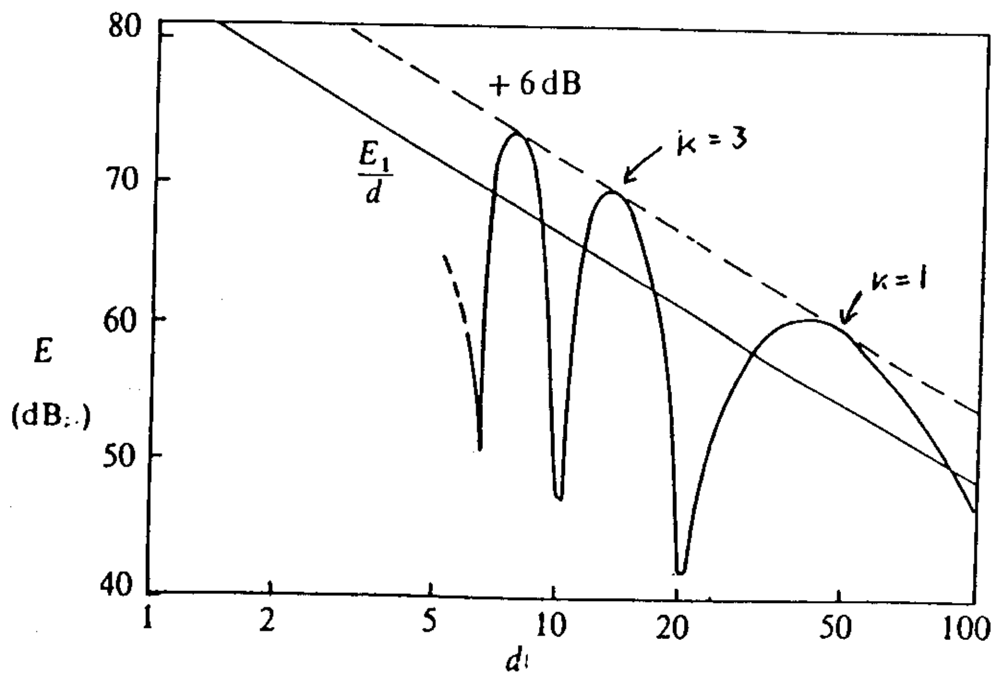
$$|e_t| = \left|2e_d \sin\left(\frac{2\pi h_t h_r}{\lambda d}\right)\right|.$$

Normalising this in terms of the cymomotive force, e_1 , where $e_d = \frac{e_1}{d}$, and expressing the field in logarithmic terms:

$$E_t = 6 + E_1 - 20\log d + 20\log\left[\sin\frac{2\pi h_t h_r}{\lambda d}\right] \text{ dB.}$$

Thus the field has the usual 20 log d distance term, but this is modified and the field is 6dB greater when $\frac{2\pi h_t h_r}{\lambda d} = \frac{k\pi}{2}$ and k is an odd integer. When k is an even integer the amplitude theoretically reduces to zero ($-\infty dB$).

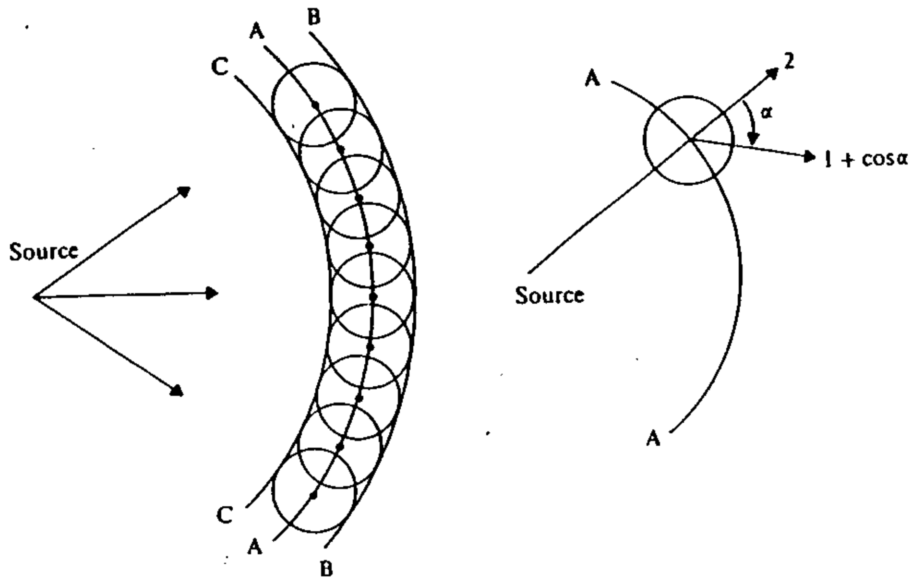
At distances beyond that where k=1, $e_t \propto \frac{1}{d^2}$, and the distance term becomes 40 log d. In practice this relationship applies for short range mobile services operating in obstructed environments.



DIFFRACTION

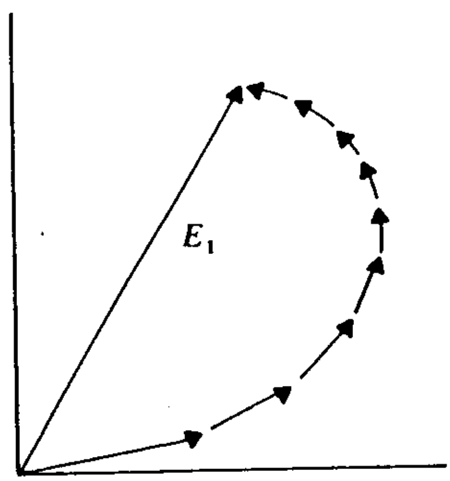
It is found that an obstruction in the path of a propagating radio wave does not cause and abrupt, dense shadow but that signals may still be observed behind an obstruction due to diffraction. Indeed it is found that along the line of the geometrical top of a thin "knife-edge" obstacle the signal amplitude is only half (-6dB) of the corresponding amplitude in free space.

To account for this behaviour, Huygens proposed that each point on a wave front may be considered as the source on a radiating "wavelet". Fresnel showed that the polar diagram of such wavelets would have a maximum in the forward propagating direction and a null to the rear. The result is that envelope of the forward propagating wavelets creates a new wave front.

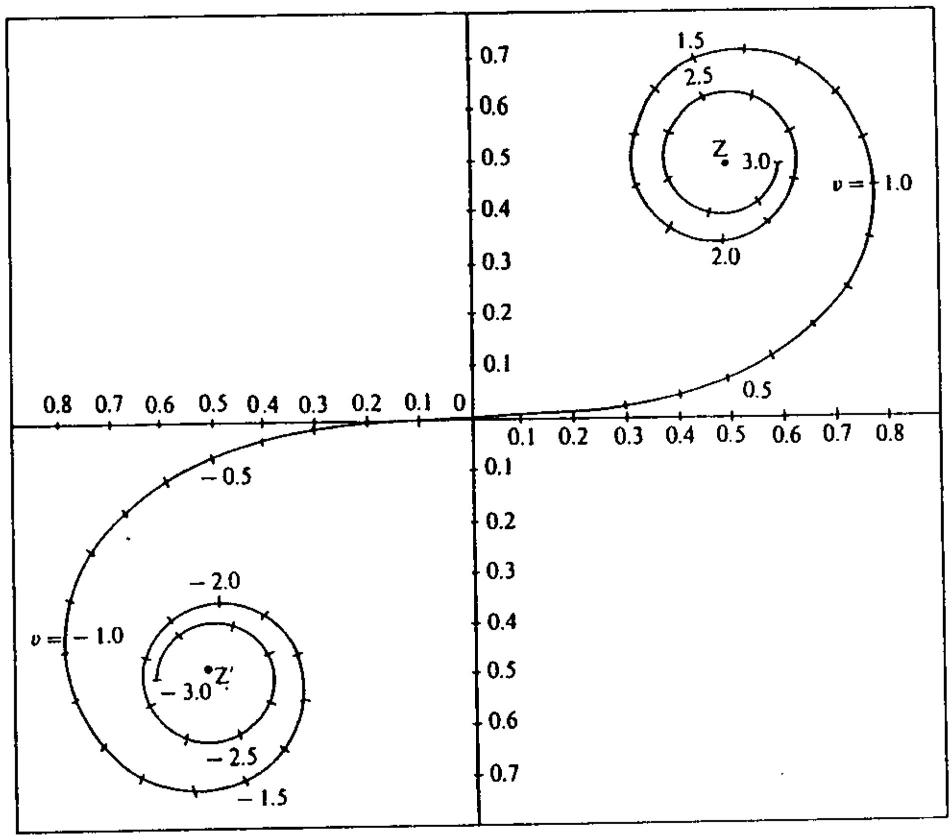


Huygens' principle applied to a spherical wavefront.

When a wave front reaches a knife edge obstruction, the wavelet sources above the edge contribute to the signal below and behind and the signal there is found by vector addition of the contributions, which have differing phases due to the increasing length of the wavelet paths.



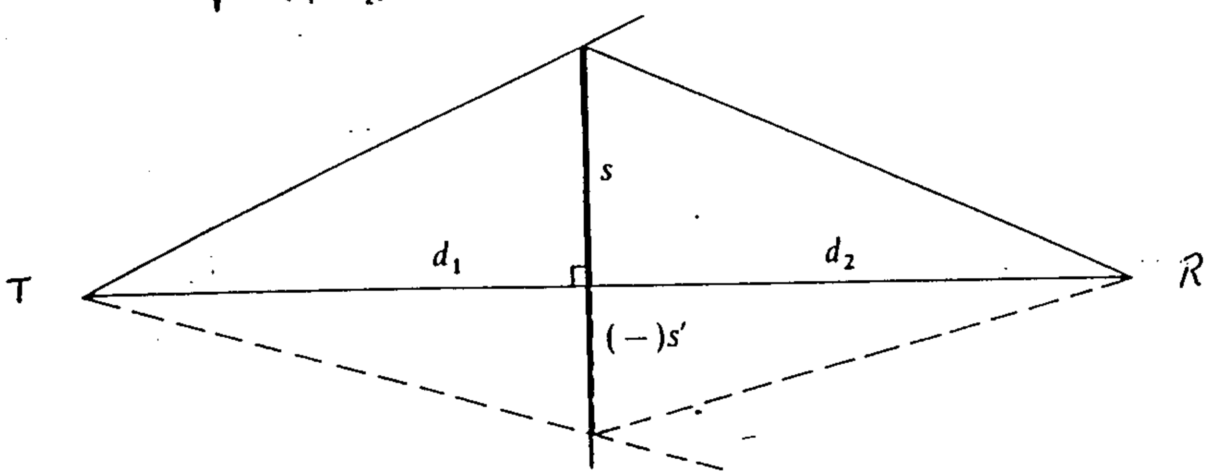
- Considering the phase addition of all wavelets in free space leads to the Cornu spiral.



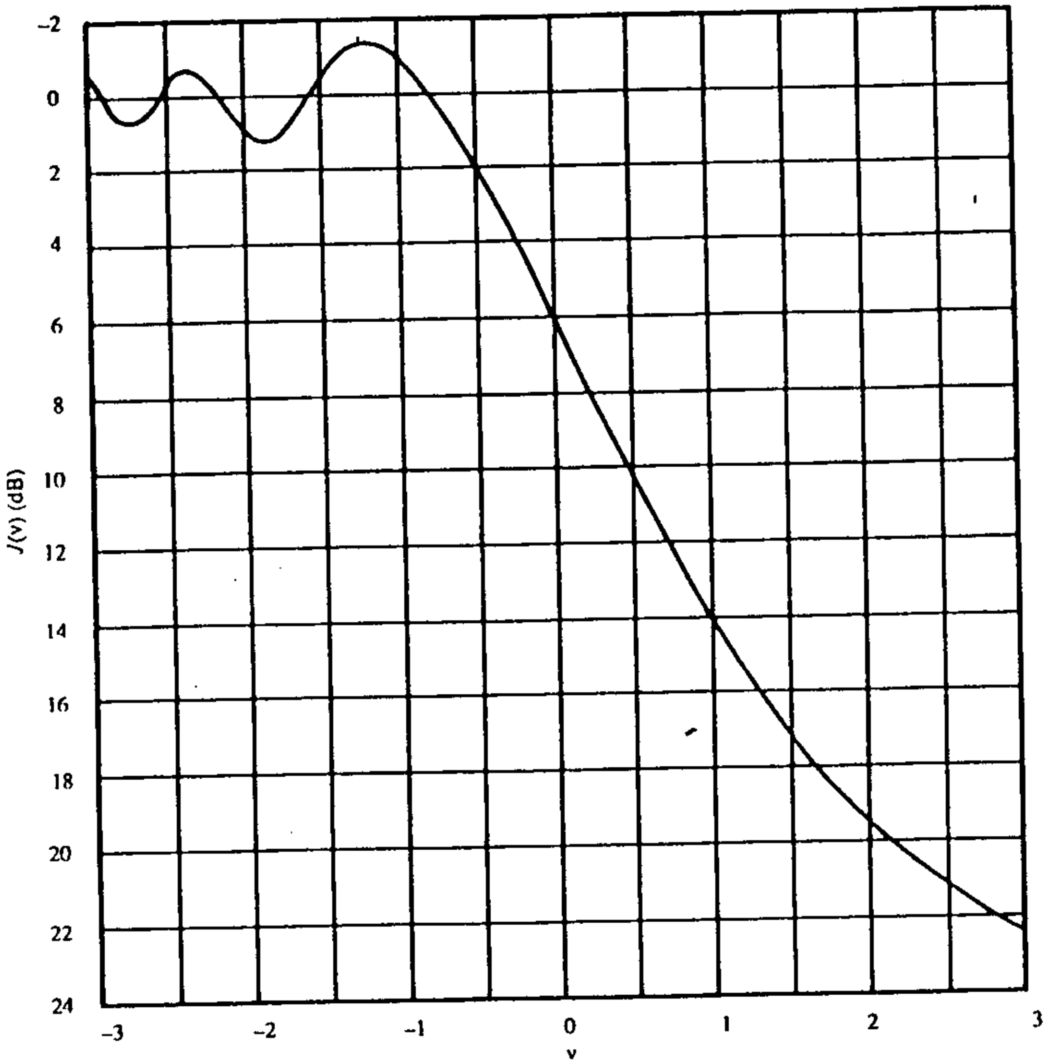
Cornu's spiral for diffraction over a knife-edge obstacle. It is a plot of the Fresnel's integrals in terms of the auxiliary parameter v.

The spiral is normalised in terms of a parameter ν.

$$\nu = s\sqrt{\frac{2}{\lambda} \bullet \left(\frac{1}{d_1} + \frac{1}{d_2}\right)}$$



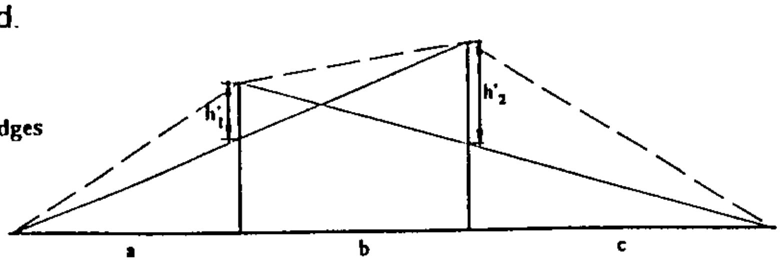
In free space the resultant signal is obtained on the Cornu spiral as the amplitude between the two asymptotic points Z and Z'. When part of the wavefront is obstructed, the amplitude is obtained by cutting off part of the spiral and taking the amplitude from the edge to the asymptotic point. The knife-edge diffraction loss obtained in this way, $J(\nu)$, is shown below.



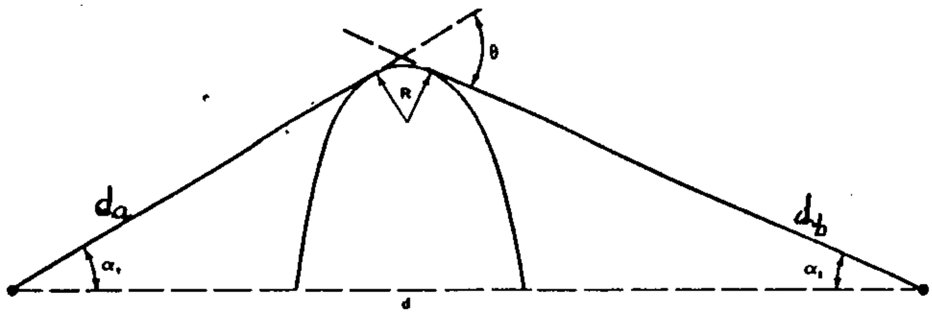
There is a ripple in the illuminated region, but the signal is essentially at its free space level if the clearance above the edge exceeds about 0.6ν. At the height of the edge there is a 6dB loss, and the signal decreases continuously farther into the shadow. Well in the shadow region the loss may be approximated as: $20 \log \frac{0.225}{\nu}$.

For paths with multiple knife-edges, the total loss is obtained by determinig the loss for each edge for a path between the two adjacent edges or to a terminal, and adding the losses obtained.

Method for double Isolated edges



However, in many practical circumstances obstructions cannot be considered as knife edges. For rounded hill tops the path may be modelled by fitting a cylinder to shape of each hill.



Rounded hills have significantly greater loss, as compared with a knife edge of equal height. The loss is given by:

$$A = J(\nu) + T(\rho) + Q(\chi)$$

$J(\nu)$ is the knife edge loss as described above, using a ν value determined from the parameters indicates in the diagram above:

$$\nu = 2\sin\frac{\theta}{2}\left[\frac{1\left(d_a+R\frac{\theta}{2}\right)\left(d_b+R\frac{\theta}{2}\right)}{\lambda d}\right]^{\frac{1}{2}}$$

$T(\rho)$ is the loss for incidence upon the curved surface, given by:

$$T(\rho) = 7.2\rho - 2\rho^2 + 3.6\rho^3 - 0.8\rho^4$$

$$\text{where } \rho = \frac{d_a+d_b}{d_a d_b} \div \left[\left(\frac{\pi R}{\lambda}\right)^{\frac{1}{3}} \bullet \frac{1}{R}\right]$$

and $Q(\chi)$ is the loss along the curved surface given by:

$$Q(\chi) = \begin{cases} \frac{T(\rho)}{\rho} & \text{for } -\rho \le \chi \le 0 \\ 12.5\chi & \text{for } 0 \le \chi < 4 \\ 17\chi - 6 - 20\log\chi & \text{for } \chi \ge 4 \end{cases}$$

where $\chi = \left(\frac{\pi R}{\lambda}\right)^{\frac{1}{3}}\theta \qquad \approx \sqrt{\frac{\pi}{2}}\,\nu\rho \text{ if } \theta << 1$

For multiple rounded hills a techniques similar to that for knife-edges is used.

16 GROUND WAVE

The section on reflection considered the resultant field produced by the combination of the direct and a ground-reflected wave. For many cases, particularly at VHF and highher frequencies, this is a quite adequate description. However it turns out that for a complete description of the resulant a third component is needed which is a function of the reflected path length, the elctrical properties of the ground, the polarisation and the frequency.

When the terminals are very close to the ground the direct and reflected rays cancel, leaving only this third surface wave component.

The surface wave propagates by virtue of currents whcih flow in the ground and does not require the presence of the atmosphere. Horizontally polarised signals are very heavily attenuated but vertically polarised surface waves provide the mechanism for MF and LF broadcasting and many other low frequency applications.

In this lecture the surface wave theory will not be given. It will only be remarked that the electric field is tilted slightly forward to an extent governed by the complex dielectric permittivity. The attenuation of wave depends on the tilt and is least for surfaces (particularly sea water) with large values of permittivity.

Typical values for the complex permittivity are:

ground type	frequency, kHz	
	200 (LF)	1000 (MF)
Sea (σ=5S/m; ε_r=70)	70 - j450 000	70 - j90 000
Good ground (σ=10mS/m; ε_r=10)	10 - j900	10 - j180
Poor ground (σ=1mS/m; ε_r=4)	4 - j90	4 - j18

The amplitude of the vertical component is given by:

$$|E_z| = \frac{300}{d}\sqrt{p}\,|F|$$ where p is the radiated power in kW, d is the path length in km, and E_z is the electric field in mV/m.

F is the attenuation function. Within a few wavelengths of the antenna, F is approximately unity and the field varies with the inverse distance. At greater ranges F becomes inversely proportional to distance and the field then varies as $1/d^2$. In a third region, where the curvature of the earth is important, the field strength decreases exponentially.

Although the atmosphere is not necessary for the propagation of the surface wave, the refractivity does modify the filed strength and the concept of effective earth radius does apply, although the factor varies with frequency. This is taken into account in the field strength curves given in ITU-R Recommendation P.368, and in the computer program GRWAVE.

When the permittivity along the path is not homogeneous, the field strength is governed in part by the those variations. In particular, when a wave which commences from a transmitter on land crosses a coast line and propagates over sea, there is a significant recovery in the filed strength. A number of computer based methods exist for calculating this effect, but a simple empirical developed by Millington provides a satisfactory method.

17 REFRACTION

The refractive index of the air, n, is very close to unity, even at the earth's surface. For practical purposes a refractivity unit, N, is used, given by:

$$N = (n-1)10^6 = 77.6\frac{P}{T} + 3.73 \bullet 10^5\frac{e}{T}$$

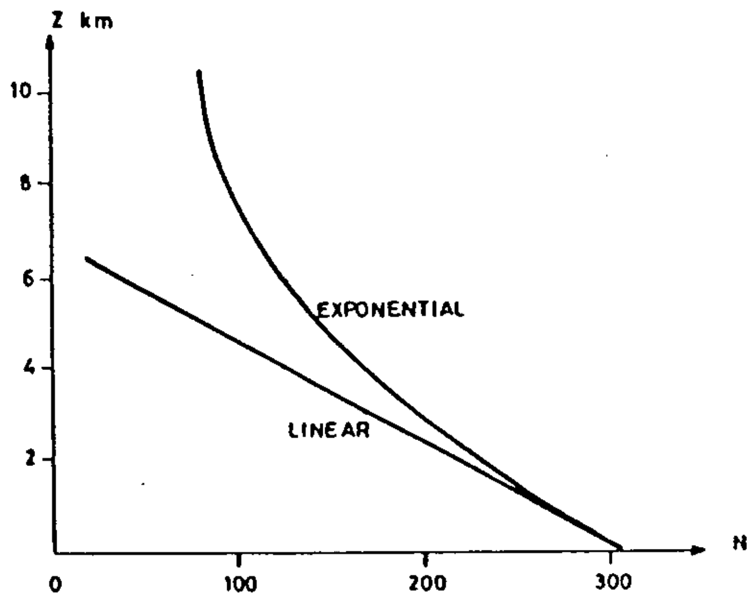
where P is the pressure (hPa or mb)
T is the temperature (K)
and e is the water vapour pressure (hPa or mb)

When the atmosphere is in equilibrium, the refractivity varies exponentially with height:

$$N = N_s e^{-\frac{z}{Z}}$$

where N_s is the value at the earth's surface,
z is the height,
and Z is the scale height (the height at which the refractivity falls to $\frac{1}{e}$ of its surface value.

The ITU-R reference atmosphere gives N_s =315 and Z=7.35km.



It is sufficient, in the first kilometre of the atmosphere, to assume a linear variation of N with height - $\Delta N \approx 40$ units per km.

i.e. $N \approx 315 - 40h$

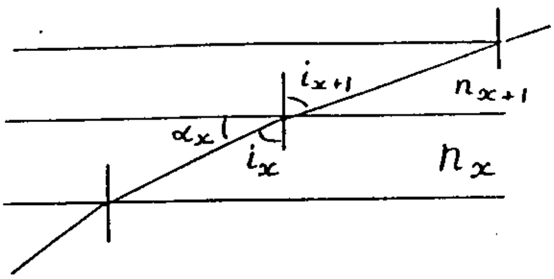
Maps of both N_s and ΔN are given in ITU-R Recommendation 453

For a horizontally stratified medium with varying refractivity, the rays are bent according to Snell's law:

$$n_x \sin i_x = \text{constant}$$

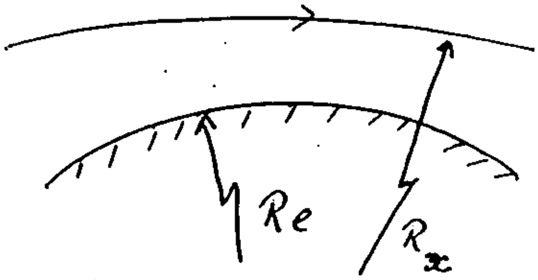
where i is the angle of incidence.
Working again in terms of the grazing angle:

$$n \cos \alpha_x = C$$



Differentiating: $\cos\alpha_x \frac{dn}{ds} - n \sin\alpha_x \frac{d\alpha_x}{ds} = 0$ and $\frac{d\alpha_x}{ds} = \frac{\cos\alpha_x}{n \sin\alpha_x}\frac{dn}{ds} = \frac{\cos\alpha_x}{n}\frac{dn}{dh} = \frac{1}{R_x}$

where R_x is the radius of curvature of the path of the rays.



For rays which are nearly horizontal, $R_x \approx 25{,}000$ km. , curving in a downwards direction. However the radius of the earth, R_e , is 6371km. For convenience, a geometrical transformation may be made to make either the ray-path, or the earth's surface, flat.

$$\frac{1}{R_x} = \frac{1}{25{,}000} = 40 \bullet 10^{-6}$$

$$\frac{1}{R_e} = \frac{1}{6{,}371} = 157 \bullet 10^{-6}$$

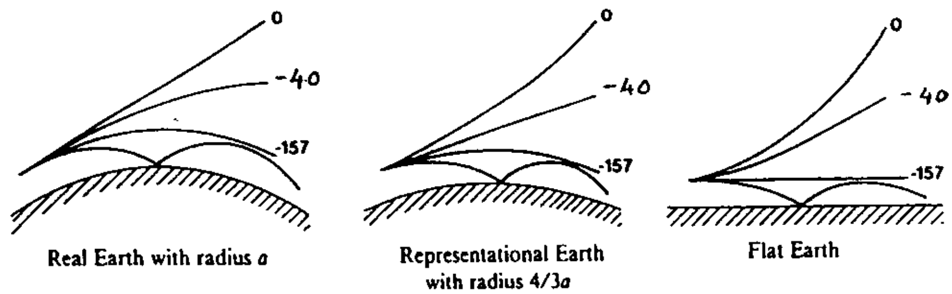
Reducing both curvatures by $40 \bullet 10^{-6}$ gives:
- a ray path with zero curvature
- an effective earth's curvature of $117 \bullet 10^{-6}$

This gives an effective earth's radius of 8547km, or approximately 4/3 of the actual radius. The effective earth radius factor is usually given as K.

Alternatively the curvature of the earth may be flattened, when the rays would have an upward curvature of $117 \bullet 10^{-6}$. This may be achieved mathematically by using a modified refractivity:

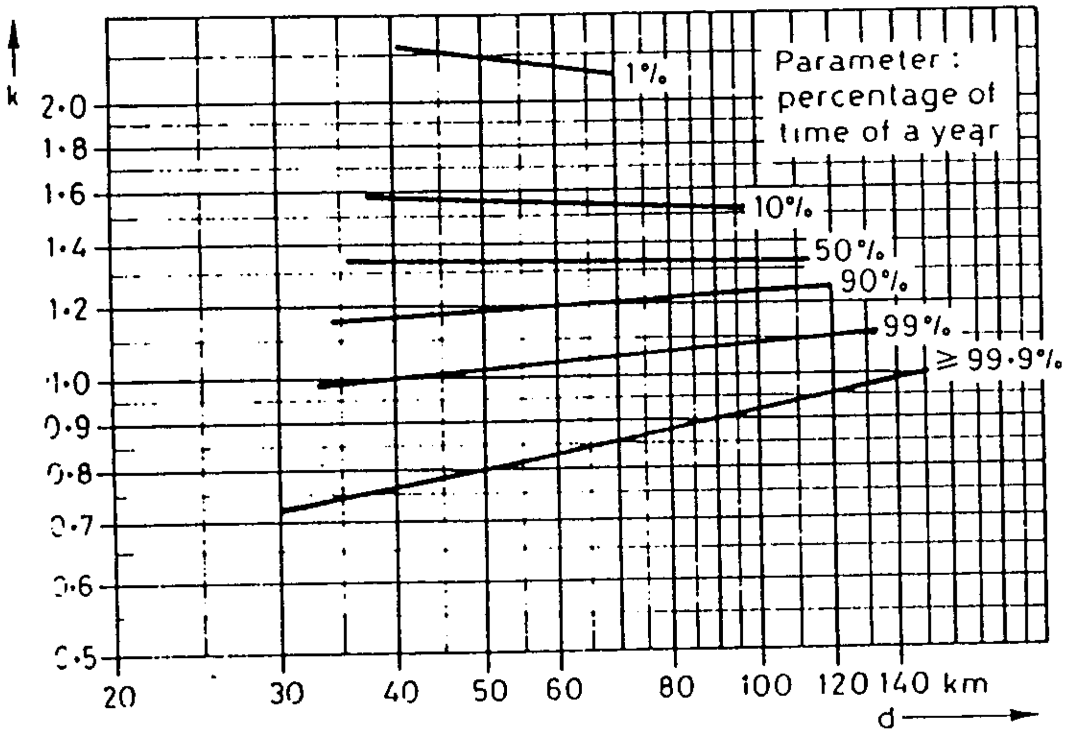
$$M = 315 + 117h$$

With actual meteorological conditions the refractivity, and the curvature of the rays, may often differ from the standard values. If the gradient is greater than -40N/km (i.e. closer to unity) ray paths are less curved and the conditions are said to be sub-refractive. Gradients smaller than -40N/km correspond to super-refraction; in particular if the gradient is smaller than -157N/km, which is a negative gradient for M, rays have a smaller curvature than the earth. Alternatively the earth may be said to have a negative effective radius. These are ducting conditions when rays may continue for a long distance by successive reflections from the earth's surface.

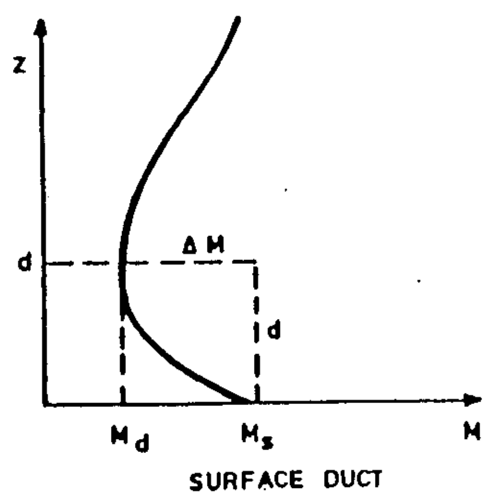


Various representations of a path starting in a horizontal direction. Parameter: three particular values of the refractive index gradient.

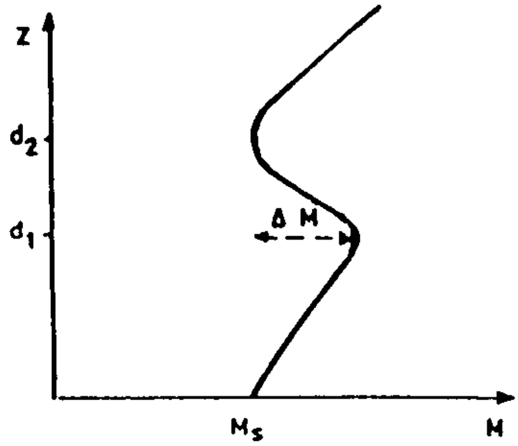
One way to model the statistical changes in the refractivity with differing climatic conditions is to use the variation of K. This may be used for example to determine with a ray-path will have sufficient clearance over an obstacle for the required percentage of time.



However, stratifications in the atmosphere, due to temperature inversions or changes in water vapour concentration, may lead to a substantial departure from an exponential variation of refractivity with height. Ducts may form in a layer extending up from the surface, with a normal atmosphere above, or elevated ducts may form due to a layer in the atmosphere. Such ducts are associated with particular meteorological and geographic conditions.



Typical types of duct are:



b) ELEVATED DUCT

- evaporation - surface duct over sea
  due to decrease in humidity with height

- advection - surface duct over colder surface (e.g. sea)
  due to winds blowing from warmer surface

- subsidence inversion - elevated duct in anticyclonic area
  due to slow settling of air from high level: the high air is warmer and drier

- radiation inversion - surface duct
  due to radiative cooling of surface after sunset

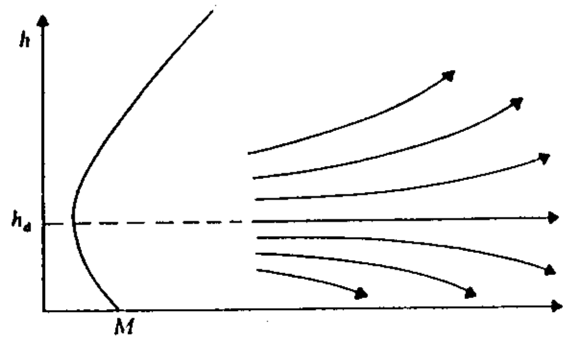
- fronts - complex refractivity changes

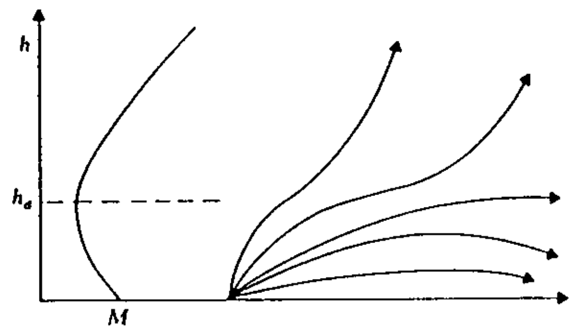
The diagrams to the right show some example ray paths in the presence of a surface duct.

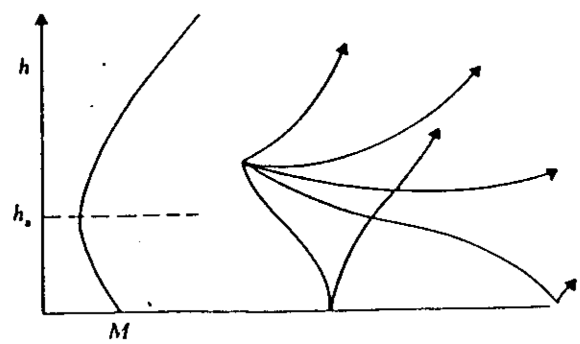
The upper diagram shows the paths of rays which start horizontally at different heights.

The centre diagram shows the paths of rays at different angles from a low antenna, well within the duct.

The lower diagram shows path from an antenna located above the duct.







18. The ionosphere

At heights in the atmosphere above about 70 km, the tenuous atmosphere is partially ionised by incoming solar radiation, which makes the atmosphere conductive and thus refractive. The density of ionisation varies with height, dependent on the atmospheric chemistry and the ionising potential of the incoming radiation, and is acted upon both by winds in the neutral atmosphere and by the Earth's magnetic field.

Maxima in the ionisation at about 100km, the E layer, and 250-400km, the F layer, provide reflecting layers which can reflect radio waves to long distances by multihop propagation between the ionosphere and the ground. The refractive nature of the layers varies with frequency and gives rise to maximum usable frequencies.

The ionosphere is very variable in location and time.

It is also subject to small scale irregularities permitting scatter propagation to about 2000 km.

Transionospheric propagation from satellite to ground is subject to polarisation (Faraday) rotation and to scintillation. The scintillation effects are greatest in the region of the magnetic equator and at high latitudes.

This very brief summary is included for completeness, but with the knowledge that the ionosphere and the propagation effects will be dealt with by other lecturers later in the week.

19 CHARACTERISTICS OF THE WAVEBANDS

In this section, consideration is given to each decade waveband, taking into account not only the propagation aspects, but also a little of the system considerations that apply, and the resulting radiocommunication usage of the spectrum (current and proposed, primarily in the UK). Here "radiocommunication" is taken in the broad sense of the ITU Radio Regulations, i.e. "any transmission, emission or reception of signs, signals, writing, images and source of intelligence of any nature by means of radio waves". Throughout the wavebands, considerations such as antenna design and bandwidth requirements are as important as those of propagation in determining this usage.

19.1 "ELF" (0.03-3000 Hz)

Atmospheric influences:	Ionosphere forms upper boundary to waveguide propagation.
Terrestrial influences:	Earth surface forms lower boundary to propagation.
System considerations:	Transmission of radio power requires enormous lengths of cable well earthed down at each end. Very low information rate.
Typical services:	Short (e.g. between divers) and long-range submarine communications. Ultra-stable worldwide communication. Mine and subterranean communication. Remote sensing under ground.

At Extremely Low Frequency (ELF), taken here to include frequencies up to 3 KHz, waves travel within the concentric-sphere cavity between the earth and ionosphere, and also propagate deep into the earth or sea. At 100 Hz, the attenuation in sea water is 0.3 dB/m (a third of that for a wave propagating in the earth-ionosphere waveguide. This becomes 1 dB/m at 1 kHz, and more than 30 dB/m between 1 MHz and the optical window). Attenuation through average ground is about a tenth of that through sea water, a hundredth for dry ground. However the transmission rate may be only about 1 bit/s, i.e. one of 1024 coded messages could be identified in 10s. In addition, antenna noise and atmospheric noise become problems, the latter having a background level due to lighting strokes from major centres around the world which is added to by very large impulses from any nearby lighting. There are no frequency allocations in this frequency range.

19.2 VLF (Myriametric waves, 3-30 kHz)

Atmospheric influences:	D region of ionosphere forms upper boundary to propagation.
Terrain influences:	Earth surface forms lower boundary to propagating wave.

System considerations:	Even 100 m height for antennas is only a small fraction of a wavelength. Difficult to make transmitter antennas directional. Only low data rates.
Typical services:	World-wide telegraphy with ships. Fixed services over long distances. Navigational aids (e.g. Omega). Electrical storm warning systems. Time standards.
Comments:	Very few channels are available, and it is difficult to design efficient antennas, so the band is reserved for a few high power transmitters with massive antenna systems. Frequencies are not allocated below 9 kHz.

At Very Low Frequency (VLF), a wave may travel over long distances guided between the D layer and the earth's surface. The wave is attenuated by loss of energy due to imperfect conductivity at the two surfaces, but only to the extent of about 2×10^{-3} dB/km at 10 kHz over sea, about 3×10^{-3} dB/km over land and 5×10^{-2} dB/km over ice. The D layer changes its height fairly regularly between 70 km by day and 90 km by night, and in view of the stability of the propagation conditions (and low attenuation), these frequencies are suitable for long-distance radio-navigation systems, such as Omega, and standard-frequency emissions. Owing to their depth of penetration, these waves are used for underground communication and underwater communication to submarines (especially the lower frequencies); also for geological surveying applications. There are no frequency allocations below 9 kHz.

19.3 LF (Kilometric waves, 30-300 kHz)

Atmospheric influences:	Still wave below D region up to about 100 kHz. Sky wave becomes distinct from ground wave above about 100 kHz, and gives a second contribution.
Terrain influences:	Ground wave follows earth curvature.
System considerations:	Even 100 m height for antennas is only a fraction of a wave-length. Difficult to make transmitter antennas directional.
Typical services:	Long-distance communication with ships. Fixed services over long distances. Broadcasting. Radio-navigational aids.
Comments:	Antennas dictate that only vertical polarisation is realistic.

At frequencies up to about 100 kHz in the Low Frequency (LF) band, the change in electron density from zero to maximum occurs within a distance small compared with a wavelength, and the layer may be regarded as an abrupt discontinuity acting as an almost perfectly reflecting surface. At frequencies above about 100 kHz, a sky wave may be separated from a ground wave, the ground wave showing more attenuation with distance at the higher frequencies. Fading occurs at shorter distances due to interference between the ground wave and sky wave, and at longer distances due to ionospheric fluctuations. The frequencies in this range are particularly suitable for medium-distance radio-navigation systems (Decca and Loran) and for radio beacons.

19.4 MF (Hectometric waves, 300-3000 kHz)

Atmospheric influences:	Sky wave separate from ground wave. Surface wave for short distances and lower frequencies. Ionospheric wave for longer distances, and upper frequencies, but also stronger at night, even at shorter distances.
Terrain influences:	Reflection.
System considerations:	Half-wavelength tower at 1 MHz is 150 m high, and quarter-wave folded unipole is 75 m high. Antennas can be directional using multi-elements. Inverted L or T aerial (height 5 m), or ferrite-loaded coil in receiver.
Typical services:	Broadcasting. Radionavigation. Some land-, maritime- and aeronautical mobile. Some fixed service.
Comments:	Antennas quite large, but quite efficient.

The ground wave becomes severely attenuated at Medium Frequency (MF), but can still provide usable signals. By day the sky wave is much absorbed in the lower region of the ionosphere, but after sunset there is less absorption, with the result that the sky wave becomes predominant even at fairly short distances from the transmitter. MF waves are largely employed for national broadcasting, a station of moderate power having a service radius of about 100 km (at 500 - 1500 kHz) provided by ground wave. Beyond this distance comes a zone in which fading occurs, and these stations are not normally receivable in daylight beyond a distance of perhaps 250 km over land or 1000 km over water. The ionospheric wave is strongly absorbed in the D layer during the daytime. During darkness, however, when ionisation is low, the ionospheric wave is only slightly attenuated, and reception by the E or F layers is possible over longer distances. The frequency band from 1.5 to 3 MHz is unsatisfactory for distant communication because of large absorption in the daytime and too little ionisation at night.

19.5 HF (Decametric waves, 3-30 MHz)

Atmospheric influences:	Ionospheric wave only beyond skip distance, especially 3-6 MHz. Surface wave only at short distance (but more over sea), especially 6-30 MHz.
Terrain influences:	Reflection (and scatter).

System considerations:	Log periodic array antennas (vertical or horizontal), vertical whip antennas, or horizontal dipole arrays.
Typical services:	Fixed point-to-point. Land (within skip distance), maritime and aeronautical mobile. Long-distance broadcasting.
Comments:	Beamed communication services.

Except at very close ranges to the transmitter, sky waves provide the principal propagation mechanism at High Frequency (HF). Frequencies are selected for each particular requirement by means of "maximum usable frequency" predictions. The region between 3 and 6 MHz is used mainly for surface-wave communication within the limits of a continent, while the part between 6 and about 30 MHz (depending on time in sunspot cycle) is used for ionospheric-wave long-distance intercontinental services. Within the skip distance, the ground wave is used for mobile land communications. Communication to great distances, including all round the world, is possible by successive ionospheric reflections.

[illegible] VHF (Metric waves, 30-300 MHz)

Atmospheric influences:	Refraction and reflection by refractive index irregularities producing transhorizon paths. Some Sporadic E and ionospheric-scatter transhorizon effects, and Faraday rotation and ionospheric scintillation on earth-space paths.
Terrain influences:	Screening by major hills, but some diffraction into valleys. Surface reflections off large areas (sea, lakes, flat ground) causing multipath effects on line-of-sight paths.
System considerations:	Multi-element dipole (Yagi) antennas, or slots, helixes, etc. Several MHz per radio channel where required.
Typical services:	Sound and (outside UK) television broadcasting (to about 100 km). Land, aeronautical and marine mobile. Portable and cordless telephones. Aeronautical radionavigation beacons.
Comments:	Line-of-sight terrestrial transmissions and somewhat beyond.

At Very High Frequency (VHF), refractive index effects in the troposphere become important, e.g. reflections from low layers causing multipath effects (often much less than multipath reflection effects from the earth's surface). Reflections from higher layers may cause transhorizon interference. Ionospheric effects are very limited, but Sporadic E layer reflections in the ionosphere can cause transhorizon interference, at lower frequencies, up to distances of the order of 200 km at 60 MHz.

The surface wave is rapidly attenuated at VHF , and communication is by the space wave within the optical horizon, and slightly beyond. Diffraction allows short-range reception into built-up areas, though mobile systems are subject to screening by hills and to multipath effects caused by scatter or reflections off obstacles. However, the diffraction loss around hills is less than for UHF. In general the precise prediction of signal level is not possible, and it is necessary to specify the deviation from the calculable median expressed for a given percentage of locations and percentage of time.

19.7 UHF (Decimetric waves, 300-3000 MHz)

Atmospheric influences:	Refraction effects. Reflection from layers at lower frequencies. Ducting possible at higher frequencies. Refractive index fluctuations - forward scatter beyond horizon above 500 MHz.
Terrain influences:	Screening by hills and collections of buildings.
System considerations:	Multi-element dipole (Yagi) antennas. Wide bandwidths available. Parabolic dishes for higher frequencies.
Typical services:	Television broadcasting. Some aircraft navigation, landing, etc. Most surveillance and secondary radars. Fixed (terrestrial point-to-point). Mobile manpacks and vehicles. Satellite mobile. Satellite tracking, telemetry and command network. Cellular radio. Cordless telephones.
Comments:	Line-of-sight and very slightly beyond. Also tropospheric scatter transhorizon for higher frequencies.

There are more severe screening effects from obstacles at Ultra High Frequency (UHF) than at VHF. At frequencies above about 500 MHz, tropospheric scatter provides a limited degree of reception at ranges up to about 300-600 km. Wider bandwidth per channel and more channels per waveband is attractive for television, as well as higher gain antennas. High gain antennas and waveguides practical for radar at higher frequencies, and still free from rain effects at 3 GHz, though some ducting problems.

19.8 SHF (Centimetric waves, 3-30 GHz)

Atmospheric influences:	Rain, hail, snow, etc. - very variable attenuation with frequency. Refraction and ducting. Refractive index fluctuations - scintillation.
Terrain influences:	Diffraction around buildings. Screening by hills. Scatter and reflection off elements of buildings and terrain. Sea reflection depends on wave height.
System considerations:	High-gain parabolic dishes and horns. Waveguides. Large numbers of channels on each carrier.

Typical services:	Fixed (terrestrial point-to-point carrying multiple voice channels and several television channels). Fixed satellite. Radar. Mobile services. Future satellite mobile. Remote sensing from satellites.
Comments:	Utilization is still being increased, even above about 15 GHz (where atmospheric effects are worst).

SHF offers large numbers of wideband channels on each carrier, with opportunities for versatility in use of channels for multipath voice, TV or high speed data. Extensive terrestrial line-of-sight networks have developed as well as Earth-space routes, usually with frequency sharing between services. Ducting on transhorizon paths may be a severe cause of interference, and multipath effects may cause severe fading on near-horizontal paths. Site-shielding from interference signals may employ hills or even groups of buildings (according to frequency). Absorption by rain, fog and cloud, as well as atmospheric gases, becomes rapidly a very severe constraint at higher frequencies for system reliability (see Figure 1.2), both on terrestrial and earth-space paths.

1.9.3 EHF (Millimetric waves, 30-300 GHz)

Atmospheric influences:	Rain, hail, snow, etc., - very severe attenuation and scatter. Cloud, mist - very variable attenuation with frequency. Dust, smoke - some effect. Refractive index gradient. Refractive index fluctuations - scintillation. Absorption by atmospheric oxygen and water vapour.
Terrain influences:	Screening by objects extending over more than a few decametres (e.g. buildings).
System considerations:	Paraboloid dish antennas become small.
Typical services;	Short line-of-sight communications - both fixed and mobile. Some satellite applications. Remote sensing from satellites.
Comments:	Frequency band developing as equipment elements become available, planning around atmospheric effects. Allocations for terrestrial and satellite services up to 275 GHz.

The Extremely High Frequency (EHF) region of the spectrum is now being developed as new technology becomes available, largely as a result of requirements of radio astronomers and for military purposes. Precipitation, clouds and fog, and atmospheric gases become a severe problem, though some "windows" remain (see Figure 1.2) In metropolitan areas, high-capacity point-to-multipoint private-user fixed-link systems are appropriate to carry data, speech and video between customer buildings and the nearest network node. Mobile high-capacity systems may operate within public places (e.g. shopping areas and travel termini), domestic and office buildings (cordless telephones) and public transport. Radar systems have particular merits at EHF. Remote sensing of the surface and the atmosphere feature strongly in this part of the spectrum, both for research and operationally. Applications are considered fully in Chapter 19.

19.10 Sub-millimetric waves (300-3000 GHz)

Atmospheric influences:	Rain, hail, snow, etc. - very severe. Cloud, mist - very severe. Dust, Smoke - very severe. Localised refractive index gradient (mirage). Refractive index fluctuations - scintillation. Absorption by atmospheric gases.
Terrain influences:	Screening by objects extending over more than a few metres (e.g. large trees).
System considerations:	Mirror or lens antennas.
Typical services:	Possibly short line-of-sight communications.
Comments:	Propagation restraints to communication are extreme, except for very short paths. Equipment is severely lacking, since requirement is very limited. Remote sensing is a user of this part of the spectrum.

19.11 Far-infra-red waves (3-30 THz)

Atmospheric influences:	Rain, hail, snow, etc. - very severe. Cloud, mist - very severe. Dust, smoke - very severe. Localised refractive index gradient (mirage). Refractive index fluctuations - scintillation. Absorption by atmospheric gases.
Terrain influences:	Screening by objects etending over more than a few decimetres (e.g. small trees).
System considerations:	Mirrors and lenses for antennas.
Typical services:	Short range and also indoor applications (e.g. to headsets in auditorium).
Comments:	Little communication use at present.

19.12 Near-infra red waves (30-430 THz)

Atmospheric influences:	Rain, hail, snow, etc. - Very severe. Cloud, mist - very severe. Dust smoke - very severe. Localised refractive index gradient (mirage). Refractive index fluctuations - scintillation. Carbon dioxide absorption.
Terrain influences:	Screening by objects extending over more than a few centimetres (e.g. posts, leaves).

System considerations:	Mirrors or lenses for antennas. Lasers.
Typical services:	Intruder alarms. Remote control systems (e.g. TV/Video recorder, etc.).
Comments:	No communication potential seen at present.

17.13 Optical waves 430-860 THz)

Atmospheric influences:	Rain, hail, snow, etc. - very severe. Cloud, mist - very severe. Dust, smoke - very severe. Localised refractive index gradients (mirage). Refractive index fluctuations - scintillation.
Terrain influences:	Screening by objects extending over more than few millimetres (e.g. cables).
System consideration:	Mirrors and lenses for antennas, very directional. Lasers.
Typical services:	Tellurometry. Line-of-sight links.
Comments:	These wavelengths are used a little for short line-of-sight communication in the atmosphere.

20 APPLICATIONS

The effects of the atmosphere and the losses due to diffraction are combined in propagation prediction procedures used as a basis for system planning. Calculations of the diffraction losses over hills, etc., undertaken with an effective earth radius factor, K= 4/3, can provide a good assessment of average conditions. For other time percentiles, other K factors may be used as described above. Complete prediction procedures must take account of the effects of rain, and other hydro-meteors at the higher frequencies; of the attenuation due to atmospheric gases at millimetric wavelengths; of the effects due to the ionosphere at the lower frequencies for terrestrial paths, and at all frequencies for earth space paths; and of scatter from irregularities in the troposphere and from the surfaces of buildings, etc. The user and service requirements are most important, and prediction procedures must provide information in an appropriate form.

It is important to take account of the variability of the signal with time and with location; loosely this may often be described as "fading". Variations occur over all time scales - with season, weather, time of day, and within a short period such as a few minutes. Long-term fading often has a log-normal distribution (a normal distribution of the signal level when this is expressed in decibels). Seasonal and climatic factors may be taken into account by predicting for the "worst month" of the year. Short term fading may be adequately modelled as having a Rayleigh distribution. There are similar considerations for variations with location for broadcasting and mobile services. The variability over an area of, say, a square of a few hundred metres, will be found to have a log-normal distribution. Within a small area, such as a section of a street, etc., the distribution may be Rayleigh. However, when the received signal is a combination of both a direct component and other diffracted and scattered components, the best model would be a Rician distribution. These aspects need to be taken into account when specifying the service requirement. The useful statistical distributions are described in Annex B.

For point-to-point applications, knowledge should be available of the terrain height profile along the great circle path, and some information may also be available about surface features such as buildings and trees. With such information a full diffraction calculation may be made. For mobile and broadcasting purposes the service has to be provided over an area, and the precise details about the location of the mobile terminal or broadcast receiving station will not be available. In these cases an area coverage prediction, which may be obtained by considering a number of terrain height profiles along radials from the transmitting or base station, must be modified to take account of the statistics of the likely locations of the receiver, etc. In some cases for initial planning, terrain information may not be available and then simple procedures are needed to give a first assessment of system performance.

One important consideration is the desired overall reliability of the prediction itself. There are many unknowns and the path and meteorological parameters have to be simplified for inclusion in the prediction models. In addition, many of the prediction methods are, either as a whole or in part, empirical, based on measurement campaigns and analysis that seeks to fit the results to some physical model so as to provide the basis for extrapolation to paths where measurements have not been made. This process introduces uncertainties that may be expressed as a statistical confidence level. For most applications it is sufficient to make no allowance for statistical confidence. At this 50% confidence it may be expected that half of a large number of actual results would be higher than the prediction, and half lower. Where very good reliability is needed, an allowance may be made to give a greater confidence. In many cases however this would result in very conservative planning, the use of uneconomically high powers, and poor spectrum utilisation. Choices have to be made, preferably with a good understanding of the basis of the prediction, and of the risks if the prediction is in error.

Digital modulation methods are now being widely introduced for all services. Digital systems will still require a specified signal to noise, or interference, ratio, although one of the benefits of digital systems is they may continue to operate in rather poor conditions. However, digital modulation will be affected by inter-symbol interference caused by the time delay associated with multipath propagation, as well as by changes of phase and frequency, which may be associated with movement, either in the atmosphere or of a terminal or a reflector (e.g. a moving car or plane) along the path.

20·1 . POINT-TO-POINT PREDICTIONS

ITU-R Recommendation 452-5 "Prediction Procedure for the Evaluation of microwave Interference between stations on the Surface of the Earth at frequencies above about 0.7GHz" is currently the best method, although some parts of it are still being reconsidered for further improvement. The method takes account of all the relevant propagation features, although as it is primarily concerned with long distance interference it does not presently include scatter from buildings, etc. nor the multipath effects for digital modulation.

ITU-R Recommendation 530-4 is appropriate for the design of terrestrial line-of-sight microwave systems, Such systems are always designed with clearance above terrain features and a simplified assessment of diffraction is then suitable. It may be expected that the radiation patterns of the antennas will be sufficiently narrow that multipath from off-great-circle will be insignificant. Multipath may occur due several paths in a complex atmosphere, but the time delays experienced will be very small for these mechanisms and will not affect system performance for the signalling speeds usually in use.

20.2 . AREA COVERAGE PREDICTIONS

Methods similar to those of Recommendation 452, may be used for area coverage purposes, with some simplifications since some of the propagation modes considered in the Recommendation are unimportant at VHF and UHF. The technique commonly used in computer based methods is to trace terrain profiles, from high resolution digital maps, at intervals of, say, 1° in azimuth and to undertake predictions along each radial. Map resolutions in the horizontal plane of, say, 50m or better are now in use in some countries. In such cases the major uncertainty in the process may be in the features that cover the terrain, both natural and man-made. While high resolutions may be important for small-cell mobile and personal communication systems, for large are coverage schemes such as broadcasting, map resolutions of 500m may be quite suitable.

However, where the terrain irregularities are not extreme, much may be done using techniques such as those given in ITU-R Recommendation 370-5: "VHF and UHF propagation curves for the frequency range from 30MHz to 1000MHz" and this will be suitable for initial planning for frequency sharing and network design. Further improvements may be made in some cases by using the supplementary information in ITU-R Report 239-7: "propagation statistics required for broadcasting services using the frequency range 30 to 1000MHz". An extension of the method, particularly for lower antenna heights, is also given in ITU-R Report 567-4 "propagation data and prediction methods for the terrestrial land mobile service using the frequency range 30MHz to 3GHz".

The method essentially gives sets of field strength curves, for differing antenna heights and time percentiles, etc. The basic curves are for a specified terrain roughness. This is defined as the inter-decile height range, Δh, which occurs between 10 and 50km from the transmitter at the azimuth being considered. Corrections are given for other values of Δh, and other percentiles. The curves assume a receiving antenna height of 10m; corrections are given for lower antenna heights.

21. Planning and Coordination

21.1. Lattice Planning

For a given S/N ratio it will be possible to define a maximum range at which the service is available. At longer ranges the signal continues to reduce until it reaches a level just at the level when the S/I protection ratio will be achieved for a similar co-channel system.

Thus the distance between two co-channel stations to permit satisfactory operation will be the sum of the coverage distance and the interference distance. Three similar stations may be accommodated at the vertices of an equilateral triangle, and broad frequency reuse planning may be undertaken using a triangular lattice. The gaps between the coverage circles may be filled by applying similar but off-set lattices for other frequencies in the band, allowing for the minimum distance obtained from a consideration of the protection ratio for adjacent channels. This outline triangular plan would then be modified for the practical aspects of the geography of the area. This process has been used for the planning of broadcast networks in Europe.

For the FM sound broadcasting service at VHF, an ITU-R Recommendation defines the minimum usable field strength for a stereophonic service as 54 dB (μV/m) in rural areas. It also defines a radio-frequency co-channel protection ratio against steady interference as 45 dB. Thus interference at the edge of the service area should not exceed 9 dB (μV/m).

ITU-R Recommendation 370 indicates that with a transmit antenna height of 150 m, these field strengths would be obtained at 45 and 250 km (over land for 10% of the time) with 1 kW erp and 78 and 330 km with 10 kW erp.

Using the principles of lattice planning, this means that the frequency can be reused beyond 295 km for 1kW and 408 km for 10 kW; the ratios of reuse distance to coverage range are 6.5 and 5.2.

The gap between these co-channel coverage areas would be filled using other frequencies, but taking account of the protection required for different frequency offsets. For example at 200 kHz frequency difference the protection ratio is 7 dB, and the frequency reuse distance in this case for the two powers is 110 and 190 km.

For mobile services the corresponding figures are much smaller, with median field strengths of about 18 dB (μV/m) at 100 MHz for hand portable stations, dependent on circumstances and the external noise levels, with co-channel protection ratios of about 7 dB for FM with 12.5 kHz channels.

21.2. Cellular Planning

To determine how many frequency channels would be needed to provide complete coverage of an area, the whole area could be considered as being covered with a system of just overlapping circular coverage areas. An approximation to this is to envisage the area as being covered with a system of hexagonal tessellations. A lattice, distorted if necessary, may be placed over these coverage areas to determine the frequency reuse pattern and thence the number of channel assignments necessary for complete coverage.

It should be emphasised that this type of spectrum requirement assessment does not purport to be sufficient for coverage planning purposes. In practice, particularly for mobile services with low antenna heights, individual coverages will be extremely distorted and should be planned using appropriate models for reflection, diffraction and scatter. In addition various techniques of cell sectoring, etc., are used to improve the frequency utilisation. However the kind of planning discussed here is suitable for determining the spectrum requirement and the statistics of interference.

Groups of hexagonal cells can be made to nest together for clusters of 3,4,7, 9, 12, etc cells. If the required coverage, r, is assumed to extend to the point of a cell from a central transmitter, then the frequency reuse distance obtained is $2\sqrt{3}$ r for a 4 cell cluster, $\sqrt{21}$ r for 7 cells and 6r for 12 cells, etc. These reuse ratios may be compared with the reuse distances obtained from the field strengths and the propagation prediction to determine the cluster size needed.

These techniques for determining spectrum needs may be extended to cases where the transmitter power, antenna height, terrain features, vary with location and the propagation characteristics vary with frequency or time (e.g. the effect of the night time sky wave at MF). However simple lattices then become of little use and the planning would be done with more complex computer based models.

21.3 Planning and coordination techniques.

The ITU Radio Regulations contain provisions aimed at maximising frequency reuse.

For example:

> RR 339: Members shall endeavour to limit the number of frequencies and the spectrum space used to the minimum essential to provide in a satisfactory manner the necessary services. To that end they shall endeavour to apply the latest technical advances as soon as possible
>
> RR340: Members shall undertake that in assigning frequencies to stations which are capable of causing harmful interference to the services rendered by the stations of another country, such assignments are to be made in accordance with the Table of Frequency Allocations and other provisions of these Regulations.
>
> RR341: Any new assignment or any change of frequency .... shall ....avoid causing harmful interference
>
> RR342: Administrations of the Members shall not assign to a station any frequency in derogation of either the Table of Frequency Allocations .... or other provisions.......... , except on the express condition that harmful interference shall not be caused ......

Thus, apart from low power and other exceptions, the use of the spectrum is governed by international procedures of planning and coordination for frequency use.

There is a hierarchy of procedures.

- frequency block allocations - as discussed earlier
- *a-priori* frequency assignment plans
- allotment plans
- modification procedures
- maximum technical parameters
- frequency coordination
- technical assessment
- field trials

21·3·1. Assignment planning

Assignment plans may be made for an allocation block, where the requirement is new or the current utilisation is modest. Although assignment plans may be made to rearrange usage of an occupied band, the practical problems of implementation and transition will lead to substantial difficulties.

In fact assignment planning has been mainly used for broadcasting services.

1.1 Terrestrial broadcasting

LF and MF broadcasting in Europe was planned in 1974. The ionospheric night time sky wave, and the high powers substantially reduced the possibilities for frequency reuse. Frequency channels are 9 kHz wide, and the assigned frequencies for the A3E transmissions are at multiples of 9 kHz, to facilitate the design of synthesised receivers.

The regional agreement for VHF and UHF broadcasting was reached at Stockholm in 1961, based on the requirements for coverage and location specified by the Administrations.

The WARCs in 1984 and 1987 sought to prepare plans for HF broadcasting. In this case the situation is very complex due to the variability of ionospheric propagation, so that a range of assignments is required to ensure a reliable service over the scheduled broadcast period. The planning is currently done by a coordination procedure. Further efforts may be made to plan these bands, when more spectrum becomes available and when R3E modulation is introduced.

21·3.2. Satellite broadcasting

The essential part of RR 36, which defines the (terrestrial) broadcasting service, limits the service to "transmissions intended for direct reception by the general public". RR 37, which defines the broadcasting-satellite service (BSS) is broader, to take account of community antenna receiving systems (blocks of flats, hotels, arguably cable networks), as follows:

> "a radiocommunication service in which signals transmitted by space stations are intended for the direct reception of the general public. In the BSS the term "direct reception" shall encompass both individual reception and community reception".

RRs 123 and 124 define these latter terms as follows:

> Individual Reception. "The reception of emissions from a space station in the BSS by simple domestic installations and in particular those possessing small antennas."
>
> Community Reception. "The reception of emissions from a space station in the BSS by receiving equipment, which in some cases may be complex, and have antennas larger than those used for individual reception, and intended for use by a group of the general public at one location or through a distribution system covering a limited area."

The BSS has been allocated frequency bands for transmissions from the satellite to the earth but not for the link from the programme source, on the Earth, to the satellite. This upward link is called a "feeder link", which RR 109 defines as:

> "a radio link from an earth station at a specified fixed point to a space station, or vice versa, conveying information for a space radiocommunication service other than for the FSS"

Feeder links for BSS satellites are permitted to operate in up-link frequency allocations of the FSS. Frequency bands were allocated to the FSS by WARC-79 specifically for this purpose.

It should be noted that satellites operating in FSS allocations, intentionally or not, already provide extensive television facilities which cannot readily be distinguished from BSS. Some of these systems require rather large dishes for reception and so may be more usually associated with community reception. However the use of high power satellites, together with the introduction of antenna feed amplifiers with very good noise figures (LNBs) has made possible the introduction of systems such as Astra.

21.4.1. TV down-links

As will be considered later in these notes, it has been agreed that the international acceptance of the right for the BSS stations of one country, to the use of a radio frequency assignment without unacceptable interference shall depend, not on priority of registration in the MIFR but on adherence to an agreed frequency assignment plan. This fact has a major effect on sharing of allocations with other services.

Allocations are made for BSS in the international frequency allocation table at about 12 GHz. These bands are also allocated to terrestrial fixed and broadcasting services with primary status and to the mobile service but with regional variations as to allocation status, and in Region 2 the FSS is also allocated this band. There is a detailed frequency assignment plan in Appendix 30 to the Radio Regulations which, for Region 1 assigns five channels to each country. It has to be said that the frequency plan was prepared at a time when low noise receivers were not envisaged and the process demonstrates the dangers of undertaking frequency planning before the technology and the market requirement is clearly defined. Programmes from the Astra system, using frequencies in the adjacent FSS band showed the market potential for BSS and extensions to that system will now also be using frequencies in the BSS band, although not at the orbit locations originally envisaged.

It remains to be seen whether a future planning conference will attempt to plan the bands, or whether the coordination process will be extended. When Astra transmissions were first introduced interference into domestic installations from terrestrial fixed services was anticipated. This has not been a major problem, perhaps due to the siting of the DBS antennas on the sides and generally rather low on buildings.

Some other bands have also been allocated for satellite television broadcasting, but will not be discussed here.

21.4.2. Sound-radio down-links.

The allocations listed above were made primarily for TV service to fixed domestic or community stations and all planning to date assumes that receiving antennas of considerable gain will be used. There is nothing to prevent a country using these bands for broadcasting sound radio programmes by satellite, provided that interference from the sound broadcast is not worse than TV would cause and provided that the protection required from interference is not made more critical. However the allocations above could not be used for sound broadcasting by satellite to low-gain receiving antennas, such as might be used on motor cars.

A frequency allocation has been made from 1452 -1492 MHz for digital audio broadcasting, although in the UK and other countries this has secondary status until the year 2007. Plans are well in hand for the introduction of a terrestrial digital audio broadcasting service at VHF using OFDM modulation. It seems likely that there will be a wish to use a compatible modulation system for a satellite service.

21.5 Frequency assignment planning for the BSS

Broadcast radio services are received by millions of laymen and technical parameters of broadcasting systems, as perceived by the public, must be kept stable over many years in order that the public should not be put avoidably to cost in accommodating changes. In the terrestrial broadcasting service this stability has been provided, for example, by frequency assignment plans, and by the use of signal processing methods and modulation methods which change very little from decade to decade, and by ensuring, wherever possible, that new types of transmission are receivable within limits, with old receivers (for example, consider the general adoption of colour TV systems which were receivable, as a black-and-white picture, on monochrome receivers.)

A WARC was convened in 1977 to draw up frequency assignment plans for use in the 12 GHz BSS bands which were available for individual reception, namely 11.7 - 12.5 GHz for Region 1 and 11.7 - 12.2 GHz for Regions 2 and 3. There was objection to this conference from some Region 2 countries, and it was maintained that there had not been enough progress in the development of the equipment for satellite broadcasting to allow good decisions to be taken about practical parameters for systems. It was also argued that the prospect of setting up BSS system was still remote. The USA also considered that the use of a priori methods of planning in radio regulation was inefficient. The outcome was that plans were drawn up for Regions 1 and 3. Some of the technical principles of the plan were held to be applicable to Region 2 also, but the drawing up of a plan for Region 2 was put off to a later conference at an unspecified date. The Region 1 and 3 Plan was incorporated into the RR as Appendix 30.

The down-link plans for all three Regions have been merged into a single text, a revised version of RR Appendix 30, and the feeder link plan has become RR Appendix 30A.

The whole process of using *a priori* planning for the BSS in frequency bands shared with other services which have nominal equality of allocation but which are not regulated by assignment planning is itself complicated. The essence of the process is as follows.

Stage 1. The services which share the down-link frequency allocation must be prevented from establishing frequency assignments with a right to use the band through priority of registration in the MIFR, to the exclusion of the BSS. One way of doing this is to down-grade primary sharing allocations to "permitted" status in advance of drawing up the plan. Assignments for these services cannot then achieve full status, equivalent to those of services with primary allocations, until after an assignment plan has been drawn up. A different way was used at 12 GHz, namely to add footnotes to the ITU frequency allocation table which had the same effect. Thus footnote RR 838 reads:

"in the band 11.7 - 12.5 GHz in Regions 1 and 3, the fixed, fixed-satellite, mobile except aeronautical mobile and broadcasting services, in accordance with their respective allocations, shall not cause harmful interference to broadcasting satellite stations operating in accordance with the provisions of Appendix 30."

Stage 2. All countries are asked to state what the requirements are for the BSS in the plan being prepared, in terms of number of channels and service area.

Stage 3.

(a) The performance objective for service to the end user is defined, assuming that equipment is up to agreed standards of performance. This objective would be expressed in terms of demodulated-signal-to-(noise plus interference) and would be split between feeder link and BSS link and probably as between noise and interference.

(b) Since it is not feasible to match the satellite antenna beam footprint exactly to the required service area, it would be necessary to decide how to relate the - 3 dB footprint to the service area. The in-beam gain of each satellite transmitting antenna can then be calculated. The minimum on-beam gain of the users' receiving antenna, the noise factor of the users' receiver and the out-of-beam gain roll-off characteristics of both the satellite transmitting antenna and the users' receiving antenna should be specified. It may be necessary to specify minimum standards for cross-polar rejection of both antennas, in-beam and off-beam, as well.

(c) Knowing the service areas to be covered, the minimum relationship between service area and satellite antenna beam cross-section, the gain of both antennas and the out-of-beam characteristics of both antennas, it is possible to prepare a matrix showing the isolation provided by the antennas between every pair of service areas as a function of satellite orbital position.

(d) It is necessary to determine a frequency channel arrangement and a policy on down-path pfd (for example, is the pfd to be a uniform value at the edge of the service area for all countries, or should consideration be given to climate). It is also necessary to select the type of modulation to be used, standard carrier parameters, picture standards, receiver selectivity standards etc. The isolation provided by channel separation can then be calculated.

Stage 4. An assignment plan is then prepared, assigning channels and orbital locations to all the requirements in such a way that the isolation provided by antennas, plus the isolation provided by channel separation, permits the performance objective to be attained. If this is not possible it will be necessary to

improve the efficiency with which service areas have been coupled with orbital positions and channels,

make antenna performance standards more stringent

make more stringent the minimum requirements for some of the various factors which determine the isolation provided by channel separation

accept worse performance, or

reduce the requirements

and reiterate the planning process until a feasible plan is achieved and agreed.

Stage 5. A feeder link plan must then be prepared. The arrangement of channels may be the same as for the down-link plan but the determination of emission parameters may well be a matter of some complexity.

Stage 6. Three sets of procedures are then required for the operation of the plan, namely,

(a) a procedure for amending the plan, for use when a country's requirements have changed, but respecting the rights of other countries holding assignments in the plan.

(b) a procedure for registering planned assignments to the BSS in the MIFR once they have been brought into service.

(c) a procedure for registering in the MIFR assignments to stations of the other services with nominal equality of allocation, and in addition, BSS assignments which are extra to the plan, subject to the protection of planned assignments.

Note that several of these stages may be complicated by Regional differences in frequency allocations.