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Propagation Information for Modern HF Systems Planning

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'Propagation information for modern HF systems planning'

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Lecture 1 <u>Ionosphere morphology</u>

- formation and causes
- ionospheric vertical sounding
- height distribution and principal layers
- diurnal, seasonal and solar-cycle variations
- geographical changes: equatorial, midlatitude, auroral and polar cap
- day-to-day variability
- irregularities: spread F and sporadic E
- storms

Introduction - the ionosphere and its importance to radio engineers

The ionosphere is an electrified region of the Earth's atmosphere situated at heights of from about 50 km to several thousand km. It consists of free electrons and charged ions produced by the ionising influences of solar radiation and of incident energetic solar and cosmic particles. The ionosphere is subject to marked geographic and temporal variations. It has a profound effect on the characteristics of radio waves propagated within or through it. By means of wave refraction, reflection or scattering it permits transmission over paths that would not otherwise be possible, but at the same time it screens some regions that could be illuminated in its absence (see figure 1). The ionosphere is of considerable importance to radio engineers because:

(i) it provides the means of establishing various communication paths, calling for system design criteria based on a knowledge of ionospheric morphology;

(ii) it requires specific engineering technologies to derive experimental probing facilities to assess its characteristics, both for communication-system planning and management, and for scientific investigations, and

(iii) it permits the remote monitoring by sophisticated techniques of certain distant natural and man-made phenomena occurring on the ground, in the air, and in space.

Formation of the ionosphere and its morphology

There is widespread interest in the characteristics of the ionosphere by scientists all over the world. Several excellent general survey books have been published describing the principal known features(3-6) and other more specialised books concerned with aeronomy and including the ionosphere and magnetosphere, are of great value to the research worker(7-14). Several journals in the English language are devoted entirely, or to a major extent, to papers describing investigations into the state of the ionosphere and of radio propagation in the ionosphere(15-20). A useful bibliography of papers published prior to 1961 is available(21).

The formation of the ionosphere is a complicated process involving the ionising influences of solar radiation and solar and cosmic particles on an atmosphere of complex structure. The rates of ion and free-electron production depend on the flux density of the incident radiation or particles, as well as on the ionisation efficiency, which is a function of the ionising wavelength (or particle energies) and the chemical composition of the atmosphere. There are two heights where electron production by the ionisation of molecular nitrogen and atomic and molecular oxygen is a maximum. One occurs at about 100 km and is due to incident X-rays with wavelengths less than about 100Å and to ultraviolet radiation with wavelengths near 1000Å; the other is at about 170 km and is produced by radiation of wavelengths 200 - 800Å.

Countering this production, the free electrons tend to recombine with the positive ions and to attach themselves to neutral molecules to form negative ions. Electrons can also leave a given volume by diffusion or by drifting away under the influences of temperature and pressure gradients, gravitational forces, or electric fields set up by the movement of other ionisation. The electron density at a given height is given from the so-called 'continuity equation' in terms of the balance between the effects of production and loss.

Night-time electron densities are generally lower than in the daytime because the rates of production are reduced. Figure 2 gives examples of a night-time and a daytime height distribution of electron density. The ionisation is continuous over a wide height range, but there are certain height regions with particular characteristics, and these are known, following E. V. Appleton, by the letters D, E and F. The E-region is the most regular ionospheric region, exhibiting a systematic dependence of maximum electron density on solar-zenith angle, leading to predictable diurnal, seasonal and geographical variations. There is also a predictable dependence of its electron density on the changes in solar radiation which accompany the long-term fluctuations in the state of the sun. Maximum E-region electron density is approximately proportional to sunspot number, which varies over a cycle of roughly 11 years.

In the daytime the F-region splits into two, with the lower part known as the F1-region and the upper part as the F2-region. This splitting arises because the principal loss mechanism is an ion-atom interchange process followed by dissociative recombination, the former process controlling the loss rates in the F2-region and the latter in the F1-region. Although maximum production is in the F1-region, maximum electron density results in the F2-region, where the loss rates are lower. The maximum electron density of the F1-region closely follows that of the E-region, but there are

significant and less predictable changes in its height. The maximum electron density and height of the F2-region are subject to large changes which have important consequences to radio-wave propagation. Some of these changes are systematic but there are also major day-to-day variations. It seems likely that the F2 region is controlled mainly by ionisation transport to different heights along the lines of force of the Earth's magnetic field under the influence of thermospheric winds at high and middle latitudes[22,23] and by electric fields at low latitudes[24]. These effects, taken in conjunction with the known variations in atmospheric composition, can largely explain characteristics of the F2-region which have in the past been regarded as anomalous by comparison with the E-region - namely, diurnal changes in the maximum of electron density in polar regions in the seasons of complete darkness, maximum electron densities at some middle-latitude locations at times displaced a few hours from local noon with greater electron density in the winter than the summer, and at low latitudes longitude variations linked more to the magnetic equator than to the geographic equator, with a minimum of electron density at the magnetic equator and maxima to the north and south where the magnetic dip is about 30°. At all latitudes electron densities in the F2-region, like those in the E- and F1-regions, increase with increase of sunspot number. The electron densities at heights above the maximum of the F2-region are controlled mainly by diffusion processes.

The D-region shows great variability and fine structure, and is the least well understood part of the ionosphere. The only ionising radiations that can penetrate the upper regions and contribute to its production are hard X-rays with wavelengths less than about 20Å and Lyman-α radiation at 1216Å. Chemical reactions responsible for its formation principally involve nitric oxide and other minor atmospheric constituents.

The D-region is mainly responsible for the absorption of radio waves because of the high electron-collision frequencies at such altitudes - see Section 5.1.3. Whilst the electron densities in the upper part of the D-region appear linked to those in the E-region, leading to systematic latitudinal, temporal and solar-cycle variations in absorption, there are also appreciable irregular day-to-day absorption changes. At middle latitudes anomalously high absorption is experienced on some days in the winter. This is related to warmings of the stratosphere and is probably associated with changes in D-region composition. In the lower D-region at heights below about 70 km the ionisation is produced principally by energetic cosmic rays, uniformly incident at all times of day. Since the free electrons thereby generated tend to collide and become attached to molecules to form negative ions by night, but are detached by solar radiation in the daytime, the lower D-region ionisation, like that in the upper D-region, is much greater by day than night. In contrast, however, electron densities in the lower D-region, being related to the incidence of cosmic rays, are reduced with increase in the number of sunspots. Additional D-region ionisation is produced at high latitudes by incoming particles, directed along the lines of force of the Earth's magnetic field. Energetic electrons, probably originating from the sun, produce characteristic auroral absorption events over a narrow band of latitudes about 10° wide, associated with the visual auroral regions [25,26].

From time to time disturbances occur on the sun known as solar flares. These are regions of intense light, accompanied by increases in the solar far ultraviolet and soft X-ray radiation. Solar flares are most common at times of high sunspot number. The excess radiation leads to sudden ionospheric disturbances (SID's), which are rapid and large increases in ionospheric absorption occurring simultaneously over the whole sunlit hemisphere. These persist for from a few minutes to several

hours, giving the phenomena of short-wave fadeouts (SWF's), first explained by Dellinger[27]. Accompanied by solar flares are eruptions from the sun of energetic protons and electrons. These travel as a column of plasma, and depending on the position of the flare on the sun's disc and on the trajectory of the Earth, they sometimes impinge on the ionosphere. Then, the protons, which are delayed in transit from fifteen minutes to several hours, produce a major enhancement of the D-region ionisation in polar regions that can persist for several days. This gives the phenomenon of polar-cap absorption (PCA) with complete suppression of HF signals over the whole of both polar regions[28]. Slower particles, with transit times of from 20 to 40 hours, produce ionospheric storms. These storms, which result principally from movements in ionisation, take the form of depressions in the maximum electron density of the F2-region[29]. They can last for several days at a time with effects which are progressively different in detail at different latitudes. Since the sun rotates with a period of about 28 days, sweeping out a column of particles into space when it is disturbed, there is a tendency for ionospheric storms to recur after this time interval.

Additional ionisation is sometimes found in thin layers, 2 km or less thick, embedded in the E-region at heights between 90 and 120 km. This has an irregular and patchy structure, a maximum electron density which is much greater than that of the normal E-region, and is known as sporadic-E (or Es) ionisation because of its intermittent occurrence. It consists of patches up to 2000 km in extent, composed of large numbers of individual irregularities each less than 1 km in size. Sporadic-E tends to be opaque to the lower HF waves and partially reflecting at the higher frequencies. It results from a number of separate causes and may be classified into different types[30], each with characteristic occurrence and other statistics. In temperature latitudes sporadic-E arises principally from wind shear, close to the magnetic equator it is produced by plasma instabilities and at high latitudes it is mainly due to incident energetic particles. It is most common at low latitudes where it is essentially a daytime phenonemon.

Irregularities also develop in the D-region due to turbulence and wind shears and other irregularities are produced in the F-region. The F-region irregularities can exist simultaneously over a wide range of heights, either below or above the height of maximum electron density and are referred to as spread-F irregularities. They are found at all latitudes but are particularly common at low latitudes in the evenings where their occurrence is related to rapid changes in the height of the F-region[31].

Ionospheric probing techniques

There are a wide variety of methods of sounding the state of the ionosphere involving single and multiple-station ground-based equipments, rocket-borne and satellite probes (see Table 2). A comprehensive survey of the different techniques has been produced by a Working Group of the International Union of Radio Science (URSI)[63]. Some of the techniques involve complex analysis procedures and require elaborate and expensive equipments and aerial systems (figure 3); others need only a single radio receiver.

The swept-frequency ground-based 'ionosonde' consisting of a co-located transmitter and receiver was developed for the earliest of ionospheric measurements and is still the most widely used probing instrument. The transmitter and receiver frequencies are swept synchronously over the range from about 0.5-1 MHz to perhaps 20 MHz depending on ionospheric conditions, and short pulses typically of duration 100 μs with a repetition rate of 50/sec are transmitted. Calibrated film records of the received echoes give the group path and its frequency dependence. In practice the records require expert interpretation because (i) multiple echoes occur corresponding to more than one traverse between ionosphere and ground (so-called 'multiple-hop' modes) or when partially reflecting sporadic-E or F-region irregularities are present; (ii) the ordinary and extraordinary

Table 2 Principal ionospheric probing techniques

Height range	Technique	Parameters monitored	Site
Above 100 km	vertical-incidence sounding	up to height of maximum ionisation-electron density	ground
	topside sounding	from height of satellite to height of maximum ionisation-electron density; electron and ion temperatures; ionic composition	satellite
	incoherent scatter	up to few thousand km - electron density; electron temperature; ion temperature; ionic composition; collision frequencies; drifts of ions and electrons	ground
	Faraday rotation and differential Doppler	total-electron content	satellite -ground
	in-situ probes	wide range of parameters	satellite
	c.w. oblique incidence	solar flare effects; irregularities; travelling disturbances; radio aurorae	ground
	pulse oblique incidence	oblique modes by ground backscatter and oblique sounding; meteors; radio aurorae; irregularities and their drifts	ground
	whistlers	out to few Earth radii-electron density; ion temperature; ionic composition	ground or satellite
Below 100 km	vertical-incidence sounding	absorption	ground
	riometer	absorption	ground
	c.w. and pulse oblique incidence	electron density and collision frequency	ground
	wave fields	electron density and collision frequency	rocket-ground
	in-situ probes	electron density and collision frequency; ion density; composition of neutral atmosphere	rocket
	cross-modulation	electron density and collision frequency	ground
	partial reflection	electron density & collision frequency	ground
	lidar	neutral air density; atmospheric aerosols; minor constituents	ground

waves are sometimes reflected from appreciably different heights, and (iii) oblique reflections occur when the ionosphere is tilted. Internationally agreed procedures for scaling ionosonde records (ionograms) have been produced(64). Since reflection takes place from a height where the sounder frequency is equal to the ionospheric plasma frequency, and since the group path can be related to that height provided the electron densities at all lower heights are known, the data from a full frequency sweep can be used to give the true-height distribution of electron density in the E- and F-regions up to the height of maximum electron density of the F2-region. The conversion of group path to true height requires assumptions regarding missing data below the lowest height from which echoes are received and over regions where the electron density does not increase monotonically with height. The subject of true-height analysis is complex and controversial(65). Commercially manufactured pulse sounders use transmitter powers of about 1 kW. Sounders with powers of around 100 kW and a lower frequency limit of a few kilohertz have been operated successfully in areas free from MF broadcast interference, to study the night-time E layer(66) - this has a maximum plasma frequency of around 0.5 MHz. Pulse-compression systems(67) and c.w. chirp sounders(68) offer the possibility of improved signal/noise ratios and echo resolution. In the chirp sounder system, originally developed for use at oblique incidence, the transmitter and receiver frequencies are swept synchronously so that the finite echo transit time leads to a frequency modulation of the receiver i.f. signals. These signals are then spectrum-analysed to produce conventional ionograms. Receiver bandwidths of only a few tens of Hertz are needed so that transmitter powers of a few watts are adequate. A prototype ionosonde, known as a 'dynasonde'. has been produced with data recorded digitally on magnetic tape[69]. An ionosonde has been successfully flown in an aircraft to investigate geographical changes in electron density at high latitudes[70]. Over 100 ground-based ionosondes throughout the world make regular soundings each hour of each day; data are published at monthly intervals[71].

Since 1962 swept-frequency ionosondes have been operated in satellites orbiting the earth at altitudes of around 1000 km. These are known as 'topside sounders' and they give the distributions of electron density from the satellite height down to the peak of the F2-region. They also yield other plasma-resonance information, together with data on electron and ion temperatures and ionic composition. Fixed-frequency topside sounders are used to study the spatial characteristics of spread-F irregularities and other features with fine structure.

Many different monitoring probes are mounted in satellites orbiting the earth at altitudes above 100 km, to give direct measurements of a range of ionospheric characteristics. These include r.f. impedance, capacitance, and upper-hybrid resonance probes for local electron density, modified Langmuir probes for electron temperature, retarding potential analysers and sampling mass spectrometers for ion density, quadrupole and monopole mass spectrometers for ion and neutral-gas analysis and retarding potential analysers for ion temperature measurements.

Ground measurements of satellite beacon signals permit studies of total-electron content, either from the differential Doppler frequency between two harmonically related HF/VHF signals[72], or from the Faraday rotation of a single VHF transmission[73]. Beacons on geostationary satellites are valuable for investigations of temporal variations. The scintillation of satellite signals at VHF and UHF gives information on the incidence of ionospheric irregularities, their heights and sizes[74].

A powerful tool for ionospheric investigations up to heights of several thousand kilometres is the vertical-incidence incoherent-scatter radar. The technique makes use of the very weak scattering from random thermal fluctuations in electron density which exist in a plasma in quasi-equilibrium. Several important parameters of the plasma affect the scattering such that each of these can be determined separately. The power, frequency spectrum and polarisation of the scattered signals are measured and used to give the height distributions of electron density, electron temperature, ionic composition ion-neutral atmosphere and ion-ion collision frequencies, and the mean plasma-drift velocity. Tristatic receiving systems enable the vertical and horizontal components of the mean plasma drift to be determined. Radars operate at frequencies of 40-1300 MHz using either pulse or c.w. transmissions. Transmitter peak powers of the order of 1MW, complex aerial arrays (figure 3) and sophisticated data processing procedures are needed. Ground clutter limits the lowest heights that can be investigated to around 100 km.

Electron densities, ion temperatures and ionic composition out to several Earth radii may be studied using naturally occurring whistlers originating in lightning discharges. These are dispersed audio-frequency trains of energy, ducted through the ionosphere and then propagated backwards and forwards along the Earth's magnetic-field lines to conjugate points in the opposite hemisphere. Whistler dispersions may be observed either at the ground or in satellites[75].

Continuous wave and pulsed signals, transmitted and received at ground-based terminals, may be used in a variety of ways to study irregularities or fluctuations in ionisation. Cross-correlation analyses of the amplitudes on three spaced receivers, of pulsed signals of fixed frequency reflected from the ionosphere at near vertical incidence, give the direction and velocity of the horizontal component of drift(76). The heights, patch sizes and incidence of F-region irregularities responsible for oblique-path forward-scatter propagation at frequencies around 50 MHz may be investigated by means of highly-directional aerials and from signal transit times(31). Measurements of the Doppler frequency variations of signals from stable c.w. transmitters may be used to study (a) ionisation enhancements in the E- and F-regions associated with solar flares (b) travelling ionospheric disturbances(77), and (c) the frequency-dispersion component of the ionospheric channel-scattering function(38, 78). Sporadic-E and F-region irregularities associated with visual aurorae may be examined by pulsed-radar techniques over a wide range of frequencies from about 6 to 3000 MHz. They may also be investigated using c.w. bistatic systems in which the transmitter and receiver are separated by several hundred kilometres. Since the irregularities are known to be elongated and aligned along the direction of the Earth's magnetic field and since at the higher frequencies efficient scattering can only occur under restricted conditions, the scattering centres may readily be located. Using low-power VHF beacon transmitters, this technique has proved very popular with radio amateurs. Pulsed meteor radars incorporating Doppler measurements indicate the properties and movements of meteor trains(51).

Two other oblique-path techniques, giving information on the regular ionospheric regions, are high-frequency ground backscatter sounding and variable-frequency oblique sounding. The former uses a co-located transmitter and receiver, and record interpretation generally involves identifying the skip distance (see figure 1) where the signal returns are enhanced because of ray convergence. It is important to use aerials with

azimuthal beamwidths of only a few degrees to minimise the ground area illuminated. Long linear aerial arrays with beam slewing, and circularly-disposed banks of log-periodic aerials with monopulsing are used(79). Oblique-incidence sounders are adaptions of vertical-incidence ionosondes with the transmitter and receiver controlled from stable synchronised sources. Atlases of characteristic records obtained from the two types of sounder under different ionospheric conditions have been produced(80, 81). Mean models of the ionosphere over the sounding paths may be deduced by matching measured data with ray-tracing results(82).

So far, no mention has been made of the height region below about 100 km. As already noted, the D-region is characterised by a complex structure and high collision frequencies which lead to large daytime absorption of HF and MF waves. This absorption may be measured using fixed-frequency vertical-incidence pulses(83), or by monitoring c.w. transmissions at ranges of 200-500 km, where there is no ground-wave component and the dominant signals are reflected from the E-region by day and the sporadic-E layer by night. There is then little change in the raypaths from day to night so that, assuming night absorption can be neglected, daytime reductions in amplitude are a measure of the prevailing absorption. Multifrequency absorption data give information on the height distributions of electron density(84). Auroral absorption is often too great to be measured in such ways, but special instruments known as riometers can be used(85). These operate at a frequency around 30 MHz and record changes in the incident cosmic noise at the ground caused by ionospheric absorption.

D-region electron densities and collision frequencies may be inferred from oblique or vertical-path measurements of signal amplitude, phase, group-path delay and polarisation at frequencies of 10 Hz-100 kHz, with atmospherics as the signal sources at the lower frequencies. Aircraft observations of the change in these parameters with range give useful additional information[86]. Vertically radiated signals in the frequency range 1.5-6 MHz suffer weak partial reflections from heights of 75-90 km. Measurements of the reflection coefficients of both the ordinary and extraordinary waves, which can be of the order of 10^{-5}, enable electron density and collision-frequency data to be deduced[87]. Pulsed signals with high transmitter powers (50-1000 kW), highly-directional circularly-polarised aerial systems and very sensitive receivers are needed. As well as in-situ probes in rockets, there are a wide range of other schemes for determining electron density and collision frequency, involving the study of wave-fields radiated between the ground and a rocket. These use combinations of frequencies in the VLF-VHF range and include the measurement of differential-Doppler frequency, absorption, differential phase, propagation time and Faraday rotation.

Theory shows that signals propagated via the ionosphere can become cross-modulated by high-power interfering signals which heat the plasma electrons through which the wanted signals pass. This heating causes the electron-collision frequency, and therefore the amplitude of the wanted signal to fluctuate at the modulation frequency of the interfering transmitter. Investigations of this phenomenon (known as the Luxembourg effect after the first identified interfering transmitter) usually employ vertically transmitted and received wanted pulses, modulated by a distant disturbing transmitter radiating synchronised pulses at half the repetition rate. Changes in signal amplitude and phase between successive pulses are

measured, and by altering the relative phase of the two transmitters, the height at which the cross-modulation occurs can be varied. Such data enable the height distributions of electron density in the D-region to be determined[88].

Using a Laser radar (Lidar), the intensity of the light backscattered by the atmospheric constituents at heights above 50 km gives the height distributions of neutral-air density and the temporal and spatial statistics of high-altitude atmospheric aerosols. Minor atmospheric constituents may be detected with tunable dye lasers from their atomic and molecular-resonance scattering[89].

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Captions to Figures

Figure 1 HF PROPAGATION PATHS VIA THE IONOSPHERE AT HIGH LATITUDES

(a) Sample distribution of electron density (arbitrary units) in northern hemisphere high-latitude ionosphere (adapted from Buchau(1)).

(b) Raypaths for signals of constant frequency launched with different elevation angles.

The ability of the ionosphere to refract, reflect or scatter rays depends on their frequency and elevation angle. Ionospheric refraction is reduced at the higher frequencies and for the higher elevation angles, so that provided the frequency is sufficiently great rays 1 escape whereas rays 2 are reflected back to ground. Rays 3 escape because they traverse the ionosphere at latitudes where the electron density is low (the Muldrew trough(2)). Irregularities in the F-region are responsible for the direct backscattering of rays 4. The low-elevation rays 5 are reflected to ground because of the increased ionisation at the higher latitudes. Note that for this ionosphere and frequency there are two ground zones which cannot be illuminated.

Figure 2 SAMPLE NIGHT-TIME AND DAYTIME HEIGHT DISTRIBUTIONS OF ELECTRON DENSITY AT MIDLATITUDES IN SUMMER

——— Night-time

- - - - Daytime

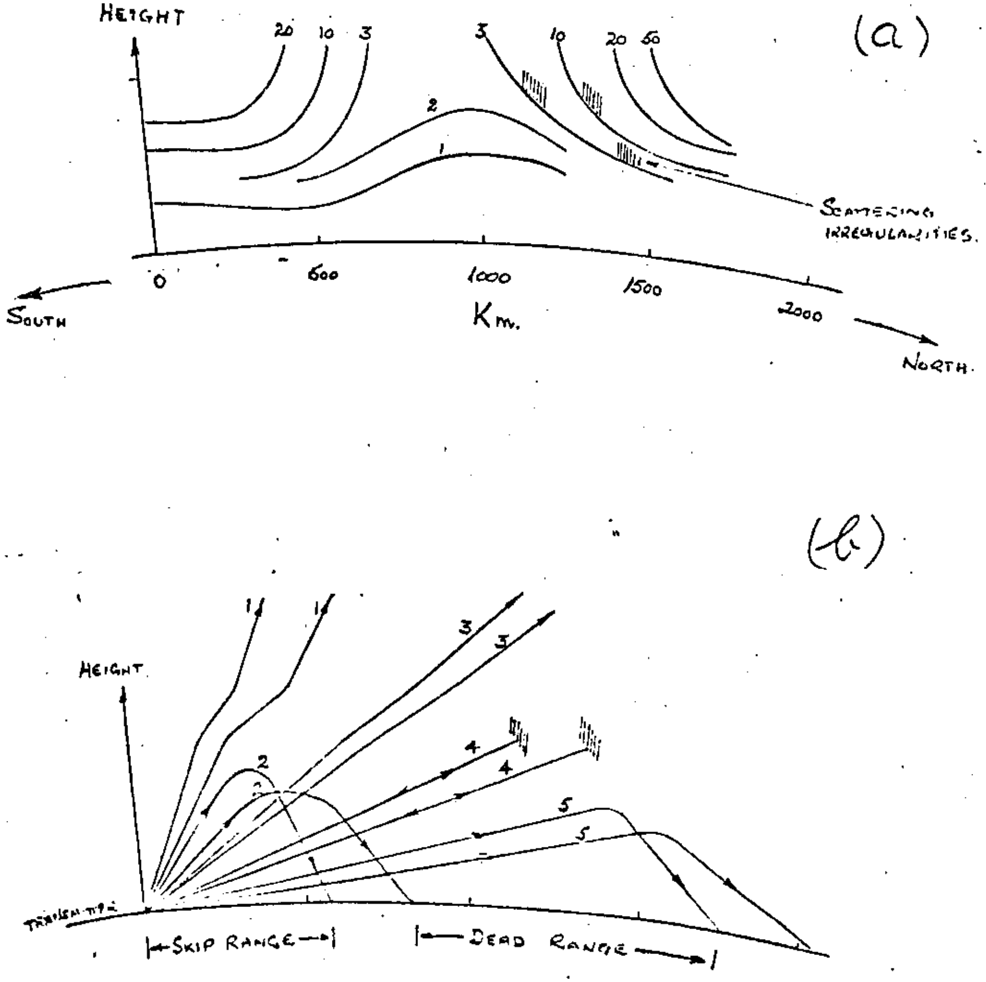

FIGURE 1

HF PROPAGATION PATHS VIA THE IONOSPHERE AT HIGH LATITUDES

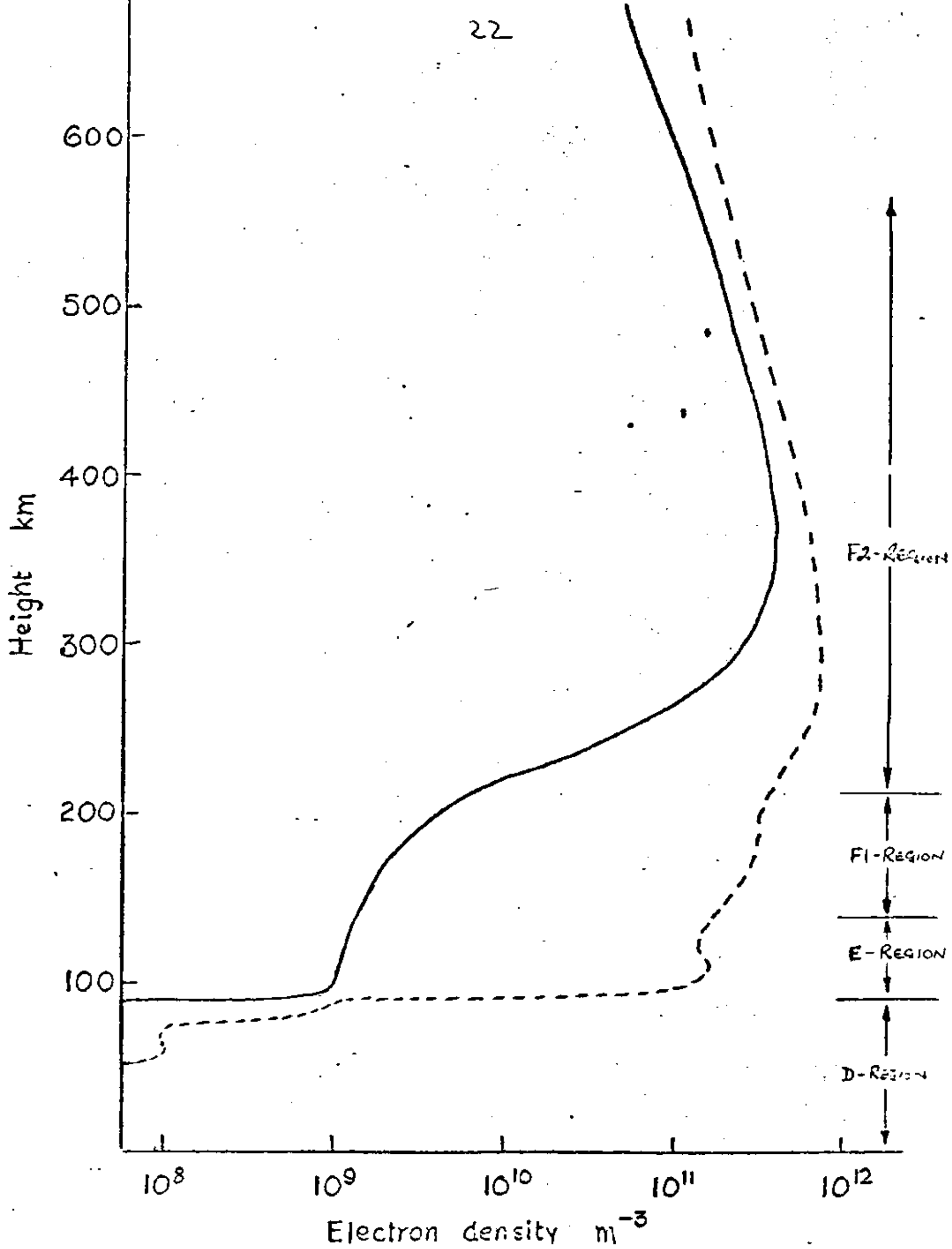

FIGURE 2

SAMPLE NIGHT-TIME AND DAYTIME HEIGHT DISTRIBUTIONS

OF ELECTRON DENSITY AT MIDLATITUDES IN SUMMER

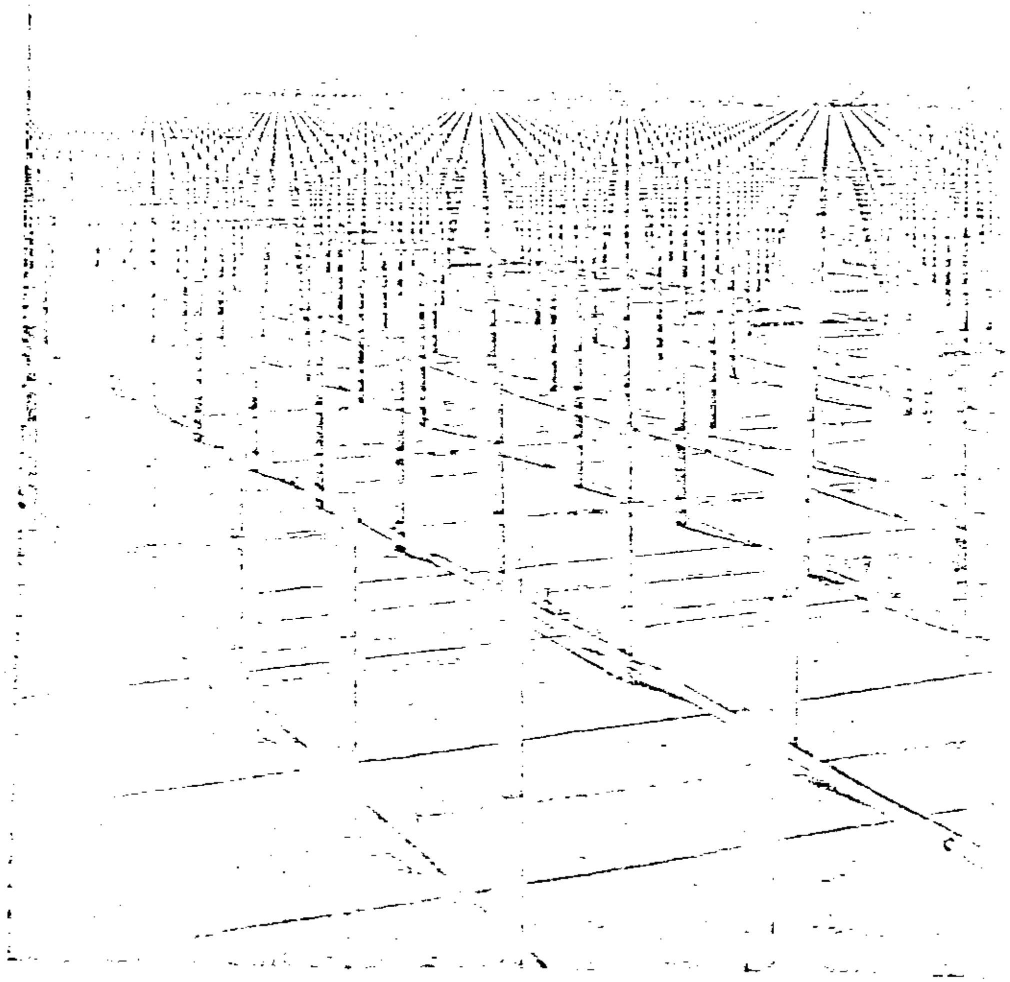

FIGURE 3

CROSSED-DIPOLE AERIAL ARRAY FOR 50 MHz INCOHERENT-SCATTER RADAR AT JICAMARCA, PERU

II

ITCP College on 'Radiopropagation: Propagation, Informatics and Radiocommunication System Planning' 30 January-3 March 1995

'Propagation information for modern HF systems planning'

P A Bradley

Rutherford Appleton Laboratory, UK

Lecture 2 HF propagation characteristics

- refraction and reflection
- propagation modes
- basic and operational MUF's
- scattered and ducted modes
- absorption
- polarisation
- amplitude fading
- time and frequency spreads

PROPAGATION IN AN IONISED MEDIUM-MAGNETOIONIC THEORY

Introduction

Radiowaves propagating in the ionosphere set the charged particles into oscillation causing them to radiate secondary wavelets in all directions. In the forward direction their path lengths are equal and so the combined secondary wave is strong. This forward-going scattered wave travels in the same direction as the original wave and combines with it. It experiences a phase advance of $\pi/2$ so that the resultant phase also is slightly advanced with respect to the original wave. The re-radiated wave is more intense and the combined wave is further advanced in phase the greater the concentration of charged particles. The change of speed is larger for electrons, which can more easily be set into oscillation than for heavier ions. For a wave obliquely incident on the ionosphere from below with an increase in the electron concentration with height, the speed of the resultant wave increases upwards. Separate parts of the wavefront find themselves in places where the charge concentration is different; the top travels more rapidly than the bottom, and so the wave is refracted earthwards. Reflection occurs when the group ceases to increase height.

During oscillations the charges may collide with the neutral air particles. The regular oscillations are interrupted and energy has to be fed in from the main wave. So the wave becomes weaker, or is absorbed as it progresses. When a charged particle travels in a magnetic field, it follows a spiral path, simultaneously moving along the field line and rotating around it. The speed of rotation depends on the charge and mass of the particle and on the strength of the field. In the Earth's magnetic field electron rotation rates are around 10^6 times per second. The refraction and the absorption of a wave is affected by this circular motion. The importance of the rotation depends on wave frequency. Greatest effect arises when the rotation rate matches the wave frequency.

The theory of wave propagation in an ionised medium in the presence of a magnetic field was first developed by Lorentz to explain light passage through crystals. However, when applied to radiowave propagation in the ionosphere, this failed to explain some observed features. The modified form developed by Appleton and Hartree is now known as the magnetoionic theory [l, 2].

The Appleton-Hartree Equations

When a linearly polarised wave passes through an assembly of charged particles in the presence of a magnetic field it causes them to spiral around the field lines. They then re-radiate wavelets in which the electric field rotates. The composite wave that results when these wavelets add to the original wave has its electric field rotating so that the polarisation is different from that of the original wave. If the original wave has its electric field rotating in a certain way it makes the charges rotate in the same way, they reradiate wavelets with the same kind of rotation, and when these are added to the original wave they produce a composite wave whose field also rotates in the original way. In this case the polarisation has not been changed, and the wave is a characteristic ordinary wave. A second characteristic extraordinary wave is possible in which the rotation is in the opposite sense.

The Appleton-Hartree theory applies for a medium which is electrically neutral with no resultant space charge and equal numbers of electrons and positive ions. A uniform magnetic field is assumed and the effect of positive ions on the wave is neglected. Steady state solutions for characteristic waves of plane polarisation are generated. The complex refractive index n at angular frequency ω is given (1) as

$$n^2 = (\mu - i\chi)^2 = 1 - \frac{X}{1 - iZ - \frac{Y_T^2}{2(1-X-iZ)} \pm \left(\frac{Y_T^4}{4(1-X-iZ} 2 + Y_L^2\right)^{\frac{1}{2}}} \qquad (16.1)$$

where $X = \frac{Ne^2}{\varepsilon_o m\omega^2}$ $Y_L = \frac{eB_L}{m\omega}$ $Y_T = \frac{eB_T}{m\omega}$ $Z = \nu/\omega$

N is the electron concentration, e and m are the electronic charge and mass and ε_0 is the permittivity of free space. ν is the electron collision frequency. The subscripts T and L refer to the transverse and longitudinal components respectively of the Earth's magnetic field B with reference to the direction of the wave normal. In particular, the refractive indices of the ordinary (upper sign) and extraordinary (lower sign) waves differ. The corresponding wave polarizations R are

$$R = \frac{i}{2Y_L}\left[\frac{Y_T 2}{1-X-iZ} \pm \left(\frac{Y_T 4}{(1-X-iZ} 2 + 4Y_L^2\right)^{1/2}\right] \qquad (16.2)$$

Eq (16.1) shows that:

(i) below the ionosphere refractive index is unity. For a given wave frequency it decreases with increasing electron concentration and for a given electron concentration it decreases with increasing wave frequency. If N is sufficiently large then ignoring the magnetic field and collision μ will become zero and X=1 at the height of reflection at vertical incidence; otherwise the wave transverses the whole ionosphere and escapes. Hence for a frequency f at reflection N satisfies.

$$f^2 = \frac{Ne^2}{4\pi^2\varepsilon_o m} \qquad (16.3)$$

(ii) in the presence of a magnetic field the ordinary wave is reflected as if the field were absent but the extraordinary wave at HF is reflected from a lower height where

$$X = 1 - Y \qquad (16.4)$$

with $Y^2 = Y_L^2 + Y_T^2$

The wave polarisations given from eq. (16.2) for the ordinary and extraordinary waves indicate the amplitude ratio and phase difference between the component electric vectors in the wavefront plane lying parallel to and normal to the projection of the magnetic field. In general wave polarisation is elliptical with the ordinary and extraordinary waves having equal axial ratios but opposite senses of vector rotation. In the case of no collisions (Z=o), R_o R_x = 1 and the two waves have orthogonal major axes. With longitudinal propagation ($Y_T^4 >> 4(1-X)^2 Y_L^2$) the two magnetoionic waves are circularly polarised. With transverse propagation ($Y_T^4 << 4(1-X)^2 Y_L^2$) the ordinary wave is linearly polarised with its electric vector parallel to the imposed magnetic field.

For a wave travelling in the z-direction

$$E = E_o \exp\left(-\frac{\omega}{c}\chi z\right)\exp i\left(\omega t - \frac{\omega}{c}\mu z\right) \qquad (16.5)$$

The quantity ($\omega\chi/c$) is a measure of the decay of amplitude per unit distance and is called the absorption coefficient k

$$k = \frac{\omega\chi}{c} \qquad (16.6)$$

In the absence of a magnetic field the absorption in nepers per metre (1 neper 8.69 dB) is given as

$$k = \frac{\omega XZ}{2c\mu(1+Z^2)} = \frac{e^2}{2\varepsilon_o mc\mu} \bullet \frac{N\nu}{\omega^2 + \nu^2} \qquad (16.7)$$

When N is small μ = 1 and eq. (16.7) gives

$$k = \frac{e^2 N\nu}{2\varepsilon_o mc\omega^2}$$

This is called 'non-deviative' absorption and arises primarily in the D-region. Near reflection when μ becomes small

$$k = \frac{\nu}{2c}\left(\frac{1}{\mu} - \mu\right) \qquad (16.9)$$

and the absorption is 'deviative' since it occurs in a region where considerable ray deviation takes place.

In the presence of collisions, the wave polarisations (eqs. 16.2) are complex. This means that the major axes of the polarisation ellipses of the ordinary and extraordinary waves are no longer orthogonal. The ellipses each rotate from the no-collision case by the same amount in opposite directions, such that each ellipse is the reflection of the other in the plane making an angle of 45° with the magnetic meridian.

The assumption that ν is independent of electron velocity is one of the major limitations of the Appleton-Hartree theory. In 1960 Sen and Wyller (3) generalised the magnetoionic theory to include the energy dependence of the electrons. The use of the generalised expressions is particularly important in considering VLF and LF propagation, and in calculating the absorption of HF waves in the D-region.

Phase and Group Velocity

The phase velocity v is

$$v=\frac{c}{\mu}=c\left[1-\frac{Ne^2}{m\varepsilon_o\omega^2}\right]^{-1/2} \qquad (16.10)$$

for propagation with no collisions and no magnetic field. This indicates that the phase velocity in the medium is greater than the velocity of light and the wavelength in the medium is greater than in free space

$$\lambda=\lambda_o\left(\frac{v}{c}\right) \qquad (16.11)$$

If the phase velocity of a wave in a medium varies as a function of the wave frequency, it is said to be dispersive. Two waves with slightly different frequency will therefore travel with slightly different velocities. It is the interference pattern between two such waves that determines where, and with what velocity, the energy of the composite wave will travel. For a wave cos (kz-wt) the group velocity u is given by

$$u=\frac{\delta\omega}{\delta k} \qquad (16.12)$$

For a non-dispersive medium in which ω/k is constant, u = v.

The group refractive index μ' may be defined as

$$\begin{aligned}\mu'&=\frac{c}{u}=c\frac{dk}{d\omega}=c\frac{d}{d\omega}\left(\frac{2\pi}{\lambda}\right)=\frac{d}{d\omega}(\mu\omega)\\&=\mu+\omega\frac{d\mu}{d\omega}=\mu+f\frac{d\mu}{df}\end{aligned} \qquad (16.13)$$

For the no field situation where $\mu^2 = 1 - (f_N/f)^2$ we have that

$$\mu'=\frac{d}{df}(\mu f)=\frac{1}{\mu} \qquad (16.14)$$

Propagation in an Anisotropic Medium

A medium is said to be isotropic if the phase velocity of a wave propagating within it is independent of direction. This is not the case within a magnetoionic medium where refractive index depends on direction of propagation relative to the field. In general the directions of the phase and ray paths then differ. It can be shown that the angle α between the wave normal and the ray direction is

$$\tan\alpha=-\frac{1}{v}\frac{dv}{d\theta}=+\frac{1}{\mu}\bullet\frac{d\mu}{d\theta} \qquad (16.15)$$

where θ is the angle at which the wave normal direction cuts a reference axis. The phase path in an anisotropic medium is

$$P=\int_s \mu\cos\alpha\, ds \qquad (16.16)$$

integrated over the raypath s. The corresponding group path is

$$P'=\int_s \mu\cos\alpha\, ds \qquad (16.17)$$

PROPAGATION PATH DETERMINATION

Ray-Tracing Techniques

General

Ray tracing is the process of determining the path of an electromagnetic signal by the successive application of ray theory over a series of thin homogenous slabs of medium. It requires that the wave parameters such as polarisation and refractive index do not change appreciably within a wavelength, that the division of energy between the ordinary and extraordinary waves is determined at the place of entry to the ionosphere and that thereafter these two waves propagate independently. Ray tracing requires a knowledge and representation of the state of the ionosphere through which the rays pass.

The most common application of ray tracing is to find the position at which a ray launched into the ionosphere returns to earth. Homing techniques can be applied to find the launch direction which give propagation to a selected reception point. Ray tracing may also be applied to determine the total phase and group paths and the ionospheric absorption. The path attenuation is given by the change in cross-section area of a small bundle of rays.

There are a number of ray-tracing techniques of varying complexity and accuracy. In any application the simplest method giving adequate accuracy should always be used, because ray tracing is expensive and time consuming, even with currently available high-speed computers. The introduction of the effects of the Earth's magnetic field is an appreciable complication. It is not usual to take account of the modifying influence of electron collisions on ray paths but to consider collisions only as responsible for absorption. At VHF and higher frequencies adequate determinations of the raypath parameters can usually be made with approximate equations in terms of the total electron content which is the number of electrons in a vertical column of ionosphere of unit cross section.

Specific procedures

Concentric model ionosphere with no magnetic field

Bouger's law may be applied to trace rays via a succession of thin concentric slabs of ionosphere. It enables the angle of incidence at a slab of refractive index μ and height h to be determined for a ray launched with elevation angle Δ_u relative to the Earth of radius R (Fig 16.1). The law gives that

$$R \cos \Delta_u = \mu\, (R+h) \sin i \qquad (16.18)$$

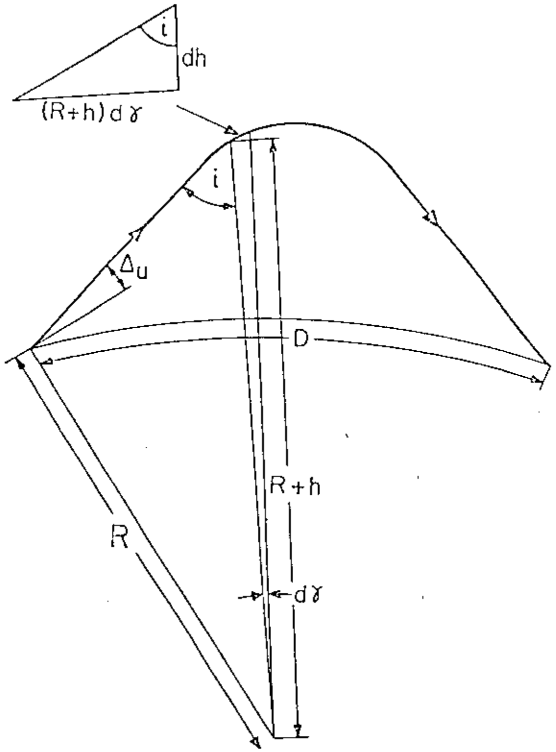

Figure 1 Raypath geometry for spherically stratified ionosphere

Application of eqs (16.16) and (16.17) yields

$$P = \int_0^h \frac{\mu\, dh}{\cos i} = \int_0^h \frac{\mu^2\, dh}{\sqrt{\mu^2 - \left(\frac{R}{R+h}\right)^2 \bullet \cos^2 \Delta_u}} \qquad (16.19)$$

$$P' = \int_0^h \frac{dh}{\sqrt{\mu^2 - \left(\frac{R}{R+h}\right)^2 \bullet \cos^2 \Delta_u}} \qquad (16.20)$$

and

$$D = R\int_0^h d\gamma = R\int_0^h \frac{\tan i\, dh}{R+h} = R^2 \cos \Delta_u \int_0^h \frac{dh}{(R+h)^2 \sqrt{\mu^2 - \left(\frac{R}{R+h}\right)^2 \cos^2 \Delta_u}} \qquad (16.21)$$

Raypaths in non-concentric layers with no magnetic field

The real ionosphere is not concentric and contains horizontal gradients. particularly at times of sunrise/sunset and for paths at high latitudes or those across the magnetic equator. The equations based on Bouger's law for segments of a concentric model ionosphere can be applied successively using appropriate electron-concentration data derived in accordance with a cumulative record of ray position. Step sizes are determined from operational tests appropriate to the models being investigated and are chosen such that further reductions of step size lead to consistent results within the desired accuracy. Small steps are needed near a reflection position but usually much larger steps are adequate elsewhere over the path. Techniques can be devised to reduce automatically the step size in accordance with an error criterion. Thereby segment sizes can be matched to the ionospheric conditions and the calculations optimised.

Ray tracing with a magnetic field

The raypaths of the ordinary and extraordinary waves differ and these are usually displaced oppositely of each other from the corresponding raypath if there were no field. Differences from the no field raypaths become significant only at frequencies below about 5-6 MHz. A widely used method of ray tracing in the presence of a magnetic field produced by the Hazelgroves involves solution of six differential equations based on Hamiltonian optics. These give three position variables in standard polar-coordinate form and three components of the direction variable of the wave normal with respect to a local coordinate system. These six equations enable changes in the positions of the rays and in the directions of the wave normals to be deduced by suitable numerical integration techniques.

Ionospheric effects on radio signals

A radio wave is specified in terms of five parameters : its amplitude, phase, direction of propagation, polarisation and frequency. In this section consideration is given to the principal effects of the ionosphere in modifying these parameters.

(a) Refraction - The change in direction of propagation resulting from the traverse of a thin slab of constant ionisation is given approximately by Bouger's law in terms of the refractive index and the angle of incidence. A more exact specification including the effects of the Earth's magnetic field is given by the Haselgrove equation solution[32]. The refractive index is determined from the Appleton-Hartree equations of the magnetoionic theory[33, 34] as a function of the electron density and electron-collision frequency, together with the strength and direction of the Earth's magnetic

field, the wave direction and the wave frequency. The dependence on frequency leads to wave dispersion of modulated signals. Since the ionosphere is a doubly-refracting medium it can transmit two waves with different polarisations - see (d) below. The refractive indices appropriate to the two waves differ. Refraction is reduced at the greater wave frequencies, and at VHF and higher frequencies it is given approximately as a function of the ratio of the wave and plasma frequencies, where the plasma frequency is defined in terms of a universal constant and the square root of the electron density[33]. Table 1 lists the magnitude of the refraction and of other propagation parameters for signals at a frequency of 100 MHz which traverse the whole ionosphere.

(b) Change in phase-path length - The phase-path length is given approximately as the integral of the refractive index with respect to the ray-path length. Ignoring spatial gradients, the change in phase-path length introduced by passage through the ionosphere to the ground of signals at VHF and higher frequencies from a spacecraft is proportional to the total-electron content. This is the number of electrons in a vertical column of unit cross section.

(c) Group delay - The group and phase velocities of a wave differ because the ionosphere is a dispersive medium. The ionosphere reduces the group velocity and introduces a group delay which for transionospheric signals at VHF and higher frequencies, like the phase-path change, is proportional to the total-electron content.

(d) Polarisation - Radio waves that propagate in the ionosphere are called characteristic waves. There are always two characteristic waves known as the ordinary wave and the extraordinary wave; under certain restricted conditions a third wave known as the Z-wave can also exist[33]. In general the ordinary and extraordinary waves are elliptically polarised. The polarisation ellipses have the same axial ratio, orientations in space that are related such that under many conditions they are approximately orthogonal, and electric vectors which rotate in opposite directions[33]. The polarisation ellipses are less elongated the greater the wave frequency. Any wave launched into the ionosphere is split into characteristic ordinary and extraordinary-wave components of appropriate power. At MF and above these components may be regarded as travelling independently through the ionosphere with polarisations which remain related, but continuously change to match the changing ionospheric conditions. The phase paths of the ordinary and extraordinary wave components differ, so that in the case of transionospheric signals when the components have comparable amplitudes, the plane of polarisation of their resultant slowly rotates. This effect is known as Faraday rotation.

(e) Absorption - Absorption arises from inelastic collisions between the free electrons, oscillating under the influence of the incident radio wave, and the neutral and ionised constituents of the atmosphere. The absorption is given by the Appleton-Hartree equations[33] and under many conditions that experienced in a thin slab of ionosphere is proportional to the product of electron density and collision frequency, inversely proportional to the refractive index and inversely proportional to the square of the wave frequency. The absorption is referred to as non-deviative or deviative depending on whether it occurs where the refractive index is close to unity. Normal absorption is principally a daytime phenomenon.At frequencies below 5 MHz it is sometimes so great as to completely suppress effective

propagation. The absorptions of the ordinary and extraordinary waves differ, and in the range 1.5-10 MHz the extraordinary wave absorption is significantly greater.

(f) Amplitude fading - If the ionosphere were unchanging the signal amplitude over a fixed path would be constant. In practice, however, fading arises as a consequence of variations in propagation path, brought about by movements or fluctuations in ionisation. The principal causes of fading are (i) variations in absorption (ii) movements of irregularities producing focusing and defocusing (iii) changes of path length among component signals propagated via multiple paths, and (iv) changes of polarisation, such as for example due to Faraday rotation. These various causes lead to different depths of fading and a range of fading rates. The slowest fades are usually those due to absorption changes which have a period of about 10 minutes. The deepest and most rapid fading occurs from the beating between two signal components of comparable amplitude propagated along different paths. A regularly reflected signal together with a signal scattered from spread-F irregularities can give rise to so-called 'flutter' fading, with fading rates of about 10 Hz/sec[35]. A good general survey of fading effects, including a discussion of fading statistics has been produced[36]. On operational communication circuits fading may be combated by space-diversity or polarisation-diversity receiving systems[37] and by the simultaneous use of multiple-frequency transmissions (frequency diversity).

(g) Frequency deviations - Amplitude fading is accompanied by associated fluctuations in group path and phase path, giving rise to time and frequency-dispersed signals. When either the transmitter or receiver is moving, or there are systematic ionospheric movements, the received signal is also Doppler-frequency shifted. Signals propagated simultaneously via different ionospheric paths are usually received with differing frequency shifts. Frequency shifts for reflections from the regular layers are usually less than 1 Hz(38), but shifts of up to 20-30 Hz have been reported for scatter-mode signals at low latitudes(39).

(h) Reflection, scattering and ducting - The combined effect of refraction through a number of successive slabs of ionisation can lead to ray reflection. This may take place over a narrow height range as at LF, or rays may be refracted over an appreciable distance in the ionosphere as at HF. Weak incoherent scattering of energy occurs from random thermal fluctuations in electron density, and more efficient aspect-sensitive scattering from ionospheric irregularities gives rise to direct backscattered and forward-scatter signals. Ducting of signals to great distances can take place at heights of reduced ionisation between the E and F regions, leading in some cases to round-the-world echoes(40). Ducting can also occur within regions of field-aligned irregularities above the maximum of the F region(41).

(i) Scintillation - Ionospheric irregularities act as a phase-changing screen on transionospheric signals from sources such as earth satellites or radiostars. This screen gives rise to diffraction effects with amplitude, phase and angle-of-arrival scintillations(42).

/Table 1

Table 1 Effect of one-way traverse of typical mid-latitude ionosphere at 100 MHz on signals with elevation angle above 60°(43)

Effect	Day	Night	Frequency dependence, f
Total electron content	5×10^{13} cm^{-2}	5×10^{12} cm^{-2}	
Faraday rotation	15 rotations	1.5 rotationa	f^{-2}
Group delay	12.5 μs	1.2 μs	f^{-2}
Change in phase-path length	5.2 km	0.5 km	f^{-2}
Phase change	7500 radians	750 radians	f^{-2}
Phase stability (peak-to-peak)	± 150 radians	± 15 radians	f^{-1}
Frequency stability (r.m.s.)	± 0.04 Hz	± 0.004 Hz	f^{-1}
Absorption (in D and F regions)	0.1 dB	0.01 dB	f^{-2}
Refraction	$\leq 1^{\circ}$	-	f^{-2}

A number of useful survey papers consider these various propagation effects in greater detail(44-47).

PROPAGATION EFFECTS AT HF

Fig. .2 shows the raypaths via the same single-layer model ionosphere for rays at three separate frequencies launched with a series of different elevation angles from a ground-based transmitter. A number of features are apparent -

(i) for the lowest frequency there is sufficient ionisation present to reflect the waves at all elevation angles, including the vertical; at the higher frequencies, rays launched with an elevation greater than some critical value escape

(ii) waves launched more obliquely in most cases travel to greater ranges

(iii) waves suffer more refraction at the greater heights

(iv) waves of higher frequency are reflected from a greater height

(v) waves launched more obliquely are reflected from a lower height.

The maximum range attainable after one ionospheric reflection arises for rays launched at grazing incidence and that this depends primarily on the height of maximum electron concentration. For typical E, Fl and F2-layers, the maximum range is 2000, 3400 and 4000 km respectively.

For a given ionosphere there will be some limiting upper frequency reflected vertically at the height of maximum electron concentration. At frequencies above this critical frequency there is a ground distance out from the transmitter at points along which illumination is not possible by waves reflected from the ionosphere. This distance is known as the skip distance. The skip distance increases as the wave frequency increases and in the limit for a very high frequency can extend to the maximum ground range possible for rays launched at grazing incidence; in that case all rays escape into space. It follows for a fixed point of reception that

there is some maximum frequency at which the waves can be reflected to it. This is the frequency making the distance from the transmitter to the point equal to the skip distance. The frequency is known as the maximum usable frequency (MUF).

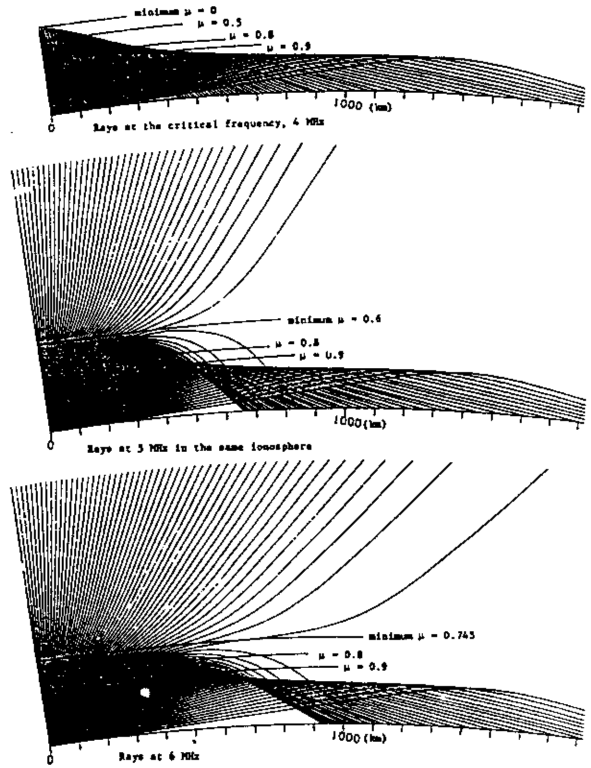

Figure 2 Raypaths for propagation at three frequencies via a single Chapman model ionosphere of critical frequency 4 MHz, height of maximum electron content concentration 300 km and scale height 100 km (from Croft, 4). Curves indicate heights with selected values of refractive index μ

The MUF increases with ground distance and depends also on the amount of ionisation present. It depends too on the height of the ionosphere since the determining factor as to whether reflection or transmission occurs is the angle of incidence at the layer. The greater the layer height, the steeper the angle of incidence to achieve propagation to a fixed range, and therefore the lower the MUF. This means that although the critical frequency of the E-layer is less than that of the F1-layer which in turn is less than that of the F2-layer, sometimes the E-MUF can be the greatest of the three separate layer MUF's. This is most likely to be the case in the summer daytime at low solar epochs (when the ratio of E to F2-critical frequencies is greatest) over path ranges of 1000-2000 km.

Since the Earth's field leads to the production of 0 and X waves which follow different raypaths, these waves also have differing MUF's. The 0 wave is refracted less than the X wave, becomes reflected from a greater height and so has a lower critical frequency and MUF. For propagation between a pair of fixed terminals the path MUF is the greatest of the individual MUF's for reflection from the different layers. This frequency undergoes systematic variations with time-of-day, season and solar epoch as the electron concentration and layer heights vary; there are also large day-to-day changes which create problems for modelling. Fig. 3 shows the maximum observed frequency (MOF) on a sample path recorded in a single month using an oblique sounder and, for comparison, the estimated monthly median basic MUF determined by conventional modelling techniques.

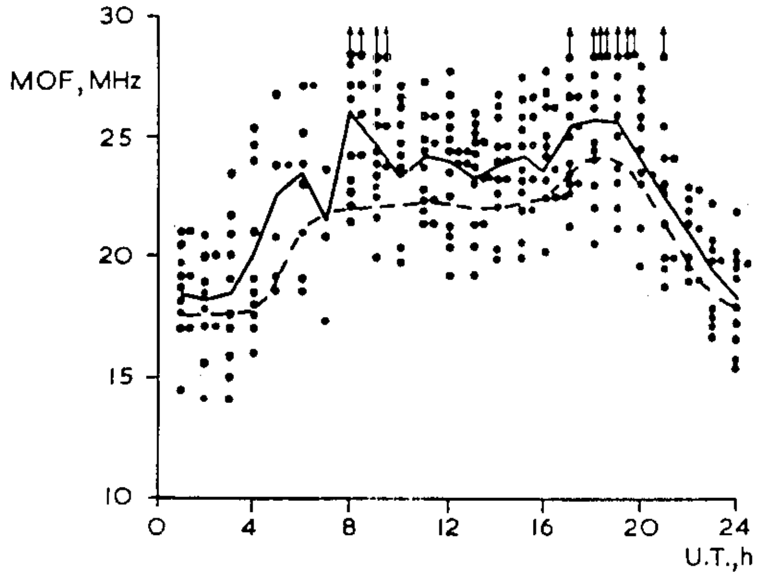

Figure 3 Maximum observed frequencies for Cyprus - Slough path in July 1969 (from Bradley and Howard, 5)

- **daily values**
- **— monthly median values**
- **--- predicted monthly median values (from CCIR Report 340)**

Now consider propagation to some point beyond the skip distance. Fig. 2 shows that as the elevation angle is increased at a fixed frequency, rays travel to shorter ground ranges until the skip distance is reached. Rays of slightly larger elevation angle do not penetrate the ionosphere into space because, contrary to a popular misconception, ray apogee at the MUF is below the height of maximum electron concentration, except in the limiting case of vertical incidence. These larger elevation rays are then reflected from a greater height, and they travel back to ground at increased range by virtue of having a significant length of near-horizontal path close to apogee. In principle such so-called high-angle or Pedersen rays can exist out to a limiting ground range where ionospheric reflection is from the layer maximum. This limiting range can exceed that of the low-angle ray and may well be in excess of 7500 km in temperate regions and 10,000 km in equatorial regions (6). The band of elevation angles providing high-angle rays is usually only a few degrees. There is then a range of ground distances at all points along which there are both low and high-angle rays. The path length through the ionosphere of the high-angle ray exceeds that of the low-angle ray by an amount which increases when moving out from the skip distance. So the strength of the high-angle ray tends to be less that of the low-angle ray both because of increased spatial attenuation and also, particularly in the case of reflection from the E-layer, because of increased ionospheric absorption. In practice signal-strength considerations determine the effective upper ground-range limit of the high-angle ray. Conversely for propagation to a fixed ground range, there is a band of frequencies below the MUF over which the high-angle ray has appreciable amplitude. As the frequency is reduced from the MUF so the excess path length and group-path length of the high-angle ray relative to the low-angle ray increase, whilst at the same time the differential absorption also rises. The presence of two rays with different group-path lengths is a disadvantage for it gives rise to signal distortions. Since the low and high-angle rays merge at the MUF, this frequency is sometimes alternatively known as the junction frequency JF. Both the 0 and X waves have their own separate families of high-angle rays and associated JF's. Figure 4 shows an oblique-incidence ionogram recorded over a 6700 km path in which propagation time is displayed as a function of wave frequency. The separate traces are associated with signals successively reflected twice, three and four times from the F2-region and being sustained by intermediate ground reflections. The corresponding junction frequencies, labelled 2F2JF, 3F2JF and 4F2JF respectively, together with the high-angle rays, can be seen. In this example there is some smearing of the record in the region of the JF's which is attributed to ionisation gradients along the path.

Aside from signal-strength considerations, for a particular mode to be present, the wave frequency must be below the MUF and, in the case of F-modes, also the lower ionosphere must not screen or blanket it. Screening of the 1F2-mode, but not of the 2F2-mode because of the lesser path obliquity, is a common summer daytime occurrence at certain frequencies. The strongest or dominant mode on a long path is usually the lowest-possible order F2-mode unless the antennas discriminate against this. Higher-order F2-modes traverse the ionosphere a greater number of times to become more absorbed and also experience more ground reflections, so that they tend to be weaker. A given range can be spanned by fewer F than E-hops. Modes involving more than two reflections from the E-layer are rarely of importance. Reflections from the F1-layer arise only under restricted conditions and the 1F1 mode is less common than the 1E and 1F2 modes. The 1F1 mode can be important at ranges of 2000-3400 km, particularly at high latitudes. Multiple-hop F1 modes are very rare in practice because the necessary ionospheric conditions to support an F1-layer reflection do not occur simultaneously at separated positions.

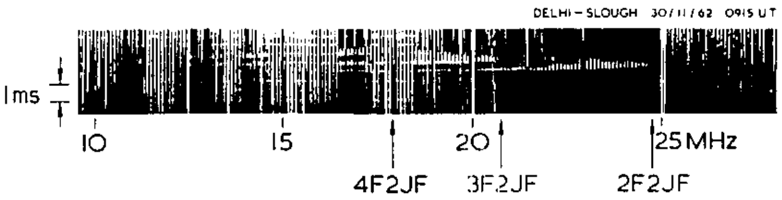

Figure 4 Sample oblique-incidence ionogram with classical 'noses' (from Kift et al, 7)

Geographical changes in ionisation cause so-called mixed modes with successive reflection from different layers. Mixed modes are a common feature of transequatorial paths and east-west paths across a daylight-darkness boundary. Other more complex examples of mixed modes are those involving upwards reflection from the E-layer between two F-reflections, known as M-modes. Changes in ionisation of a smaller scale size influence raypaths on single hops. These are variously referred to as ionisation gradients, horizontal gradients, or ionospheric tilts. They cause the upwards and downwards legs of a hop to differ in length and direction.

Longitudinal tilts produce differences in the elevation angles on the two legs; lateral tilts create off-great circle paths. Longitudinal tilts are usually the more important because they can give rise to changes in propagation modes. Lateral deviations are generally small in comparison with antenna beamwidths. An exception, even for propagation via the regular modes, where ionospheric tilts lead to marked departures from the great-circle-path, arises when the transmitter and receiver are almost antipodal. Simultaneous propagation may then take place in several directions and the dominant mode direction may vary with time of day, season and frequency. An effective tilt may result from geographical changes in either electron concentration or layer height. It follows that longitudinal tilts modify the MUF over a fixed path length. On long paths with low elevation angles these longitudinal tilts can give rise to modes involving multiple reflection from the ionosphere without intermediate ground reflection. In such cases, if ray perigee at the middle of the path is within the ionosphere and above the D and lower E-regions there is little resulting absorption so that received signals are relatively strong. These so-called perigee modes can be particularly important across the equator and at high latitudes where significant ionisation gradients commonly exist. Associated with perigee modes are ground dead zones, additional to the skip zone, for which raypath illumination is not possible.

As well as propagation modes resulting from ionospheric reflections, there are others associated with scattering and ducting. Various mechanisms are believed involved and so it is not surprising that there are uncertainties in the interpretation of particular observational data and therefore in assessing the relative importance of the different phenomena. These create modelling difficulties. Signals are scattered by ionospheric irregularities in the D, E and F-regions - patches of varying electron concentration such as those which give rise to the phenomena observed on vertical-incidence ionograms known as sporadic-E and spread-F. The scattering may result in onwards propagation (forward scatter), deviation out of the great circle (sidescatter) or return along the same path (backscatter). Ionospheric scatter modes are usually weaker than the corresponding reflected modes and they tend to fade more. However, they are important at the higher frequencies of the HF band since they enhance the practical (operational) MUF so that it exceeds the basic MUF. Their geographical and temporal occurrence is governed by the incidence of the irregularities. Sporadic-E is most prevalent at low latitudes in the daytime and at auroral latitudes by night. It tends to be opaque to the lower HF waves and partially reflecting at the higher frequencies. F-region irregularities can exist simultaneously over a wide range of heights. They are found at all latitudes, but are particularly common at low latitudes in the evenings where their occurrence is related to rapid changes in the height of the F-region. Hence forward-scatter modes associated with spread-F are important on long transequatorial paths. F-region irregularities are field aligned and sidescatter from these has been observed on paths at high and low latitudes; in some instances the received signals were incident simultaneously from a range of directions.

Normal ground terrain is sufficiently rough that it too scatters significant signal power out of the great-circle direction. Ground sidescatter and backscatter result. Since sidescatter paths are longer than the more direct routes, they tend to have correspondingly greater MUF's. There is some practical evidence supporting a dependence of signal intensity on scattering angle and whether sea or land is involved. The backscatter mechanism is of value in providing a means of remote probing (e.g. studying the state of the sea) or for monitoring ionospheric conditions. Special backscatter sounders can be used to determine the skip distance and deployed in support of systems operation. It is believed that another mechanism for wave propagation in the ionosphere concerns channelling as in a waveguide. This waveguide may be formed within the F-layer and have an upper but no lower boundary, being sustained by the concave ionosphere, or it may be a double-walled duct in the electron-concentration minimum between the E and F-regions. The waveguide is sometimes known as a whispering gallery. Signal coupling into the waveguide is assumed to involve ionospheric tilts like those which develop in the twilight periods or to be caused by the existence of ionisation irregularities such as Es or those responsible for spread-F. A further ducted type of signal propagation occurs along columns of field-aligned ionisation.

Mention has been made of ionospheric absorption in For propagation along the direction of the Earth's magnetic field the absorption in decibels $L(f_v)$ at vertical incidence in traversing a height region h at a wave frequency f_v is given as

$$L(f_v) = K \int_h \frac{Nn}{m} \cdot \frac{dh}{(f_v - f_L)^2 + \frac{n^2}{4p^2}} \qquad (16.31)$$

where K is a constant of proportionality. This equation applies approximately' over a considerable range of wave directions with f_L taken as the electron gyrofrequency about the component of the Earth's magnetic field along the direction of propagation. The positive sign applies for the O-wave and the negative sign for the X-wave. For ground-based reflection the limits of integration are from the base of the ionosphere to the height of wave reflection. For propagation at oblique incidence the absorption is proportionately increased because of the greater lengths of path traversed. Inspection of eq. (16.31) shows:

(i) the absorption in a given slab of ionosphere is proportional to the product of electron concentration and collision frequency. Electron concentration increases with increase of height whereas the collision frequency for electrons, which is proportional to the atmospheric pressure, decreases. Hence the absorption reaches a maximum in the lower E-region with most of the contribution to the total absorption occurring in the D-region.

(ii) large amounts of additional deviative absorption arise near the height of reflection where m is small.

(iii) absorption decreases with increase of frequency.

(iv) the O-wave absorption is less than that of the X-wave and differences are accentuated the lower the frequency, provided the first term of the denominator of eq. (16.31) remains dominant.

The absorption is low at night-time because of the reduced D and E-region ionisation. The non-deviative absorption reaches a maximum around local noon in the summer, but the influence of deviate absorption can modify the resultant seasonal variation. Ionospheric absorption is one of the most important factors influencing received skywave signal strengths at MF and HF so that accurate methods of modelling it are needed. There are particular difficulties at MF because raypath reflection heights of around 85-90 km are common and much of the absorption is deviative absorption occurring within 2-3 km of ray apogee. Such electron-concentration data as exist at these heights display considerable irregular variations.

When signals are propagated between terminals via multiple paths, whether these involve different modes, low and high-angle rays or 0 and X-waves, there exists a difference in the group paths of the separate components. Hence there is a spread in time of the received signals. Multipath time dispersions can limit system performance just as can an inadequate signal/noise power ratio. Large time spreads are often associated with scatter propagation. There are also large variations in the angles of elevation of the incident signals.

If the ionosphere were unchanging the signal amplitude over a fixed path would be constant. In practice, however, fading arises as a consequence of variations in propagation path, brought about by movements or fluctuations in ionisation. The principal causes of fading are: (i) variations in absorption (ii) movements of irregularities producing focusing and defocusing (iii) changes of path length among component signals propagated via multiple paths, and (iv) changes of polarisation, such as for example due to Faraday rotation. These various causes lead to different depths of fading and a range of fading rates. The slowest fades are usually those due to absorption changes which have a period of about 10 minutes. The deepest and most rapid fading occurs from the beating between two signal components of comparable amplitude propagated along different paths. A regularly reflected signal

Amplitude fading is accompanied by associated fluctuations in group path and phase path, giving rise to time and frequency-dispersed signals. When either the transmitter or receiver is moving, or there are systematic ionospheric movements, the received signal is also Doppler-frequency shifted. Signals propagated simultaneously via different ionospheric paths are usually received with differing frequency shifts. Frequency shifts for reflections from the regular layers are usually less than 1 Hz, but shifts of up to 20 Hz have been reported for scatter-mode signals at low latitudes. Frequency spreads associated with individual modes are usually a few tenths of a Hertz.

The effect of ionospheric propagation on a radio signal may therefore be expressed in terms of a corresponding channel-scattering function (Fig. 5) in which each mode has its own attenuation due to transmission loss and its own time and frequency offsets and dispersions. As a caution, it must however be noted that even this representation is an over simplification. Particularly for transequatorial and auroral paths the modes coalesce because the spread associated with each is so great. Time spreads of several milliseconds and frequency spreads in excess of 10 Hz have been reported under such conditions.

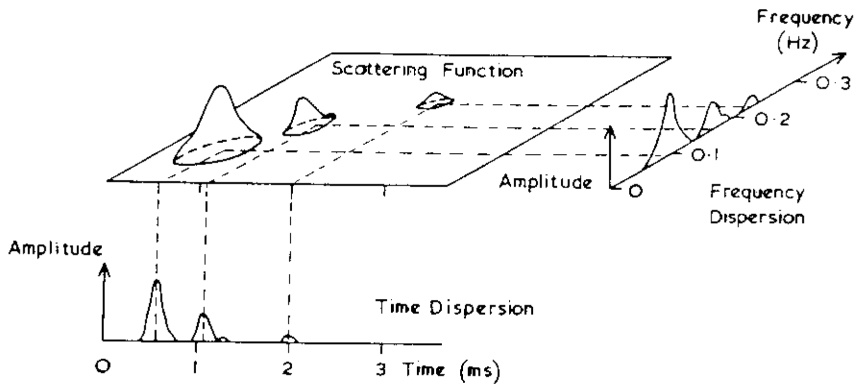

Figure 5: Channel-scattering function for three-moded ionospheric signal propagation

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III

ITCP College on 'Radiopropagation: Propagation, Informatics and Radiocommunication System Planning' 30 January-3 March 1995

'Propagation information for modern HF systems planning'

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Lecture 3 Use of the HF spectrum and propagation information requirements

- communication systems: fixed, mobile, broadcasting
- surveillance systems: over the horizon radars; passive target location systems
- planning parameters: frequency coverage, transmitter power, antennas
- real time propagation information needs

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.

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. 8.1. 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. 8.1 shows that the median range for the fixed circuits is around 1500 km.

RECEPTION QUALITY AND WAYS OF IMPROVING IT

Current ionospheric radio usage by the various radio services within the limited available spectrum is a compromise, taking account as far as possible of operational requirements and propagation constraints. Service planning is directed towards establishing controlled and unified system characteristics and the introduction of new systems is constrained to a considerable extent by the need for compatibility with those systems already in existence (viz. the introduction of SSB into hf broadcasting). The civilian user has to balance circuit reliability with installation and operating costs in relation to alternate means of transmission.

The greatest changes in the foreseeable future seem likely to be those directed towards improving the reliability of existing services and concerned with spectrum conservation techniques. Propagation predictions based either on a fit to past measurements or some kind of wave or ray tracing applied to ionospheric models will improve as knowledge increases,

leading to better estimates of necessary transmitter powers, frequencies and antenna characteristics. However, these predictions relate to median conditions and the likelihood seems low of ever being able to quantify other than in a statistical sense, conditions at a particular instant. Rather the consensus view is that there is a need to produce adaptive systems that can respond to the changes which occur. In this respect, developments in digital techniques, microprocessor control systems and in the stability and spectral purity of frequency synthesisers now permit the building of systems which even a decade ago would have been unthinkable. For earth-space links too, there is a move towards the introduction of dual-frequency systems, so that ionospheric influences can be determined in real time and thereby eliminated, rather than having to base them on median predictions.

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 offset 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. The next few years seem likely to see the operational exploitation of adaptive antennas on practical radio circuits.

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 3kHz 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.

Changes in the Radio Regulations would undoubtedly be needed before there could be general introduction of wideband spread-spectrum systems. The same is likely for future services relying on new propagation mechanisms yet to be discovered; nonetheless the pursuit of these mechanisms should be encouraged. A distinction must be drawn between anomalous propagation modes which are of merely academic interest and those worthy of operational exploitation. Whereas in this latter respect it is tempting to speculate that as far as ionospheric communications are concerned the end of the road has been reached, mention should nonetheless be made of possible future systems based on vlf and lf transionospheric propagation via the whistler mode and on various effects arising from ionospheric modification by high-power ground-based transmissions and chemical releases.

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 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.

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.

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.

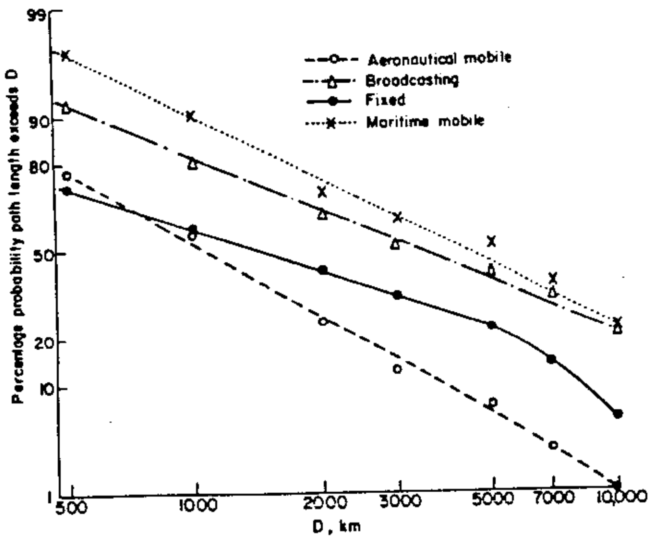

Fig. 8.1 Distribution of path lengths of sample circuits for different radio services (from Samuel and Hurst)

FREQUENCY MANAGEMENT IN HF SKY-WAVE REMOTE SENSING

1. Introduction

Remote sensing via HF sky waves can involve the determination of distant characteristics by the monitoring of sensor-controlled beacon emissions over a one-way path (eg from buoys providing oceanographic and meteorological information), the interrogation and recording of signals radiated from transponders, and the collection of information from returns from discrete or extended targets (eg as in aircraft surveillance and ocean-wave investigations). Hence requirements encompass one-way and backscatter paths, active and passive, discrete and spatially extended targets. In some cases there is a requirement for target location and also to be able to deduce target properties from the resulting signature.

It follows therefore that there is no unique best approach to frequency management; the solution to adopt depends on the application. Section 2 discusses those features which need to be addressed and Section 3 examines approaches which have been followed by certain groups.

2. Factors affecting frequency management

2.1 Adequate signal/noise ratio

The available frequency window for satisfactory signal reception is between the maximum usable frequency (MUF) and the lowest usable frequency (LUF). The basic MUF is the highest frequency that can propagate to a given ground location by refraction alone; ionospheric scatter modes are rarely of operational use in remote sensing. Basic MUF undergoes systematic variations with location, time-of-day, season, solar epoch and path length. Typical figures at European latitudes range from say 5 MHz at night near vertical incidence to 10-25 MHz depending on solar epoch around noon for a 3000 km path-the greatest range for which it is probably meaningful to deploy remote-sensing techniques; solar-cycle changes are more important in the daytime than at night. There are also day-to-day variations about these median values of some ± 20%.

The LUF is the lowest frequency for which the system can perform in the required manner. LUF's can be increased within limits by the use of greater transmitter powers and higher-gain antennas, but it is rare in sky-wave remote sensing to have an LUF below 5 MHz, except by night at very short ranges. From a signal/noise ratio standpoint interest usually centres on the 5-25 MHz frequency range, with greatest ratios being achieved when using frequencies as close as possible to the MUF.

Signal/noise ratio on one-way paths usually decreases with reduction of frequency below the MUF, primarily because of increased ionospheric absorption and increased atmospheric and man-made noise; antennas also tend to be less efficient the lower the frequency. Absorption by night on a short path might be some 2-5 dB, but by day for a 3000 km path it is inversely proportional to the square of frequency, ranging from say 5 dB at 20 MHz to 80 dB at 5 MHz. Nighttime atmospheric noise increases in intensity by 20 dB between 20 MHz and 5 MHz. In the daytime there can be less noise at the lower frequencies because of ionospheric absorption, but then man-made noise from local sources usually provides the limit to satisfactory clear-channel signal reception. Man-made noise intensities increase by 15 dB in the same sense over this frequency range.

In practice, the background to satisfactory signal reception may be co-channel interference. Current international legislation requires the use of fixed-frequency channel assignments, but alternate approaches could involve frequency flexibility within bands of perhaps a few tens of kiloherz or full frequency flexibility across the spectrum in a general dynamic frequency assignment procedure. Figure 1 shows 'snapshots' of spectral occupancy taken using a spectrum analyser during two successive single sweeps of part of the HF band 30s apart. There is evidence that some channels remain unoccupied only the order of tens of seconds. For signal reception from beacons frequency agility based on receive site noise is usually not possible, but with transponders or backscatter systems real-time selection of unoccupied channels could well lead to 20 dB or more increase in effective system sensitivity. However, careful consideration needs to be given to frequency switching rates in relation to necessary signal integration times and hardware constraints. Whatever procedure is employed there may well be merit in radiating frequencies somewhat less than those giving greatest signal/noise ratio, because the general level of sky-wave interferers tends to decrease with decrease of frequency as the absorption rises.

In the backscatter case, whether dealing with discrete or distributed targets, there are two other important factors influencing system sensitivity: these are the target and clutter cross-sections. Available receiver power P_r at wavelength λ and range R in the absence of ionospheric and system losses is given from the radar equation by

$$P_r = P_t \, G_t \, G_r \cdot \frac{\lambda^2 \, \sigma^2}{(4\pi)^3 R} \qquad (1)$$

where P_t is the transmitter power, G_t and G_r are the transmitting and receiving antenna gains and σ is the radar cross-section. Target cross-sections depend on target size, shape, material of construction and aspect with respect to boresite. Cross-sections for ships are typically in the range 40-50 dBm^2 and for aircraft between 20-30 dBm^2 (1). Excluding small targets with sizes appreciably less than the radio wavelength, for which Rayleigh scattering applies, target cross-sections tend to be essentially independent of frequency over the HF range.

Land and sea clutter may come from the vicinity of the target within the antenna footprint and range gate, or may arise from elsewhere, either via sidelobe pick up or by means of some other propagation mode. Ionospheric clutter can also occur through direct scattering from ionospheric irregularities. Figure 2 shows a backscatter sweep ionogram taken firing northwards from the UK. This clearly illustrates direct scattering from ionospheric irregularities associated with auroral activity over a wide continuous frequency range. When this auroral clutter is present it commonly extends across the full HF band.

The ground clutter cross section σ_c is

$$\sigma_c = \frac{c}{2W} \, R \, \theta \, \sigma_o \qquad (2)$$

where W is the effective radar bandwidth, θ is the azimuthal beamwidth of the receiving antenna, c is the velocity of light and σ_o is the radar cross-section per unit surface area. For sea clutter, values of σ_o lie in the range -35 to -20 dB, increasing with frequency throughout the HF band. σ_c shows less change because of the corresponding reduction of θ with increasing frequency. Figures for auroral clutter are not available. Backscatter signals from land and sea can be many orders of magnitude greater than those from ships and aircraft, but in the detection of targets with finite radial velocity these can be resolved because of the relatively low Doppler frequency shift and spread (1-2Hz) of the clutter. On the other hand, auroral clutter extends over tens of Hertz and cannot be obviated in this way.

For most targets clutter characteristics are not of prime consideration in frequency management. The exception is in resolving a slow-moving target buried in sea clutter, since the target Doppler shift is directly proportional to the wave frequency, but the Bragg spectral line centre frequency moves in proportion to the square root of frequency.

2.2 Minimum distortion

Tolerable time and frequency distortions depend on the application, but the aim should always be to use frequencies which avoid multipath. This is particularly important in the case of sea-state sensing where backscatter returns from different regions are combined within a time window. For discrete targets multipath leads to 'phantom' returns and erroneous deductions about numbers of targets and their positions. Whilst signal processing can be applied to eliminate such multiple returns this is not always effective because of signature decorrelation for the different modes.

Caution should also be exercised in using frequencies too close to the basic MUF because of interference between the high and low-angle rays. Figure 3 compares the spectral width of sea spectra at different ranges for a given wave frequency (2). The width increase near to the skip distance is very apparent. The Doppler spread imparted to a signal by ionospheric motion is reduced the lower the frequency. In general E, Es and F1-reflected signals are spectrally cleaner than those reflected from the F2-region (3). Both coherent and incoherent integration techniques can be applied to discriminate targets within clutter. Integration times of tens of seconds are used in ship detection. Stable propagation modes are essential over these durations, which again calls for frequencies not too close to the MUF.

2.3 Target location determination

Target location in a radar context is determined from measured group delay and antenna pointing direction. The conversion from slant to ground range and the allowance for off-great-circle propagation ideally involves 3D ray tracing through a known ionosphere, but the extent to which this is necessary or possible depends on the accuracy sought. Simple triangulation geometry shows that a 50 km error in effective F-region mirroring height transposes to 150 km of ground range at 500 km and to 30 km at 3000 km.

Ranging accuracies can be improved using real-time ionospheric sounder information. Unfortunately though, often the path midpoint lies over the ocean and spatial extrapolation of measured values from other places is necessary. There are also difficulties in obtaining such data in a timely fashion. The use of calibration repeaters in known positions can be worth consideration. The optimum deployment again depends on the scenario. In general, the lower the frequency the less the effects of group retardation, travelling ionospheric disturbances and lateral tilts responsible for off-great-circle propagation; hence the more likely that simple empirical conversion relationships are valid. For frequencies giving reflection from the E and F1-layers, ranging accuracies of 10-20 km are possible, but surveillance is then restricted to the shorter distances.

2.4 Multifrequency operation

With single-frequency beacon emissions intended for several recipients it may not be practicable to optimise the frequency for any one; multifrequency operation may be desirable. Likewise, with area target surveillance the use of a number of separate frequencies for different sub-areas may prove advantageous. If, as is likely, some form of frequency and antenna switching rather than simultaneous operation is necessary, the existence of blind periods between cycling needs to be recognised. The use of multifrequency emissions in backscatter, perhaps a few megahertz apart, can sometimes help in eliminating 'phantom' targets due to multimode propagation. Most discrete targets do not have radar signatures which change sufficiently with frequency over the HF band to be useful for identification, but in sea-state monitoring second-order Bragg spectral lines exhibit characteristics varying with frequency which can aid in the determination of the associated driving wind speeds (4). Again, frequencies several megahertz apart need to be used.

3. Examples of approaches to frequency management

It follows from the foregoing that there are many conflicting factors to take into account in choice of frequency. In some cases a rule-of-thumb such as taking a frequency equal to say 0.7 times the predicted monthly median basic MUF may well suffice. Where, however, there is a requirement for high performance it is necessary to expend considerable resources on hardware and software; choice of optimum frequency becomes important and the costs incurred in doing this as well as possible should not be neglected. Even so there will be some times and some paths where the system will fail.

Beacons typically employ a wide range of fixed frequencies with recipients selecting to record those for which propagation is best. For example, the same meteorological information is radiated from Bracknell on frequencies of 4.8, 8.0, 9.2, 11.1, 14.4 and 18.3 MHz.

For a number of years a joint experimental programme of backscatter sky-wave sea-state measurements aimed at area surveillance was carried out by the Rutherford Appleton Laboratory and Birmingham University. Pulses were radiated on frequencies selected from among 24 assignments distributed across the HF band and sweep backscatter ionograms were collected with the same system. A quick-look facility for displaying the Doppler spectrum integrated over a few seconds for selected range cells was available. The backscatter ionograms indicated the frequencies which could support propagation to the different distances. Frequencies were chosen on the basis of: (a) appearing aurorally and from a monitor display to be clear channels (b) providing strong backscatter signal intensities over a band of distances of interest and (c) giving visually 'clean' spectra. Soundings at one frequency were usually followed by those at a different frequency in order to extend area coverage.

Measurements in Canada by Winacott (5) made use of a bistatic FMCW radar for the collection of backscatter ionograms and the determination of sea spectra from narrow-frequency chirps centred about a number of assigned frequencies. Separate receiving systems and antennas were used for the ionograms and the spectra. With ionograms recorded at 15-minute intervals, operating frequencies were taken as the highest assigned frequency that placed the range of interest behind the leading edge of the backscatter trace.

The Wide Aperture Research Facility (WARF) operated by SRI International in California is a bistatic radar used for the study of sea state, ship and aircraft targets (6). The diagnostics available for frequency management consist of quasi-vertical incidence (QVI) soundings between transmitter and receiver over a separation of nearly 200 km, backscatter ionograms recorded every 10 min. and a spectrum analyser providing an updated record of channel occupancy. The QVI data are converted to effective vertical-incidence ionograms and, assuming that these are valid for the radar midpath, a modified overlay approach in terms of radar range is applied in order to synthesise the leading edges of the separate modes on the backscatter ionograms. In this way, modal identification is achieved and frequency selection can take account of the differing requirements of the separate targets. With aircraft detection where scattering cross-sections are low and integration times are limited to a few seconds, sub-clutter visibility needs to be maximised; for ships with integration times of tens of seconds, maximum spectral purity is of prime concern.

The JINDALEE sky-wave radar in Central Australia (7) uses similar techniques to those at WARF. In addition a co-located low-power frequency agile mini-radar is employed in either the backscatter mode or for oblique one-way swept soundings on the fixed path to Darwin at distance 1250 km to provide better estimates of the radar midpath ionosphere.

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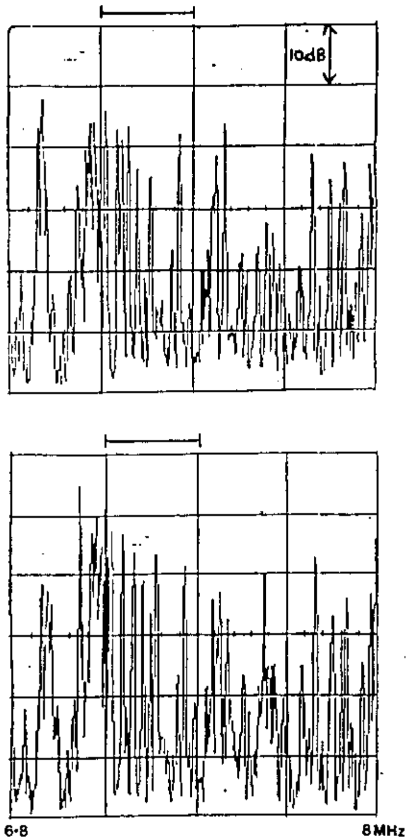

Fig.1 Successive spectrum analyser sweeps of the 6.8-8.0 MHz band 30s apart using a bandwidth of 3 kHz and a sweep rate of 100 kHz.s⁻¹

|——| broadcast band

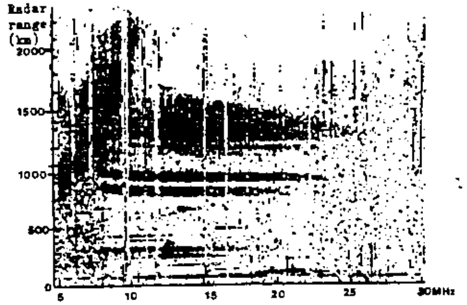

Fig.2 Backscatter ionogram showing direct auroral returns from constant range over a wide band of frequencies

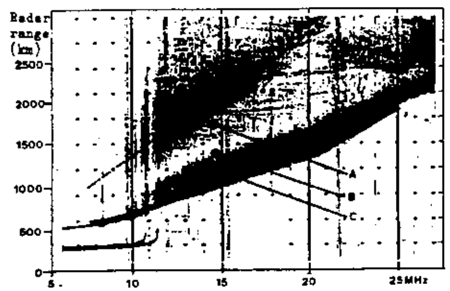

Fig.3 Mean spectral width for three indicated backscatter ranges (from Kotaki and Georges (2)) A 0.043Hz, B 0.058Hz, C 0.097Hz

——— theoretical F2-mode leading edge of backscatter

IV

ITCP College on 'Radiopropagation: Propagation, Informatics and Radiocommunication System Planning' 30 January-3 March 1995

'Propagation information for modern HF systems planning'

P A Bradley

Rutherford Appleton Laboratory, UK

Lecture 4 Methods of determining propagation factors

- world-wide ionospheric sounding data bases
- ionospheric long term mapping and modelling
- ray tracing and ray path determination
- spatial attenuation, focusing and defocusing
- absorption modelling
- polarisation - coupling loss
- ground reflection loss
- above-the-MUF loss
- the ITU field strength measurement data base and the match of predictions

PRINCIPLES OF LONG-TERM PREDICTION AND AVAILABLE TECHNIQUES

Introduction

Prediction procedures have been devised to give estimates of median values of the basic and operational maximum usable frequencies (BMUF and 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, (v) statistical quantification of the random day-to-day variability of signal and noise intensities and (vi) choice of some reference required signal/noise ratio and achievement probability 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 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 International Union of Radio Science (URSI) has developed such a model [1] which is available in either smoothed or segmental options where the various segments correspond to D, E, F1 and F2 layers of parabolic or polynomial function form. The model (Fig 1) is 'anchored' by the different layer peak heights and maximum electron concentrations, together with other empirical relationships.

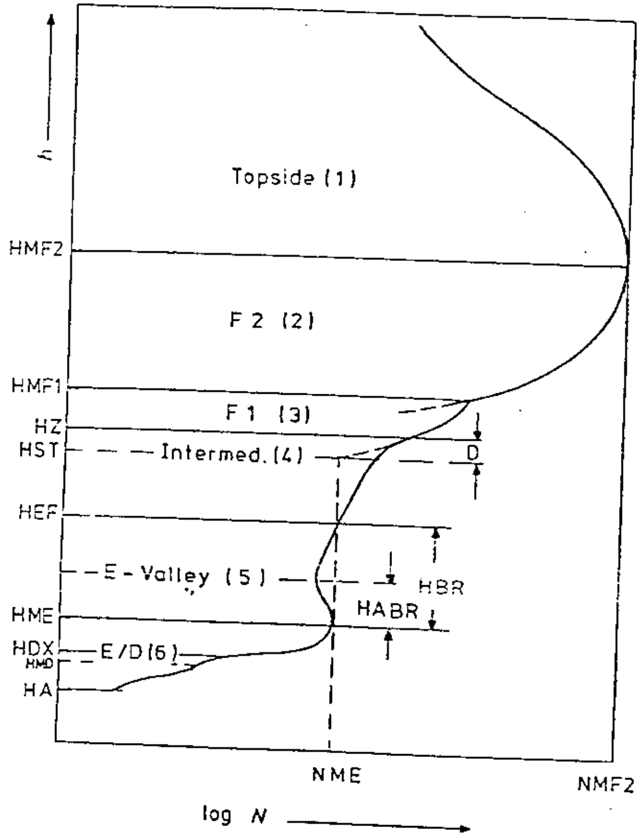

Figure 1: Diagrammatic build up of the International Reference Ionosphere (IRI) electron-concentration profile (segment 'anchor' points are labelled but not defined here)

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 ITU Radiocommunication Sector has produced reference data [2] giving monthly median 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:

$$\Omega(\lambda,\theta,T)=\sum_j [a_j(\lambda,\theta)\cos jT+b_j(\lambda,\theta)\sin jT] \qquad (17.1)$$

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

$$a_j(\lambda,\theta)=\sum_k U_{2j,k}\bullet G_k(\lambda,\theta)$$
$$b_j(\lambda,\theta)=\sum_k U_{2j-1,k}\bullet G_k(\lambda,\theta) \qquad (17.2)$$

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. Fig. 2 gives an example of a prediction map for foF2 based on 988 numerical coefficients U.

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 (BMUF) of any mode reflected from the different layers, so that it is necessary to first determine the separate F2-, E- and F1-BMUF's depending on the path length. Basic MUF's may be evaluated by ray-tracing procedures. However, a simpler alternative approach recommended by the ITU [2] 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.

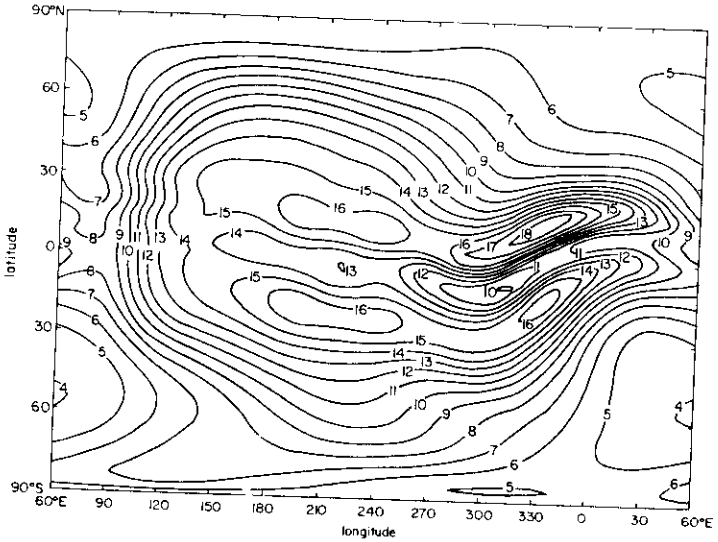

Figure 2: Predicted median foF2, MHz for 00 h UT in March 1958 (from 2)

For paths lengths beyond the limit of single-hop F2-mode propagation, itself a variable depending on ionospheric layer height, the so-called two-control-point procedure is used in which the path BMUF is taken as the lower of the two BMUF's for the maximum length single hop along the great circle closest to the transmitter and closest to the 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 [3]. 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 [3]. 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 Fl-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 [2].

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.

Empirical relationships have been developed based on a quasi-parabolic segment approximation to the ionospheric mode! giving mirror-reflection height as a function of wave frequency, time, location and path length [2]. 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. E-layer screening of F-modes is of importance and needs to be taken into account as a function of path obliquety and the prevailing E-region ionisation. In the ITU recommended HF field-strength prediction method [4] it is given on paths up to 2000 km range in terms of foE at the midpath and on paths up to 9000 km in terms of the foE values at two control points located 1000 km from each end of the path.

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. The ITU signal prediction method [4] does not attempt to separately estimate propagation modes and their losses for path lengths exceeding 9000 km since raypath errors increase with range making that technique particularly unsuitable at long ranges.

Monthly median values of mean available receiver power are determined in terms of transmitter radiated power, transmitting and receiving antenna gains and the basic transmission loss

$$P_r = P_t + G_t + G_r - L_b \qquad (17.3)$$

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

$$E = P_r + 20 \log_{10} f + 107.2 \qquad (17.4)$$

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 used for broadcast planning [5]. These give radiation patterns over imperfect earth assuming sinusoidal current distributions and determine absolute gain by integrating over a hemisphere.

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. In [6] 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. In [4] however focusing is incorporated indirectly via an empirical excess loss adjustment factor.

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 [6] 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. 3). In other prediction methods [e.g. 4] 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 in [6] is taken as resulting from two separate sources of particle For each there is a gaussian variation with latitude and time-of-day about the maximum value. Longitudinal and seasonal dependencies are included. Important solar-cycle changes in the intensities, positions and widths of the auroral absorption zones are also modelled in the representation. By contrast, in [7] auroral absorption is included at the higher latitudes together with other losses as a variable empirical correction factor taken to be dependent on geomagnetic latitude, season, midpath local time and path length.

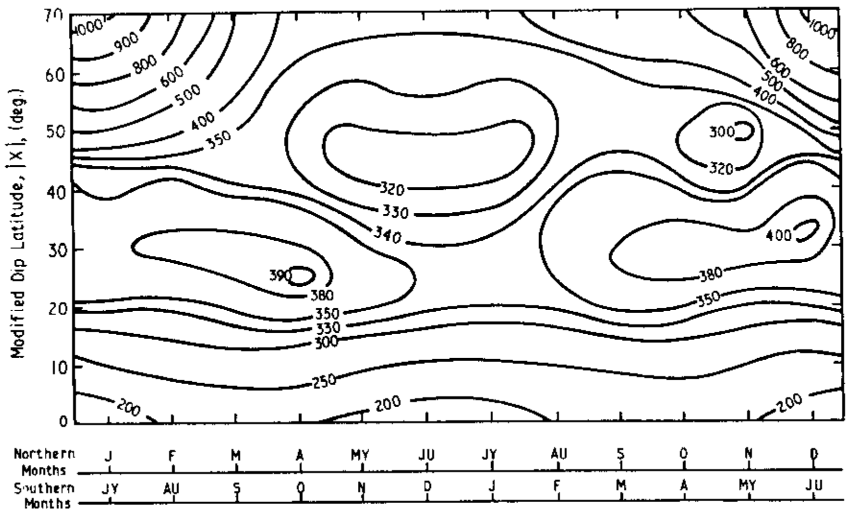

Figure 3: Absorption factor A_T shown for the different months as a function of modified latitude |X|, for an overhead sun and smoothed sunspot number of zero (from 6)

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

with 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 [6]. 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 should be calculated separately for each leg of each hop.

Above-the-MUF loss

Strong signals are often received at frequencies above the predicted basic 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 BMUF. 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 number of composite empirical allowances for these various effects based on both measured data and theoretical studies have been developed. International efforts are currently concentrated on attempting to model losses separately attributable to the different phenomena. A review of the current position has been published [7]. The formulation adopted in [4] involves separate expressions for E and F-modes. In both cases there is an additional above-the-MUF loss term which increases rapidly with increase of frequency from 0 dB at the basic MUF. It attains a value of 20 dB at about 1.4 times the basic MUF.

Ground-reflection loss

Multiple-hop ground-reflection losses can be 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. Prediction method [6] involves a full calculation assuming circularly polarised incident waves, but a constant loss of 2 dB per hop irrespective of terrain, frequency or angle is adopted in [4].

Path lengths exceeding 9000 km range

An empirical formulation based on the fit to oblique-path measurement data collected over many paths for several decades to receiving sites located in Germany in place of a full modal treatment is used in [4]. This gives that the field strength depends on path distance and is a variable function of frequency, rising to a peak intermediate between reference lower and upper cut-off frequencies. These frequencies are given by empirical expressions in terms of the basic MUF and the LUF. Transmitting antenna gain is taken as the largest value along the great-circle path with an elevation below 8° and an expression for antipodal focusing is also incorporated. For path lengths between 7000-9000 km there is an interpolation procedure with the short-path predicted values.

Excess-system loss and prediction accuracy

For the purposes of standardisation and testing the accuracy of HF signal prediction models, the ITU has established a data bank of past measurements and has formulated reference procedures for the collection, tabulation and analysis of future data [8]. 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. Current work is aimed at the development of a new data bank with measured values expressed in terms of available receiver power. In this way improved prediction method standardisation factors avoiding errors arising from certain present assumptions are anticipated, thereby giving predictions of improved accuracy.

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 BMUF 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 optimum working frequency or frequency of optimum traffic (FOT) is defined as the lower decile of the daily values of operational MUF [3].

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].

Likewise, the ITU has reference models of composite atmosphere, man-made and galactic noise at HF [10].

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 important 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 known distribution 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.

Various other types of reliability have been defined and methods of their determination formulated [11] depending on whether a single circuit is involved, whether transmission of the same information is made at more than one frequency and whether reception is at a point or over an area The reliability is referred to as basic reliability when the wanted signals are competing against the natural noise background and an overall reliability (or simply reliability) when interfering signals are considered. The case of multiple adjacent channel interferers has recently been taken into account in [11] for the determination of circuit reliability.

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 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.

17.4 PREDICTION PROCEDURES

With the general availability of microcomputers there has been a proliferation of different implementations of prediction procedures incorporating variations depending on input/output requirements and the personal viewpoints of the originators. Here examples of procedures developed and available from the ITU are presented. Software for specific circuit diagnostics involving ray tracing through near-real time model ionospheres is outside the scope of this

A list of computer programs available from the ITU associated with ionospheric propagation data is given in [12]. As an example of one available program HRMNTH based on procedures described in [2], 4 gives a tabulation for any mapped ionospheric characteristic (median or decile values) for a specified location in different hours, months and levels of solar activity.

PROGRAM 'MICRO-HRMNTH' VERS-MF JUNE '94

MEDIAN foF2 USING ITU-R COEFFICIENTS(OSLO) DISK SET B

LATITUDE 51.5 LONGITUDE 359.4 SLOUGH,UK 1988

	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC
R12	55.0	59.0	63.0	69.0	75.0	81.0	88.0	94.0	101.0	108.0	114.0	120.0
UT												
2.0	2.8	3.1	3.6	3.9	4.5	4.8	4.9	4.3	4.3	4.4	3.7	3.6
4.0	2.5	2.6	3.0	3.6	4.5	4.9	4.6	4.1	3.6	3.4	3.0	3.3
6.0	2.1	2.7	3.7	4.5	5.2	5.5	5.3	5.2	4.7	4.5	3.4	2.8
8.0	4.7	5.4	5.8	5.7	6.2	6.1	6.0	6.4	6.5	7.9	7.4	6.7
10.0	6.8	6.9	7.1	6.7	6.6	6.3	6.5	6.8	7.5	9.9	10.3	10.1
12.0	7.5	7.6	7.7	7.1	6.7	6.3	6.4	6.7	7.9	10.7	11.4	11.3
14.0	7.3	7.6	7.6	7.1	6.8	6.2	6.3	6.6	7.8	10.6	11.1	11.1
16.0	6.0	7.1	7.5	7.1	6.6	6.0	6.1	6.5	7.7	10.0	9.5	9.2
18.0	4.1	5.5	6.8	7.1	6.9	6.3	6.5	7.0	7.6	8.1	6.4	6.2
20.0	3.0	3.9	5.3	6.3	6.8	6.6	6.7	7.0	6.4	5.7	4.1	4.2
22.0	2.7	3.1	4.2	5.0	5.9	6.1	6.1	5.9	5.2	4.7	3.6	3.5
24.0	2.8	3.1	3.7	4.4	5.2	5.4	5.6	5.1	4.7	4.5	3.6	3.5

Fig. 4 Example of program HRMNTH output

Fig. 5 shows a printout from program MUFFY. This program also following [2] gives path basic MUF, operational MUF and FOT at different UT hours for a specified month and level of solar activity between given transmitter and receiver terminals. Either the short or long great-circle paths may be selected. The propagation modes considered are 1E, 2E, 1F1, single and multiple-hop F2, depending on path length.

PROGRAM 'MUFFY' -JULY 90

BASIC MUF,OPERATIONAL MUF AND FOT DETERMINATION - CCIR REPORT 340-6

OSLO FOF2 COEFFICIENTS

MAY 1990 SUNSPOT NO. 152.0

SYDNEY 33.93S 151.17E TO ADELAIDE 34.92S 138.58E AZIMUTHS 261.01 88.15 MILES 720.4 KM. 1159.3

SHORT PATH TX PWR 1.0 KW

UT	BMUF	MUF	FOT	UT	BMUF	MUF	FOT	UT	BMUF	MUF	FOT
01	19.8	21.7	18.5	09	12.6	15.1	12.9	17	7.5	9.0	7.6
02	19.9	21.9	18.6	10	10.7	12.8	10.9	18	6.7	8.0	6.8
03	19.9	21.9	18.6	11	9.2	11.1	9.4	19	5.8	7.0	6.0
04	19.7	21.6	18.4	12	8.1	9.8	8.3	20	6.4	7.7	6.5
05	19.4	21.4	18.2	13	7.7	9.2	7.8	21	9.6	10.5	9.0
06	19.0	20.9	17.8	14	7.7	9.2	7.8	22	14.4	15.9	13.5
07	17.6	19.3	16.4	15	7.8	9.4	8.0	23	18.2	20.0	17.0
08	15.1	16.6	14.1	16	7.8	9.4	8.0	24	19.6	21.5	18.3

Fig. 5 Example of program MUFFY output

Evaluation of the current version of the HF field-strength prediction procedure [4] using program REC 533A is illustrated in Fig. 6. For a series of UT hours and specified frequencies this gives the propagation mode with strongest signals and its associated elevation angle, the median strength of the resultant signal, the median resultant signal/noise ratio and the probability that a specified signal/noise ratio will be achieved. Other optional program outputs are available.

```
              METHOD  6    REC533A VERS-2.0   21.JULY.93            PAGE   1

              JUL    1977            SSN =  29.
   NORFOLK ANT=103       LUECHOW VM NO SCREEN  AZIMUTHS    SP   N. MI.       KM
   36.80 N    76.50 W   52.98 N   11.22 E      43.91  292.73    3612.6   6690.0
   MIN ANG  3.0 DEG       TBEAR  53.0              RBEAR   0.0       PWR   1.00 KW
   TX AHR/4/3/0.5/S0/10   7.0- 14.0 MHz  RX VM  8/0/0/0          2.0- 13.1 MHz
      S/N% 50          -157 NOISE DBW         3000 HZ RX BDWTH       REQ S/N  8 DB

 UT  MUF                                                              LUF  FOT OPM

   2 12.0  5.0  7.2  8.1 10.9 12.5 16.4 20.0  0.0  0.0  0.0 FREQ  7.0 11.7 13.
      3F2  3F2  4F2  3F2  3F2  3F2  3F2  3F2  0    0    0   MODE
       14    5   14    8   13   14   15   16    0    0    0 ANGL
       26 -106   19   22   26   17 -110 -117 -999 -999 -999 DBU
       32 -107   19   23   31   24 -201 -207 -999 -999 -999 S/N
      .93  .01  .81  .88  .92  .85  .01  .01  .00  .00  .00 FS/N

   6  9.9  5.0  7.2  8.1 10.9 12.5 16.4 20.0  0.0  0.0  0.0 FREQ  7.0 10.5 12.
      3F2  6F2  4F2  4F2  3F2  3F2  3F2  3F2  0    0    0   MODE
       13   29   19   19   13   14   14   15    0    0    0 ANGL
       24 -115   15   17   14    6 -117 -123 -999 -999 -999 DBU
       29 -108   21   22   19   13 -208 -213 -999 -999 -999 S/N
      .90  .01  .82  .82  .78  .64  .01  .01  .00  .00  .00 FS/N

  10 13.7  5.0  7.2  8.1 10.9 12.5 16.4 20.0  0.0  0.0  0.0 FREQ 11.9 13.4 15.
      3F2  3F2  6F2  5F2  4F2  3F2  3F2  3F2  0    0    0   MODE
       11   11   27   22   17   11   11   11    0    0    0 ANGL
       12 -245  -37  -22   -2   10 -114 -119 -999 -999 -999 DBU
      -80 -239  -29  -14    6   17 -206 -209 -999 -999 -999 S/N
      .01  .01  .01  .01  .39  .74  .01  .01  .00  .00  .00 FS/N

  14 16.6  5.0  7.2  8.1 10.9 12.5 16.4 20.0  0.0  0.0  0.0 FREQ 12.7 15.6 18.
      2F2  2F2  5F2  5F2  4F2  3F2  2F2  2F2  0    0    0   MODE
        6    6   26   26   20   14    6    6    0    0    0 ANGL
     -100 -245  -56  -45  -17    0 -100 -111 -999 -999 -999 DBU
     -191 -239  -48  -37   -9    7 -192 -201 -999 -999 -999 S/N
      .01  .01  .01  .01  .05  .45  .01  .01  .00  .00  .00 FS/N

  18 16.5  5.0  7.2  8.1 10.9 12.5 16.4 20.0  0.0  0.0  0.0 FREQ 11.9 15.4 18.
      3F2  3F2  6F2  5F2  4F2  3F2  3F2  3F2  0    0    0   MODE
       14   14   30   25   20   14   14   14    0    0    0 ANGL
     -102 -245  -52  -33  -10    5 -102 -113 -999 -999 -999 DBU
     -194 -240  -46  -28   -5   10 -194 -203 -999 -999 -999 S/N
      .01  .01  .01  .01  .11  .58  .01  .01  .00  .00  .00 FS/N

  22 17.1  5.0  7.2  8.1 10.9 12.5 16.4 20.0  0.0  0.0  0.0 FREQ  8.3 16.0 18.
      3F2  8F2  5F2  5F2  3F2  3F2  3F2  3F2  0    0    0   MODE
       11   30   19   20   10   11   11   12    0    0    0 ANGL
      -91 -145    1    5   21   23  -90 -103 -999 -999 -999 DBU
     -182 -144    2    7   24   28 -182 -194 -999 -999 -999 S/N
      .01  .01  .26  .42  .89  .94  .01  .01  .00  .00  .00 FS/N
```

Fig. 6 Example of program REC 533A output

This particular propagation program embodies a gain package based on [5] for a range of common antennas and antenna arrays deployed at both transmitter and receiver. With antenna type selected it is necessary to specify element numbers, dimensions and dispositions, as well as ground terrain characteristics. A free-standing version of that program HFANT provides both tabular gain and graphical outputs. As well as standard vertical and azimuthal pattern displays the novel Sanson-Flamstead projection showing both front and back-lobe azimuth-elevation angle patterns is available (Fig. 7).

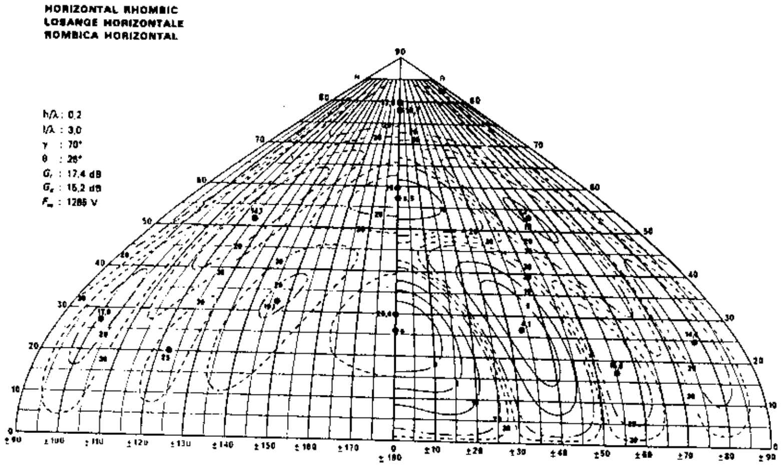

Fig. 7 Example of Sanson-Flamstead projection graphical output for program HFANT

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. 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 [13] 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. 8 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 an uncertainty of the order of 0.5 MHz exists at all times and when extrapolating 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. 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. 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.

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. It is hoped that the next few years will see the emergence of a variety of systems available for purchase.

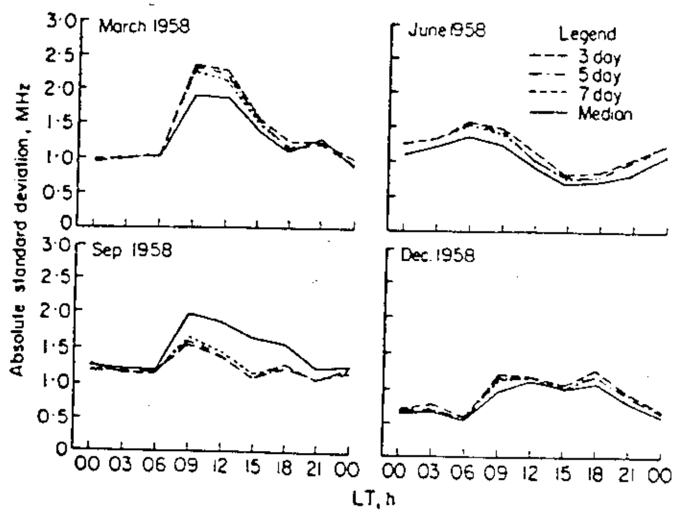

Figure 8: Errors in estimates of daily values of foF2 at Slough using monthly median and weighted means of past days measurements (from Rush and Gibbs, 13)

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