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**FOURTH ICTP-URSI-ITU(BDT) COLLEGE ON RADIOPROPAGATION:
Propagation, Informatics and Radiocommunication System Planning**

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The Application of Radiopropagation Studies to System Planning

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1. INTRODUCTION

The whole basis of radio communication depends upon the phenomenon of electromagnetic-wave propagation. In free-space, far from the influence of the earth and its atmosphere, propagation is rather simple and it is only necessary to consider the spreading of the radiated power as it extends from a transmitting source into the surrounding space. However closer to the earth's environment the propagation of electromagnetic - in our case, radio - waves is strongly affected by the ionosphere, the troposphere, the earth's surface, and the presence of man-made and natural obstacles. The effects to be considered include reflection, refraction, diffraction and scatter.

Propagation considerations are a major factor in system planning. However, it is also important to consider the impact of noise (both the external noise arriving via the antenna and the internal receiver noise), interference (both from other radio transmissions and due to spurious emissions from other equipments), and the specified requirements of the radio service. These requirements will include specifications for signal-to-noise and signal-to-interference ratios for given percentages of time and/or location, as well as specifications where appropriate for the time and frequency shifts and spreading of the received signal. Such system deaign aspects are outside the scope of this group of lectures.

At the lower frequencies, below about 30 MHz, the ionosphere has a strong effect. Propagation is possible to long ranges, even to the antipodes, due to multiple reflection and refraction in the ionosphere, but the ionosphere is highly variable and considerable attention must be paid to frequency management so as to ensure moderately reliable communications.

At higher frequencies, propagation over paths with terminals near the earth's surface is essentially limited to the line-of- sight, but with important extensions beyond the geometrical limit due to refraction in the troposphere. The density of the atmosphere decreases with height so that there is a corresponding decrease in the refractive index with height, resulting in a characteristic curvature of radio wave paths to just beyond the horizon. However, the troposphere itself is subject to variation and stratification so that the propagation characteristics vary with the weather.

In addition, the effect of diffraction is important, both around the bulge of the spherical earth, leading to useful and reliable ground-wave modes at the lower frequencies, and over and around smaller scale hills and obstacles at the higher frequencies.

At frequencies above about 10 GHz, the effect of the atmospheric gases themselves become important with attenuation of signals due to absorption near the resonance spectrum lines of Oxygen and water vapour.

Scatter is also significant from particles and atmospheric structures with dimensions similar to, or smaller than, the radio wavelength. The most important aspect of this is rain. There is significant scatter, in all directions, from the drops in rain for frequencies above about 5 GHz, and there is some associated attenuation. Other hydro-meteors, such as snow, ice and hail may also give rise to scatter propagation and changes in polarisation.

Scatter and attenuation, as well as increased noise in the radio system due to static discharges, will also occur in sand and dust storms.

Propagation between earth and space, for communication using satellites, is affected by the passage of the waves through the ionosphere and troposphere. Although communication using geo-stationary satellites is general rather stable and suitable allowances for the propagation paths may be made, the use of non-geostationary satellites in lower orbits introduces important effects due to the changing geometry and to Doppler frequency changes, and uses paths traversing other latitudes where further ionospheric variability will be important.

This short set of lectures will concentrate on the propagation effects in the VHF, UHF and the lower part of the SHF bands, for frequencies between say 50MHz and 6GHz, although these limits are by no means sharply defined. Thus the emphasis will be on reflection, refraction and diffraction, and on the troposphere and the earth's surface features. This is the frequency range most used for applications such as broadcasting (apart from MF broadcasting), mobile and personal communications, and terrestrial point-to-point links.

The complicated considerations of ground wave and ionospheric sky wave modes at lower frequencies cannot be covered in the time. The effects of rain and atmospheric attenuation at higher frequencies, which are most important when the vast bandwidths available at millimetric wavelengths are exploited, can also not be covered. In addition the propagation over earth-space paths to satellites will also only be mentioned.

Propagation considerations and performance prediction procedures are important for planning the coverage or grade of service of the wanted transmissions, and also for determining the frequency re-use or sharing possibilities. For this purpose it is necessary to consider the radiation patterns and side-lobes of the antennas in addition to the propagation. Coordination between the plans and operation of differing radio service requirements is a most important topic in these days when the demand for radio services is so high and the spectrum is being used very intensively. The International Telecommunication Union, in Geneva, is concerned with the establishment of agreed procedures for coordinating and planning the use of radio and of the geo-stationary satellite orbit, in different countries and for different purposes. Propagation prediction forms the key-stone on which much of the procedural agreements depend. However, again, this big topic is beyond the scope of this set of lectures.

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

$$s = \frac{p_t}{4\pi d^2}$$

Using logarithmic ratios:

$$S = -71 + P_t - 20\log d$$

where S is the power flux density in decibels relative to 1W.m^{-2}

P_t is the power in decibels relative to 1kW and d is in km.

The corresponding field strength, e, is given by:

$$e = \sqrt{120\pi s} = \frac{\sqrt{30p_t}}{d}$$

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 Annex A) and in this case the field strength is:

$$e \approx \frac{7\sqrt{p_t}}{d}$$

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

$$p_r = sa_e;$$

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,

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

and the free space basic transmission loss is 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. $$L_{bf} = 10\log\left[\frac{p_t}{p_r}\right] = P_t - P_r = 20\log\left[\frac{4\pi d}{\lambda}\right]$$

or $L_{bf} = 32.44 + 20 \log f_{r} + 20 \log d$

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;

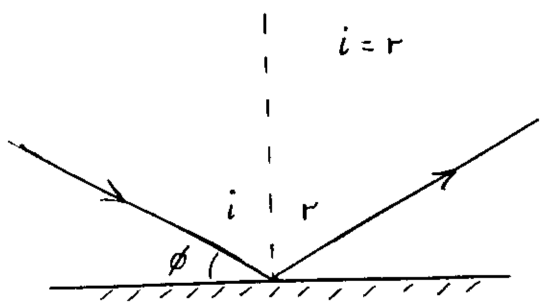
System loss, L_s, is obtained from the powers at the antenna terminals; and

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

It is important to be quite precise when using the terms, and the full definitions are given in ITU-R Recommendation 341.

3. 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:

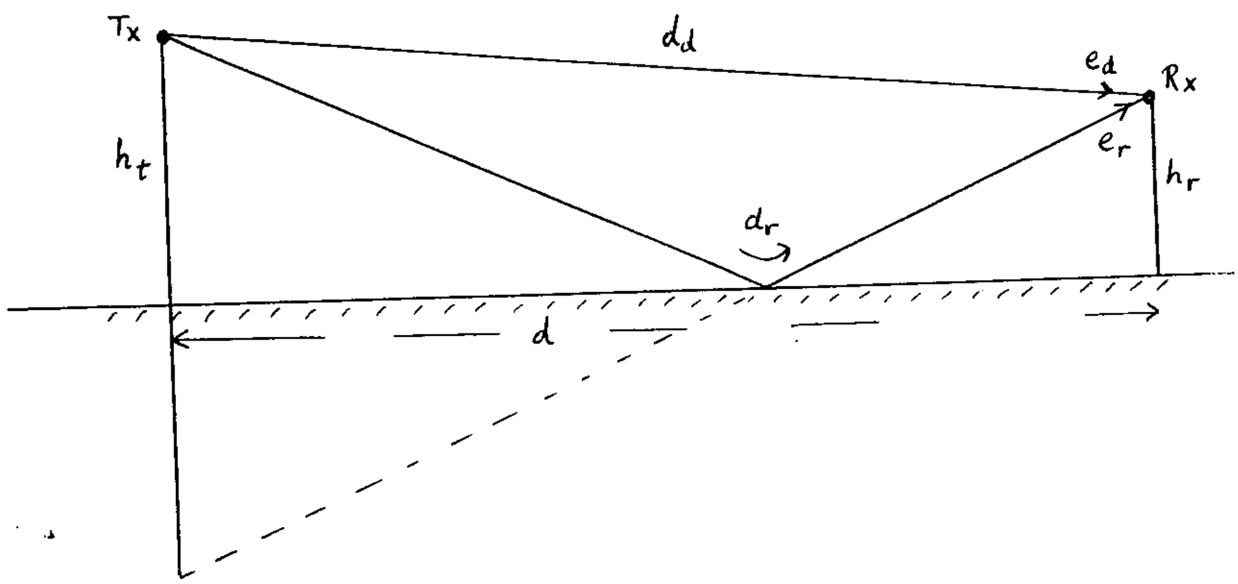
$$R_H = \frac{\sin\phi - \left(\varepsilon_r^* - \cos^2\phi\right)^{0.5}}{\sin\phi + \left(\varepsilon_r^* - \cos^2\phi\right)^{0.5}}$$

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:

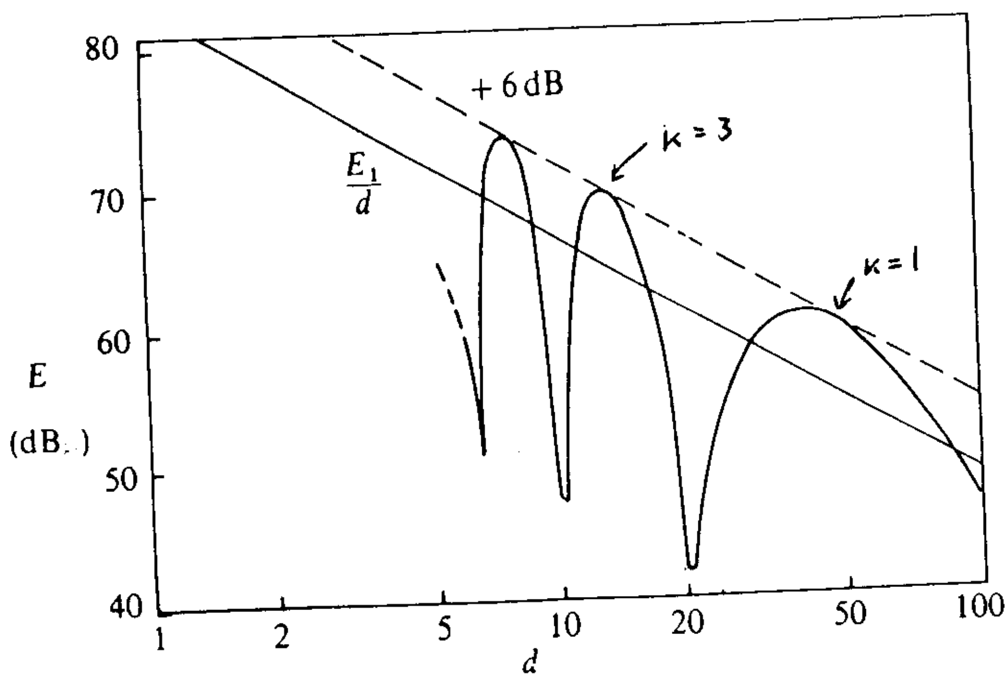
$$|e_t| = \left|2e_d \sin\left(\frac{2\pi h_t h_r}{\lambda d}\right)\right|.$$

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 ($-\infty dB$).

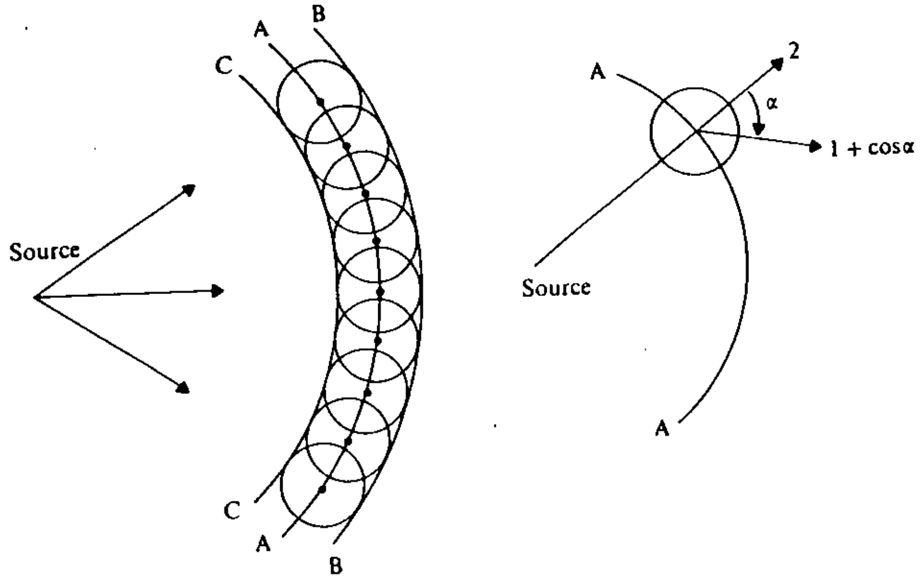
At distances beyond that where k=1, $e_t \propto \frac{1}{d^2}$, and the distance term becomes 40 log d. In practice this relationship applies for short range mobile services operating in obstructed environments.



4. DIFFRACTION

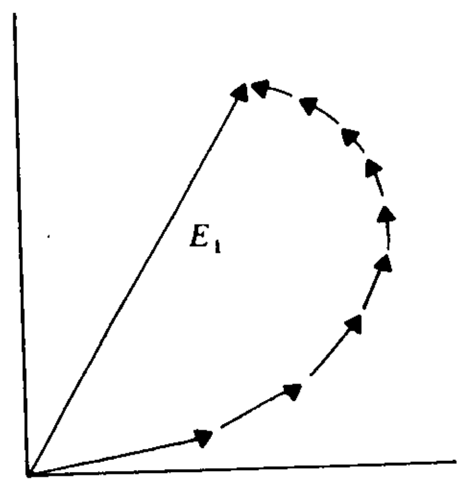
It is found that an obstruction in the path of a propagating radio wave does not cause and abrupt, dense shadow but that signals may still be observed behind an obstruction due to diffraction. Indeed it is found that along the line of the geometrical top of a thin "knife-edge" obstacle the signal amplitude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

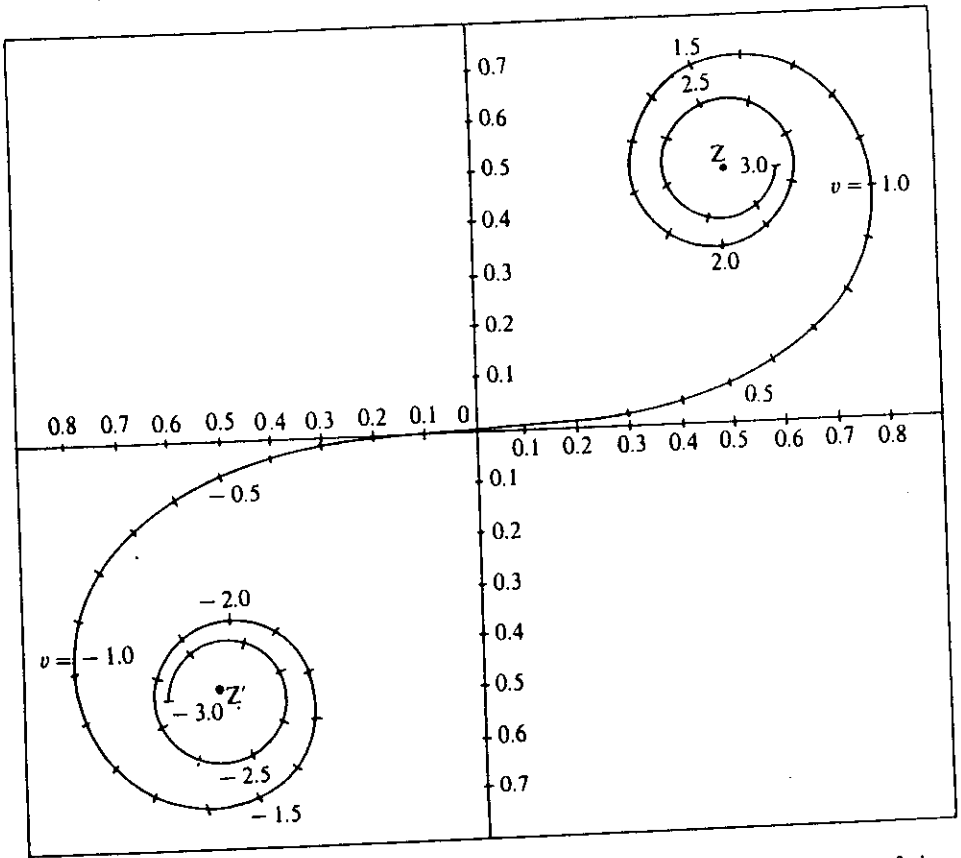


Huygens' principle applied to a spherical wavefront.

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.



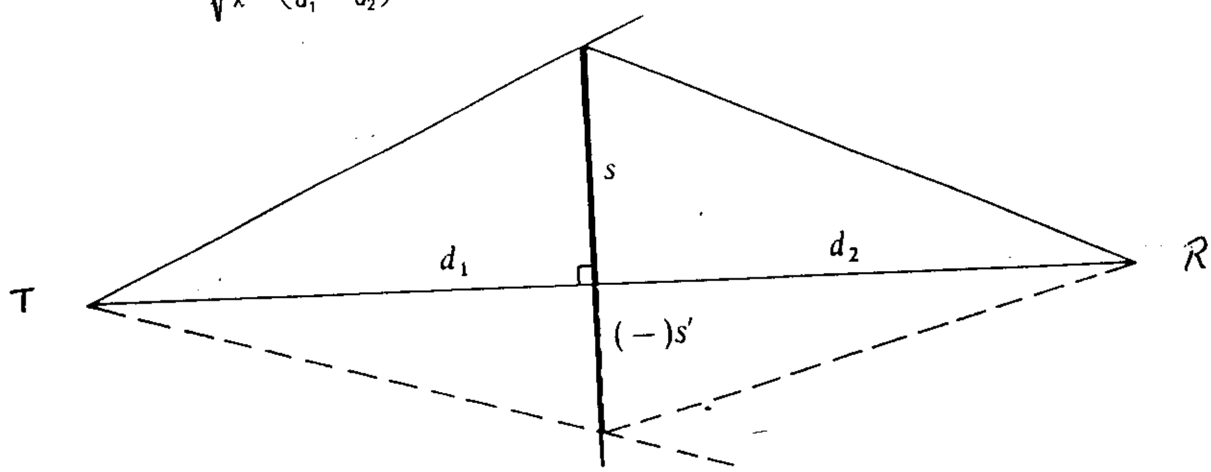
- Considering the phase addition of all wavelets in free space leads to the Cornu spiral.



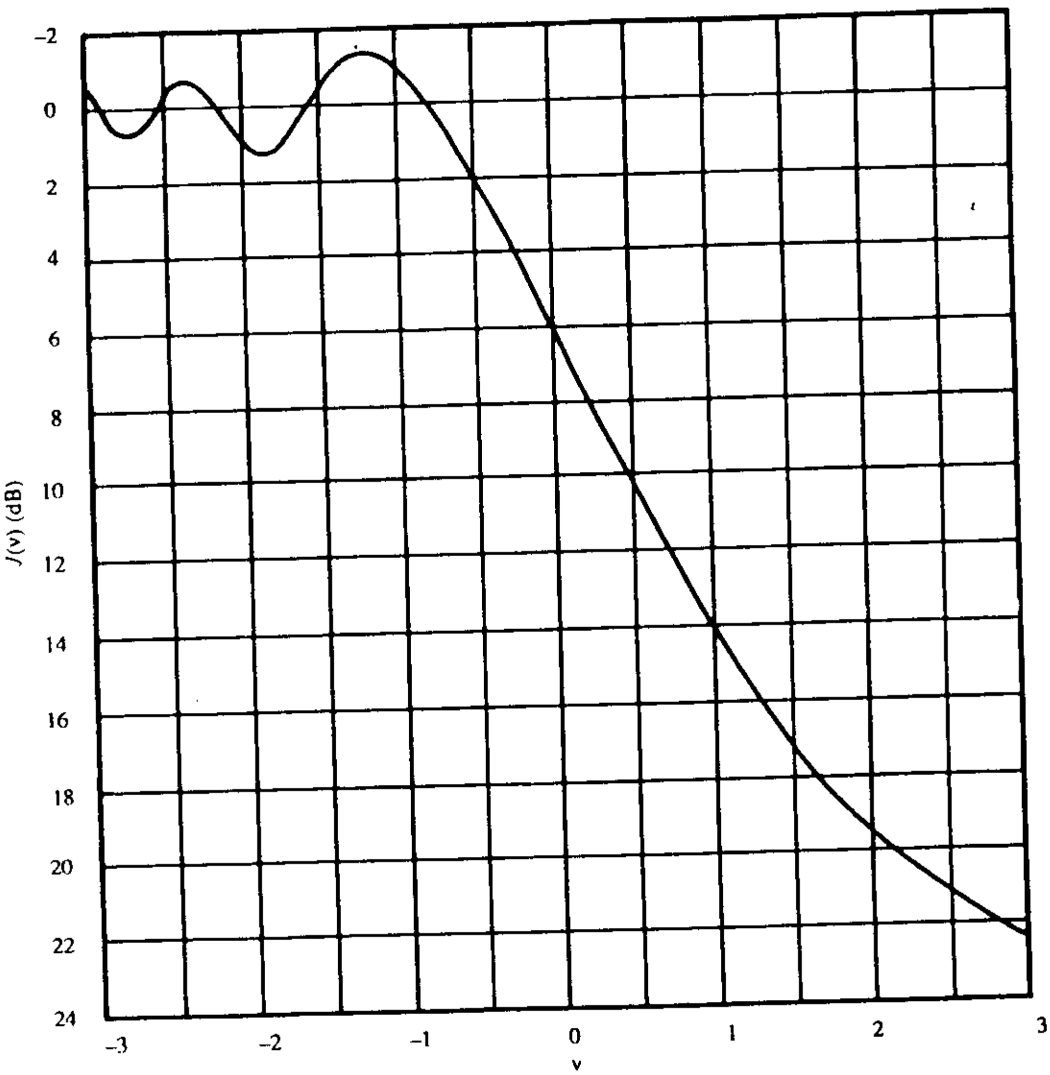
Cornu's spiral for diffraction over a knife-edge obstacle. It is a plot of the Fresnel's integrals in terms of the auxiliary parameter v.

The spiral is normalised in terms of a parameter ν.

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



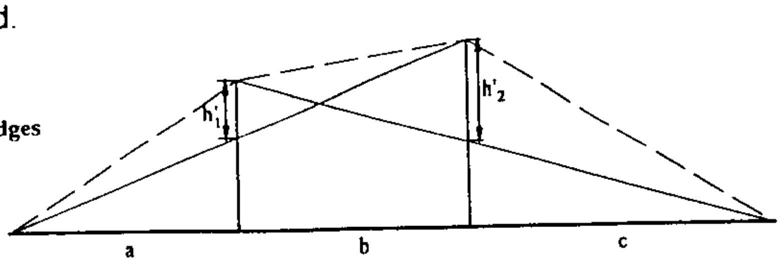
In free space the resultant signal is obtained on the Cornu spiral as the amplitude between the two asymptotic points Z and Z'. When part of the wavefront is obstructed, the amplitude is obtained by cutting off part of the spiral and taking the amplitude from the edge to the asymptotic point. The knife-edge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



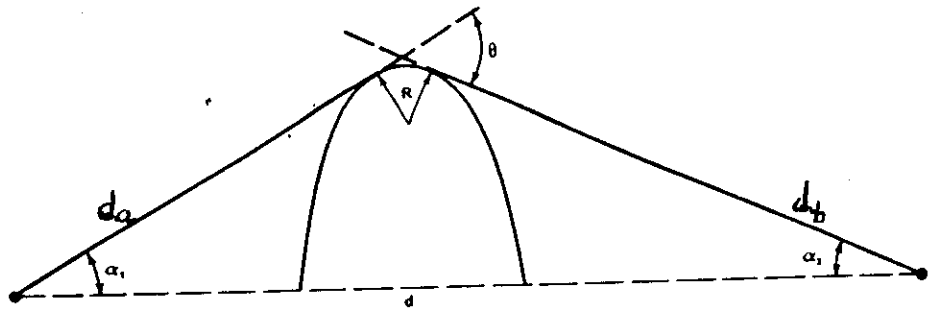
There is a ripple in the illuminated region, but the signal is essentially at its free space level if the clearance above the edge exceeds about 0.6v. At the height of the edge there is a 6dB loss, and the signal decreases continuously farther into the shadow. Well in the shadow region the loss may be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

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.

5. 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:

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

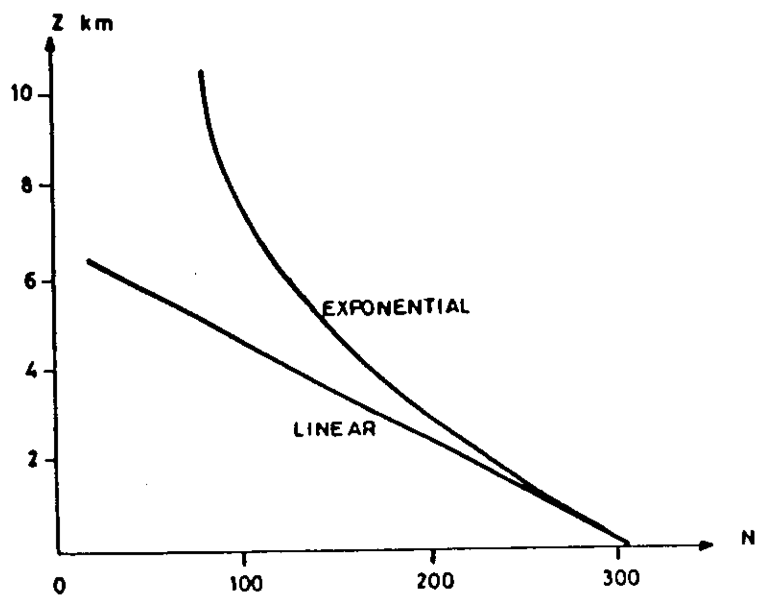
where P is the pressure (hPa or mb)
T is the temperature (K)
and e is the water vapour pressure (hPa or mb)

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. $N \approx 315 - 40h$

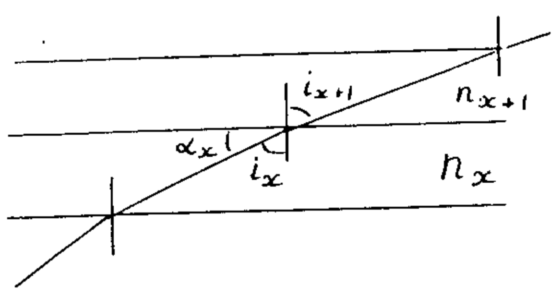
Maps of both N_s and ΔN are given in ITU-R Recommendation 453

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

$n_x \sin i_x$ =constant

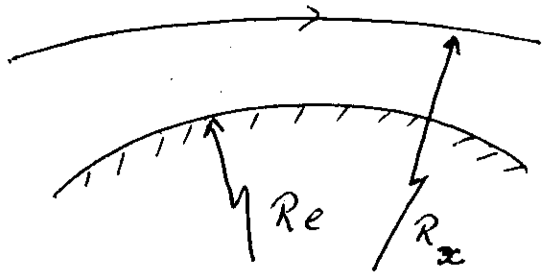
where i is the angle of incidence.
Working again in terms of the grazing angle:

$$n \cos \alpha_x = C$$



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:

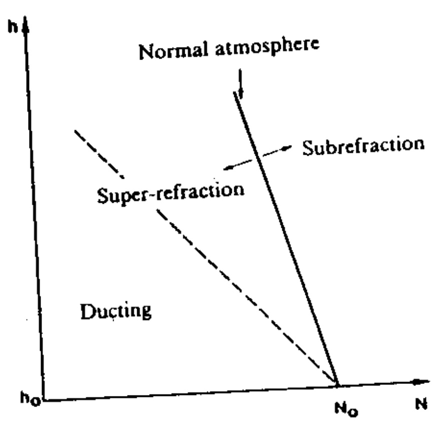
- a ray path with zero curvature
- an effective earth's curvature of $117 \bullet 10^{-6}$

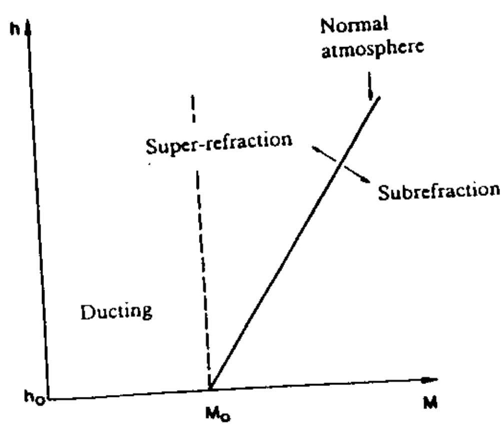
This gives an effective earth's radius of 8547km, or approximately 4/3 of the actual radius. The effective earth radius factor is usually given as K.

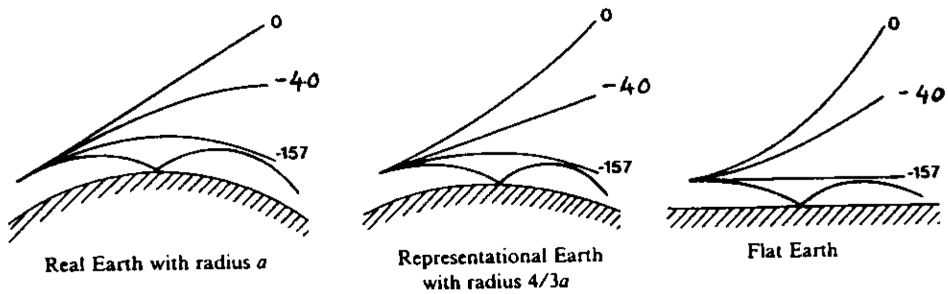
Alternatively the curvature of the earth may be flattened, when the rays would have an upward curvature of $117 \bullet 10^{-6}$. This may be achieved mathematically by using a modified refractivity:

$$M=315+117h$$

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.

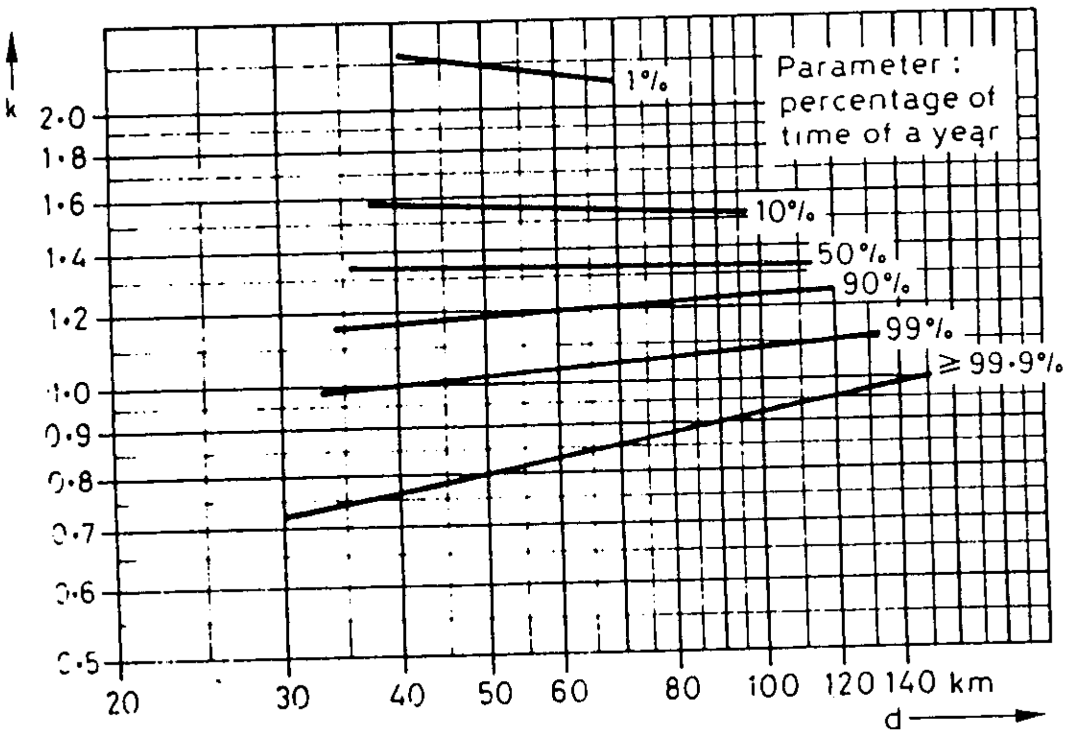




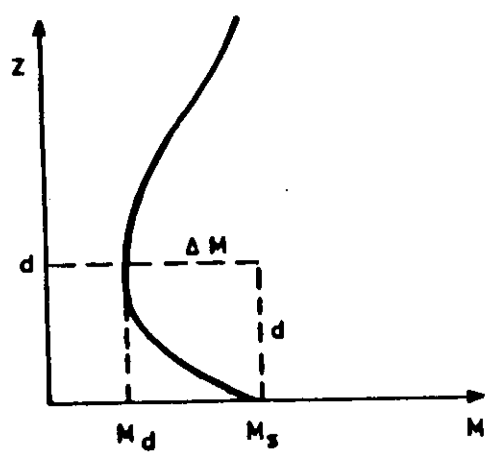


Various representations of a path starting in a horizontal direction. Parameter: three particular values of the refractive index gradient.

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.



SURFACE DUCT

Typical types of duct are:

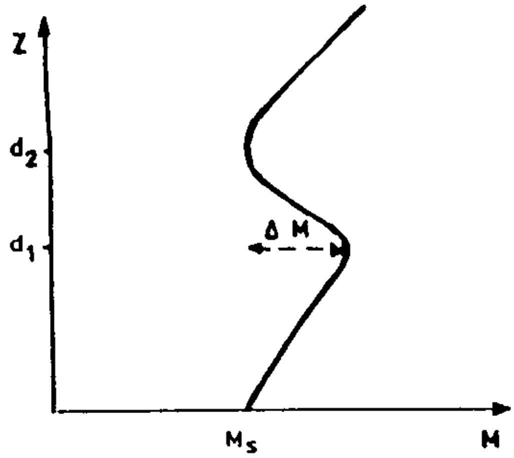
- evaporation - surface duct over sea
  due to decrease in humidity with height

- 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



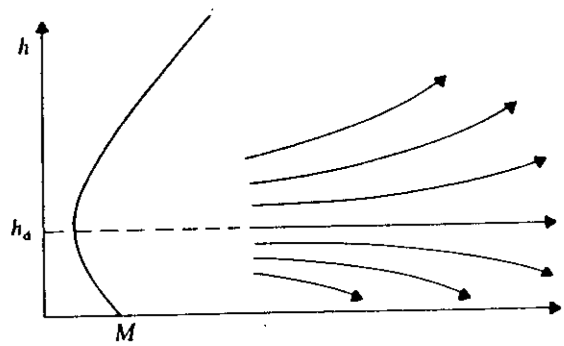
b) ELEVATED DUCT

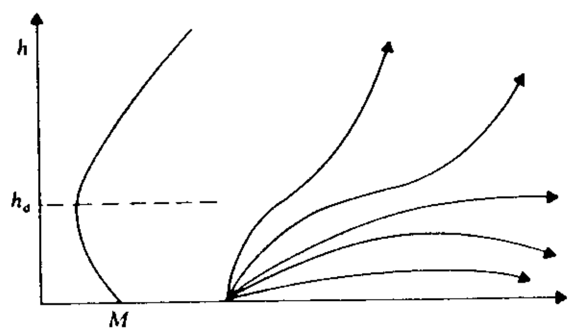
The diagrams to the right show some example ray paths in the presence of a surface duct.

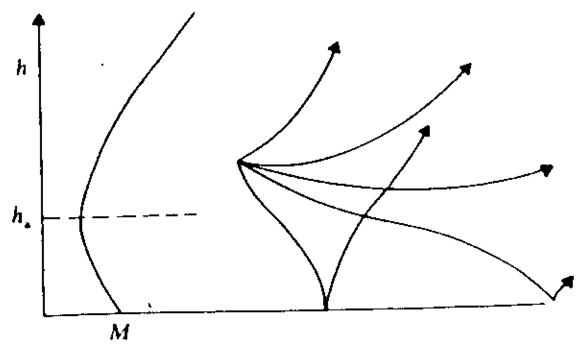
The upper diagram shows the paths of rays which start horizontally at different heights.

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.







6. 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.

7. 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.

An example of earlier prediction tools is the Japanese "M-LINK" programme, described in CCIR Document IWP 1/2-214 of 18 May 1988. This programme is written in BASIC, and comprises 29 items. These items include a tutorial explanation of aspects of propagation and 13 of them allow for the input of parameters and calculation. The menu which is given on screen is also reproduced as Fig 2 of the CCIR Document.

The version of M-LINK available here runs under GWBASIC, and this is included on the disk. First load GWBASIC, then LOAD and RUN the programme "START".

8. 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.

The software package PLANTVFM, prepared in India, under the direction of All India Radio, is based on the method of Recommendation 370-5. The method uses a digitised version of the basic prediction curves, and these may be displayed within the program. Use of the method is fully explained within the software manual, and may be followed using the screen displays. The package includes system planning and interference assessment as well as the propagation elements.

ANNEX A

1. 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 polarization. Gain greater than unity (positive in terms of decibels) will increase the power radiated in a given die#rection 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, 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 A-1.

2. 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 eirp 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 A-1 The Gain of Typical Reference Antennas

Reference Antenna	g_i	G_i (1) dB	Cymomotive force (for a radiated power of 1kW)
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 a short vertical monopole, 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 particularly 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 1kW is radiated from the reference antennas are also given in Table A-1.

ANNEX B

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 which occurs 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.

1.1 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:

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

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:

$$F(x) = \frac{\exp\left[-(y^2 y2\right]}{\sqrt{2\pi}\left[0.661y+0.339\sqrt{y^2+5.51}\right]} \qquad \text{and} \qquad y = \frac{\bar{x}-x}{\sigma}$$

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 B-1 gives some examples taken from the distribution.

TABLE B-1 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 discused below.

1.2 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 the same: the centre of the distribution, when F(x) = 0.5, is still the median, whereas the mean of the numerical values is given by $\bar{x}+\sigma^2/2$.

Figure B-1 is an example of normal probability graph paper, for which a normal distribution is plotted as a straight line with a slope dependent on the standard deviation.

1.3 The Rayleigh distribution

The combination of a number (say, more than 3) 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

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

and

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

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),

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

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 property. This property is shown in Table B-2 which gives some examples from the Rayleigh distribution. Special graph paper is also available on which the distribution is plotted as a straight line, this presentation is used in Fig B-2; 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.

TABLE B-2 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

1.4 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 B-2. 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.

1.5 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:

$$p(r) = \frac{2r}{b^2} \exp\left[-\frac{r^2+a^2}{b^2}\right] I_0\left(\frac{r\,a}{\sigma^2}\right)$$

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 B-3.

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.

1.6 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.

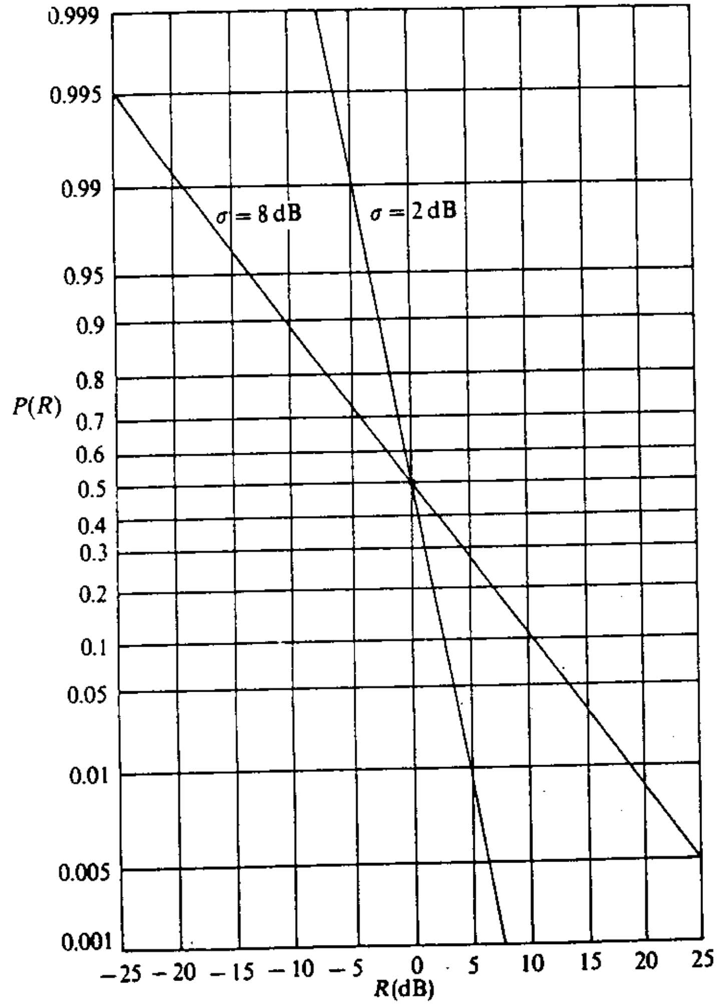
For applications concerned with the quality and performance of a wanted signal, or with the interference effects of an unwanted signal, it is seldom necessary to consider both tails of a distribution at the same time. In some cases half-log-normal distributions, applying a different value of the standard 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.

2. 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.

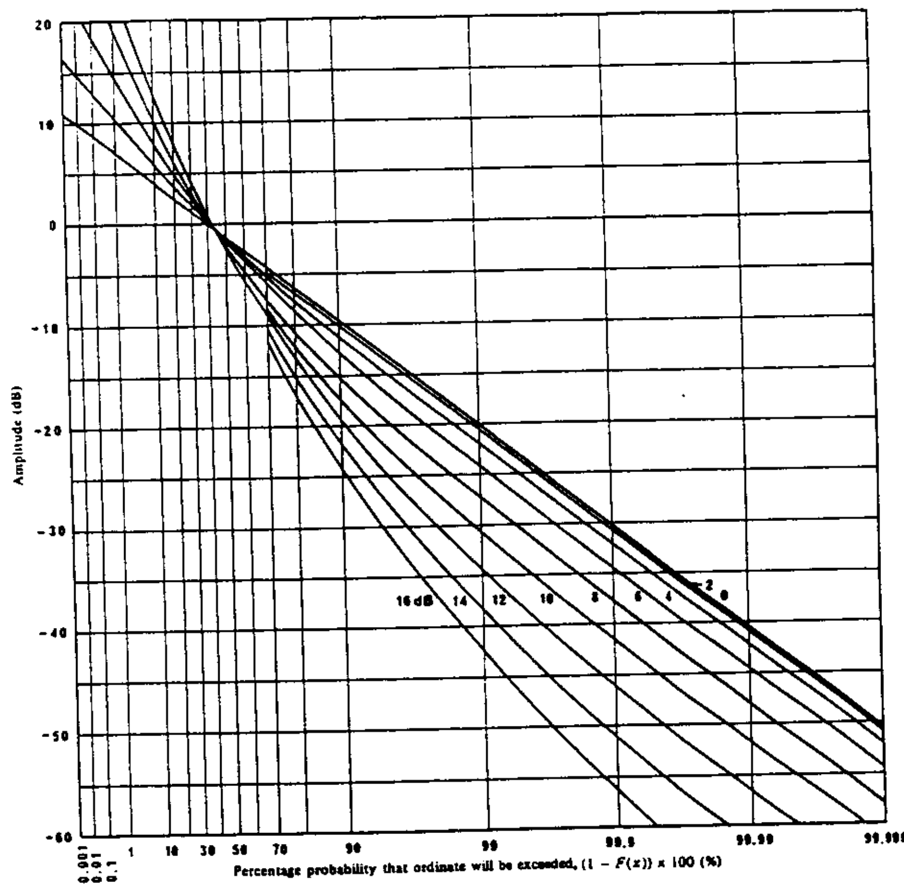
i.e. $\sigma^2 = \sigma_1^2 + \sigma_2^2 + \dots$

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. This has been described by Barclay (1978).



Normal or log-normal probability paper with two lines representing $\sigma = 2\,dB$ and 8 dB as examples.

Fig B-1



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

Fig B-2

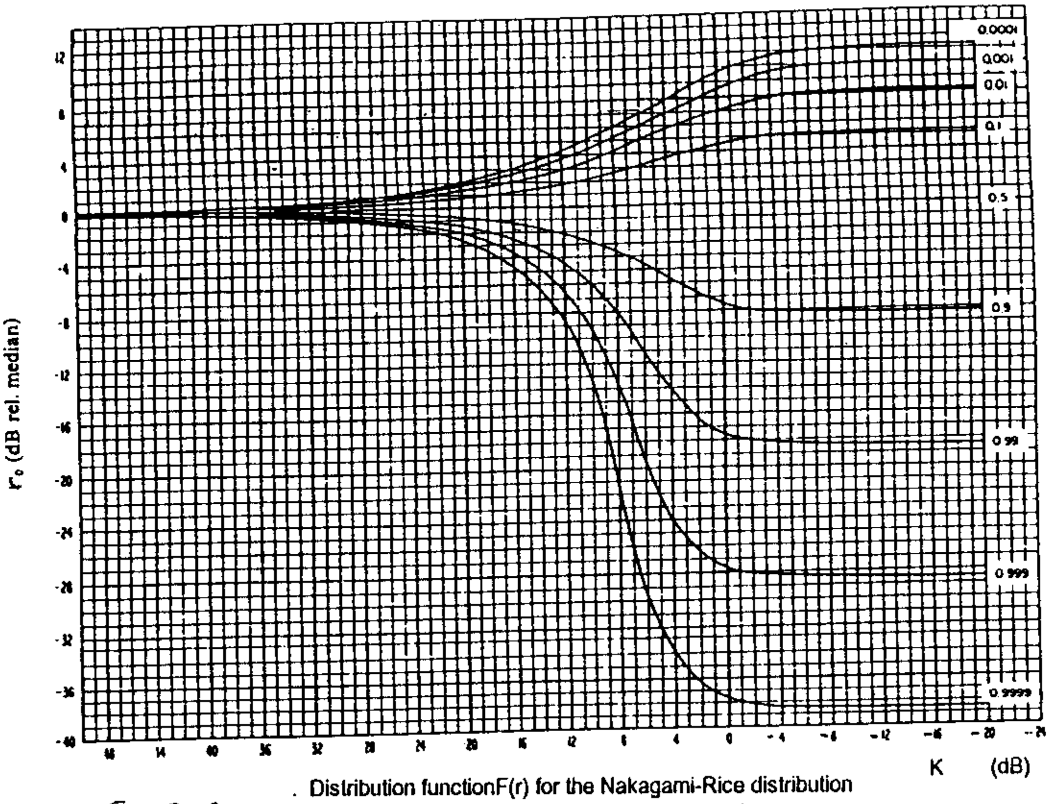


Fig B-3 . Distribution functionF(r) for the Nakagami-Rice distribution
(The values of F(r) are shown on the curves)

BIBLIOGRAPHY

ITU texts are contained in the volumes of the XVIIth Plenary Assembly (Dusseldorf, 1990), in the volumes of CCIR Recommendations (Geneva 1992) and in the output from the First Radiocommunication Assembly (Geneva 1993) (to be published in 1994) The text numbering includes a suffix which indicates the number of times the text has been revised. These texts are published by the International Telecommunication Union; see the List of Publications issued by the ITU Sales Service: CH-1211, Geneva 20, Switzerland

Barclay, L W. "Statistical modelling of HF Links", AGARD Conference proceedings No.238 Ottawa 1978.

Boithias L, "Radio Wave Propagation" English translation 1987 North Oxford Publishers ISBN 0-946536-06-6

Griffiths J, "Radio Wave Propagation and Antennas", Prentice Hall Int. 1987 ISBN 0-13-752312-2

Griffiths, J and J P McGeehan, "Inter-relationship between some statistical distributions used in radiowave propagation", IEE Proc. Vol 129 ,PtF No.6, pp 411-417, December 1982

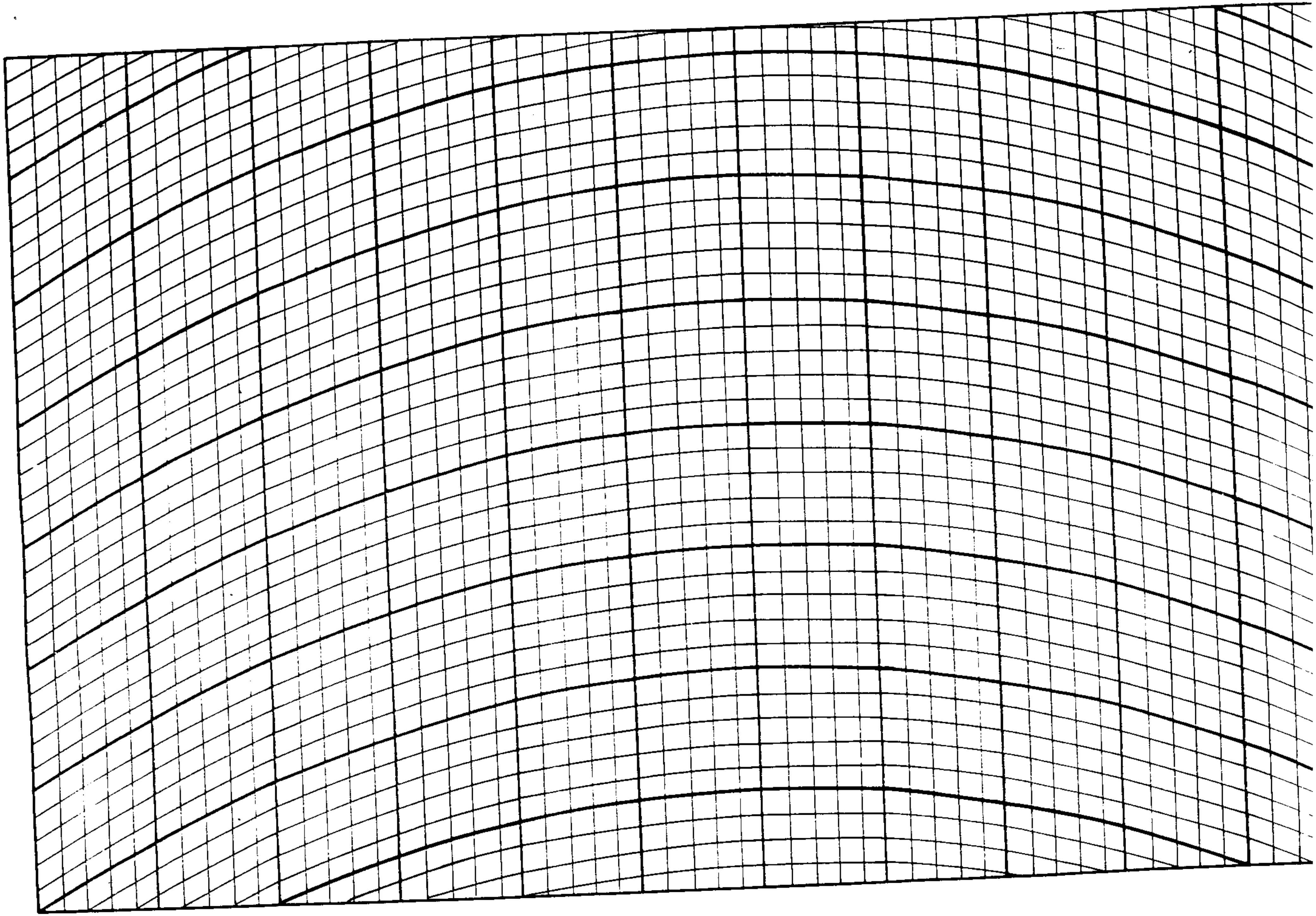
Hall, M P M and Barclay, L W "Radiowave Propagation" Peter Peregrinus Ltd, London, 1989. ISBN 0 86341 156 8

Hall, M P M , Barclay, L W and Hewitt, M T "The Propagation of Radio Waves" Peter Peregrinus, Ltd - to be published late 1994

Lorenz, R W, "Field strength prediction method for mobile telephone system using a topographical data bank", IEE Conf. Publ. No. 188, pp 6-11, 1980.

Parsons J D, "The Mobile Radio Propagation Channel" Pentech Press, 1992. ISBN 0-7273-1316-9

Picquenard A, "Radio Wave Propagation" Macmillan, 1974, SBN 333 13312 9



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