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Ionospheric Radio Wave Propagation

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Ionospheric Radio Wave Propagation

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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 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 earthward. Reflection occurs when the group ceases to increase height.

During oscillations the charges often collide with the neutral air particles bouncing off in random directions. 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 (1,2).

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 move round in circles. 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

$$n^2=(\mu-i\chi)^2$$

$$= 1 - \frac{X}{1 - iZ - \dfrac{Y_T^{\,2}}{2(1-X-iZ)} \pm \left(\dfrac{Y_T^{\,4}}{4(1-X-iZ)^2} + Y_L^{\,2}\right)^{1/2}} \qquad (\;\;1)$$

where $X = \dfrac{Ne^2}{\varepsilon_o m\omega^2}$ $\quad Y_L = \dfrac{e\,B_L}{m\omega}$ $\quad Y_T = \dfrac{e\,B_T}{m\omega}$ $\quad Z = \nu/\omega$

N is the electron concentration, e and m are the electronic charge and mass and ε_o 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

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

Eq. (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 collisions μ will become zero and X=1 at the height of reflection at vertical incidence; otherwise the wave traverses the whole ionosphere and escapes. Hence for a frequency f at reflection N satisfies

$$f^2 = \frac{Ne^2}{4\pi^2\varepsilon_o m} \qquad (\;\;3)$$

(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

$$X = 1 - Y \qquad (\;\;4)$$

with $Y^2 = Y_L^{\,2} + Y_T^{\,2}$

The wave polarisations given from eq. (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 ($Y_T^{\,4} >> 4(1-X)^2Y_L^{\,2}$) the two magnetoionic waves are circularly polarised. With transverse propagation ($Y_T^{\,4} << 4(1-X)^2Y_L^{\,2}$) the ordinary wave is linearly polarised with its electric vector parallel to the imposed magnetic field.

For a wave travelling in the z-direction

$$E = E_o\exp(-\tfrac{\omega}{c}\chi z)\,\exp i(\omega t - \tfrac{\omega}{c}\mu z) \qquad (\;\;5)$$

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

$$k = \frac{\omega\chi}{c} \qquad (\;\;6)$$

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

$$k = \frac{\omega X Z}{2c\mu(1+Z^2)} = \frac{e^2}{2\varepsilon_o mc\mu} \cdot \frac{N\nu}{\omega^2 + \nu^2} \qquad (\ 7)$$

When N is small $\mu \approx 1$ and eq. (7) gives

$$k = \frac{e^2 N\nu}{2\ \varepsilon_o mc\omega^2} \qquad (\ 8)$$

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

$$k = \frac{\nu}{2c}\left(\frac{1}{\mu} - \mu\right) \qquad (\ 9)$$

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. 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 known 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.

6.1.3 Phase and Group Velocity

The phase velocity v is

$$v = \frac{c}{\mu} = c\left[1 - \frac{Ne^2}{m\varepsilon_o\omega^2}\right]^{-1/2} \qquad (\ 10)$$

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

$$\lambda = \lambda_o \left(\frac{v}{c}\right) \qquad (\ 11)$$

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

$$u = \frac{\delta\omega}{\delta k} \qquad (\ 12)$$

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

The group refractive index μ' may be defined as

$$\mu' = \frac{c}{u} = c\,\frac{dk}{d\omega} = c\,\frac{d}{d\omega}\left(\frac{2\pi}{\lambda}\right) = \frac{d}{d\omega}\,(\mu\omega) \qquad (\ 13)$$

$$= \mu + \omega\,\frac{d\mu}{d\omega} = \mu + f\,\frac{d\mu}{df}$$

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

$$\mu' = \frac{d}{df}\,(\mu f) = \frac{1}{\mu} \qquad (\ 14)$$

6.1.4 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

$$\tan\alpha = -\frac{1}{v}\,\frac{dv}{d\theta} = +\frac{1}{\mu}\cdot\frac{d\mu}{d\theta} \qquad (\ 15)$$

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

$$P = \int_S \mu\cos\alpha\,ds \qquad (\ 16)$$

integrated over the raypath s. The corresponding group path is

$$P' = \int_s \mu\cos\alpha\,ds \qquad (\ 17)$$

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 gives 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 1). The law gives that

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

Application of eqs. (16) and (17) yields

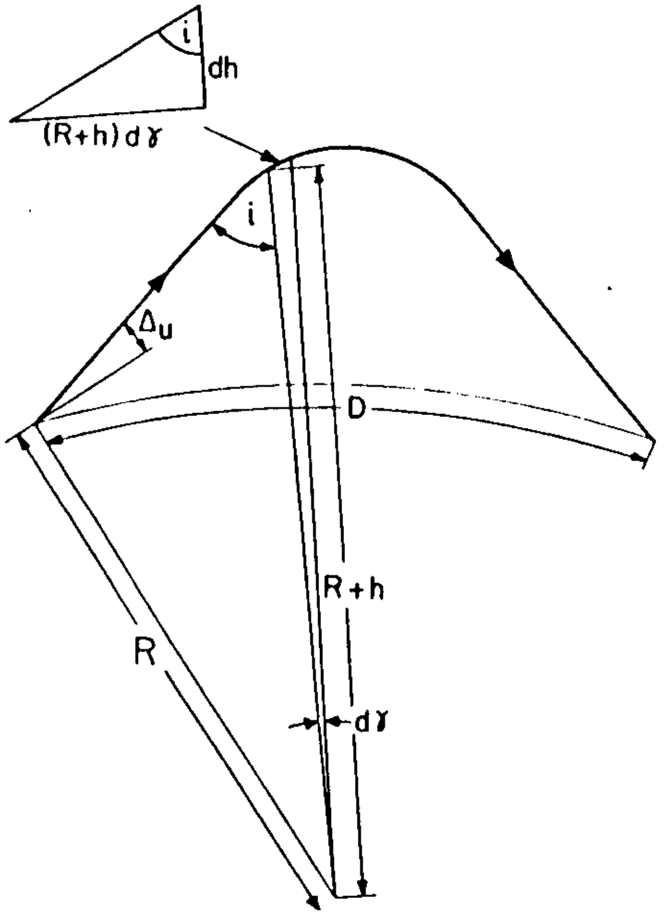

Fig. 1 Raypath geometry for spherically stratified ionosphere

$$P = \int_0^h \frac{\mu \, dh}{\cos i} = \int_0^h \frac{\mu^2 \, dh}{\sqrt{\mu^2 - \left(\frac{R}{R+h}\right)^2 . \cos^2 \Delta_u}} \qquad (\; 19)$$

$$P' = \int_0^h \frac{dh}{\sqrt{\mu^2 - \left(\frac{R}{R+h}\right)^2 . \cos^2 \Delta_u}} \qquad (\; 20)$$

and

$$D = R \int_o^h d\gamma = R \int_o^h \frac{\tan i \; dh}{R + h} \qquad (21)$$

$$= R^2 \cos \Delta_u \int_o^h \frac{dh}{(R+h)^2 \sqrt{\mu^2 - \left(\frac{R}{R+h}\right)^2 \cos^2 \Delta_u}}$$

Raypaths in non-concentric layers with no magnetic field The real ionosphere is not concentric and contains horizontal gradients. 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 Haselgroves 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.

Raypaths at VHF and higher frequencies

Propagation is nearly always quasi-longitudinal to the magnetic field. Hence from eq. (1) ignoring electron collisions and setting X <<1 gives

$$\mu \sim 1 - \frac{X}{2} (1 \mp Y_L) \qquad (22)$$

where the - and + signs refer respectively to the ordinary and extraordinary waves. Further, under conditions when the magnetoionic splitting of the rays may be ignored (putting $Y_L = o$) :

$$\mu = 1 - \frac{X}{2} \qquad (23)$$

Thus, the change in phase path due to the presence of the ionosphere is

$$\Delta P = \int_s (\mu - 1) \; ds = - \frac{e^2}{8\pi^2 \varepsilon_o m f^2} \int_s N \; ds \qquad (24)$$

The ordinary and the extraordinary waves at these frequencies are essentially circularly polarised and they suffer no change of polarisation during propagation. However, because they have different phase velocities, the plane of polarisation of their resultant, which is a linearly polarised wave, rotates gradually. This phenomenon is known as Faraday rotation.

The difference in phase paths of the ordinary and extraordinary waves is

$$P_o - P_x = \int_s (\mu_o - \mu_x) \; ds = \int_s XYL \; ds \qquad (25)$$

$$= \frac{|e^3|}{8\pi^3 . \varepsilon_o m^2 f^3} \int_s B \cos \theta . N \; ds$$

Often results of adequate accuracy are obtained using a mean value of Bcos θ over the raypath. Hence Ω the angle through which the plane of polarisation of the resultant wave rotates during ionospheric passage is

$$\Omega = \frac{\pi f}{c} (P_o - P_x) = \frac{|e^3| B . \cos \theta}{8\pi^2 \varepsilon_o m^2 \; c f^2} \int N \; ds \qquad (26)$$

Note that both change in phase path and resultant wave rotation are proportional to total electron content and inversely proportional to frequency squared.

The change in group path due to the presence of the ionosphere is

$$\Delta P' = \int_s (\mu' - 1) \; ds \qquad (27)$$

Substituting $\mu' = \frac{1}{\mu}$ from eq. (14) in the expression of eq. (23) for μ leads to

$$\mu' = 1 + \frac{X}{2} \text{ or } \mu' - 1 = 1 - \mu \qquad (28)$$

Hence, from eq. (24)

$$\Delta P' = -\Delta P \qquad (29)$$

The refractive effects of the ionosphere may be considered in terms of the angular bending β of the raypath from the line-of-sight direction. β is the integral over the raypath of the change in i, the angle of incidence, i.e. $\beta = \int di$. It is given from Snell's law as

$$\beta = \int_s \tan i \, \frac{d\mu}{\mu} \qquad (30)$$

Analytical expressions are available for β in the case of certain ionospheric models. As with the other path parameters considered above, β is also proportional to total electron content and inversely proportional to frequency squared.

PROPAGATION EFFECTS AT HF

Fig. 2 shows 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 range
(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 this depends primarily on the height of maximum electron concentration. For typical E, F1 and F2-layers, the maximum range is 2000, 3400 and 4000 km respectively.

For a given ionosphere there is 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).

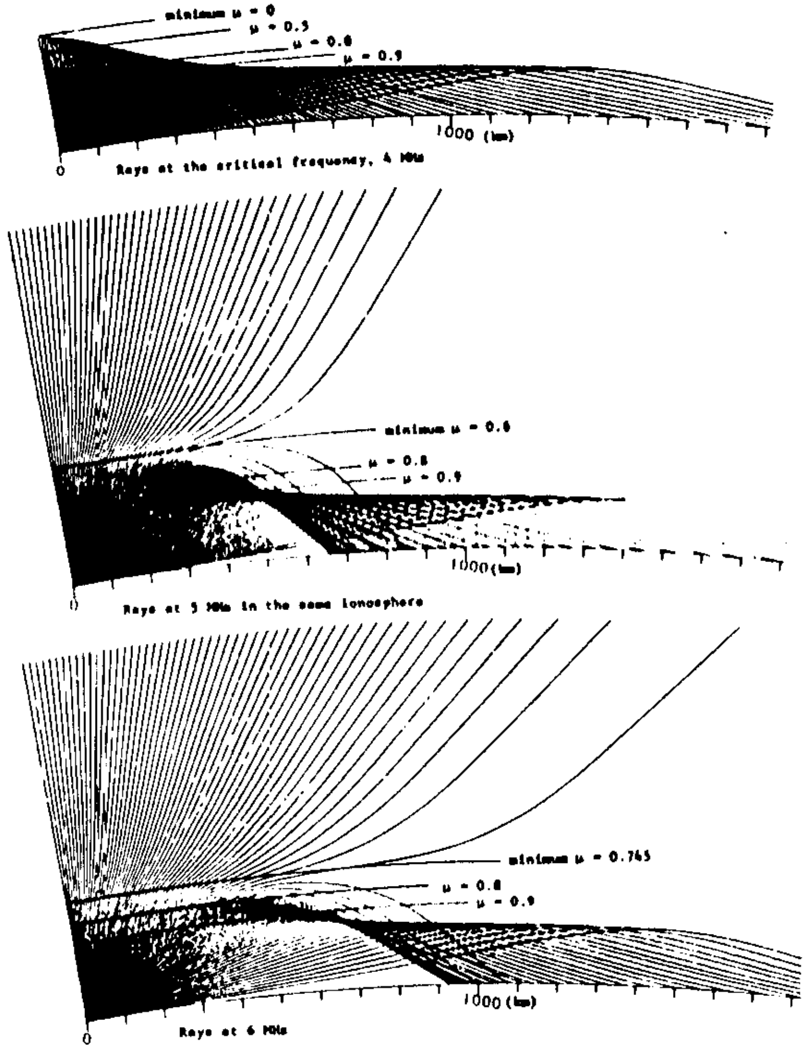

Fig. 2 Raypaths for propagation at three frequencies via a single Chapman model ionosphere of critical frequency 4 MHz, height of maximum electron concentration 300 km and scale height 100 km (from Croft, 4). Curves indicate heights with selected values of refractive index μ

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. Again, the F1-MUF may exceed the F2-MUF beyond the maximum E range at distances of 2000-3000 km.

Since the Earth's field leads to the production of O and X waves which follow different raypaths, these waves also have differing MUF's. The O 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.

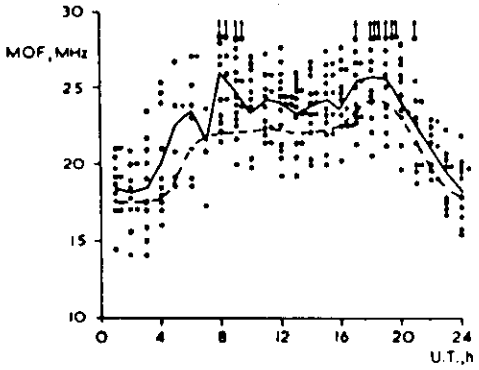

Fig. 3 Maximum observed frequencies for Cyprus - Slough path in July 1969 (from Bradley and Howard, 5)

- • 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 O and X waves have their own separate families of high-angle rays and associated JF's. Fig. 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.

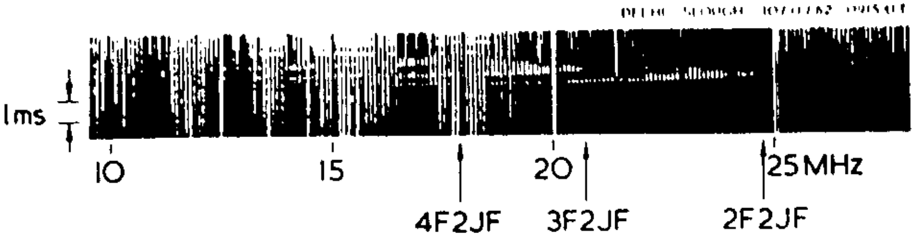

Fig. 4 Sample oblique-incidence ionogram with classical 'noses' (from Kift et al., 7)

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.

Geographical changes in ionisation cause so-called mixed modes with successive reflection from different layers. Mixed modes are a common feature of trans-equatorial 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 influence ray-paths 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 chanelling 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 abscrption

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

$$L(f_v) = K \int_h \frac{N\nu}{\mu} \cdot \frac{dh}{(f_v \pm f_L)^2 + \frac{\nu^2}{4\pi^2}} \qquad (\ 31)$$

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 proportionally increased because of the greater lengths of path traversed. Inspection of eq. (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 μ 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. (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 deviative 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 O 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 together with a signal scattered from spread-F irregularities can give rise to so-called 'flutter' fading, with fading rates of about 10 Hz.

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.

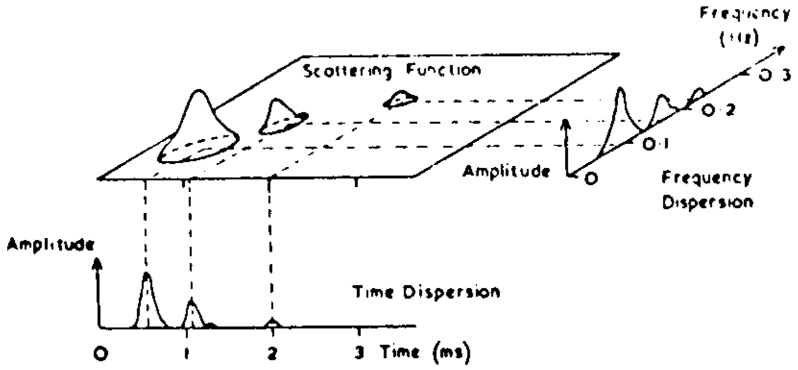

Fig. 5 Channel-scattering function for three-moded ionospheric signal propagation

PROPAGATION EFFECTS AT VHF AND HIGHER FREQUENCIES

Radio waves at VHF and beyond traverse the whole ionosphere but as noted are subject to refraction, phase and group delay and Faraday rotation. In the presence of ionospheric irregularities, particularly at low and high latitudes, scintillations also arise. Ionospheric effects generally decrease the greater the frequency but can still be important to the operation of earth-space communication, navigation and surveillance systems.

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