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COLLEGE ON THEORETICAL AND EXPERIMENTAL RADIOPROPAGATION SCIENCE

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# LECTURE 1: RAYPATHS IN THE IONOSPHERE

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# 2. THEORY OF IONOSPHERIC RADIOPROPAGATION

## Lecture 1: Raypaths in the ionosphere

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## 1 PROPAGATION EFFECTS AT MF AND HF

Fig. 1 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 from the ionosphere and travel into space

(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.

In this example, the curvature of the Earth is taken into account and it is assumed that the same ionosphere exists at all ranges from the transmitter and is concentric with the Earth. It follows that the maximum range attainable after one ionospheric reflection arises for rays launched at grazing incidence and that this depends on the height and form of the model ionosphere and on the wave frequency. Changes with frequency and model form tend, however, to be of a secondary nature, and the principal dependence is on the layer height of maximum electron concentration. For typical E, F1 and F2-layers, the maximum range is 2000, 3400 and 4000 km respectively. Whilst undoubtedly greater ranges are sometimes possible, the above values represent practical upper limits when account is taken of poor antenna performance at low elevation angles and its influence on signal strength.

For a given ionosphere there will be some limiting upper frequency which is reflected vertically. For this frequency the reflection occurs at the height of maximum electron concentration. The frequency is known as the critical frequency. At frequencies above the 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).

The MUF increases with ground distance. Clearly it depends also on the amount of ionisation present - if the critical frequency is doubled, so will be the MUF for all distances. 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 same incidence angle yields different ground ranges for different layer heights. 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. 2 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.

Now consider propagation to some point beyond the skip distance. Fig. 1 shows that as the elevation angle is increased at a fixed frequency, rays travel to shorter ground ranges until the skip distance is reeached. 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 i.e. propagation to zero ground range. 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 (1). 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. It is usual then in practice that 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. 3 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 propagation path to be possible, i.e. that 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 tend to occur simultaneously at separated positions.

So far, no discussion has been made of the effects of geographical changes in ionisation. These cause so-called mixed modes with sucessive reflection from different layers. Mixed modes are a common feature of transequatorial paths and east-west paths across a daylight-darkness boundary. Figs. 4(a) and (b) show cases of a 1F2 + 1E mode for an eastwards path at dawn and of a 1E + 1F2 mode arising at dusk. (Modes are labelled in succession outwards from the transmitter). Other more complex examples of mixed modes are those involving upwards reflection from the E-layer between two F-reflections, known as M-modes (Fig. 4(c)).

Now geographical changes in ionisation of a smaller scale size influence raypaths on single hops. These changes 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 they modify their directions so that the equivalent triangular path must be regarded as involving reflection from a tilted plane mirror. Longitudinal tilts (Figs. 5(a) and (b) produce differences in the elevation angles on the two legs; lateral tilts give rise to 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. For an upwards ray of elevation angle $\Delta$ a longitudinal plane-mirror tilt $\theta$ results in a downwards ray of elevation angle $\Delta \pm 2\theta$, i.e. there is a difference of $2\theta$ for the two legs in the sense indicated in Figs. 5(a) and (b). 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 (Fig. 5(c)). 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. Hence these so-called perigee modes can be important on long paths, particularly 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.

In addition to 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 the vertical-incidence ionogram phenomenon of 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 cooncerns 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. Fig. 6 illustrates a number of the separate propagation features discussed in the above paragraphs arising on paths at high latitudes.

Mention has been made of ionospheric absorption. 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

$$L(f_v) = K \frac{N\nu}{\mu} \cdot \frac{dh}{(f_v \pm f_L)^2 + \frac{\nu^2}{4\pi^2}} \qquad (1)$$

where K is a constant of proportionality, N is the electron concentration, $\nu$ is the collision frequency, $\mu$ is the refractive index and $f_L$ is the electron gyrofrequency. 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 is taken 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. (1) 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 whith 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 $\mu$ 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. (1) remains dominant.

Some of the above features can be seen in the data of Fig. 7 showing estimated values of oblique-path ionospheric absorption at two high frequencies in different seasons. 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 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 and under these conditions classical-type oblique-incidence ionograms are replaced by others with diffuse traces; in some cases the traces associated with the different modes coalesce (Fig. 8). There are also large variations in the angles of elevation of the incident signals (Fig. 9). It seems unlikely that such features can ever be modelled satisfactorily.

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 (Fig. 10).

The effect of ionospheric propagation on a radio signal may therefore be expressed in terms of a corresponding channel-scattering function (Fig. 11) 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. 10).

## 2 PROPAGATION EFFECTS AT VHF AND HIGHER FREQUENCIES

Radio waves at VHF and beyond traverse the whole ionosphere but 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.

## REFERENCES


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6. Vincent, W R, Daly R F and Sifford B M (1968). Modeling communication systems. Ionospheric radio communications in the artic, Ed. K. Folkestad, Proc. NATO institute, Plenum Press, New York, 321-340.


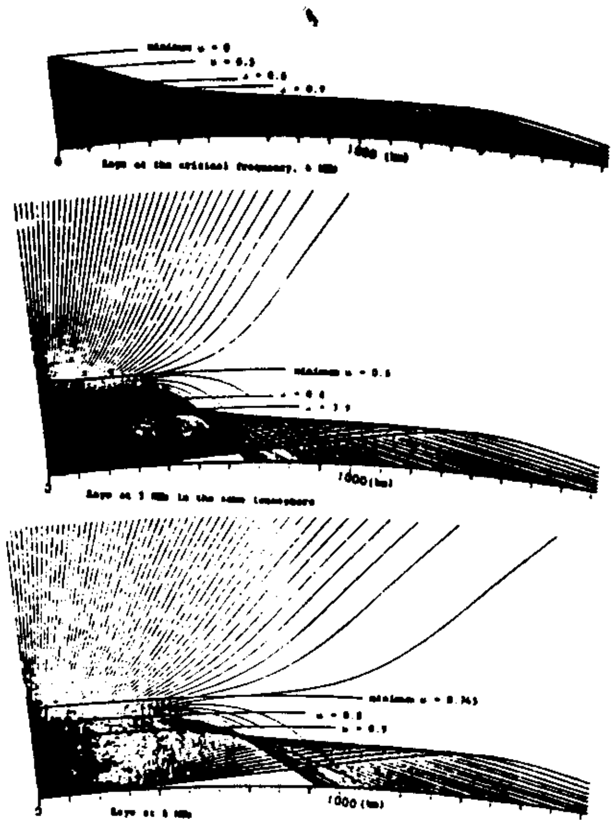

Fig. 1 Raypaths for propagation at three frequencies via a single Chapman model ionosphere of critical frequency 4 MHz, height of maximum electron concentration 300 km and scale height 100 km (from Croft, 2). Curves indicate heights with selected values of refractive index μ

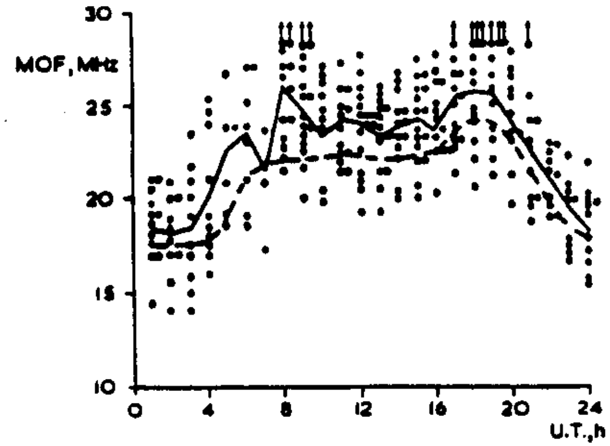


Fig. 2 Maximum observed frequencies for Cyprus - Slough path in July 1969 (from Bradley and Howard, 3 )

• daily values

____ monthly median values

---- predicted monthly median values (from CCIR Report 340)

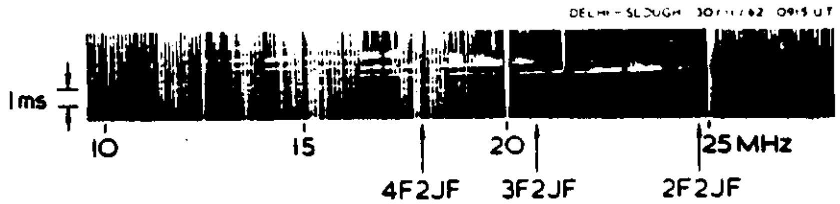


Fig. 3 Sample oblique-incidence ionogram with classical 'noses' (from Kift et al., 4 )

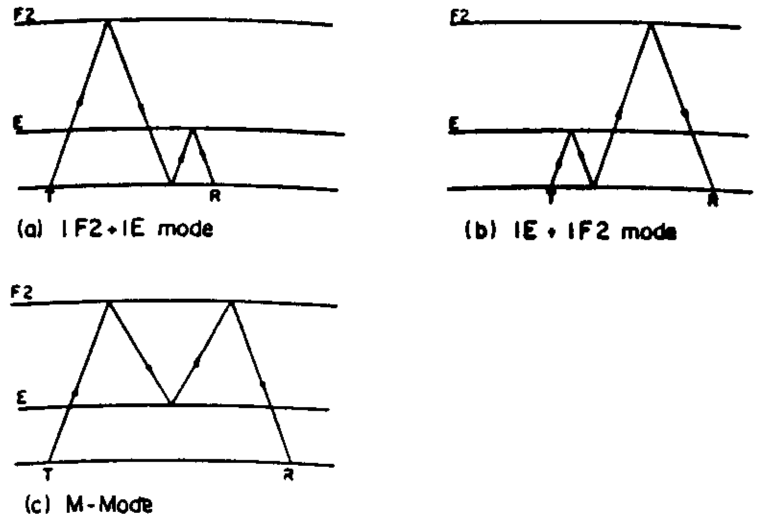


Fig. 4 Propagation modes for a geographically varying ionosphere

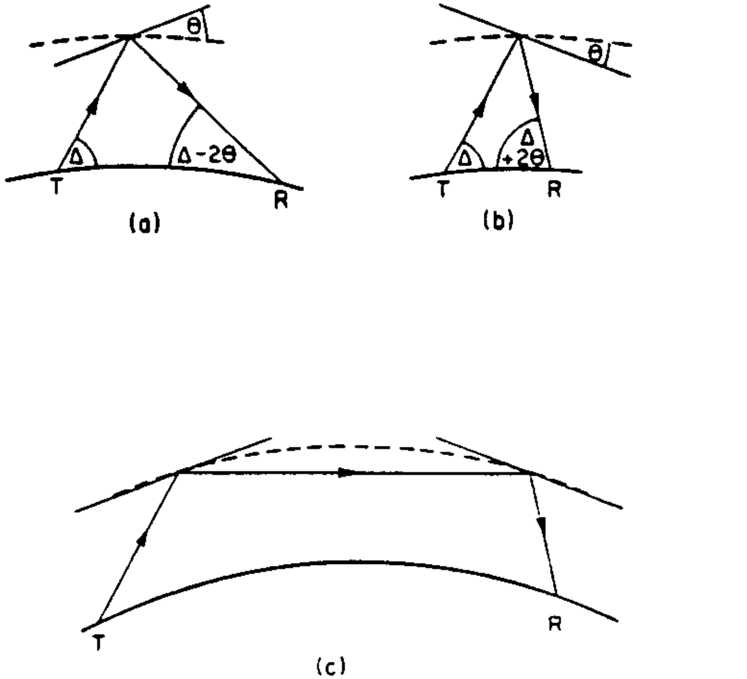


Fig. 5 Propagation modes for a tilted ionosphere

(a) equivalent mirror height increasing with range from transmitter

(b) equivalent mirror height decreasing with range from transmitter

(c) perigee mode involving multiple ionospheric reflections without intermediate ground reflection



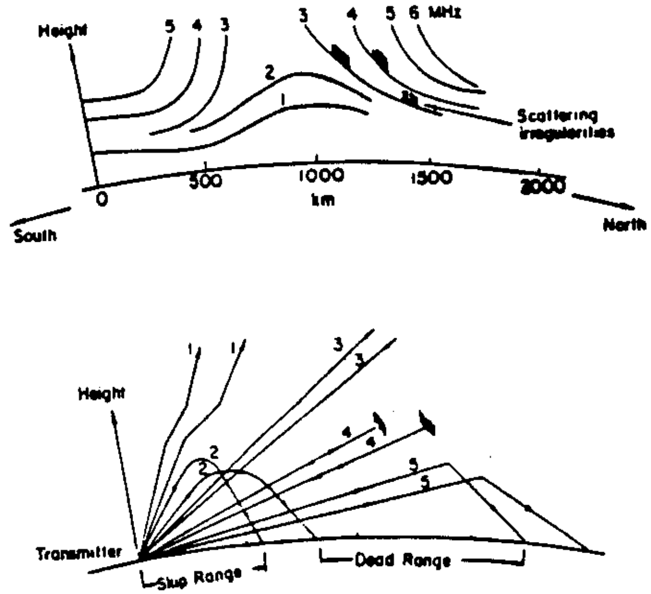


Fig. 6 HF propagation paths via the ionosphere at high latitudes (from Buchau, 5)

top section: sample distribution of electron concentration (arbitrary units) in northern hemisphere high-latitude ionosphere

lower section: raypaths for signals of constant frequency launched with different elevation angles

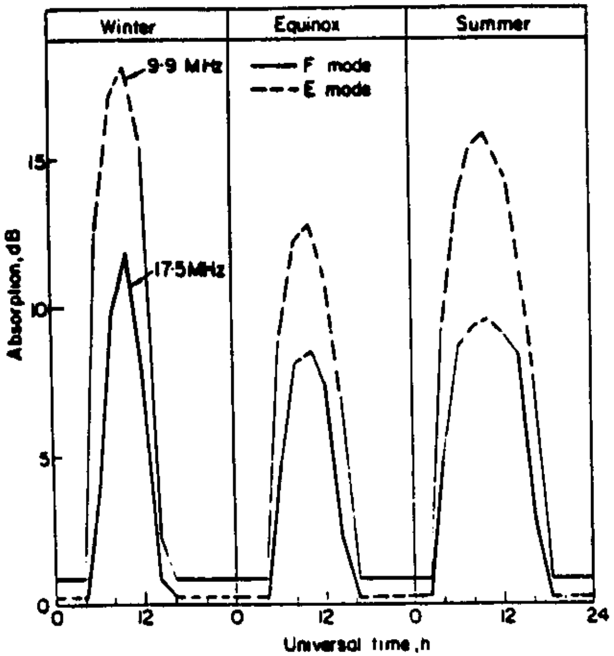


Fig. 7 Ionospheric absorption given by the method of the Supplement to CCIR Report 252-2

The calculations relate to 1F2 and 1E-modes each with an elevation angle of 1° over paths centred on 45°N, 20°E at high solar activity ($R_{12}$ = 100)

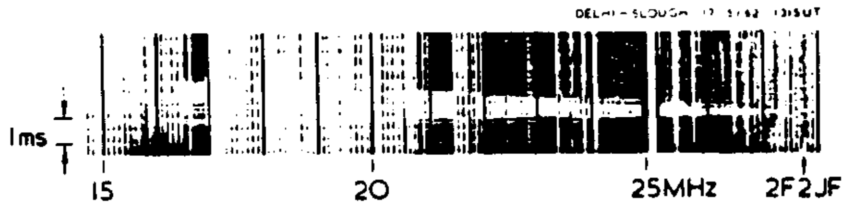


Fig. 8 Sample oblique-incidence ionogram with single diffuse trace (from Kift et al., 4)

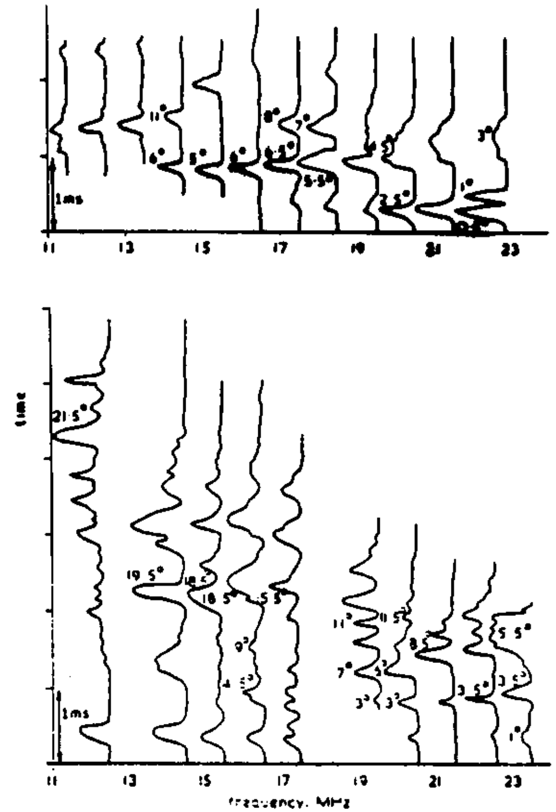


Fig. 9 Received instantaneous pulse patterns and associated measured angles of elevation for Delhi - Slough path (from Kift et al., 4)

top section: 0804-0847h UT on 30 November 1962
lower section: 1340-1427h UT on 17 May 1962

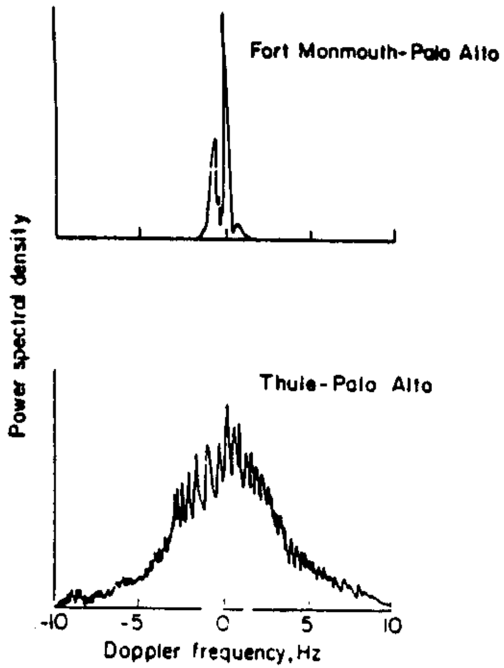


Fig. 10 Doppler spectra of received HF sky-wave signals (from Vincent et al., 6)

top section: temperate-latitude path
lower section: trans-auroral path

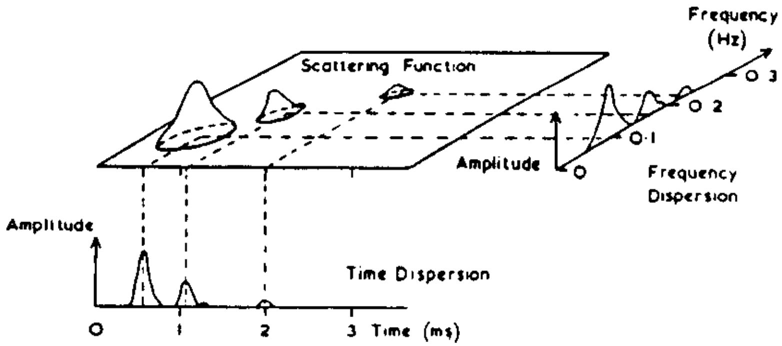


Fig. 11 Channel-scattering function for three-moded ionospheric signal propagation