INTERNATIONAL ATOMIC ENERGY AGENCY
UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION
INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
I.C.T.P., P.O. BOX 586, 34100 TRIESTE, ITALY, CABLE: CENTRATOM TRIESTE

UNITED NATIONS INDUSTRIAL DEVELOPMENT ORGANIZATION

INTERNATIONAL CENTRE FOR SCIENCE AND HIGH TECHNOLOGY
c/o INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS 34100 TRIESTE (ITALY) VIA GRIGNANO, 9 (ADRIATICO PALACE) P.O. BOX 586 TELEPHONE 040-224572 TELEFAX 040-224575 TELEX 460449 APH I

H4.SMR/537-4

SECOND COLLEGE ON THEORETICAL AND EXPERIMENTAL RADIOPROPAGATION PHYSICS

(7 January - 1 February 1991)

Co-sponsered by ICTP, URSI, ICSU
and with the participation of ICS

High Frequency Communications problems

P. A. Bradley
Rutherford Appleton Laboratory
Chilton, Didcot, Oxon UK

High Frequency Communications problems

P A Bradley
(Rutherford Appleton Laboratory, Chilton, Didcot, Oxon OX11 0QX, UK)

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. 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.

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.

REQUIREMENTS FOR PROPAGATION PREDICTIONS

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.

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. 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.

Frequency Management

Frequency management may be defined as the selection of the frequency to use on a particular occasion from those assigned and available. 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 such as path sounding and real-time channel evaluation and in the light of existing operating practices which differ appreciably for the separate radio services. Military applications for reliable short-term predictions can be envisaged but most civilian systems work satisfactorily with the user selecting the best of a number of simultaneous transmissions. In all cases storm predictions would be of particular value.

PRINCIPLES OF LONG-TERM PREDICTION AND AVAILABLE TECHNIQUES

Introduction

Prediction procedures give estimates of median values of the maximum usable frequency (MUF), received signal strength, background noise and lowest usable frequency (LUF), and indicate their diurnal, seasonal and solar-cycle variations. The techniques adopted usually involve 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.

Model of the Ionosphere

A first requirement for accurate predictions must be a model of the vertical distribution of electron concentration in the E and F regions. This needs to 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 have parameters 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 yielding the best fit to measured data consists of parabolic E and F2 layers and a linear increase of electron concentration with height in the F1 region (1).

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. The CCIR has produced an Atlas (1) giving monthly median estimates by means of charts, nomograms and computer-based formulations. foE and foF1 are obtained from empirical expressions which assume a variation with latitude, time-of-day and season depending on the solar-zenith angle χ. A solar-activity dependence is included in terms of R_{12} the smoothed sunspot number.

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:

$$\Omega(\lambda,\theta,T) = \sum_j [a_j(\lambda,\theta)\cos jT + b_j(\lambda,\theta)\sin jT] \qquad (1)$$

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

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

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

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. 1 gives an example of a prediction map for foF2 for one epoch based on 988 numerical coefficients U.

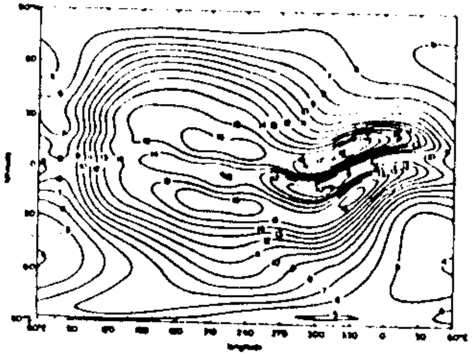

Fig. 1 Predicted median foF2, MHz for 00 h UT in March 1958 (from CCIR Report 340)

Basic MUF, Operational MUF and FOT

Propagation by means of F2-, E- and F1 modes is allowed for, depending on the path length. The path basic MUF is taken as the highest basic 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 takes them as the product of critical frequency and an 'M'-factor given from empirical equations as a function of path length and reflecting layer height.

For path lengths beyond 4000 km 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.

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. Empirical relationships between the operational MUF and the basic MUF are available (2).

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_l, 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).

Oblique Ray Paths

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 to a particular ground range can be determined by an iterative process for rays launched in different directions. 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.

Signal Strength

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.

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.

$$P_r = P_t + G_t + G_r - L_b \qquad (3)$$

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

$$E = P_r + 20 \log_{10} f + 107.2 \qquad (4)$$

where f is the wave frequency in Megahertz.

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 adopted for broadcast planning (5). At this time reference patterns for antennas typically employed on point-to-point links are in preparation.

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 at grazing incidence determined by ionospheric roughness of 9 dB. Other equations predict the antipodal focusing that occurs on very long paths.

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 (3) based on vertical-incidence data are that:

(i) the variation with frequency includes 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. 2). 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. 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.

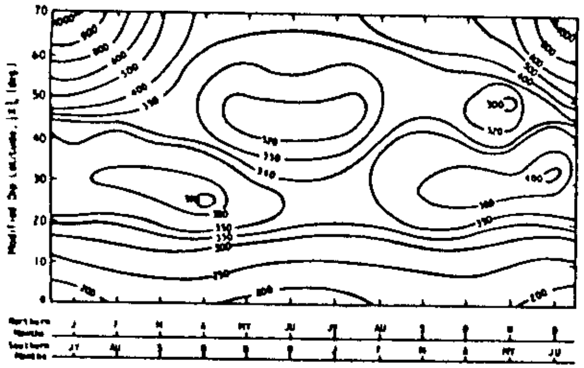

Fig. 2 Absorption factor A_T for an overhead sun and smoothed sunspot number of zero (from Supplement to CCIR Report 252-2)

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

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

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.

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 (3). 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. 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.

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 (3). 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.

Ground-reflection loss. Multiple-hop ground-reflection losses are evaluated in terms of Fresnel 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.

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 20 dB.

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. The distributions of daily MUF are assumed to follow a given law, so that it is possible to determine for each wave frequency and examined mode the fraction of days for which that mode can exist over the path. This is known as the availability. 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 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 (7).

An important monthly median system performance parameter is the LUF or lowest usable 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 parameters quantifying system performance 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. The day-to-day distribution of signal/noise ratio is estimated 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.

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.

By combining predictions for different modes, the probability of multipath also 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.

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 1. Table 2 provides an example of the types of output 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 (2) produced and refined over the last few years for use in service planning by the World Administrative Radio Conference on HF Broadcasting, but also of general applicability.

TABLE 1. 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.

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

TABLE 2 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       91.84  281.42         702.6    130'.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 0.67 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 -148 -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.  95.  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. 115. 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  7.5  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
```

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 generate system-performance predictions of the form already described, but with the forecast ionosphere replaced by a more accurate representation. The greatest fractional variations in the E and F regions arise in foF2. Hence 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.

Procedures involving vertical-incidence sounders at one of the path terminals to measure foF2 directly have only limited use because typically the correlation of daily departures from the median 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. Rush and Gibbs (8) 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. 3 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. Nevertheless an uncertainty of the order of 0.5 MHz exists at all times and when extrapolating to locations where measured data are not available errors are likely to be prohibitive.

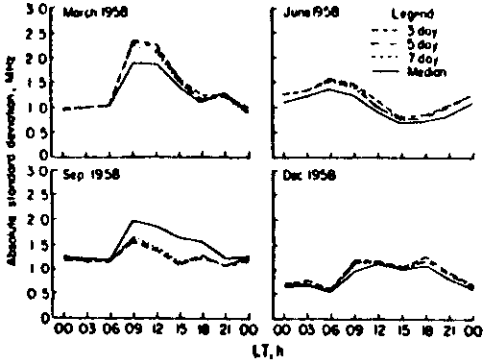

Fig. 3 Errors in estimates of daily values of foF2 at Slouth using monthly median and weighted means of past days measurements (from Rush and Gibbs, 8)

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. During magnetically quiet periods daily and 60-day average 10.7 cm solar flux values are equally good in predicting hourly foF2 a day ahead (9). Ionospheric disturbance forecasts and short-term prediction services are currently offered in the USA by the National Oceanic and Atmospheric Administration, Boulder Colorado and in the UK by the Marconi Research Centre, Great Baddow Chelmsford.

There is much attraction and current interest in developing intelligent receivers with embedded micro-computers 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 commercially available systems.

REFERENCES

1. CCIR, 1983, 'Atlas of ionospheric characteristics'. Report 340, Documents of XVth Plenary Assembly, International Telecommunication Union, Geneva.

2. CCIR, 1986, 'A simple HF propagation prediction method for MUF and field strength'. Report 894, Documents of XVIth Plenary Assembly, International Telecommunication Union, Geneva.

3. CCIR, 1980, 'Second CCIR computer-based interim method for estimating sky-wave field strength and transmission loss at frequencies between 2 and 30 MHz'. Supplement to Report 252-2, Documents of XIVth Plenary Assembly, International Telecommunication Union, Geneva.

4. Lockwood, M, 1984, 'Simplified estimation of raypath mirroring height for HF radiowaves reflected from the ionospheric F region', Proc. IEE, Part F, 131, 117-124.

5. CCIR, 1986, 'A set of simplified HF antenna patterns for planning purposes'. Report 1062, Documents of XVIth Plenary Assembly, International Telecommunication Union, Geneva.

6. Foppiano, A J and Bradley, P A, 1983, 'Prediction of auroral absorption of high-frequency waves at oblique incidence'. Telecomm J. 50, 547-560.

7. CCIR, 1986, 'Bandwidths, signal-to-noise ratios and fading allowances in complete systems'. Recommendation 339, Documents of XVIth Plenary Assembly, International Telecommunication Union, Geneva.

8. Rush, C M and Gibbs, J, 1973, 'Predicting the day-to-day variability of the midlatitude ionosphere for application to HF propagation predictions'. AFCRL Tech. Rep. 73-0335, 2-9. Defense Documentation Center, Alexandria, Va.

9. McNamara L F, 1976, 'The correlation of individual values of foF2 and M(3000)F2 with the solar 10.7 cm flux under magnetically quiet conditions'. Ionospheric Prediction Service (Australia), Series R No. 30.