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SMR.380/22

COLLEGE ON THEORETICAL AND EXPERIMENTAL RADIOPROPAGATION SCIENCE

6 - 24 February 1989

LECTURE 6: PROPAGATION AND SYSTEM-PERFORMANCE PREDICTIONS AT HF

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2. THEORY OF IONOSPHERIC RADIOPROPAGATION

Lecture 6: Propagation and system-performance predictions at HF

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1 INTRODUCTION - GENERAL PROPERTIES OF HF PROPAGATION

HF here is taken as the frequency band 1.6-30 MHz. At the lower of these frequencies by daytime the useful distance range is limited to that available from the ground wave, with greater signal strengths over water than for land paths. The ground wave provides a stable signal, though signal/background ratios vary with changes in noise and interference. At night sky-wave signals propagating by means of the ionosphere are also present. These fade with temporal changes in ionisation and as a result of ionospheric motions and are also subject to multipath. At short distances interference with the ground wave can lead to rapid 'beating' effects and signals of poor quality. The majority of the HF band is used for services supported by the ionosphere; generally the higher frequencies are employed for the longer-distance paths both because of the lower ionospheric absorption and because maximum usable frequencies increase with path range.

2 SERVICES RELYING ON HF

At HF there are a multitude of frequency sub-bands for the different services with many of these being shared among services. Some sub-bands are common to the land mobile and maritime mobile services; others are separate. Of the 28 MHz of available spectrum this is estimated as being occupied approximately as follows:

Fixed service	55%
Land and maritime mobile services	15%
Sound broadcasting service	15%
Aeronautical mobile service	10%

The remaining 5% of spectrum is used by the amateur service, the standard frequency and space-research services.

Maritime elements include coast stations, ship station radiotelephone working to coast stations and intership working. Aeronautical systems include single-sideband HF radiotelephone links between aircraft and the ground in the aeronautical mobile channels of the 2-22 MHz band and radioteletype links between ground terminals in the aeronautical fixed channels in the 2.5-30 MHz band. These employ FSK modulation with frequency shifts of 200-500 Hz. Variations in frequency allocations between different geographical regions arise principally from changes in operational requirements, rather than from propagation effects. However, the tropical region has been defined to allow specifically for the differing propagation phenomena and increased background noise from thunderstorms at low latitudes. Some broadcasting in the tropical zone is permitted between 2300-2495 kHz, as well as in three other special sub-bands in the lower part of the HF band.

To obtain information on the path lengths of typical circuits operating in the principal separate services and for which propagation data are needed, a statistical study has been carried out at HF using samples of information contained within the International Frequency List of the IFRB. Here results for all frequencies grouped together are shown in Fig. 1. There are seen to be proportionately greater numbers of circuits of range 500 km or less operating in the fixed and aeronautical mobile services than in the broadcasting and maritime mobile services. The maritime mobile service aims to provide longer-distance communication than the aeronautical mobile service. Use of broadcasting at the longer distances is no doubt associated with the apparent needs of many countries to provide overseas news and propaganda information. There is currently an upsurge in the use of the HF band, both for civilian and military applications. Whereas the majority of long-distance fixed radio circuits now rely on satellites and cables, increases in the numbers involved mean that there are actually more HF circuits than say 20 years ago. Particularly for military purposes, HF systems are regarded as providing a necessary back-up service to fixed links primarily established by other means. High frequencies create a useful way of establishing communications with small isolated communities in such places as the Arctic and Middle Eastern desert areas. Commercial use of HF systems continues in the provision of feeder links to satellite terminals. The requirements are for high-grade circuits that can be integrated into a general network. Fig. 1 shows that the median range for the fixed circuits is around 1500 km.

3 RECEPTION QUALITY AND WAYS OF IMPROVING IT

At HF there are needs to improve the performance of radiotelephony and radiotelegraphy circuits, both by better system design and with better operating procedures. Objectives must include the integration, via automatic control, with other circuits of the general telecommunications network. Ionospheric channel simulators exist in which the channel taps can be set to correspond to the various amounts of multipath time delay, frequency off-set and spread likely to be experienced. Background noise may also be introduced. Data thereby collected complement results of theoretical calculations usually based on idealised approximations and show the merits of different modulation methods, diversity procedures and error-correction techniques. The use of directional antennas is clearly important to improved signal/noise ratio. Additionally, if unimode reception can thereby be achieved, this provides some fading suppression. On the other hand there may be greater advantages sometimes in interference rejection with adaptive receiving antennas producing steerable nulls.

Critical to any HF circuit operation is the requirement for good frequency management. Without reliable daily predictions there are particular advantages, except for sound broadcasting where flexibility is denied, in introducing real-time channel evaluation techniques. These can form part of the communication link or be implemented independently. They may involve low-power idle tones or consist of coded transmissions sent from the normal receiving site to the transmitter containing information on channel occupancy, as in the CHEC system operated over air-ground links. Otherwise, use can be made of oblique-path sounders which sweep the whole HF band. The early hopes of limited networks of sounders providing information to control large numbers of circuits have not been fulfilled, largely because of the extreme spatial variability of the ionosphere; the optimum way ahead is not clear. Certainly with microprocessor control, frequency-agile systems can now be implemented fairly readily.

Diversity systems provide a means of improving reception quality. Space diversity is most common, but other forms such as polarisation diversity, frequency, time and wave-arrival-angle diversity can all have merit. Channels may be switched or combined, for example by linear or quadratic addition. The optimum configuration depends on the received signal characteristics and there is scope both for improving the specification of these and for determining which systems perform best. For example, optimum separations in space, frequency or time under different conditions remain to be quantified.

In the field of radiotelephony there are obvious advantages in the introduction of band compression techniques involving SSB with reduced or suppressed carriers, both in order to provide greater interference rejection and so as to minimise selective fading effects. Lincompex companders consist of a compressor and expander linked by a control channel separate from the speech channel. With the increasing use of vocoders for digital telephony, the need is for optimum syncompex systems involving a synchronised digital control channel.

For radiotelegraphy the best approach to channel multiplexing in terms of time and frequency division rests with a knowledge of the transmission medium. Improvements in procedures are to be expected. There is much work in progress in the study of error control techniques providing forward error correction. The need is for error correcting codes which detect errors and automatically call for repetition (ARQ). Block codes with a burst error correction capability, adaptive convolution codes and soft-decision techniques are all under investigation.

Variable data-rate systems, adapted to changing ionospheric conditions, are expected to be evolved. Although fixed data transmission rates of up to 2.4 kbit/s are now being used with differential phase shift keying, mention should be made of the particular advantages of other modulation systems. Multifrequency shift keying synchronous systems such as Piccolo provide very low error rates without error coding, even for low signal/noise ratios. There is current interest in spread-spectrum techniques and a 300 bit/s system within a 3 kHz channel has been successfully implemented in Canada. Spread-spectrum systems have the advantages of being resistant to narrowband interference, and immune from selective fading, multipath intersymbol interference and Doppler shifts. Further study of both narrowband and wideband prospective systems seems desirable.

4 REQUIREMENTS FOR PROPAGATION PREDICTIONS

4.1 System Design

Long-term predictions based on estimates of propagation conditions are needed for radio-circuit design. Ray-path launch and arrival angle data are of value for optimum antenna determinations. Studies of the relationships between transmitter power and received field strengths at a range of frequencies enable the necessary size of transmitter and its frequency coverage to be determined, when also the noise background intensities are known.

There is no major restriction on the permissible amount of calculation or the speed with which the results are needed. Accuracy is the prime consideration and most radio users are willing either to apply accepted procedures or to have these carried out for them by some agency. Computing costs are low compared with installation costs. It is difficult to obtain statistics on how much use is made in practice of predictions for system design and how much reliance is placed on past experience. It seems probable though, where comparable services are already in operation under conditions similar to those planned, that their performance data may be extrapolated with adequate results. Under other conditions and where a contractor needs to convince his customer or sponsor that proposals being made are valid, recourse to predictions is essential.

Some circuit-design parameters, such as maximum permitted transmitter power, channel centre frequencies, types of modulation and bandwidth are fixed under the ITU Radio Regulations and by Conventions of other international agencies. For example, HF radiotelephone links of the aeronautical mobile service are governed by Annex 10 to the Convention of the International Civil Aviation Organisation. Other parameters, notably the choice of antennas and the approximate frequencies for which assignments are wanted, must be determined by the operator. Cases where predictions are potentially of particular value are those where the transmitter location can be varied for optimisation and where networks of transmitters are required to provide area coverage, say for broadcasting or distress protection. Long-term predictions similarly serve an important role in the siting and planning of surveillance systems such as HF over-the-horizon radars and passive monitoring stations.

4.2 Service Planning

To date, relatively little effort has been applied on a worldwide basis to the optimisation of the different radio services. Most of these have grown in a haphazard fashion and their spectrum utilisation is far from efficient. The ideal arrangements of optimum modulation techniques, channel bandwidths and spacings are understood, but the inertia to change is overwhelming. Arrangements which assume continuous use of a frequency, when this is employed for only a fraction of the time, are a luxury that ultimately cannot be accepted, yet the administrative machinery to supervise any alternative procedure seems insurmountable. As social and economic patterns change, requirements for different types of radio systems vary. At the present, with the greater availability of satellite and cable links, there is a reduction of the number of HF point-to-point circuits, particularly for long-haul routes, but a growing demand for new broadcasting stations. Frequency sharing is a useful means of optimising spectrum utilisation but any changes to current practice need very careful review before being introduced. There is plenty of scope for further studies based on long-term predictions to determine the ideal service-planning strategies.

4.3 Frequency Management

Frequency management may be defined as the selection of the frequency to use on a particular occasion from those assigned and available. The circuit operator's ideal is to have a large number of frequencies assigned and to be able to choose the best; alternatively to employ frequency diversity. However, in the interests of efficient spectrum utilisation the objectives must be to keep the number of frequency assignments and simultaneous transmissions to a minimum. Given a realistic set of assigned frequencies, frequency management in principle could be aided by some form of short-term prediction procedure. It is evident that any short-term method adopted needs to be capable of rapid evaluation and requires on-line data links to a mainframe computer, or local use of a microcomputer. Such an approach must be seen in perspective in comparison with alternative techniques and in the light of existing operating practices which differ appreciably for the separate radio services.

Major use is made of HF for sound broadcasting. At present broadcasting schedules, consisting of frequency assignments to each operating agency, are determined four times a year. Broadcasters need to publish their frequencies well in advance and listeners prefer them to be fixed. Transmissions are planned to optimise site resources, so that a choice of frequency for one coverage area can influence what frequences are used for another. Simultaneous three-frequency band working is not uncommon, particularly where the same programme is being radiated to different coverage areas. In principle, day-to-day changes in propagation conditions can be overcome by the listener himself selecting the best frequency received. Short-term predictions appear to have little application, though storm warnings could be useful in advising listeners how to retune.

For point-to-point communications in the fixed service, duplex working is commonplace. Commercial applications require running costs to be minimised and so frequency diversity is avoided as far as possible. Where 24-hour operation is required, three different frequencies are normally used : one for daytime, one for night and one for the dawn/dusk transitional periods. With frequencies already assigned, the times when these ought to be most effective are determined on the basis of long-term predictions of the MUF and LUF. Then a schedule is prepared involving dual-frequency transmissions over periods of 1-2 hours centred on the times when the predictions indicate that a frequency change is needed, thereby giving means of allowing for the day-to-day fluctuations in propagation conditions. The signals at the new frequency are monitored at the receiver, and when their quality is judged to be better, that channel is used and a short coded message sent to cease transmissions of the original frequency. The approach is a form of real-time channel sounding aided by long-term predictions and again it seems to preclude the need for short-term predictions on a regular basis. However, storm predictions could be of particular value when conditions differ appreciably from those normally experienced.

The maritime mobile service at HF provides long-range radiotelegraph, radiotelex, radiotelephone and radio facsimile links between ships and shore stations. Slightly different frequencies are used for each of these, but in every case the shore stations operate in a broadcast role, transmitting the call signs simultaneously on defined groups of frequencies in the 4, 6, 8, 12, 17 and 22 MHz bands of all ships for which there is traffic. The ships then answer on a prespecified paired frequency to that for which reception is found to be best and the messages are passed. Since the requirement is to serve ships over a wide area, the use of so many frequencies by the shore station is justifiable. The system works well and there is no need for prediction aids. A somewhat similar situation applies for the aeronautical mobile (route) service mainly using HF for long-distance radio telephone links between commercial aircraft and air-traffic control centres. Ground stations transmit using groups of frequencies and aircraft respond in a time-sharing mode on the one of these same frequencies found to be best. The channel noise background can be monitored in the aircraft and the operator has the advantage in his frequency selection of also being able to assess how well communication is achieved between ground and other aircraft in his vicinity. Again then the arrangement provides its own real-time channel sounding.

From the foregoing it may be concluded that there is no case for routine short-term predictions in support of civilian communications systems, but storm predictions would be of particular value to the sound broadcasting and point-to-point services. There are, however, other examples of where routine short-term predictions would be useful, such as in the frequency management of over-the-horizon radars. A further situation is that of an off-route aircraft with a small crew making short flights where the objective is for limited but reliable communications to one of a number of ground stations which are not necessarily transmitting signals. Other military applications for short-term predictions can be envisaged.

5 PRINCIPLES OF LONG-TERM PREDICTION AND AVAILABLE TECHNIQUES

5.1 Introduction

Since the earliest days of radio, the objective of developing accurate predictions of received HF sky-wave signal characteristics has been pursued vigorously in many countries. Prediction procedures were devised to give estimates of median values of the maximum usable frequency (MUF), received signal strength, background noise and lowest usable frequency (LUF), and to indicate their diurnal, seasonal and solar-cycle variations. The techniques adopted have usually involved the following stages : (i) determination of a representative model of the electron concentration over the propagation path, taken as being along the great circle between transmitter and receiver, (ii) some kind of ray assessment leading to an estimate of the modes present, (iii) calculation of the received signal intensity in terms of the various separate transmission-loss factors judged to be significant, (iv) estimation of the intensities of atmospheric noise and background man-made noise arising from unintended emissions, and (v) choice of some reference required signal/noise ratio to yield an acceptable grade of service.

5.2 Model of the Ionosphere

Since at HF the active modes and their elevation angles depend markedly on ionospheric conditions, transmitter frequency and path length, a first requirement for accurate predictions must be a model of the vertical distribution of electron concentration in the E and F regions. This must take account of the known large geographic and temporal variations in the ionosphere. The most extensive ionospheric data base is that derived from the world network of ionosondes. Hence models of the vertical distributions are produced with the parameters of the models given by empirical equations in terms of the ionospheric characteristics which are scaled on a routine basis at all ionosonde stations.

The model adopted by the CCIR as giving the best fit to measured data consists (see Fig. 2) of

(i) a parabolic E layer of fixed height and semithickness

(ii) a parabolic F2 layer with height of maximum electron concentration and semithickness given by empirical equations in terms of the ionospheric characteristics foF2, foE, M(3000)F2 and h'F2

and

(iii) a linear increase of electron concentration with height from the height of maximum E layer ionisation to the F2 layer at a plasma frequency of 1.7 foE.

Other models which find practical application involve combinations of parabolic and Chapman layers.

5.3 Numerical Representation of the Ionospheric Characteristics

To generate the model for a given place and time, predicted values of the ionospheric characteristics are used. Numerical representations have been applied to past measured vertical-incidence ionosonde data from many locations throughout the world where standardised recordings are made each hour of every day to provide predicted values of these ionospheric characteristics. The CCIR has produced an Atlas(1) giving monthly median estimates by means of charts, nomograms and computer-based formulations. foE is obtained from empirical expressions which assume a variation with latitude, time-of-day and season that depends on the solar-zenith angle χ. This angle is calculated readily. The solar-activity dependence is included by means of a multiplying factor in terms of R_{12} the smoothed sunspot number. foF1 obeys the empirical equation

$$foF1 = f_s \cos^n \chi \qquad (1)$$

where both f_s and n depend on geomagnetic latitude and R_{12}.

There are separate computer formulations for foF2 and M(3000)F2 for every month of two reference years with an assumed linear dependence on R_{12} for intermediate solar epochs. Each consists of orthogonal polynomial expressions in terms of geographic latitude λ, geographic longitude θ and Universal Time T. The general characteristic $\Omega(\lambda,\theta,T)$ is expressed as a time series:

$$\Omega(\lambda,\theta,T) = \sum_j \left[a_j(\lambda,\theta) \cos jT + b_j(\lambda,\theta) \sin jT\right] \qquad (2)$$

where the a's and b's give the latitude and longitude variations, being defined as:

$$a_j(\lambda,\theta) = \sum_k U_{2j,k} \cdot G_k(\lambda,\theta)$$

$$b_j(\lambda,\theta) = \sum_k U_{2j-1,k} \cdot G_k(\lambda,\theta) \qquad (3)$$

The U's are numerical coefficients and the G's are trigonometric functions of geographic longitude and a combined geographic and magnetic latitude parameter. Several tens of thousands of coefficients are involved in defining foF2, M(3000)F2 and the other ionospheric characteristics which are represented in this same way. These coefficients are contained on a special data tape. Fig. 3 gives an example of a prediction map for foF2 based on 988 numerical coefficients U.

5.4 Basic MUF, Operational MUF and FOT

Waves travel via the ionosphere at HF with reflection from the E, Es, F1 and F2 layers. The path basic MUF is defined as the highest frequency that can propagate between a pair of specified terminals via any ionospheric mode by refraction alone. It is a function of path length, geographic position and time. There are systematic variations with time-of-day, season and solar epoch, and also irregular day-to-day changes. Methods of prediction are restricted to determining smoothed monthly median values and to providing statistical parameters descriptive of the daily figures. Propagation by means of F2-, E- and F1 modes is allowed for, depending on the path length. The path MUF is taken as the highest MUF of any mode reflected from the different layers, so that it is necessary to first determine the separate F2-, E and F1-MUF's depending on the path length.

Basic MUF's may be evaluated by ray-tracing procedures. However, a simpler alternative approach recommended by the CCIR and relying on empirical relationships makes use of the equation:

$$MUF - D = f_o \cdot M(D) \qquad (4)$$

where

MUF-D is the basic MUF for a single-hop mode reflected from a given ionospheric layer and propagated to ground distance D

f_o is the critical frequency of the layer

and M(D) is known as the 'M' or 'MUF' factor for distance D.

There are three separate stages in the MUF determination process:

(i) selection of procedures to define positions along the propagation path at which ionospheric information should be sought and to formulate appropriate single-hop path lengths D

(ii) evaluation of f_o and M(D) for paths centred on these positions, and

(iii) use of eq. (4) and where appropriate the comparison of MUF's for modes reflected from the different layers.

For paths shorter than 4000 km predictions are made for both an F2 mode and an E mode. Between 2000 km and 3400 km the F1 mode is also considered. For longer paths only an F2 mode is taken into account. For path lengths of 4000 km and less, calculations are based on single-hop propagation via the ionosphere given at the midpath position. With greater distances the so-called two-control-point procedure is used in which the path MUF is taken as the lower of the two MUF's for a 4000 km hop centred on locations 2000 km along the great circle from the transmitter and receiver. Although there is no rigorous basis for this approach and opinions are divided on its merits, its use is considered justifiable in many applications.

On the basis of transformation relationships from vertical to oblique propagation, standard MUF factors have been determined for reflection from the different layers. These factors depend principally on layer height. Curves showing representative factors as a function of distance for single-hop reflection from the F2-, E- and F1- layers are given in Fig. 4. Values are larger the lower the layer height and so are greatest for E-modes. A fixed MUF factor relationship is adopted for all E reflections since this layer maintains a nearly constant height. A family of MUF factor relationships parametric in smoothed sunspot number is used for F1-modes. These are consistent with F1-layer heights being significantly geater at sunspot maximum. The temporal and spatial changes of F2-layer heights are so complex that a more detailed treatment is needed for F2-modes. Families of MUF factor curves have therefore been defined which are parametric in the value for a 3000 km path, M(3000)F2.

The operational MUF is the highest frequency that would permit acceptable operation of a radio service between given terminals at a given time under specified working conditions. It depends, among other factors, upon the types of antenna used, the transmitter power, class of emission, information rate and required signal/noise ratio. The differences between the operational MUF and the basic MUF can be explained by various ionospheric phenomena, such as scattering in the E and F regions, off-great-circle propagation and propagation by unusual modes when ionisation irregularities exist; also spread-F may be an important factor. An equation relating the operational MUF to the basic MUF was first proposed by Beckmann(2). Values of the ratio of the operational MUF to the basic MUF given by the CCIR for different conditions are contained in Table 1.

TABLE 1. Ratio of the operational MUF to the basic MUF

e.i.r.p., dBW	Summer Night	Summer Day	Equinox Night	Equinox Day	Winter Night	Winter Day
<30	1.20	1.10	1.25	1.15	1.30	1.20
>30	1.25	1.15	1.30	1.20	1.35	1.25

The frequency of optimum traffic (FOT), known alternately as the optimum working frequency, is defined as the highest frequency that is likely to propagate at a given time between a specified pair of terminals via any ionospheric mode for 90% of the days. It is given in terms of the monthly median predicted path operational MUF from a knowledge of day-to-day ionospheric variability. The E- and F1-layers experience relatively little variability from one day to another, and when these control the path MUF the FOT is taken as 0.95 of the MUF.

For F2-modes F_1, the ratio of the lower decile to median MUF, has been evaluated from a wide range of past signal measurements and tabulated as a function of solar epoch, season, local time and geographic latitude to provide a reference set of values(3).

5.5 Oblique Ray Paths

For a mode to be possible at a given frequency the following conditions must be met and are tested:

(i) the ray is reflected from the layer for the frequency and angle of elevation that apply

(ii) the elevation angle exceeds a limiting minimum value which is specified. This can be non-zero to take account of terrain screening in undulating or mountainous regions.

(iii) in the case of reflection for the F-layer, screening by the E-layer does not occur.

The assessment of the active modes and their elevation angles is based on a representation of the ray paths by undeviated propagation between the ground and mirror-reflecting points in the ionosphere. The heights of the mirroring points are taken as the virtual heights of reflection of waves of 'equivalent' frequency at vertical incidence. Raypaths are assumed to follow the great circle and in some predictions are deduced from a single model of the vertical distribution of electron concentration taken as applying over the whole path. The values of the parameters of this model are given in terms of the average of the predicted ionospheric characteristics at defined positions, depending on path length.

Lockwood(4) has developed empirical relationships giving mean mirror-reflection height over a band of frequencies below the basic MUF as a function of time, location and path length. Other techniques involve a different model ionosphere for each hop of the path.

Oblique ray paths at a given wave frequency are determined by an iterative process which involves supposing a ray is launched in a given direction, tracing its passage via the ionosphere, comparing its ground-arrival position with the desired reception point and using the difference to give a more appropriate launch direction. Longitudinal tilts in the neighbourhood of ray reflection can be estimated from changes in virtual heights and allowed for in terms of a tilted plane-mirror mechanism (Fig. 5).

5.6 Signal Strength

5.6.1 General. Two different approaches to sky-wave signal-intensity prediction are possible. One is to fit empirical equations to measured data for different paths, times and frequencies. The other is to estimate intensity in terms of a number of separate factors known to influence the signals. These factors may be given by expressions which have been deduced either from theory or measurement. Unfortunately both approaches have limitations. The former is likely to be simpler but unless a large data base exists, trends must be inferred and are liable to error. The latter approach is conceptually more elegant and enables variations to be specified in a physically meaningful manner. However, there remains the possibility of error due to failure to allow for a significant term or to an inexact allowance. There is also a likelihood of devising a method which is over-complex and for which the accuracy achieved does not merit some of the complications that have been introduced. Existing models differ in regard to what factors to include and what allowances to use for these.

With those modes which can exist known and their associated elevation angles given, the next stage is to evaluate the corresponding signal intensities at the receiver. Monthly median values of mean available receiver power for the separate propagation modes are determined in terms of transmitter radiated power, transmitting and receiving antenna gains and the basic transmission loss.

$$P_r = P_t + G_t + G_r - L_b \quad (5)$$

where P_t = transmitter power (dBW)

P_r = received power (dBW)

G_t = transmitting antenna gain (decibels relative to an isotropic antenna)

G_r = receiving antenna gain (decibels relative to an isotropic antenna)

L_b = basic transmission loss (decibels).

The corresponding rms sky-wave field strengths E (dB>1μV/m) are given in terms of P_r by

$$E = P_r + 20 \log_{10} f + 107.2 \quad (6)$$

where f is the wave frequency in Megahertz.

5.6.2 Antenna gain. Antenna gains are those appropriate to the raypath launch and arrival angles. Because of uncertainties in determining these angles, models of antenna performance which include sharp nulls should be avoided. Instead, use of smoothed reference antenna patterns with nearest equivalence for non-standard types is recommended, such as those now being used for broadcast planning(5). At this time reference patterns for antennas typically employed on point-to-point links are in preparation.

5.6.3 Spatial attenuation and focusing. For the estimation of basic transmission loss the spatial attenuation is taken to be that which would arise in free space at a distance equal to the mirror-reflection slant-path total length. Ray-path convergence focusing may be allowed for by means of empirical equations derived from raypath calculations for sample ionospheric conditions. Horizon focusing, which arises principally on low-elevation paths, is given separately for E and F-modes as a function of elevation angle. It is taken as having a maximum value determined by ionospheric roughness of 9 dB (Fig. 6). Other equations predict the antipodal focusing that occurs on very long paths.

5.6.4 Ionospheric absorption. Equations for the normal ionospheric absorption arising at low and middle latitudes may be based principally on measured vertical-incidence data and the results of ray calculations for sample model ionospheres or on oblique-path measurements. It is to be noted that the absorption experienced in traversing a thin slab of ionisation is directly proportional to the product of the electron concentration, the collision frequency and the slab thickness, and inversely proportional to the refractive index. The important advantages of one such procedure based on vertical-incidence data are that:

(i) the variation with frequency includes, through the multiplicative term ϕ_n (Fig. 7), an allowance for the change in height of reflection and for the different refractive indices at different heights, also for the way these depend on path obliquity.

(ii) latitude and seasonal variations indicated by the measurements are included independently from the diurnal variation (Fig. 8). In other prediction methods position and time changes are combined via an assumed solar zenith-angle dependence.

(iii) finite absorption is predicted at night-time.

Explicit allowances may be included for auroral absorption arising at high latitudes from precipitating-particle induced ionisation. The absorption is taken by Foppiano and Bradley(6) as resulting from two separate sources of particles (Fig. 9). For each there is a gaussian variation with latitude and time-of-day about the maximum value. Longitudinal and seasonal dependences are included. Important solar-cycle changes in the intensities, positions and widths of the auroral absorption zones are also modelled in the representation.

5.6.5 Polarisation-coupling loss. When an upgoing wave is incident on the ionosphere it leads to the excitation of an ordinary (O) and an extraordinary (X) wave. These two waves have different but related polarisations which change as they progress, may be regarded as propagating independently within the ionosphere, and are subject to different amounts of absorption. The polarisation of a wave radiated from a transmitting antenna depends on the antenna configuration and the wave direction and frequency; likewise for the wave polarisation to which a receiving antenna responds. Waves travel through free space with unchanged polarisation but the power coupling between incident or emergent waves and the O and X-waves at the base of the ionosphere depends on their relative polarisations. This coupling may be explicitly calculated using the magnetoionic expressions for wave polarisation. In particular these require a knowledge of the wave and Earth's magnetic-field directions. The X-wave absorption may also be estimated and the resultant received power from the O and X-waves thereby deduced.

5.6.6 Sporadic-E losses. Improved understanding of the properties of sporadic-E ionisation now permits the inclusion of allowances for reflection from and transmission through this layer. These allowances are based on oblique path measurements at HF and VHF. Es-modes are assumed to be mirror reflected from a height of 110 km and the resulting reflection loss is given as an empirical function of distance, mode order, and the ratio of the wave frequency to foEs (Fig. 10). Other equations give the obscuration loss of transmitted waves in terms of this ratio and elevation angle. Sporadic-E obscuration losses suffered by F-modes are calculated separately for each leg of each hop. The obscuration loss for a single traverse of the Es layer, L_q, is given as:

$$L_q = -10 \log_{10} (1 - R^2) \text{ , dB} \quad (7)$$

where

$$R = \frac{1}{1 + 10\left(\frac{f}{foEs \cdot \sec i_{110}}\right)^8} \quad (8)$$

f is the wave frequency in megahertz and i_{110} is the zenith angle of the oblique ray at a height of 110 km.

5.6.7 Above-the-MUF loss. Strong signals are often received at frequencies above the predicted MUF, not just because of prediction errors. The predicted values are monthly median figures so that for half the days the ionosphere can support higher frequencies. Other reasons are that significant signal contributions arise-via sidescatter paths and from sporadic-E modes. It has also been suggested that the regular F-layer is composed of separate patches of ionisation each with its own MUF. This would mean that the number of patches supporting wave reflection falls with increase of frequency, no single frequency giving an abrupt cut-off. A single empirical allowance for these separate effects based on measured data is included in the transmission loss expression. This takes the form of an above-the-MUF loss term L_m which increases with increase of frequency. It is 0 dB at the basic MUF and has a value of 20 dB for a frequency of 1.4 times the basic MUF.

$$L_m = 130 \left(\frac{f}{MUF} - 1\right)^2 \text{ , dB} \quad (9)$$

5.6.8 Ground-reflection loss. Multiple-hop ground-reflection losses are evaluated in terms of the ground-reflection coefficients for vertically and horizontally polarised waves. These depend on frequency, elevation angle and ground constants as deduced from a numerical world map of ground conductivity and relative dielectric constant. In the absence of a full polarisation treatment, circularly polarised incident waves are assumed.

5.6.9 Excess-system loss and prediction accuracy. An additional term included in the basic transmission loss is known as the excess-system loss. This is intended to take account of losses not explicitly allowed for. Reference values of excess-system loss in the range 9-29 dB adopted from measured signal data depend on midpath geomagnetic latitude and time of day, season and whether short or long-paths are involved.

For the purposes of testing the accuracy of HF signal prediction models, the CCIR has established a data bank of past measurements and has formulated standardised procedures for the collection, tabulation and analysis of future data. A representative sample of the data already deposited for 16 paths with ranges of 450-16200 km is available. The measurements have been normalised to give the corresponding monthly median values of rms sky-wave field strength for 1 kW radiation from an isotropic transmitting antenna. A further fixed factor can be included in predictions based on such tests to make the median error zero. When this is done, typically for 90% of the paths and hours the rms difference is less than 20dB.

5.7 Noise

The different types of noise which produce the limiting background to satisfactory signal reception are discussed.
Based on past measurements, predicted values of atmospheric noise power at a frequency of 1 MHz(7) are available for four-hour time blocks for each of three seasons. Curves showing the variation of noise power with frequency and the ratio of rms-to-average noise intensity as a function of receiver bandwidth also exist for each time block. Expected manmade noise powers for different frequencies, recommended for use in prediction studies, are quoted for four levels of urbanisation(8).

5.8 System Performance

HF prediction methods usually yield monthly medians of hourly smoothed field strengths and available receiver powers and their statistical day-to-day variations about these values. The distributions of daily MUF about the monthly median values are assumed to follow a given law. Use is made of the reference tabular values, noted in Section 5.4 of F_l the ratio of the lower decile to the median MUF and also of corresponding values of F_u, the ratio of the upper decile to the median, to determine for each wave frequency and examined mode the fraction of days for which the mode can exist over the path. This is known as the availability. Since the day-to-day MUF variability of E-modes is very small, their availability is taken as either 0.99 or zero, depending on whether or not the median MUF exceeds the oblique-wave frequency. Reference values exist for the upper and lower standard deviations of the day-to-day signal variability to permit the estimation of the signal strengths exceeded for different fractions of the month. The probability that a given mode produces a mean available receiver power exceeding some specified required power (the dependability) is given as the product of the availability and the probability that it has the necessary strength.

The type and quantity of information to be conveyed over a proposed radio circuit determine the modulation system and necessary receiver bandwidth. The next step in the circuit design is to specify the wanted signal/noise power ratio at the receiver. Reference minimum signal/noise ratios judged to give satisfactory reception for different services are available(9).

An important monthly median system performance parameter is the LUF or lowest usable frequency. Since in general at HF signal intensity falls with reduction of frequency, principally because of the greater ionospheric absorption, and because this change is more rapid than for the noise, signal/noise ratio is reduced at the lower frequencies. The LUF is the lowest frequency for which the monthly median signal/noise ratio equals that which is wanted. The LUF may be specified for a particular propagation mode, or for the circuit as a whole via any mode.

Two other important parameters that have been introduced to quantify system performance by taking account statistically of day-to-day variations are the reliability and the service probability. Again these may relate to a single mode or to the circuit as a whole. The reliability of a mode is given as the probability that this mode shall be present and that its signal/noise power ratio equals or exceeds the wanted value. Means of evaluation of the availability have already been discussed. The day-to-day distribution of signal/noise ratio is estimated similarly from the monthly median signal/noise ratio by combining the day-to-day variabilities of the signals and noise, assuming these to be uncorrelated, and by again assuming that some distribution such as the chi-square law holds. Thereby the probability that a specified signal/noise ratio will be equalled or exceeded is given. On the assumption that the day-to-day ionospheric changes influencing mode support are not correlated with those giving rise to changes in signal/noise ratio, the mode reliability is then taken as the product of the mode availability and the probability that the mode provides a specified signal/noise ratio. Whilst undoubtedly there is some correlation between daily variations of the ionospheric support of different modes, and likewise in their relative signal strengths, a means of allowing for this has yet to be found.

All parameters used in the reliability predictions are somewhat uncertain, and a standard error may be ascribed to each. The terms involved include the uncertainty in the predictions of the monthly median noise and signal powers, and of the standard deviations of the noise and signal day-to-day variations. The total uncertainty variance, found by adding the appropriate individual uncertainty variances may be used to define an uncertainty distribution giving the probability that a required reliability is achieved. This is known as the service probability.

So far, the concern has been entirely with system-performance parameters depending on signal and noise intensities. Mention should also be made of signal multipath distortion. By combining predictions for different modes, the probability of multipath can be estimated.

Multipath is defined as existing when two or more modes are jointly present having a difference in signal powers of less than some specified amount and a difference in group-path times exceeding a given figure. Predictions of multipath involve a simple extension of the procedures described.

6 PREDICTION PROCEDURES

There are a large number of prediction procedures for mainframe computer evaluation in use by different organisations. A selection of the more familiar of these is listed in Table 2. Tables 3 and 4 provide examples of the outputs yielded. International coordination in prediction procedure development is carried out under the auspices of the CCIR. Mention should be made particularly of the method of Report 894,(10) produced and refined over the last few years, specifically for use in service planning by the World Administrative Radio Conference on HF Broadcasting, but also of general applicability.

The now widespread availability of microcomputers has led to significant recent efforts both in the development of microcomputer versions of mainframe programs (Table 5) and of other programs specifically tailored to the resources of particular machines (Table 6). The portability of microcomputers offers potential for applications not hitherto possible.

7 SHORT-TERM PREDICTION AND REAL-TIME CHANNEL SOUNDING

Short-term models for frequency management are directed towards assessing the best frequency to use with an existing system in the light of the prevailing ionospheric conditions of the time. Therefore the requirement is to use system-performance predictions of the form already described, but with the forecast ionosphere replaced by a more accurate representation. King and Slater(11), and Rush et al(12) have studied the day-to-day variability of different ionospheric characteristics. They conclude that the greatest fractional variations in the E and F regions arise in foF2. Therefore a useful improvement in modelling capability would be achieved if it were possible to use near real-time values of foF2 and to retain monthly-median estimates of the other ionospheric characteristics. Hence effort has centred on deducing foF2. Although forecasts can sometimes be made of solar disturbance effects leading to enhanced D-region ionisation, models of daily absorption are not feasible at the present time.

Procedures involving vertical-incidence sounders at one of the path terminals to measure foF2 directly have only limited use because from such measurements it is possible to infer values at other locations separated only by short distances. Rush and Miller(13) have shown that at mid-latitudes the correlation of daily departures of foF2 from the monthly median values at different point separations depends markedly on path orientation, time-of-day and season. The correlation at a fixed Universal Time extends over a greater distance in the E-W direction than for N-S paths, despite the change in local time along the paths in the former case. Typically the correlation falls to a value of 0.7 in a distance of about 2000 km for E-W paths and 1000 km for N-S paths. Suggestions have been made that foF2 values at different locations should correlate better if they are compared at the same local time, and the possibility merits further study. This would mean that measured data could be used to provide better forecasts of conditions on westerly than easterly paths.

There are two approaches: to use past foF2 data or to find other parameters that can be measured and on which foF2 depends. Rush and Gibbs(14) have compared the accuracy of forecasts of daily foF2 in terms of observed monthly median models with those deduced from weighted means of the preceding past days. Fig. 11 is an example from their published results. They found that on average for a series of locations and times the use of a previous five-day period value gives estimates that are comparable or better than from the observed monthly median. This means they are to be preferred to using predicted monthly median figures. Nevertheless they conclude that an uncertainty of the order of 0.5 MHz exists at all times and that when attempts are made to extrapolate results to remote locations where measured data are not available, errors are likely to be prohibitive.

Interest centres on the identification of precursors of solar disturbances responsible for changes in the ionosphere and in the Earth's magnetic field. Optical, X-ray and radio emissions from the sun are observed daily at a number of ground-based sites and also aboard satellites. Ionospheric disturbances following solar flares occur either in close time succession and last for several hours, or begin 24-36 hours later and last for several days. The former arise from enhanced X-ray, ultraviolet and high-energy particle radiation, while the latter are associated with lower-energy particles.

Various attempts have been made to correlate daily foF2 values with indices of solar and magnetic activity. The 10.7 cm solar flux and the extreme ultraviolet flux producing the ionosphere are well correlated, so that monthly median foF2 varies in a systematic manner with monthly median flux. McNamara(15) has compared daily flux and foF2 values. He finds that during magnetically quiet periods daily and 60-day average flux values are equally good in predicting hourly foF2 a day ahead. Ionospheric disturbance forecasts and short-term prediction services are currently offered in the USA by the National Oceanic and Atmospheric Administration, Boulder Colorado and the Marconi Research Centre, Great Baddow Chelmsford.

Oblique forward sounders and backscatter sounders are available commercially for use as direct probes of propagation conditions in support of point-to-point radio systems. Coupled with real-time measures of channel occupancy these offer the advantages to operators with multi-frequency assignments of being able to select best frequencies from both signal/noise and multipath considerations. However, there are difficulties in data interpretation as well as additional system complexity and costs which make the approach unattractive in many applications. Furthermore, data collection should involve the use of similar transmitter powers, antennas and system sensitivities as for the circuits to be supported. Extrapolation of results to other paths adjacent to those being sounded is rarely possible.

There is much attraction and current interest in developing intelligent receivers with embedded microcomputers which incorporate a crude propagation prediction for frequency management, real-time spectrum occupancy measurement of assigned channels and real-time examination of reception quality for potentially good channels to identify the optimum. The next few years should see the emergence of a variety of systems available for purchase.

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Table 2. Mainframe computer prediction models for ionospheric characteristics, MUF's, noise and system performance

MODEL	PROGRAM NAME	SOURCE ORGANISATION
IONOSPHERIC CHARACTERISTICS	WOMAP HRMNTH	CCIR CCIR
MUF's	MUFFY MINIMUF 3.5	CCIR NOSC
NOISE	NOISEY	CCIR
SYSTEM PERFORMANCE	HFMUFES IONCAP APPLAB PROPHET AMBCOM CCIR 252 CCIR SUP252 REP 894	ITS ITS RAL NOSC SRI CCIR CCIR CCIR

ITS - Institute for Telecommunication Sciences, Boulder Colorado

NOSC - Naval Ocean Systems Center, San Diego, California

RAL - Rutherford Appleton Laboratory, Didcot, Oxon

SRI - SRI International, Menlo Park, California.

TABLE 3 Sample printout from the mainframe computer program IONCAP for system-performance prediction

```
                              METHOD 16   IONCAP 85.04   PAGE  2
         JAN    1970                SSN = 100.
BOULDER,COLORADO TO ST. LOUIS,MO.            AZIMUTHS                N. MI.       KM
40.03 N  105.30 W - 38.67 N   90.25 W       91.04  281.42           702.6    1301.1
                              MINIMUM ANGLE   0.0  DEGREES
ITS- 1 ANTENNA PACKAGE
XMTR   2.0  TO  30.0  CONST. GAIN  H   0.00 L   0.00 A   0.0  OFF AZ    0.0
RCVR   2.0  TO  30.0  CONST. GAIN  H   0.00 L   0.00 A   0.0  OFF AZ    0.0
POWER =  30.000 KW  3 MHZ NOISE = -150.0 DBW   REQ. REL = .90  REQ. SNR = 55.0
MULTIPATH POWER TOLERANCE = 10.0 DB   MULTIPATH DELAY TOLERANCE =  0.850 MS
 UT  MUF

11.0  6.1  2.0  2.6  3.1  3.2  3.7  4.3  4.9  5.4  6.0  6.6  7.2 FREQ
      1F2  1 E  1 E  1F2  1F2  1F2  1F2  1F2  1F2  1F2  1ES  1ES MODE
     28.6  5.6  6.0 21.4 21.4 21.3 21.5 22.0 23.1 25.5  6.6  6.6 ANGLE
      5.3  4.4  4.4  4.9  4.9  4.9  4.9  4.9  4.9  5.1  4.4  4.4 DELAY
     412.  99. 103. 302. 302. 299. 303. 310. 325. 362. 110. 110. V HITE
     0.50 1.00 0.97 1.00 1.00 1.00 0.98 0.92 0.77 0.55 0.72 0.62 F DAYS
     120. 110. 111. 117. 117. 115. 114. 114. 115. 117. 125. 127. LOSS
      49.  49.  51.  49.  48.  50.  52.  52.  53.  53.  47.  43. DBU
      -72  -63  -64  -68  -68  -67  -67  -68  -68  -69  -76  -81 S DBW
     -155 -143 -146 -140 -148 -149 -151 -152 -153 -155 -156 -157 N DBW
      82.  80.  82.  80.  79.  81.  83.  84.  85.  86.  80.  77. SNR
     -11. -16. -18. -17. -16. -18. -20. -21. -20. -16. -11. -10. RPWRG
     0.99 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 0.99 0.99 REL
     0.00 0.00 0.00 1.00 1.00 0.98 0.00 0.00 0.00 0.00 0.00 0.00 MPROB
12.0  5.8  2.0  2.5  3.1  3.6  4.1  4.3  4.7  5.2  5.7  6.3  6.8 FREQ
      1F2  1 E  1 E  1 E  1 E  1F2  1F2  1F2  1F2  1F2  1ES  1ES MODE
     28.4  5.3  5.5  5.7  6.0 21.9 22.0 22.2 23.1 25.5  6.6  6.6 ANGLE
      5.2  4.4  4.4  4.4  4.4  4.9  4.9  4.9  5.0  5.1  4.4  4.4 DELAY
     410.  99.  98. 100. 103. 309. 310. 313. 326. 363. 110. 110. V HITE
     0.50 1.00 1.00 1.00 0.96 0.97 0.96 0.91 0.76 0.54 0.83 0.74 F DAYS
     120. 113. 113. 114. 114. 115. 115. 115. 119. 118. 125. 126. LOSS
      49.  46.  49.  50.  52.  54.  51.  51.  51.  52.  46.  43. DBU
      -73  -66  -65  -66  -66  -65  -68  -69  -69  -69  -77  -80 S DBW
     -155 -144 -146 -148 -150 -151 -152 -152 -154 -155 -156 -157 N DBW
      81.  77.  80.  82.  83.  86.  83.  83.  84.  85.  79.  77. SNR
     -11. -14. -17. -19. -20. -22. -20. -20. -19. -15. -10. -10. RPWRG
     0.99 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 0.99 0.99 0.99 REL
     0.00 0.00 0.00 0.99 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 MPROB
13.0  7.9  2.0  2.7  3.4  4.1  4.9  5.6  6.1  6.3  7.0  7.7  8.4 FREQ
      1F2  1 E  1 E  1 E  1 E  1F2  1F2  1F2  1F2  1F2  1ES  1ES MODE
     25.7  4.9  5.2  5.5  5.7 21.3 21.0 21.3 21.4 22.5  6.6  6.6 ANGLE
      5.1  4.4  4.4  4.4  4.4  4.9  4.9  4.9  4.9  4.9  4.4  4.4 DELAY
     366.  90.  94.  97.  99. 300. 296. 300. 301. 317. 110. 110. V HITE
     0.50 1.00 1.00 1.00 1.00 1.00 0.99 0.94 0.92 0.72 0.64 0.53 F DAYS
     120. 119. 118. 117. 117. 117. 117. 117. 117. 117. 130. 132. LOSS
      54.  40.  43.  48.  51.  52.  54.  51.  51.  52.  47.  40. DBU
      -70  -72  -71  -68  -68  -68  -67  -71  -71  -71  -78  -85 S DBW
     -159 -144 -148 -151 -153 -154 -156 -157 -157 -158 -160 -161 N DBW
      88.  71.  76.  82.  84.  86.  88.  86.  86.  87.  82.  76. SNR
     -14.  -8. -13. -19. -21. -23. -25. -23. -23. -21.  -8.  -7. RPWRG
     0.99 0.99 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 0.97 0.97 REL
     0.00 0.00 0.00 1.00 1.00 0.94 0.00 0.00 0.00 0.00 0.00 0.00 MPROB
```

TABLE 4 Sample printout from the mainframe computer program MUFFY for MUF prediction

PROGRAM 'MUFFY' VERSION-JAN 82

BASIC MUF AND FOT DETERMINATION IN ACCORDANCE WITH CCIR REPORT 340-4

OSLO FOF2 COEFFICIENTS

AUGUST 1986 SUNSPOT NO. 25.0

LONDON 51.50N 0.06W TO NEW YORK 40.65N 73.78W AZIMUTHS 288.17 51.22 MILES 3457.9 KM. 5564.6

SHORT PATH

UT	MUF	FOT	UT	MUF	FOT	UT	MUF	FOT	UT	MUF	FOT
01	11.5	8.6	07	7.8	6.7	13	15.7	13.1	19	15.5	13.2
02	9.9	7.4	08	8.8	7.4	14	15.8	13.1	20	16.2	13.8
03	8.9	6.7	09	11.0	9.0	15	16.0	13.3	21	16.9	14.2
04	8.6	6.4	10	13.7	11.2	16	15.7	13.0	22	16.4	13.7
05	8.5	7.2	11	15.4	12.6	17	15.4	13.1	23	14.7	12.3
06	8.0	6.8	12	15.8	13.0	18	15.3	13.0	24	13.1	11.0

TABLE 5 Sample printout from the microcomputer program MICROP in accordance with CCIR Report 894 for system-performance prediction (produced by Rutherford Appleton Laboratory)

```
                    METHOD  1   MICROP2 86.07                 PAGE  1
            OCT    1978            SSN = 111.
DERBY                  ALICE SPRINGS             AZIMUTHS    SP     N. MI.      KM
17.32 S  123.65 E - 23.53 S  133.68 E           125.13  301 62      676.0    1251.9
MIN ANG  3.0 DEG, PWR    1.00 KW, XLZ  7.3 DB, XLY -3 9 DB, FTZ DIST  7000. KM
  TX-ANT  ISOTROPIC    TBEAR  0.0               RX-ANT  ISOTROPIC   RBEAR  0.0
```

MEDIAN FIELD STRENGTH FOR STRONGEST MODE IN DB ABOVE 1 UV/M ITS CODE

UT	MUF	DBU	3.0	5.0	7.0	9.0	12.0	15.0	18.0	22.0	26.0	0.0	0.0	LUF	FOT	OPMUF
1	17.7	29	-73	-24	3	20	25	28	29	23	3	0	0	7.7	15.7	20.4
2	18.4	29	-90	-34	0	18	24	27	29	25	9	0	0	7.8	16.2	21.1
3	19.2	29	-99	-39	-2	18	23	26	28	27	14	0	0	7.8	16.5	22.1
4	19.6	29	-98	-38	-2	18	23	27	28	28	17	0	0	7.8	16.9	22.5
5	19.7	29	-88	-33	0	19	24	27	29	28	17	0	0	7.7	16.9	22.6
6	19.6	30	-70	-10	4	21	25	28	29	29	17	0	0	7.6	16.9	22.5
7	19.2	31	-44	-1	10	23	27	29	30	28	16	0	0	7.2	16.6	22.1
8	18.4	31	-16	9	23	27	29	30	31	27	10	0	0	5.9	14.0	21.2
9	17.5	32	14	25	28	30	31	32	32	24	2	0	0	3.1	13.3	20.1
10	16.7	33	21	28	30	31	32	32	32	20	-7	0	0	2.0	12.7	19.2
11	16.2	33	26	29	30	31	32	33	31	16	-15	0	0	2.0	13.3	20.2
12	15.8	33	26	29	31	31	32	33	30	13	-22	0	0	2.0	13.8	19.7
13	15.4	33	26	29	31	31	32	33	29	9	-28	0	0	2.0	13.5	19.3
14	14.7	33	25	29	31	31	32	33	27	2	-43	0	0	2.0	12.9	18.4
15	13.6	32	25	29	31	31	32	31	19	-17	-48	0	0	2.0	11.9	17.0
16	12.4	32	26	29	31	31	32	27	7	-44	-48	0	0	2.0	11.2	15.5
17	11.8	32	26	29	30	31	32	23	-3	-48	-48	0	0	2.0	10.6	14.8
18	11.2	32	26	29	30	31	31	18	-14	-48	-48	0	0	2.0	10.1	14.1
19	10.3	32	26	29	30	31	28	5	-41	-48	-48	0	0	2.0	9.2	12.8
20	9.8	32	26	29	30	31	25	-4	-48	-48	-48	0	0	2.0	8.1	12.2
21	11.2	32	21	28	30	31	31	18	-13	-48	-48	0	0	2.0	8.5	12.9
22	14.2	32	10	20	27	29	31	31	23	-6	-48	0	0	3.3	10.8	16.3
23	16.7	31	-20	6	16	26	29	30	30	19	-9	0	0	5.9	13.2	19.2
24	17.5	30	-48	-3	9	22	27	29	30	22	1	0	0	7.4	14.7	20.1

TABLE 6 Sample printout from the microcomputer program MINIFTZ for system-performance prediction (produced by FTZ, Darmstadt)

```
HF-FIELD STRENGTH PREDICTION ESTIMATED BY MINIFTZ2

CIRCUIT : MASIRAH      - DELHI                      MONTH  :     SEP. 84
LOCATION: 20.6N  58.9E   28.7N  77.2E               SSN    :          34
AZIMUTH :  60.4 DEG.      248.1 DEG.                POWER  :    1.000 KW
DISTANCE:  2054 KM                                  TX-GAIN:      0.0 DB
MIN-ANG.:   3.0 DEG.
```

FIELD STRENGTH IN DB ABOVE 1 UV/M FOR 50 PERCENT OF TIME

UTC	MUF	DBU	FOT	3.0	5.0	7.0	9.0	12.0	15.0	18.0	22.0
1	11.3	30	9.0	26	33	34	33	28	17	5	-4
2	15.4	28	11.9	-12	17	26	30	30	28	21	9
3	18.2	27	14.3	...	1	18	25	28	29	27	18
4	19.2	26	15.3	...	-9	12	21	27	28	27	20
5	19.9	26	16.2	...	-16	8	19	26	27	27	22
6	21.2	26	17.6	...	-21	6	18	25	27	27	24
7	22.5	26	17.1	...	-23	5	17	25	28	28	26
8	23.6	26	19.7	...	-23	5	17	25	28	29	27
9	24.1	26	20.0	...	-21	6	18	26	29	29	28
10	24.5	27	20.1	...	-16	9	20	27	29	30	28
11	24.3	27	19.7	...	-9	13	22	28	30	30	29
12	23.2	27	18.7	...	1	18	26	30	31	31	28
13	21.6	28	18.2	-10	18	28	32	34	33	31	28
14	19.4	29	15.5	8	26	32	34	35	33	31	23
15	16.9	29	13.4	16	30	34	35	34	32	27	16
16	15.0	30	11.9	22	32	35	35	33	30	21	8
17	14.0	30	11.1	26	34	35	35	33	27	18	4
18	13.4	30	10.6	26	34	35	35	32	25	15	3
19	12.8	30	10.2	26	34	35	34	31	23	12	1
20	12.1	30	9.5	26	33	35	34	30	20	9	-1
21	11.5	30	9.0	26	33	34	33	29	17	6	-3
22	10.2	30	7.9	26	33	33	32	23	10	2	-9
23	8.7	30	6.7	26	32	32	29	15	4	-4	-16
24	8.7	30	6.7	26	32	32	29	15	4	-4	-17

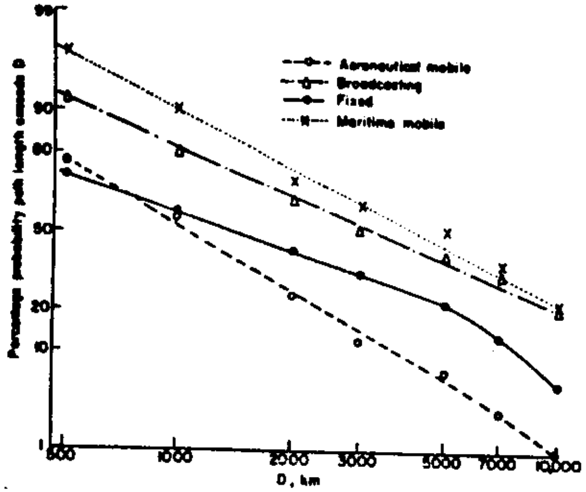

Fig. 1 Distribution of path lengths of sample circuits for different radio services (from Samuel and Hurst)

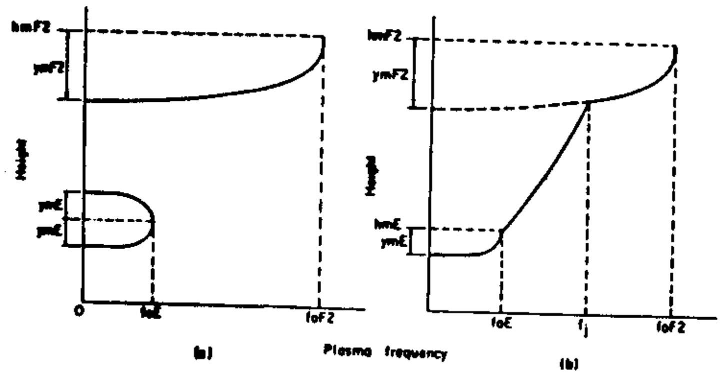

Fig. 2 Models of height distribution of electron concentration

(a) First CCIR procedure
(b) Second CCIR procedure

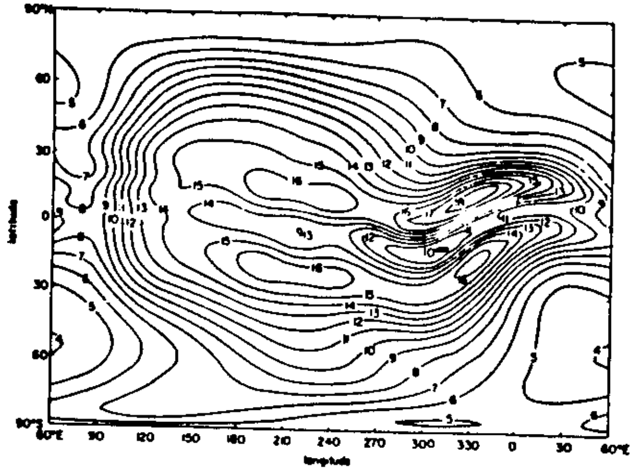

Fig. 3 Predicted median foF2, MHz for 00 h UT in March 1958 (from CCIR Report 340)

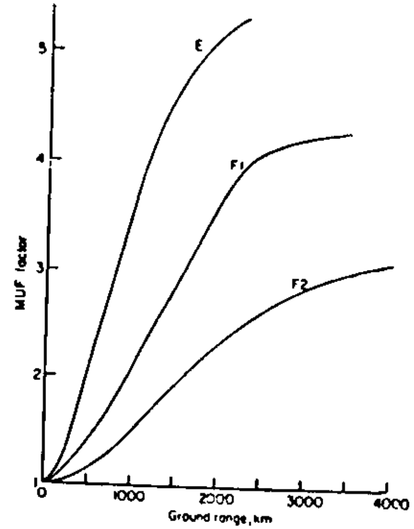

Fig. 4 MUF factors for single-hop E, F1 and F2 modes

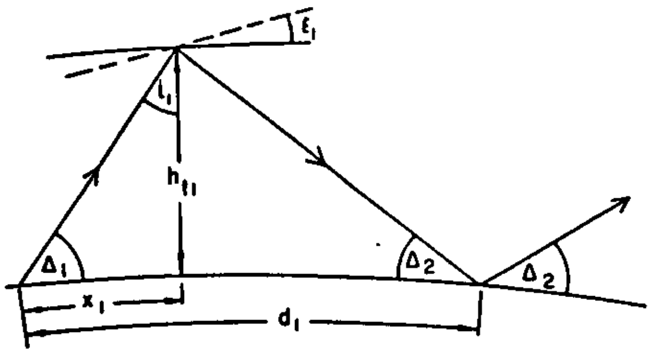

Fig. 5 Ray-hop geometry for reflection from a plane tilted mirror (from Supplement to CCIR Report 252-2)

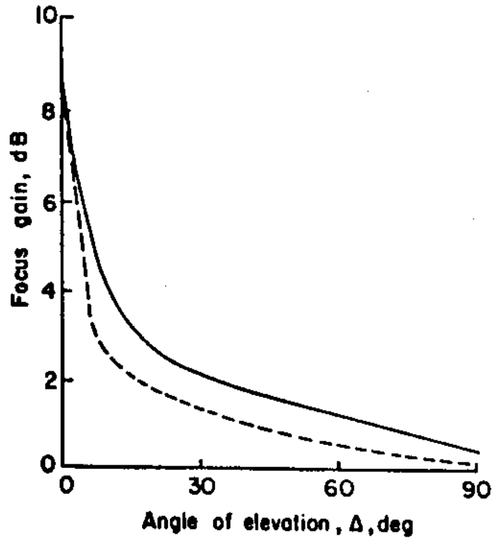

Fig. 6 Horizon focus gain (from Supplement to CCIR Report 252-2)
——— F modes
- - - - - E modes

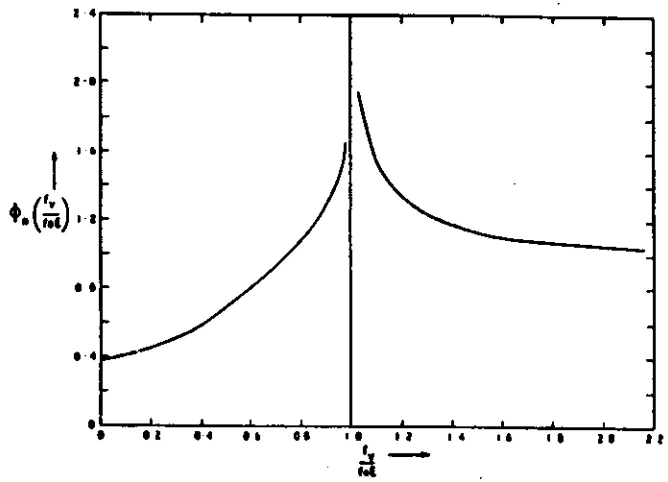

Fig. 7 Absorption factor ϕ_n for equivalent vertical-incidence frequency f_v (from Supplement to CCIR Report 252-2)

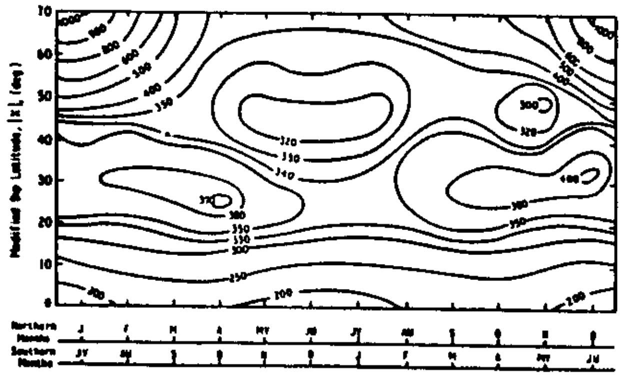

Fig. 8 Absorption factor A_T for an overhead sun and smoothed sunspot number of zero (from Supplement to CCIR Report 252-2)

$$x = \arctan \frac{I}{\sqrt{\cos \lambda}}$$

where I = magnetic dip in radians and λ = geographic latitude

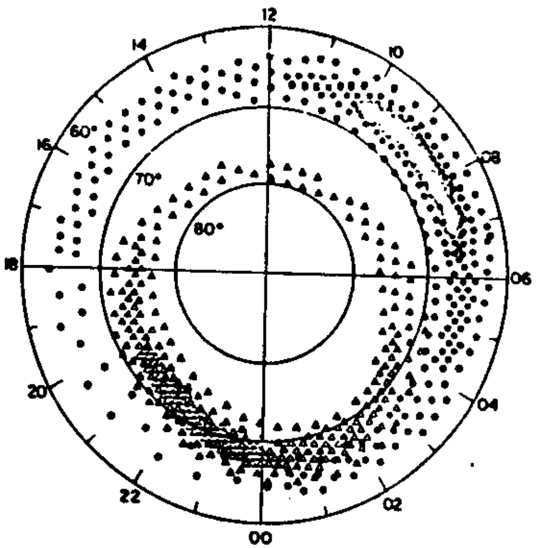

Fig. 9 Zones of precipitating auroral electrons as a function of corrected geomagnetic latitude and time (from Hartz and Brice)

- • drizzle precipitation - energy tens of keV
- ▲ splash precipitation - energy few keV

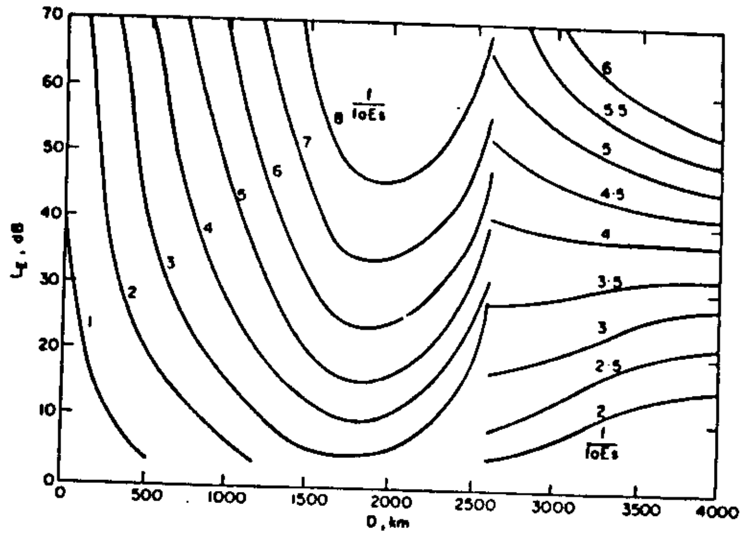

Fig. 10 Sporadic-E reflection loss, L_r (from Supplement to CCIR Report 252-2)

Curves relate to a single hop for ground range D < 2500 km and to two hops for greater distances

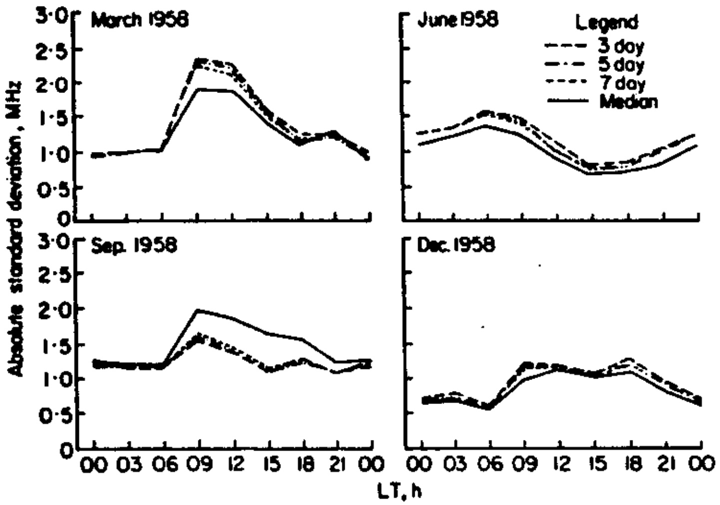

Fig. 11 Errors in estimates of daily values of foF2 at Slough using monthly median and weighted means of past days measurements (from Rush and Gibbs)