CHAPTER II

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CHAPTER II

GENERAL DISCUSSION OF IONOSPHERIC ABSORPTION

1 - THEORY OF IONOSPHERIC ABSORPTION

The ionosphere contains free electrons and ions which are set in motion by the passage of an electromagnetic wave. The ions being more massive, their movements can be neglected in comparison with those of electrons. If each electron is assumed to be entirely free, so that its movement under the influence of the wave is uninterrupted, it will execute regular periodic oscillations so long as the wave is passing. The system is wattless; i.e., on the whole, no energy is absorbed from the wave. The oscillating electrons however scatter some of the incident radiation and the scattered wavelets add up with the incident radiation causing a change of phase of the transmitted wave and hence a retardation. The intensity of the incident waves undergo some attenuation due to scattering. On the whole no net work is done on the electron, as the electron re-radiates what it receives. If, however, the electrons are not entirely free, they collide with the molecules and ions which are present in the ionosphere and in doing so they change the ordered energy of oscillatory motion which they acquire from the electromagnetic wave, into the kinetic energy of random movement. The energy is then lost
from the point of view of wave and the latter therefore becomes attenuated. The overall attenuation per unit length of the path will depend upon \( N \nu \) and \( \omega \) where \( N \) is the electron concentration \( \nu \), the collisional frequency of the electron and \( \omega \), the angular frequency of the wave. If \( \omega \) is very much larger than \( \nu \), then attenuation decreases as the frequency increases. \( N \) and \( \nu \) are functions of height and the absorption per unit length of path at any height depends directly on the product \( N \nu \).

2 - ABSORPTION COEFFICIENT 'K'

Magneto-ionic theory shows that, provided the direction of phase propagation is not perpendicular to the magnetic field, the absorption coefficient is given by the expression

\[
K = \frac{2 \pi e^2}{mc} \cdot \frac{1}{\mu} \cdot \frac{N \nu}{\nu^2 + (\omega \pm \omega_L)^2} \tag{1}
\]

where \( c \) is the velocity of electromagnetic waves in vacuo, \( e \) and \( m \) are the charge and mass of the electron, \( \omega \) is the angular frequency of the wave, \( \omega_L \) is the angular gyro-frequency corresponding to the longitudinal component of the earth's magnetic field. The positive sign refers to ordinary wave and negative sign to extraordinary wave.
a) DEVIATIVE ABSORPTION

If \( \omega \) is large compared with \( \omega_L \), the influence of the earth's magnetic field may be neglected and the absorption coefficient may be written.

\[
K = \frac{2 \pi e^2}{mc} \cdot \frac{1}{\mu} \cdot \frac{N \omega}{\nu^2 + \omega^2} \quad \ldots (2)
\]

Further, if \( \nu^2 \ll \omega^2 \), then equation (2) becomes

\[
K = \frac{2 \pi e^2}{mc} \cdot \frac{1}{\mu} \cdot \frac{N \nu}{\omega^2} \quad \ldots (3)
\]

where

\[
\mu^2 = 1 - \frac{4 \pi Ne^2}{mc \omega^2} \quad \ldots (4)
\]

Combining equations (3) and (4), we get

\[
K = \frac{\nu}{2c} \left( \frac{1}{\mu} - \mu \right) \quad \ldots (5)
\]

Equation (5) shows that the absorption index \( K \) and the total absorption \( \int K \, ds \) will depend critically on the value of the refractive index \( \mu \). Since the bending or deviation of a group of waves is also governed by the value of the refractive index, this type of absorption is termed Deviative Absorption.
b) NON-DEVIATIVE ABSORPTION

When \( \mu \approx 1 \), then equation (1) takes the form

\[
K = \frac{2\pi e^2}{mc} \cdot \frac{N\nu}{\nu^2 + (\omega + \omega_c)^2} \quad \ldots(6)
\]

If \( \nu^2 < (\omega + \omega_c)^2 \), then the total non-deviative absorption may be written

\[
\left( \int K \, ds \right)_{\mu \approx 1} = \frac{2\pi e^2}{mc} \cdot \frac{1}{(\omega + \omega_c)^2} \int N\nu \, ds \quad \ldots(7)
\]

The above expressions apply only to the so-called "quasi-longitudinal" propagation of waves of angular frequency much greater than the collision frequency of electrons.

c) COLLISION FREQUENCY OF ELECTRONS WITH NEUTRAL PARTICLES AND IONS

If the average velocity \( v_e \) of the electrons is known, the average \( \nu_{ea} \) of their collision with neutral particles is given by the relation
\[ \nu_{ea} = \frac{v_e}{l_e} \]  

where \[ l_e = (\pi r_a^2 n_a)^{-1} \]

where \( r_a \) = radius of molecule
\( n_a \) = number density of atoms or molecules.

From gas-kinetic theory,
\[ \frac{1}{2} m \ v_e^2 = (3/2)kT \]

or \[ v_e = \sqrt{\frac{3kT}{m}} \]

\[ \therefore \nu_{ea} = \pi r_a^2 n_a \frac{3kT}{m} \frac{1}{2} \]  

...(9)

For levels below 100 km where the air is not appreciably dissociated, Nicolet\(^{19}\) has given the formula
\[ \nu_{ea} = 5.4 \times 10^{-10} n_a \frac{T}{m} \frac{3}{2} \]  

...(10)

At higher levels, \( r_a \) will get smaller owing to the dissociation of oxygen and nitrogen. The motion of an electron is influenced by the presence of ions at a much greater distance, because the Coulomb force: between charged particles increases at a much more rapid rate when they approach each other. It has been shown by Cowling\(^{20}\) and Nicolet\(^{19}\) that the collision frequency of an electron with a positive ion is given by the relation
where \( \lambda \) is the ratio of negative ions and electrons.

In most parts of the ionosphere, \( \lambda \) can be neglected in comparison with \( l \) and \( n_1 \) can be taken to be equal to \( n_e \). The equation (11) then becomes

\[
\psi_{e^+} = (34 + 8.36 \log_{10} T^{3/2}/n_e^{4/3}) (1 + \lambda) n_e T^{-3/2} \quad \cdots (12)
\]

3 - INFLUENCE OF NON-DISSIPATIVE PHENOMENA

Theoretically, ionospheric absorption can be measured by studying the changes in the amplitudes of radio waves reflected from the ionosphere, but absorption is not the only cause of variability of the measured amplitude. Changes due to other processes may often exceed those due to ionospheric absorption. The main non-dissipative phenomena which may influence amplitude-measurements are: (a) Polarisation, (b) Unevenness and curvature of the ionosphere and (c) Scattering by ion and electron clouds.

4 - METHODS OF MEASURING IONOSPHERIC ABSORPTION

There are three main techniques for studying ionospheric absorption:
a) Measurement of the amplitudes of signals reflected from the ionosphere.

b) Study of the minimum frequencies at which echoes can be obtained in ionospheric soundings, and

c) Study of radio noise from constant extra-terrestrial sources.

We shall restrict ourselves to the discussion of method (c).

(c) EXTRA-TERRESTRIAL RADIO WAVES AND IONOSPHERIC ABSORPTION

Until quite recently, the normal method of investigating ionospheric absorption was to measure the strength of man-made signals reflected from the ionosphere. Such a method, in essence, measures the total attenuation undergone by radio signals in their path from the transmitter to the receiver and includes contributions due to divergence of beam, partial reflections, polarisation effects, collision losses, losses due to scattering and deviative absorption. The use of extra-terrestrial radio waves for the study of the changing transparency of the ionosphere has certain important and useful features. These are: the constancy of the source, the relative simplicity of the equipment since no transmitters are required, and the fact that radio waves from the galaxy traverse the whole ionosphere instead of only the region below
the level of reflection or scattering. Moreover, if frequencies well above the critical frequency are used, the absorption can be measured even when it is very much increased as during SID's associated with solar flares and polar blackouts. The use of frequencies well above the gyromagnetic and critical frequencies has the advantage that uncertainties arising from polarisation effects and deviative absorption are much reduced. But the exact level at which the absorption takes place cannot be determined.

The cosmic-noise method of measuring ionospheric absorption was first used in 1953 by Mitra and Shain. They compared the signal strength of extra-terrestrial radio waves actually received on a fixed receiving system under different ionospheric conditions with the signal strength received on the same system at the same sidereal time under conditions of negligible absorption.

(i) The simplest equipment capable of absorption measurements by the "Cosmic-noise" method consists of a receiver connected to an aerial by means of a transmission line and a pen-recorder to measure the noise power of the receiver output. Calibration is done by means of a constant noise generator. This system is susceptible to variations of receiver gain, and it is therefore necessary to use electronically stabilised a.c. and d.c. power supplies for the receiver.
(ii) Little and Leinbach\textsuperscript{13} devised an instrument called a riometer (relative ionospheric opacity meter) which is a sensitive, self-balancing noise-measuring equipment. The riometer incorporates sweep-frequency and minimum-signal detector circuits in conjunction with the receiver. The riometer registers the minimum noise level as a 6 Kc/s exploring band is swept across at the rate of 2.5 Kc/s through a 100 Kc/s search band. The sweep-frequency minimum-detector technique was previously used by Lee\textsuperscript{22} in a total-power cosmic-noise receiver.

Advantages of the riometer: The riometer has three important advantages over a simple total-power type receiver. (1) It provides a linear input/output characteristics. (2) The equipment is capable of operating with high accuracy in the presence of narrow band R.F. interference and (3) the equipment possesses good long-term stability since receiver acts as a null-detector rather than as an amplifier.

5 - SUMMARY OF RECENT EXPERIMENTAL RESULTS OF IONOSPHERIC ABSORPTION

a) FREQUENCY DEPENDENCE

Piggott\textsuperscript{21}, Appleton and Piggott\textsuperscript{23} and Allcock\textsuperscript{24} have carried out a detailed analysis of observations extending over
a number of years at stations in England. They find that
the variation of absorption with the inverse square of
frequency, as predicted by theory, is generally valid.
Expressing the absorption in the form

\[ -\log \rho = \frac{A}{(\omega_{+} + \omega_{L})^2} \]

the factor \( A \) for southern
England (where \( f_L = \omega L / 2\pi = 1.2 \text{ Mc/s} \)) comes out to be 505 db.
This value is subject to considerable enhancement at frequencies
near the critical frequencies of \( E \) and \( F \) layers where the
deviative-type absorption comes in play.

At Ibadan (lat. 7°26'N, long. 3°54'E), Skinner and
Wright\(^25\) found that non-deviative absorption was proportional
to the inverse frequency instead of to inverse square of the
frequency. A similar frequency dependence was noticed at
Singapore.

b) REGION OF PRINCIPAL ABSORPTION

Bracewell and Straker\(^26\) observed sudden phase
anomalies in the low frequency waves propagated through the
D-region during an SID (Dellinger Effect). Beynon and Davies\(^27\)
showed that obliquely reflected radio signals from both \( E \) and
\( F \) layers were almost identically affected by absorption changes
in vertical sounding records. This implies that the absorption
occurs at relatively low levels. Further Dieminger\(^28\), Heppner\(^30\)
Gardner and Pawsey\(^29\) and Appleton and Piggott\(^23\) have reported
that high absorption occurs in frequent association with unusually low-lying vertical-incidence sounding echoes of a sporadic nature from the height interval 65 to 90 Km.

These facts leave little doubt that a large part of the non-deviative absorption is due to excess ionization in the regions below the normal E layer.

Evidence that there is nevertheless appreciable absorption ascribable to higher regions was obtained by Mitra and Shain\textsuperscript{9} and Bhonsle and Ramanathan\textsuperscript{15}, who found a correlation between total attenuation of cosmic radio noise and $f_0F_2$, when the value of $f_0F_2$ exceeded a certain minimum.

c) SOLAR CONTROL

More than one agency can be responsible for the production of ionization in the D-layer. On the average, however, there are regular diurnal and seasonal variations of absorption depending on the cosine of the sun's zenith angle through a relationship of the form

$$\alpha = \alpha_0 \left(\cos \chi\right)^n$$

where $\alpha_0$ is the maximum or noon-time absorption.

Taylor\textsuperscript{31}, Appleton and Piggott\textsuperscript{23}, and Rawer\textsuperscript{32} have shown that the exponent is definitely smaller than the theoretical value of 3/2 derived by Appleton. The exponent varies with season, latitude and with sunspot cycle, but with
anomalies which lead to the conclusion that something more than solar radiation is involved for the absorption. Davies and Hagg\textsuperscript{33}, for example, have analysed the absorption effects at Prince Rupert (54.3°N, 130.3°W) and find that the exponent 'n' expressing the influence of solar radiation comes down to a value of about 0.5. This result may be compared with Piggott's\textsuperscript{21} value of 0.75 for the observations made at Slough. At equatorial latitudes, Skinner and Wright\textsuperscript{25} investigated the variation of \(-\log \rho\) with the sun's zenith distance both diurnally and seasonally. They found that for diurnal variation

\[-\log \rho \propto (\cos \chi)^n\]

where \(n\) is about 0.7. However, from the seasonal variation of the monthly means of the noon values of \(-\log \rho\), they obtained much higher value of 'n'. In 1953-54, they found that 'n' was about 2. The seasonal high values of \(-\log \rho\) at Singapore and Ibadan remain in a class apart.

d) VARIATION OF \(-\log \rho\) WITH SUNSPOTS

Lange-Hesse\textsuperscript{34} has investigated the relation of absorption to sunspot number at several latitudes and has found that there is a close relationship in equatorial regions and in high latitudes, but that they are quite irregular at Slough in winter. Appleton and Piggott\textsuperscript{23} have shown that for any one calendar month, over a series of years, the noon value of 'A' varies nearly linearly with the annual mean sunspot number R i.e.
\[ A_{\text{noon}} = \lambda + \beta R. \]

Both \( \lambda \) and \( \beta \) are least in winter and greatest in summer. \( \lambda \) increases from 230 in December to about 350 in July and \( \beta \) from about 2 in mid-winter to 3 in midsummer.

e) WINTER ANOMALY

Appleton and Piggott\textsuperscript{23}, from their studies of the seasonal dependence of \(-\log \phi\) on \(\cos \chi\), have confirmed the existence of a "Winter Anomaly" in the months November to February ever since the series of observations started in 1935. The winter anomaly is characterised by the occurrence of excessive absorption on certain groups of days during the winter. A statistical study showed that the occurrence of these days of high absorption was correlated with the occurrence of sporadic reflecting strata below the level of E layer. Dieminger\textsuperscript{28} found that the days of high absorption were often associated with weak reflections from low heights of the order of 75 to 95 Km. Appleton and Piggott\textsuperscript{23} attempted to find if days of high absorption and periods of magnetic activity were connected but could not find any correlation. They suggested that either an additional ionizing source was present or some agency was operative which caused a redistribution of ionization which caused an increase in the integrated value of \(N\nu\) within the absorbing stratum.
A comparison of Slough, Singapore and Falkland Islands data showed that no anomalous behaviour was evident at Singapore at any time during the year, but that it occurred at Falkland Islands in the local winter. They concluded that the phenomenon was connected with low $\cos \chi$ conditions and not to change in the intensity of solar radiation.

Morris reported on the anomalous winter midday absorption of cosmic radio waves of 24.3 Mc/s at Cambridge. He concluded, from the data collected from January 1957 to May 1958 that the average midday absorption in winter (December and January) was about twice as great as that in summer (June and July). This could not be adequately explained in terms of changes in $F_2$ critical frequency. According to him, this anomalous absorption can be explained, if one assumes that $\nu^2 \lesssim (\omega + \omega_L)^2$ in summer and on 'normal' days in winter, but that on abnormal days $\nu \simeq \omega + \omega_L$. This suggestion implies that on some days in winter, which are of the abnormal type, absorbing electrons are found in abnormally large numbers near the level where $\nu \simeq \omega + \omega_L = 2.6 \times 10^7 \text{ sec}^{-1}$, that is, at a height of about 60 km.

6 - HIGH LATITUDE ABSORPTION EFFECTS

Little and Leinbach have studied the radio absorption characteristics of the Arctic ionosphere using 30 Mc/extra-terrestrial radio waves. Their observations have shown
that regions of anomalous high latitude absorption have typical lateral dimensions in excess of 100 km and that marked differences can occur during disturbed periods between stations 800 km apart. Almost all the absorption occurs below the E region. The absorption correlates well with local geomagnetic \( k \)-index and is apparently associated with the bombardment of the upper atmosphere by corpuscular streams which produce the aurorae.

Reid and Collins\(^3\) have studied cosmic noise absorption on 30 Mc/s at Ottawa and Churchill, and shown the existence of two apparently distinct types of abnormal absorption events apart from sudden cosmic noise absorptions (SCNA's) associated with solar flares. One of these (Type II) is predominantly a night-time phenomenon and closely associated with aurorae and geomagnetic disturbances. When type II (auroral) absorption occurs at Churchill, it does not necessarily occur at Ottawa, but occurrence at Ottawa always seems to be accompanied by occurrence at Churchill. The magnitude of absorption can be as high as 8-10 db only for short periods.

Chapman and Little\(^5\) have suggested mechanism to explain type II (auroral absorption) by an increase in ionization in the lower ionosphere due to bombardment of electrons of solar origin and their associated Bremsstrahlung radiation.
Another type of high-latitude absorption (Type III) is confined to polar latitudes. The cosmic noise recordings of this type of absorption are much more uniform in appearance than recordings of the auroral absorption (Type II) described above, and the magnitude of the absorption is much greater during day than during night. It is closely correlated with great solar activity and is very similar to the absorption events described by Bailey\textsuperscript{51} which occurred in polar latitudes following the great solar flare of 23 February 1956. This type III (high-latitude) absorption appears to set in within a few hours of the onset of a major solar flare and usually persists 2-3 days, gradually declining in intensity during this period. This absorption is predominantly a daytime phenomenon; in contrast to type II (auroral absorption).

Reid and Leinbach\textsuperscript{37} have reported on 24 type III (high-latitude) events. More recently, they named them as "Pre-SC Polar Cap blackouts". They attribute this ionospheric absorption in Arctic regions to low-energy cosmic ray protons associated with solar flares. Confirmation of proton theory has come from Balloon observations of cosmic-rays over Fort Churchill by Anderson and others\textsuperscript{38} during a type III event and later by University of Minnesota and State University of Iowa groups on August 22, 1958. These observations showed the presence of a flux of protons at balloon heights whose energies were not high enough to allow them to penetrate to ground level.
The normal sequence of events is as follows:

(1) A major solar flare occurs, usually accompanied by a short-wave fade-out over the sunlit hemisphere of the earth. The fade-outs and the associated SCNA are caused by e.m. radiation from the flare.

(2) The flare is followed by a strong low frequency solar radio noise storm which lasts for several hours.

(3) Within a few hours after the flare the type III absorption begins over the entire polar cap, the actual onset often being obscured by solar noise storm; the absorption reaches a maximum within a few hours, then decays slowly during following few days.

(4) After a day or two a SC-magnetic storm occurs, accompanied by ionospheric disturbances.