CHAPTER 1

INTRODUCTION TO IONOSPHERE

1.0 DISCOVERY OF IONOSPHERE

The name ionosphere was first introduced by Watson-Watt to describe the regions of the 'Earths' upper atmosphere which exhibit appreciable electrical conductivity due to the ionization of the air. It is now known that this ionization is primarily caused by the effect of solar ultra-violet radiation on the constituent gases of the upper atmosphere, a process which extends upwards to the highest regions from a height of about 50 km above the Earth's surface.

Historically, the first mention that electrically conducting regions might exist in the Earth's atmosphere was made in 1878 by Balfour Stewart, who explained the well established small daily variation of the Earth's magnetic field. He postulated the existence of a conducting ionized region in the upper atmosphere in which electric currents were induced by a dynamo type action resulting from a tidal movement of the conducting region across the permanent magnetic field of the Earth.

The ionosphere plays a fundamental role of the long distance propagation of radio waves. The first recorded observation of radio transmission round an appreciable part of the curved surface of the Earth dates from 1901, when Marconi successfully received a Morse signal in Newfoundland from his transmitter situated 1800 miles away in Cornwall England.Calculations of the amount of diffraction expected for such path showed that this was quite inadequate for the "bending" of the radio waves. In 1902

Kennelly in America and Heaviside in Great Britain independently suggested an explanation in terms of a conducting layer in the upper atmosphere capable of detecting a radio wave incident obliquely on it so as to return it to the ground and be received at a great distance from the source. It was further suggested that the conductivity is due to the presence of positive and negative ions. Indeed , basic theory of the manner in which such charged particles would affect the propagation of a radio wave was developed in 1912 by Eccles, although the details of this theory were only completed in 1924 by Larmor. It was in the following two years that direct experimental evidence was obtained for the existence of down coming or sky radio waves at a receiver by Appleton and Barnett(1925) and by Smith-Rose and Barfield (1926). These pioneer experiments demonstrated that radio waves could be reflected in the upper atmosphere, and hence established direct conformation of the earlier suggestion for the existence of an "ionosphere". It is now known that there are two main "strata" or "layers" in the ionized atmosphere and these were originally linked with the names of Kennelly-Heaviside (for the lower layers) and Appleton (for the upper layer). Modern usage, however, has tended to replace these names by the terms "E layer" and "F layer" respectively, a nomenclature originally suggested by Appleton.

1.1 CHAPMAN THEORY OF IONOSPHERIC LAYER FORMATION :

The vertical structure of the ionosphere has been observed and studied for many years, and is understood fairly well in terms of physical and chemical processes at work in the upper atmosphere. The various layers tend to emphasize the inflections of the profile. For detailed explanation of the structure one has to take account of the atmospheric photochemistry. However, the first step is to examine the formation of the ionosphere in the more general terms of the physical processes. It should apply to ionospheric formation of any planet having a gaseous atmosphere.

The Chapman theory, dating from 1931, starts with a few simplifying with assumptions and works out the form of an ionospheric layer, and how it should change with time. In essence the assumptions are as follows :

(a) An exponential atmosphere with only one gaseous component and constant scale height.

b) Plane stratification

c) Absorption of solar radiation in proportion to the number density of gas particles.

d) Constant absorption coefficient i.e. monochromatic radiation and a single absorbing component.

Ionizing radiation enters the atmosphere at a zenith angle χ its intensity (energy flux per unit area) is I_∞ above the atmosphere & I at altitude h, corresponding to slant distance ´l´ from the ground. If there are ´n´ absorbing atoms per unit volume and each has an absorption cross section σ as in fig. 1.1, the intensity of the radiation changes with the distance as

$$dI/dl = -I\sigma n \qquad (1)$$

If the probability that the absorbed radiation will ionize the atom is η (ionization efficiency) the rate of ionization with height ´h´ is $q = \eta\sigma n I$

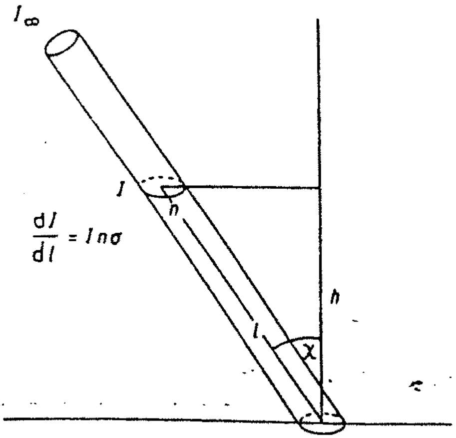

Figure 1.1 Ionizing radiation in the atmosphere.

since σni is the energy absorbed by unit volume of the gas, q maximizes where

$$dq/dl = n\sigma(n\ dI/dl + I\ dn/dl)$$

Thus $$(1/I\ .\ dI/dl\ )_m + (1/n\ .\ dn/dl)_m = 0 \qquad (2)$$

where the subscript m denotes values at the maximum of q now

$$1/n\ dn/dl = \cos\chi/n.\ dn/dh = \cos\chi/H$$

by definition of scale height (H). Thus form 1 & 2

$$(dI/dl)_m = I_m\sigma n_m = I_m \cos\chi/H_m$$

Therefore

$$\sigma n'_m H_m\ \mathrm{Sec}\,\chi = 1 \qquad (3)$$

Note that when the Sun is overhead $\sigma n_m H_m = 1$ and H is independent of height

$$n_m \propto \cos\chi$$

by integration of eq^n (1)

$$\int_\lambda^\infty dI/I = -\sigma n\ dl$$

$$\ln\ (I/I_\infty) = -\sigma\int_l^\infty n\ dl = -\sigma\sec\chi\int_l^\infty n\ dh = -\sigma nH\sec\chi$$

Thus $$I/I_\infty = e^{-\sigma nH\sec\chi} = e^{-\tau} \qquad (4)$$

by definition of the optical depth (T)
Thus $\sigma nH \sec \chi$ is the optical depth and is unity at the level of maximum production. I is reduced to 1/e of its original value at this level. Except as noted the foregoing results hold for any single component atmosphere, irrespective of its height variation.

In an exponential atmosphere $n = n_o \exp(-h/H)$ where H is now constant. The maximum rate of production now occurs (from eq 3) where

$$\sigma n_o \exp\,(h_m/H).H \sec \chi = 1$$

hence

$$h_m = H \ln(\sigma n_o \sec \chi) = \text{constant} + \ln\,(\sec \chi) \qquad 4(a)$$

from eq^n. (3) & (4),

$$I/I_\infty = \exp\,(-n/n_m)$$

Therefore

$$q/q_m = \frac{\eta \sigma n I}{\eta \sigma n_m I_m} = \frac{n}{n_m} * \frac{\exp(-n/n_m)}{\exp(-1)}$$

but

$$n/n_m = \exp\,(-(h-h_m)/H)$$

hence

$$q/q_m = \exp(-(h-h_m)/H).\exp(-e^{-(h-hm)/H}) \,.\, e^{+1}$$

$$= \exp(1-(h-h_m)/H - \exp(-(h-h_m)/H))$$

$$= \exp\,(1-Y-e^{-Y}) \qquad (5)$$

where $Y = (h-h_m)/H$ and is the reduced height referred to the height of maximum production. eq^n. 5 is the Chapman production function.

The expression can be also be derived in terms of the maximum rate of production when the Sun is overhead (q_{mo}), the height of maximum then being h_{mo} :

$$q/q_{mo} = \exp\,(1-z-\sec\chi\ e^{-z})$$

Where

$$z = (h-h_{mo})\ /H$$

The Chapman production function serves as a basis of reference for ionospheric behavior, and several points about it are worthy of special note.

(a) The result, $q = q_{mo}\ \exp(1-z-\sec\chi\ e^{-z})$, where z is the reduced height ($z = (h-h_{mo})\ /H$) and X is the zenith angle of the Sun. q_{mo} is the production rate at the maximum if h_{mo} is the height of the maximum, when the Sun is overhead.

(b) The shape of the curve is shown in fig.(1.2). At great altitude, z is large and positive and

$$q \rightarrow q_o e^{-z}$$

independent of the zenith angle. At altitudes well below the maximum, z is large and negative.

$$q \rightarrow q_o\ \exp\,(-\ \sec\chi\ e^{-z}\ )$$

with a rapid cut-off. Physically, the production rate is limited by a lack of ionizable molecules at high altitude and a lack of ionizing radiation at low altitude. When plotted as $\log(q/q_o)$ against z, all curves have the same shape and move upwards and to the left as χ increases. See fig. 1.2.

(c) Maximum production rate occurs when the optical depth is unity.

(d) From eq^n.4(a) $h_m = H\ \ln(\sigma n_o H \sec\chi) = \text{constant} + \ln\,(\sec\chi)$ it

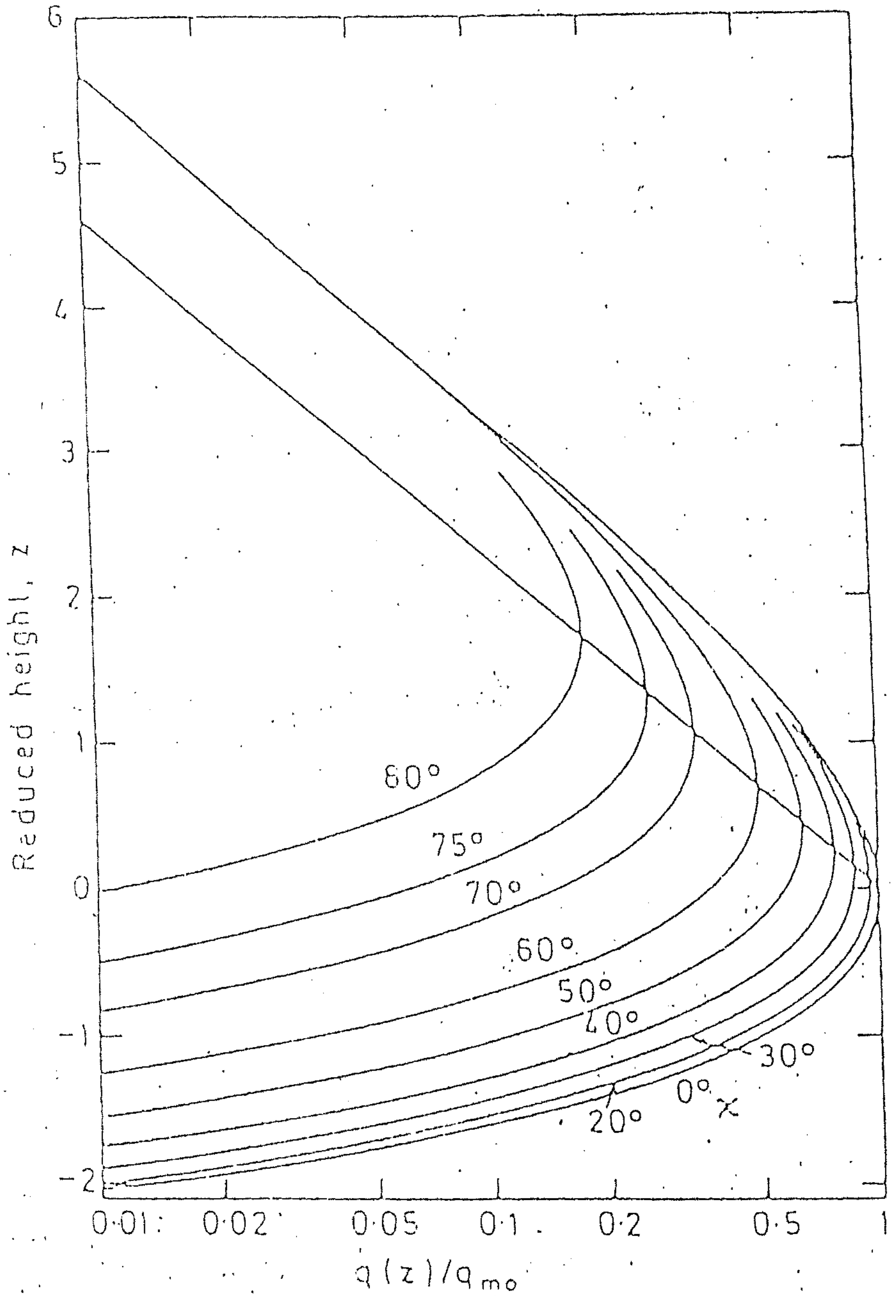

Fig: 1·2 Chapman production function.

is readily shown that

$$z_m = \ln \sec \chi$$

where z_m is the reduced height of the maximum, reckoned from the maximum with overhead Sun.

(e) From this and equation $q/q_{mo} = \exp(1-z-\sec\chi\, e^{-z})$

$$q_m = q_{mo} \cos \chi$$

provide useful tests of whether or not an observed ionospheric layers obeys the Chapman law.

The continuity equation gives the rate of change of electron density (N) at a given place.

Rate of increase = Rate of production - recombination rate
- loss by movements.

$$dN/dt = q - L - \mathrm{div}\,(Nv) \qquad (6)$$

where v is mean drift velocity of the electrons. Equilibrium is reached when the production and loss processes balance, and when $dN/dt = 0$.

1.2 STRUCTURE OF IONOSPHERE :

The ionosphere may be defined as the part of the earth's upper atmosphere where ions and electrons are present in quantities sufficient to affect the propagation of radio waves. It extends down to perhaps 50 km and thus overlaps the ozonosphere; the symbols D, E, F1 & F2 are used to distinguish it's various parts. It has no well-defined upper boundary but merges into the protonosphere, which is composed principally of ionized hydrogen. Up to about 100 km, the atmosphere is well mixed by turbulence. The relative abundance of major constituents, such as ozone, are subject to variation, as are constituents such as water vapor and contaminants in the troposphere. In the lower thermosphere, the composition can be modified by photochemical reactions, such as dissociation of molecular gases.

The level at which turbulence ceases may be called the turbopause; it is rather sharply defined and lies at about 100 km. At greater heights the lack of turbulence enables a condition of diffusive separation to be established, in which the vertical distribution of each neutral gas depends on it´s molecular weight. The distribution of chemically active gases, however, may be influenced to some extent by diffusion. This is especially true of the ionization which attains a diffusion controlled distribution only at heights well above the F2 peak, at 400 km or so.

Finally there is the magnetosphere, the region in which the earth´s magnetic field controls the dynamics of the atmosphere. It is difficult to define a lower limit, since the movements of ionization is geomagnetically controlled at all heights above about 150 km, but the magnetosphere certainly includes the whole atmosphere above the level at which ionized constituents become predominant over neutral constituents probably at about 1500 km. Because of this magnetic control the earth´s atmosphere may be said to terminate at the magnetopause, the boundary of geomagnetic field which lies at about 10 earth radii on the day side of the earth and at a greater distance on the night side.
Typically ionospheric vertical structures are illustrated in fig. 1.3.

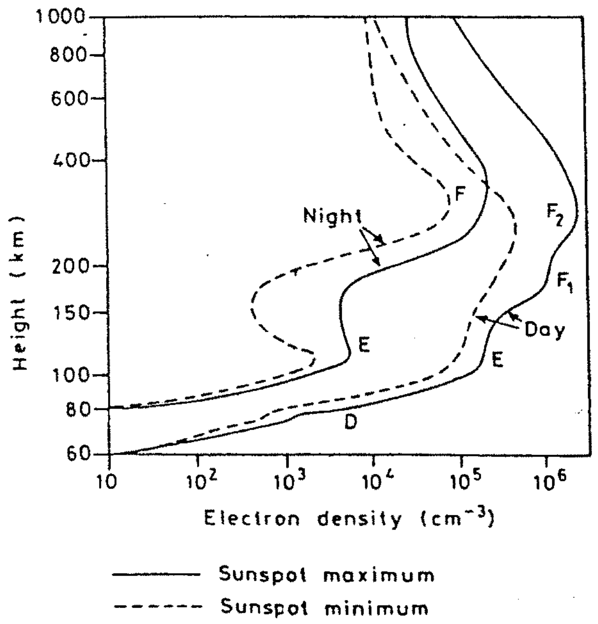

Figure 13 Typical vertical profiles of the mid-latitude ionosphere. (From wallchart *Aerospace Environment*, W. Swider, Air Force Geophysics Laboratory, Hanscom Air Force Base, Massachusetts.)

The various layers were originally identified from ionograms which tend to emphasize the inflections of the profile. In fact the layers are not necessarily separated by minima. The main region can be summarized thus

D region : 60km -- 90 km, N 10^2 - 10 ^{4} cm^{-3} by day
E region :105km --160 km, N several x 10^5 cm^{-3} by day
F region : above 180 km N up to several X 10^6 cm^{-3} at peak of day, factors of 10 smaller by night, height maximum ~ 300km but variable.

The layer variation and calculations of electron density is based on the equation derived between the critical frequency and electron density as given below in section 1.3.

1.3 RELATION OF CRITICAL FREQUENCY TO ELECTRON DENSITY:

Ionosphere consists of a weakly ionized plasma. An important characteristic of plasma is its characteristic eigen freqequency.

(f_N) for electrostatic waves in the plasma and is given by

$$2\pi(f_N) = (4\pi e^2 N/m)^{1/2} \qquad (1.5)$$

where e = electron charge, m = electron mass and N= electron density. As the electrons have very small mass,they quickly respond to the disturbances and the plasma frequency (f_N) is usually given in terms of the electron component, therefore for (f_N) in KHz and N in cm^{-3} eq^n. (1.5). reduces to

$$(f_N) = (e^2 N/\pi m)^{1/2} \simeq (81N)^{1/2} \qquad (1.6)$$

The above equations are very much important by which the electron density calculations are made in ionospheric studies using radio waves.

1.4 APPLETON-HARTEE FORMULA OF REFRACTIVE INDEX :

The propagation of electromagnetic waves in an ionized medium is treated by magneto-ionic theory. This was developed during the first part of the present century, following Marconi´s experiments in long-distance radio propagation and Kennelly and Heaviside´s suggestions in 1902 that the waves were reflected from an electrified layer in the upper atmosphere. Contributions were made by several theorists, including Eccles who treated the layer as a metallic reflector in 1912, an Larmor who treated it as a dielectric in 1924. The dielectric approach is in fact the appropriate one for most radio frequencies; the absorption is relatively small inside the medium, and the wave is returned to the ground by gradual refraction. In the form now used the theory is mainly due to the work of E.V.Appleton between 1927 and 1932.

The formula for the refractive index of an ionized medium is generally known as the Appleton equation or the Appleton-Hartree equation :

$$n^2 = 1 - \frac{X}{1-jZ-(Y_T{}^2/2(1-X-jZ)) \pm ((Y_T{}^4/4(1-X-jZ)^2)+Y_L{}^2)^{1/2}}$$

where n is complex in the general case, n=u-jX. X,Y,Z are dimensionless quantities as follows :

$X = \omega^2{}_N/\omega^2 \quad Y = \omega_B/\omega \quad Y_L = \omega_L/\omega \quad Y_T = \omega_T/\omega \quad Z = \nu/\omega$

in which $_N$ is the angular plasma frequency, ω_B is the electron gyrofrequency, and ω_L and ω_T are respectively the longitudinal and transverse components of ω_B with respect to the direction of propagation. That is, if θ is the angle between the propagation direction and the geomagnetic field,

$$\omega_L = \omega_B \cos\theta$$

and

$$\omega_T = \omega_B \sin\theta$$

ν is the electron collision frequency and ω is the angular wave frequency.

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