INTERNATIONAL ATOMIC ENERGY AGENCY
UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION

INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
34100 TRIESTE (ITALY) - P.O.B. 586 - MIRAMARE - STRADA COSTIERA 11 - TELEPHONE: 2240-1
CABLE: CENTRATOM - TELEX 460392-1

H4.SMR.203 - 17

" SPRING COLLEGE ON GEOMAGNETISM AND AERONOMY "

(2 - 27 March 1987)

" Ionospheric absorption "

presented by :

S.M. RADICELLA
PRONARP
Julian Alvarez 1218
1414 Buenos Aires
Argentina

These are preliminary lecture notes, intended for distribution to participants only.

I O N O S P H E R I C   A B S O R P T I O N

Sandro M. Radicella
Programa Nacional de Radiopropagación (PRONARP)
Argentina

1. BASIC THEORY OF THE IONOSPHERIC ABSORPTION OF RADIO WAVES

When an electromagnetic wave propagates through a plasma is refracted and generally is also attenuated by forced oscillations of the electrons due to the alternating field of the wave. These effects are frequency dependent and the amplitude of the forced oscillations is greater at lower frequencies. The energy transfer over a given path lenght is also proportional to the electron concentration. Most of the energy passed to the electrons is restored to the wave by secondary emission. Each electron reradiate on the same frequency as the propagating wave, but the fields are shifted in phase relative to the original field. This fact leads to a continous phase shift along the propagation path and the phase velocity becomes different from that of the free space.

This transfer of energy from the wave to the electrons and back is lossless if the electrons suffer no collisions. When electrons collide with other particles, the energy balance is altered and the process leads to the loss of energy from the original propagating wave. Collisions, that are mostly elastic, can take place with neutral particles or with ions and the energy is lost finally heating the medium.

The process described is responsable for what is called absorption of radio waves in the ionosphere. In principle the absorption can be calculated when the height distribution of electrons and collision frecuency are know. Starting from the classical Maxwell equations, Happleton (1928) and Hartree (1929) introduced equations to describe the propagation of radio waves in the presence of the geomagnetic field and collisions. In the so called Happleton-Hartree theory the collision frequency is assumed independent of the

electron velocity. However, Phelps and Pack (1959) found that the frictional force actually depends upon the velocity of the electrons colliding with N_2 particles, the dominant neutral gas in the lower region of the ionosphere where collisions are important. Using these results, Sen and Wyller (1960) introduced a generalization of the Appleton-Hartree scheme. Their theory is mostly used for conditions of strong absorption. Using a proper definition of the collision frequency the Appleton-Hartree theory is recovered when the collision frequency is less than one tenth of the propagating wave frequency. Rawer (1976) treated in details the notion of collision frequency and introduced the concept of "mean transport collision frequency" which takes account of the collision efficiency in terms of angles of deflection. This frequency is the one that should be used in the practical applications of Appleton-Hartree theory.

In this theory the complex refractive index n is given by:

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

where the positive and negative signs refer to the ordinary and extraordinary waves originated in the ionosphere when a wave propagates in the presence of the geomagnetic field. The effect of absorption is described by the imaginary component of the complex equation (1). The various terms are defined as follows:

$X = \frac{f_N^2}{f^2}$

f_N = plasma frequency

f = wave frequency

$Y_T = Y \sin \theta$

θ = angle between magnetic field and direction of wave propagation

$Y = \frac{f_H}{f}$

$Y_L = Y \cos \theta$

f_H = gyrofrequency of electrons about the geomagnetic field

$Z = \frac{\nu}{f}$

ν = effective collision frequency.

This collision frequency ν should be interpreted, following Rawer (1976), as a "mean transport collision frequency". In equation (1), the real part μ defines the angular refraction and χ is the absorption index. This can be expressed by:

$$\chi = \frac{c}{2\pi f} \cdot K$$

where c is the velocity of light in free space and K is called "absorption coefficient" and gives the absorption per unit distance.

Equation (1) can be salved in terms of χ and used to study the variations of K. This approach is the basic one for the ray tracing numerical procedures used for the calculation of ionospheric absorption.

Looking back to equation (1) it can be seen that the absorption coefficient for the ordinary and extraordinary components differs substantially. This is shown in Fig. 1, where K and μK appear as a function of X for different values of f and ν. The lower part of the figure shows that μK is proportional to ν. From these results Rawer (1976) introduces approximations that allow the practical use in absorption studies. One of these is given by:

$$\mu^2 = \frac{f^2 - f_N^2 \pm f.[f_L]}{(f \pm [f_L])^2} \tag{3}$$

$$K = 1.344.10^{-7}\ m^{-1}\ \frac{1}{\mu}\ \frac{(\nu/s^{-1}).(N/m^{-3})}{((f \pm [f_L])\ Hz)^2} \tag{4}$$

where f_N and f are respectively the plasma frequency and the frequency of the propagating wave and f_L is the projection of the gyrofrequency vector (parallel to the magnetic field) on the direction of the wave normal:

$$f_L = f_B \cos\theta;$$

at the equator is $f_L = 0$.

A detailed discussion of different approximations that can be used in absorption studies can be found in Rawer (1976).

Equation (4) shows that K is proportional to the product ν.N. Along an ionospheric propagation path these parameters can change by orders of magnitude as does the value of K. The total absorption must therefore be written as an integral expression:

$$\int K ds = -\ln \frac{E}{E^*} \tag{5}$$

where s is the path lenght, E is the field strenght at the receiver and E* is the field which would have been observed if the medium did not absorb.

By international convention the absorption loss along an ionospheric path should be designated by A and measured in dB.

$$A\ [dB] = 20 \log_{10} \left(\frac{E}{E^*}\right) = 8.686 \int K ds$$

The factor $1/\mu$ in equation (4) is such that the portion of the wave path that influences more the coefficient K is the one with larger values of electron concentration. Moreover if the wave is reflected at a certain height the contribution of K in the vicinity of that point is greatly increased because μ becames small and the bending of the path is important. This type of absorption is called "deviative". The increase of the absorption is particularly noticeable when reflection accurs near the maximum of a layer like the E region peak electron density.

If $f^2 \gg f_N^2$ in equation (3), then $\frac{1}{\mu}$ can be assumed as 1 in equation (4) and it reduces to the so called "non-deviative" absorption approximation. This situation occurs in the D region and for very high frequencies also in the E region. Fig. 2 taken from Rawer (1976) shows a typical daytime case of absorption. The top subfigure shows model height distribution of N and ν and the bottom one the contribution of different heights to the absorption integral. Note that a wave of low frequency is considered in the model calculations.

Before going into a brief description of ionospheric absorption measurements it is useful to mention the factors that influences the measurements, giving misleading information on the actual absorption if they are not taken into account.

Distance attenuation of energy is the most important influence originated by the geometry of propagation that is not real loss.

Another important factor is reflection. It may occur at the interface of two different media or inside a continously varying medium. Reflection losses can be due to reflections from the ground and in the ionosphere. These may be partial or total. Partial reflections are normally small and they occur where steep gradients of electron density or collision frequency occur mainly in the lower ionosphere. Total reflection becames important under specific conditions at oblique incidence.

Other factors influencing absorption measurements are diffraction and scattering on patches or holes of ionization in the ionosphere where the wave is propagating.

2. ABSORPTION CALCULATIONS FOR GIVEN DISTRIBUTIONS OF ELECTRON DENSITY AND COLLISION FREQUENCY

The Appleton-Hartree and Sen-Wyllen theory allow to calculate ray path and ionospheric absorption when the height distribution of electron density and collision frequency is known. A convenient numerical procedures for vertical incidence propagation, based on the so called phase integral approach, has been developed by Altman (1965). This approach avoid the limitation introduced by the fact that at vertical incidence the Appleton-Hartree theory gives infinite absorption at the level of wave reflection, when $\mu \longrightarrow 0$. The phase-integral formulation leads to the following expression for the absorption in decibels:

$$L(f) = 8.69 \left(\frac{4\pi f}{c}\right) \text{Imag} \left(\int_0^{z_0} n dz\right) \qquad (6)$$

The variable z is a complex "height" and the integration is done in the complex space from z=0 (the ground) to $z=z_0$, the complex "height" at which the complex phase-refractive index n becomes zero.

George and Bradley (1973) have published results obtained usirg the solution of equation (6). Their calculations are useful to check some of the statements given in the previous section.

Fig. 3 shows three height distributions of the electron censity assumed by George and Bradley (1973) in the D and E regions. These are taken as representative profiles for daytime low and middle latitudes. From the E region peak to the F region base electron density is considered constant. The factor $N\nu$, to which the non deviative absorption is considered proportional, is shown for the three cases in Fig. 4 as a function of height. This figure reveals that the main contribution to the absorption cames from the height region between 80 and 100 Km and that the contribution of higher heights is comparatively small, making of less importance the accuracy of the electron density model assumed for those levels in the calculations. Fig. 5 shows the absorption factor A(f) given by:

$$A(f) = L(f)\,(f - f_L)^2 \qquad (7)$$

and computed solving equation (6) for vertical incidence and variable frequency in the model electron distributions of Fig. 3. In particular, the presence

of important deviative absorption is shown for frequencies close to the critical frequency foE of the E region, this last marked with dashed lines in the figure, by the high values of A(f). For frequencies higher than foE the absorption factor tends to a constant.

For oblique incidence propagation ray path calculations became necessary. These can be made solving iteratively a set of six differential equations derived from the Hamiltonian formalism. These equations give the ray direction changes and the wave-normal direction changes and the wave-normal directions in an anisotropic medium in terms of the associated refractive indices. A ray tracing computer program based on those equations has been developed by Jones (1966). This is a very versitile tool for absorption calculations and studies.

3. ABSORPTION MEASUREMENTS

Ionospheric absorption measurements are made using different techniques. In the following paragraphs a brief description of these techniques will be given stressing their main advantages and limitations.

3.1 Vertical Incidence Pulse Reflection Technique (A1)

The A1 technique is based on the emission of pulsed signals at an appropiate frequency from a vertically directed antenna and the reception at the same location of echoes after reflection in the ionosphere. The monitored parameter is the amplitude of the reflected signals.

The frequency is selected such that it is not close to the critical frequency of an ionospheric layer, in order to avoid deviative absorption. In most cases the frequency chosen is reflected from E region heights.

Transmitter power need to be monitored carefully during the measurement time and maintained constant or properly corrected. The receiver should have linear response and adecuate dynamic range.

The technique needs a correct identification of the propagation mode. Normally it is a single-hop E or F mode. It must be taken into account that echoes from Es layers, which can be recognized only with the help of ionosondes placed at the same location, often are associated with partial reflections.

The received signal strenght can change or fade due to causes other than the real absorption variations. These are:

i. Interference between modes.

ii. Changes in path lenght and wave polarization due to increase or movement of ionization.

iii. Diffraction focusing and defocusing due to irregularities in the electron concentration along the propagation paths.

To avoid these variations not caused by absorption it is critical the choise of adecuate probing frequency and antenna system, and time averaging of the measurements. This time is of the order of 15 minutes. These problems are treated in details by Rawer (1976).

The A1 technique has been widely used to monitor dayly noon values of ionospheric absorption at frequencies ranging from 2 to 6 MHz. It has also been used to a lesser extent to study diurnal variations of the parameter.

This technique is useful at low to middle latitudes but is less adecuate for high latitudes where the critical frequency of the E layer is too low and absorption quite high.

3.2 Riometer Technique (A2)

An important advance in absorption measurements at high latitudes was the introduction of the technique first used by Mitra and Shain (1953). In this technique extraterrestrial radio noise at frequencies normally close to 30 MHz are continously monitored. Absorption is determined by comparing received intensities with those at the same sidereal time on occasions when the absorption is assumed negligible. The term "riometer" used to name this technique is an acronym for "Relative Ionospheric Opacity METER" (Little and Leinbach, 1959). The basic hardware is a highly sensitive and stable receiver with built in calibration facilities.

Being the advantage of this technique the possibility of its use in high latitudes in a continous way, the main limitations of riometers are:

i. The reference noise level for the assumed unabsorbed conditions are difficult to determine. This fact makes more reliable the estimate of changes of absorption than absolute values.

ii. The measure is sensitive not only to the absorption occuring in the D and E regions, but also to the one produced in the F region.

iii. The screening of the incident noise by the F region, leading to the so called "window effect".

iv. The measurement sensitivity to enhancements of solar radio noise.

v. The measurement sensitivity to the size of the ionization patches produced by the precipitation of particles when these cover only sectors of the antenna collecting area.

All these limitations created a wide international debate on the significance of riometer measurements in relation to other types of absorption measurements (Agy, 1979). Reviews on the riometer technique are given by Mitra (1970) and Taubenheim et al (1976). Measurement error sources and the comparison with other techniques have been analyzed by Foppiano (1976). In particular it has been noted that the F region contribution and the obliquity of incident cosmic radio noise lead to riometer absorption values higher than those obtained with the vertical pulse technique (A1). On the other hand the finite size of ionization patches and the uncertainties introduced by the reference value assumed without absorption tends to give lower values. Foppiano (1976) found that as a first order approximation, A1 and A2 techniques yield similar values when the riometer antenna is oriented toward the sidereal pole rather than the zenith.

It must be noted that the A2 technique is particularly suitable for the study of Sudden Ionospheric Disturbances produced by solar flares.

3.3 Oblique Incidence Field Trenght Measurements Technique (A3)

This technique described in details by Schwentek (1976) uses high or medium low frequencies to estimate the variation with time of the field strenght of signals reflected from approximately the same height in the ionosphere at oblique incidence.

For high frequencies, the antenna system can be designed in such a way to minimize the effect of small changes of the height of reflection providing it always occurs in the same layer. From field strenght measurements, the total absorption given by equation (5) can be obtained.

It must be taken into account that in all cases a careful choise of propagation conditions must be made in order to obtain information that can be converted into useful absorption data. For this reason is desirable that the frequency chosen be such that reflections occur in the E region throughout the day. The changes in reflection height that take place when the working frequency varies with reference to the E region critical frequency must be considered when analyzing the diurnal and annual variations of absorption obtained with this technique.

The working frequency is usually in the range 2-3 MHz for E region reflections and 5-6 MHz for F region reflections.

The transmission distance is of the order of 200-400 Km, and it must be chosen so to avoid contamination from ground wave and to ensure that signals are received always from directions that do not present substantial changes of antenna gain.

The technique needs calibrations by total reflections on sharp bounded layers like Es at night. Calibrations should take place from time to time under similar conditions.

The necessary operating conditions include stable transmitter and receiver and appropiate recording unit.

The main advantages of this technique are:

i. The low cost of the instrumentation involved.

ii. The relatively simple derivation of absorption from the measured parameter, under well chosen probing conditions.

A less used technique based on the same principle is the medium-low frequency oblique incidence field strenght measurement. In the lower range of the frequencies used in this case the evaluation method is more complicated. This range of frequencies are used mainly in central Europe. A full description of the technique is given by Lauter (1976).

The A3 technique provides a good way to obtain a continuos monitoring of the total absorption in order to investigate time variations of the parameters at fixed locations. Diurnal, seasonal and solar cycle variations of the absorption can be easily studied with this technique. It can be also used to analyze the effect of solar-geophysical disturbances on the lower ionosphere.

3.4 Other Techniques of Absorption Measurements

Techniques to measure ionospheric absorption, other than the A1, A2, and A3 ones, will be just breafly mentioned in the next few paragraphs. They include the use of the lowest frequency fmin at which echoes appear in the vertical incidence ionograms, partial reflection measurements and satellite borne HF transmission received at the ground.

The first one takes into account the fact that when all the other factors are mantained constant, changes in fmin can be related to absorption variations. Such situation is particularly useful at high latitudes where the expected changes in absorption are large enough to be seen by fmin variations. However, these observations are in all cases essentially cualitative in nature, due to the variable performance of the measuring device both in time and from one equipment to another.

The partial reflection theory and measurement technique has been reviewed by Dieminger and Schlegel (1976). When high power vertical signals

are transmitted toward the ionosphere, echoes are detected with appropiate receivers from partial reflections at heights down to 60 Km. Received amplitude data can be converted into electron concentration values at the height of reflection using the adecuate theory. If differential phase is measured between the upgoing and downcoming waves for both magnetoionic components, the theory allows to determine also the values of electron collision frequency.

The measurement of ionospheric absorption of radio waves transmitted from a satellite could be considered a promising technique. However it presents serious problems related to the uncertainties regarding the characteristics of the wave transmitted from the satellite.

4. ABSORPTION MORPHOLOGY

4.1 Diurnal Variations

Fig. 6 displays a tipical example of absorption measurements at a fixed frequency using the A1 technique that show the diurnal behaviour of the parameters in local summer and winter, for a location in Europe. The figure also gives a good example of day to day variability at each hour.

The diurnal variation of the median values of absorption in decibels can be represented by:

$$L = Lo \cos^n \chi \qquad (8)$$

where χ is the solar zenith angle.

The constant n present also a latitudinal variation that can be seen in Table 1 obtained using data published by Shapley et al. (1974). From the values of n it can be observed that the sensitivity of L to the solar zenith angle is larger at low latitudes and reduced at high latitudes.

4.2 Seasonal Variations

Fig. 7, from Gnanalingham shows the seasonal variation of noon absorption obtained with the A1 technique at Colombo, an equatorial location. The figure present evidences of clear equinoxial maxima and summer values similar to the winter ones. Those maxima can be reproduced at the equatorial station by the seasonal excursion of cos χ through a relation of the type:

$$L = Lo \cos^m \chi \qquad (9)$$

However, summer values appears to be always lower than expected from the given relation.

Fig. 8, from Schwentek (1976) shows the noon absorption obtained with A3 technique in middle latitude Europe throughout a solar cycle. Each dot is a monthly median value and the continous line is the best-fit curve with m=0.75. The most evident feature is the very high values of absorption during winter. This characteristic of the seasonal variation of the ionospheric absorption can be better studied when median absorption values at a fixed solar zenith angle χ are scaled as a function of month of the year.

Fig. 9 shows the seasonal variation at fixed χ, average AM-PM, for two locations with different latitudes in the northern hemisphere (data source: Shapley et al., 1974). The winter increase of absorption is more important at the geomagnetic latitude of 52º than at 25º.

Schwentek et al. (1980) found that there is a real asymmetry in the seasonal variatiation of the absorption in the northern and southern hemisphere as it can be seen in Fig.10. The authors remark the fact that a normal winter anomaly appears with high absorption, being more pronounced at Ushuaia in the south than at Lindau in the north. The winter "excess absorption" is, however, smaller at the southern location. They attribute the first result to the differences in geomagnetic conditions and the excess winter absorption to differences in the meteorological processes occurring in the two hemisphere. The authors conclude that it is convenient not to combine northern and southern data of absorption to describe the phenomenon at middle latitudes.

The same Fig. 10 can be used to show that at the northern location the winter excess ionospheric absorption do not occur uniformly over all days but is confined to consecutive groups of days of increased absorption. However this behaviour is not as clear at the southern location of Ushuaia where high absorption is observed more often at isolated days in winter.

The "winter excess absorption" has been studied extensively during recent years and it is now clear that it is due to an increase of electron concentration and NO^+ ion density. Under such conditions the level where the water cluster ions density in the mesosphere equal the molecular ions (NO^+ and O_2^+) densities is typically 5 Km below normal (Brasseur and Solomon, 1984).

Both experimental evidences (Offerman, 1979) and model calculations (Koshelev, 1979 and Solomon et al., 1982) show that the origin of the winter anomaly probably can be found in the sporadic injection of large amounts of nitric oxide from the thermosphere to the mesosphere in association with changes of atmospheric dynamics.

Solomon et al. (1982) and other authors have shown that D-region models that include chemistry and dynamics can reproduce the observed large electron densities in winter, in comparison with summer, even under normal conditions due to greater NO densities in winter. This is a reasonable explanation for the so called "normal winter anomaly" mentioned above.

No cuantitative explanation appears to be found yet for the "anomalous" low values of absorption in equatorial regions and for the observed north-south asymmetries.

4.3 Solar Cycle Variations

The solar cycle influence on the behaviour of ionospheric absorption is fairly well represented by a relation of the type:

$$L = Lo\ (1 + bR) \qquad (10)$$

where Lo and b are constants and R is the smoothed sunspot number. The constant b is of the order of 0.002-0.005, indicating the degree of influence of the solar activity on absorption. It must be taken into account that only a limited ammount of data are available in order to determine this variation.

4.4 Geographical Variations

It is important to note that most of the available ionospheric absorption data are from the northern hemisphere. With these data George (1971) went on to make a detailed study of the latitudinal variations using different latitude parameters. He found that the least scatter of points was obtained when the "modified dip angle X " was used. This is defined by:

$$X = \text{arc tn}\left(\frac{I}{\sqrt{\cos \lambda}}\right) \qquad (11)$$

where I is the magnetic dip in radians and λ the geographic latitude.

The value of absorption adopted by George in his analysis is AT, given by:

$$A_T = \frac{A(f)}{\left(\frac{\Phi_n}{foE}\right)} \qquad (12)$$

where A(f) is the absorption at the probing frequency f and Φ is a function of foE. Fig. 11 present the function Φ_n, and associated limits, that reminds

Fig. 4 obtained theoretically. Fig. 12 shows the variation of the absorption parameter A_T as a function of latitude and season, for overhead sun and high sunspot number. From this figure the following features can be enphasized:

i. Reduced absorption at the magnetic equator.

ii. A smooth maximum for X = 20-30°.

iii. Very pronounced winter peak of absorption in a latitude band of approximately 20° at middle latitudes, that brings in evidence the "winter anomaly".

To explain cuantitatively these results became necessary to introduce in the absorption calculations electron density models that take into account the complex relationship between chemistry and dynamics in the mesosphere.

4.5 Aperiodic and Irregular Variations of Absorption

We have been dealing in the previous sections with variations periodic in time and regular in the geographical space. We will mention briefly in the following paragraphs four types of absorption variations of irregular nature:

i. short wave fadeout

ii. polar-cap absorption

iii. auroral absorption

iv. after storm effects.

The first ones,called "SWF", are associated with solar flares and occurs as result of enhanced ionization in the daytime D region produced by increased fluxes of solar X rays during the flare. They last from few minutes up to several hours. Fig. 13 a) shows an idealized representation of this phenomenon. SWF are more severe at the subsolar point but can be seen in all the sunlit hemisphere.

Polar-cap absorption (PCA) and auroral absorption are features of the high latitudes region. The first one is produced by additional ionization in the polar D region due to solar protons emitted during some types of solar flares that enter the ionosphere above their geomagnetic cut-off latitudes. The flux of solar protons that produce PCA vary smoothly with time and can last from few hours to several days. Fig. 13 b) shows the diurnal modulation produced by the nighttime recombination effect in the enhanced ionization region.

Auroral absorption is probably due to the increased ionization in the D and E regions at polar latitudes produced by precipitated electrons. This type of absorption occurs as a series of discrete absorption enhancements

of short duration, from minutes to a few hours, and irregular structure in time as is seen in Fig. 13 c) and d).

From the HF communication point of view PCA are of less frequency and rare during low solar activity but auroral absorption if less intense occurs very often and affect the circuit quality for an appreciable period of time at high latitudes.

Another type of large increase of absorption is observed following major magnetic storms. These "storm after effects" last in cases for several days. Fig. 14 obtained from Perés (private communication) shows this feature at two locations in the southern hemisphere using A1 (Ushuaia) and A2 (Kerguelen) techniques. The geomagnetic storm started on April 1, 1976. The two locations at different L values present in one case (Kerguelen) storm primary effects and secondary storm after effects, but in the other one (Ushuaia) a clear storm after effect starting several days following the start of the geomagnetic disturbance.

This storm after effect appears to be related to enhanced ionization by precipitated electrons from the radiation belt into sub auroral to middle latitudes.

5. ABSORPTION MEASUREMENTS AND THE INTERNATIONAL REFERENCE IONOSPHERE

It is known that the International Reference Ionosphere (IRI) needs improvements, in particular for the D region electron concentration profile and time variations. The main source of data used to define these characteristics have been rocket measurements and it is well known the limited ammount of such measurements available, more so at night and in the southern hemisphere.

Ionospheric absorption data are in all cases integrated cuantities of the term N.ν mostly in the D and E regions. To try to convert such data into useful information for comparison with other data it is in all cases necessary to know the collision frequency and its seasonal and geographic variations. Taking into account this statement it is possible to use ground based absorption measurements to improve the solar zenith angle, solar activity, seasonal and geographic dependencies of some characteristics electron densities in the lower ionosphere model given by the IRI.

This line of approach has been applied in recent years by Datta et al. (1983), Rawer and Ramanamurty (1984), Singer et al. (1984) and Serafimov et al. (1985). A detailed discussion on the problem of intercomparison of ground based absorption measurements in relation to the IRI model has been given recently by Ramanamurty (1985).

6. PREDICTION OF IONOSPHERIC ABSORPTION

The effect of absorption in the field strenght of MF and HF signals propagating in the ionosphere make necessary to introduce it in radiopropagation predictions. A good deal of contributions on this matter were presented at the Solar-Terrestrial Predictions Workshop held in 1979 at Boulder, USA. Davies (1981) have briefly reviewed these papers colling the attention on the empirical formula used by All India Radio (for tropical areas) and presented by Sehgal and Agrawal in that Workshop. The formula for oblique incidence is:

$$L = \frac{635n\ (1 + 0.0017\ R_{12})\ \sec \Phi}{(f \pm f_L)^2\ ch\ (\alpha, \chi)^{0.77}}\quad [dB] \qquad (13)$$

where:

- n the number of path hops
- R_{12} 12-month running overage sunspot number
- Φ angle of incidence of the wave at the D region
- f the wave frequency in MHz
- f_L the longitudinal gyro frequency in MHz
- ch Chapman function
- $\pm$ refers to the ordinary and extraordinary rays, respectively

7. REFERENCES

- Agy, V. (1979). AGARD Conf. Proc. 263.
- Altman, C. (1965). J. Res. Nat. Bur. Stds., 69D, 511.
- Appleton, E.V. (1928). Proc. Union Radio Sci. Intern. (URSI), 2, 1.
- Brasseur, G. and Solomon, S. (1984). Aeronomy of the Middle Atmosphere (p.367), D. Reidel P.C., Dordrecht.
- Davies, K. (1981). Radio Science, 16, nº 6, 1407.
- Datta G.; Pradhan, S.N. and Kotadia, K.M. (1983). Adv. Space Res. 2, nº 10, 209.
- Dieminger, W. Schlegel, K. (1976). Manual on Ionospheric Absorption Measurements (Rep. UAG-57, WDC-A).
- Foppiano, A. (1976). Prediction of auroral absorption at high and medium frequency waves at oblique incidence. Ph. D. Thesis, University of London, England.
- Gnanalingham, S. (1969). 3rd Int. Symp. Equat. Aeronomy, Ahmedabad. India.
- George, P.L. (1971). J. Atmos. Terr. Phys., 33, 1893.
- George, P.L. and Bradley, P.A. (1973). Proc. IEE, 120, 1355.
- Hartree, D. (1929). Proc. Cambridge Phil. Soc. 25, 97.
- Jones, R.M. (1966). ESSA Tech. Rep. IER 17-ITSA17, US Gov. Print. Office.
- Koshelev, V.V. (1979). J. Atmos. Terr. Phys. 41, 431.
- Lauter, E.A. (1976). Manual on Ionospheric Absorption Measurements (Rep. UAG-57, WDC-A).
- Little, C.G. and Leinbach, M. (1959). Proc. Inst. Radio Eng., 47, 315.
- Mitra, A.P. (1970). J. Atmos. Terr. Phys., 32, 623.
- Mitra, A.P. and Shain, C.A. (1953). J. Atmos. Terr. Phys., 4, 204.
- Offerman, D. (1979). J. Atmos. Terr. Phys., 41, 1047.
- Phelps, A.V. and Pack, J.L. (1959). Phys. Rev. Letters, 3, 340.
- Ramanamurty, Y.V. (1985). Adv. Space Res., 5, nº 10, 79.
- Rawer, K. (1976). Manual on Ionospheric Absorption Measurements (Rep. UAG-57, WDC-A).
- Rawer, K. and Ramanamurty, Y.V. (1984). Adv. Space Res., 4, nº 1, 71.
- Schwentek, H. (1976). Manual on Ionospheric Absorption Measurements (Rep. UAG-57, WDC-A).
- Schwentek, H.; Elling, W. and Perés, M. (1980). J. Atmos. Terr. Phys., 42, 545.
- Sen, H.K. and Wyller, A.A. (1960). J. Geophys. Res. 65, 3931.
- Serafimov, K.B.; Serafimova, M.K.; Ramanamurty, Y.V. and Rawer, K. (1985). Adv. Space Res., 5, nº 10, 99.
- Shapley, A.H.; Piggott, W.R. and Rawer, K. (1974). Rep. UAG-34, WDC-A.
- Singer, W.; Bremer, J. and Taubenheim, J. (1984). Adv. Space Res., 4, nº 1, 79.
- Solomon, S.; Reid, G.C.; Roble, R.G. and Crutzen, P.J. (1982). J. Geophys. Res., 87, 7221.
- Taubenheim, J.; Reid, G.C.; Mitra; A.P. and Ramanathan, K.R. (1976). Manual on Ionospheric Absorption Measurements (Rep. UAG-57, WDC-A).

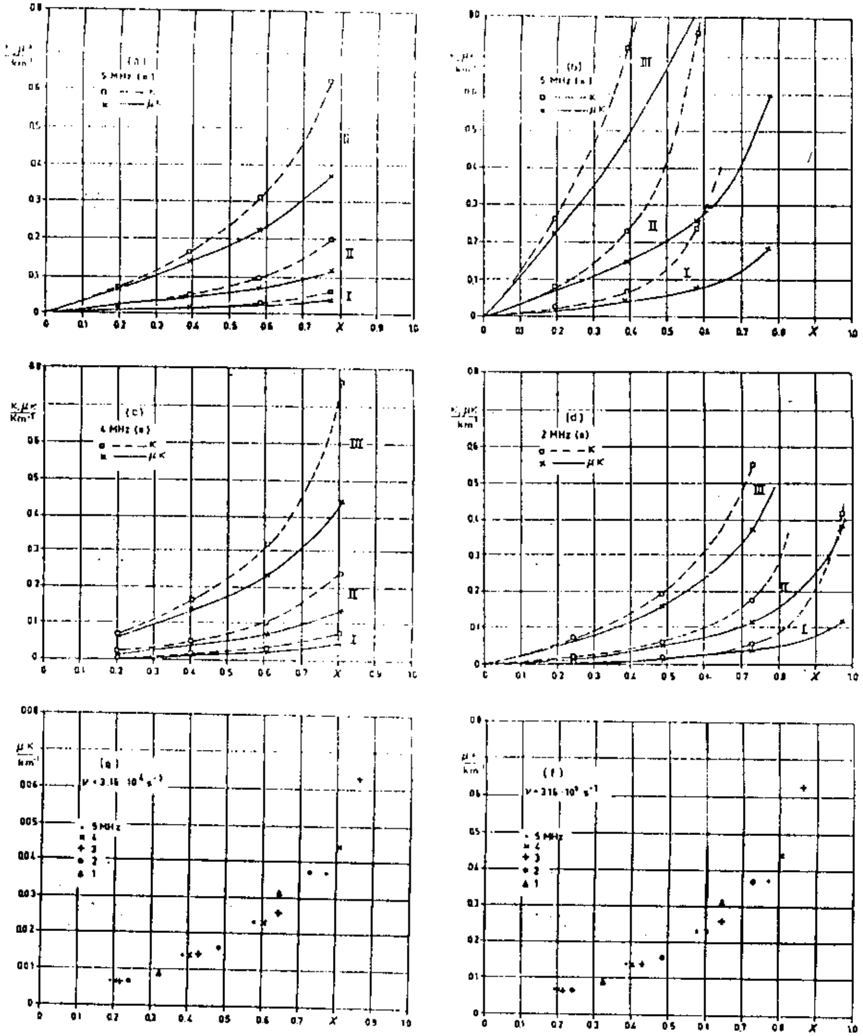
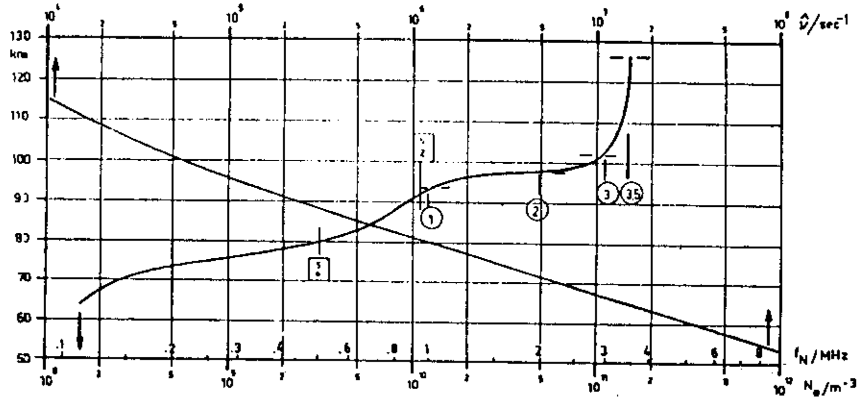


Figure 1 Absorption coefficient κ obtained with the Appleton-Lassen dispersion formula as a function of the reduced electron density $X = f_N^2/f^2$. Magnetic parameters for southern Spain. Indices I, II, III identify collision frequency as $\nu = 3.16 \cdot 10^4$, $1 \cdot 10^5$ and $3.16 \cdot 10^5$ s^{-1} respectively.

(a) and (b) give absorption coefficient κ [illegible] and product μκ (full curve for f = 5 MHz);

(a) ordinary (o) component,
(b) extraordinary (x) component,
(c) same curves for f = 4 MHz, o component,
(d) same curves for f = 2 MHz, o component,
(e) and (f) show product μ·κ just for the ordinary component and $\nu = 3.16 \cdot 10^4$ s^{-1} and $3.16 \cdot 10^5$ s^{-1}, respectively. The symbols identify the frequencies 1,2,3,4 and 5 MHz as indicated. (Wavelength λ = 300, 150, 100, 75 and 60 m, respectively.) Note that 1 MHz is less than the gyrofrequency, the other frequencies are greater. Comparison of Figures (e) and (f) show proportionality with ν but more than proportionality increase with X. Warning: When κ·λ becomes greater than about 0.3, the Appleton-Lassen formula must be replaced by the Sen-Wyller formula, see text and Figure 2.3.



Model N_e and $\hat{\nu}$ from Piggott and Thrane (courtesy W. R. Piggott).

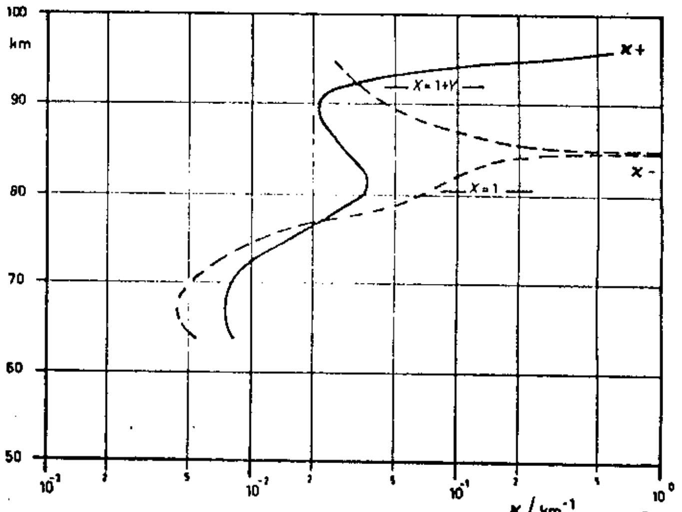


Figure 2 Contributions at different heights (ordinate) to the absorption integral. Model of Figure 2. frequency 512 kHz (for Θ=32°, B=0.52 Gauss, after Mechtly [1959].

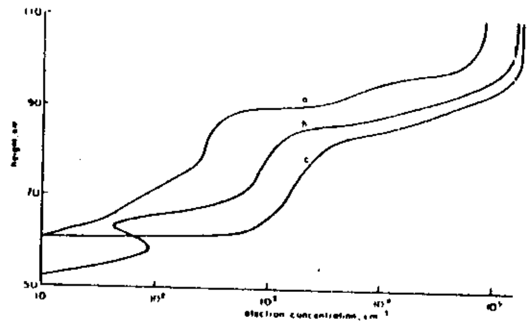
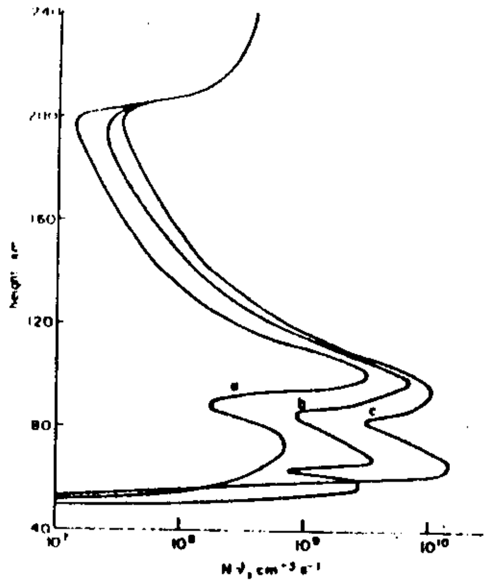


Figure 3 Sample electron concentration-height profiles (from George and Bradley 1973)

(a) low latitude model typical of March equinox with smoothed sunspot number R_Z = 10 and solar-zenith angle $\chi = 60^0$

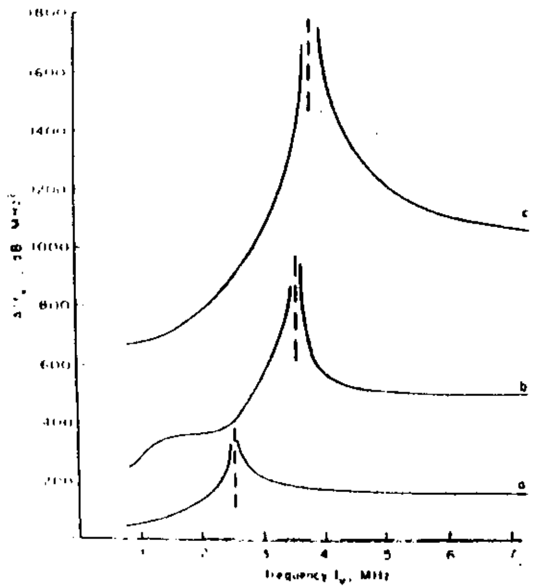
(b) mid-latitude model typical of European region between $50-55^0$ in summer with R_Z = 70 and $\chi = 35^0$

(c) mid-latitude model based on data for Kokubunji (36^0N) in February/March with R_Z = 250 and $\chi = 50^0$



The product of electron concentration and collision frequency, $N\nu$, for the model ionospheres of Fig. 3 (from George and Bradley, 1973)

Figure 4



The absorption factor $A(f_v)$ for vertical-incidence propagation via the model ionospheres of Fig.3 (from George and Bradley, 1973)

Figure 5

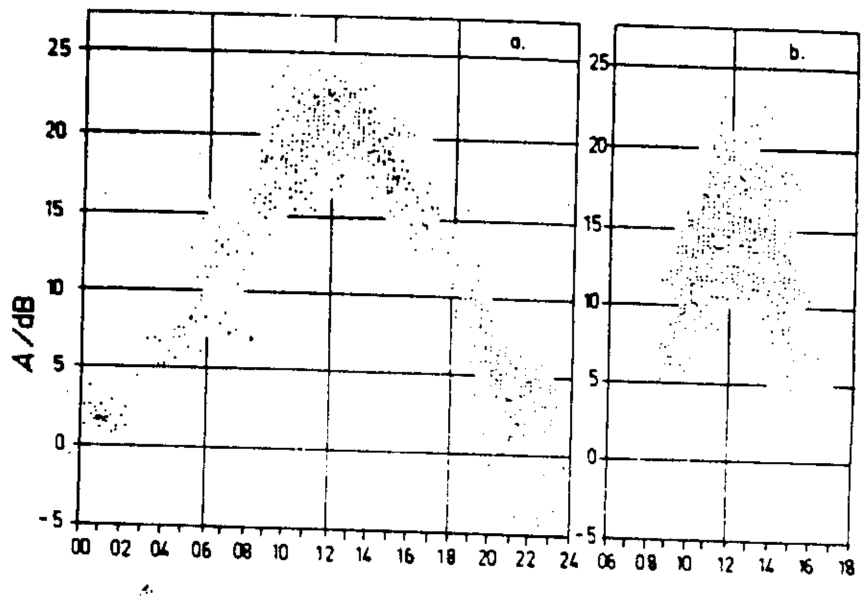
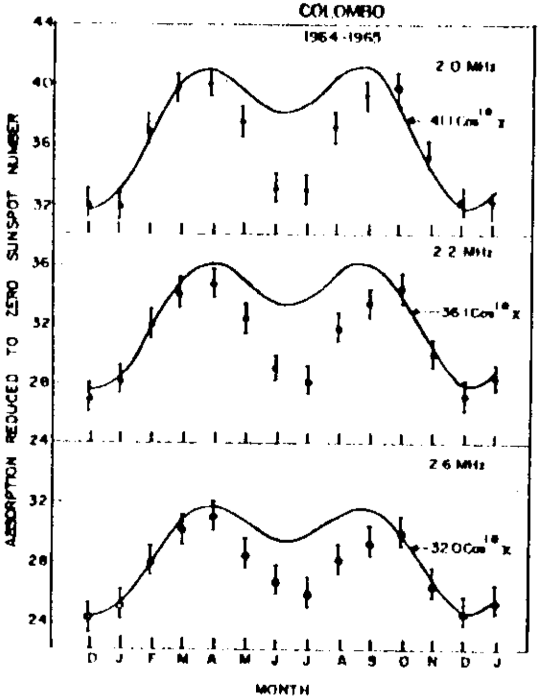


Figure 6 **Daily values of absorption at vertical incidence on 3.86 MHz measured at Juliusruh in (a) June 1964 and (b) December 1965 (from Rawer 1976)**



Seasonal variation of noon absorption at Colombo (from Gnanalingham, 1969)

Figure 7

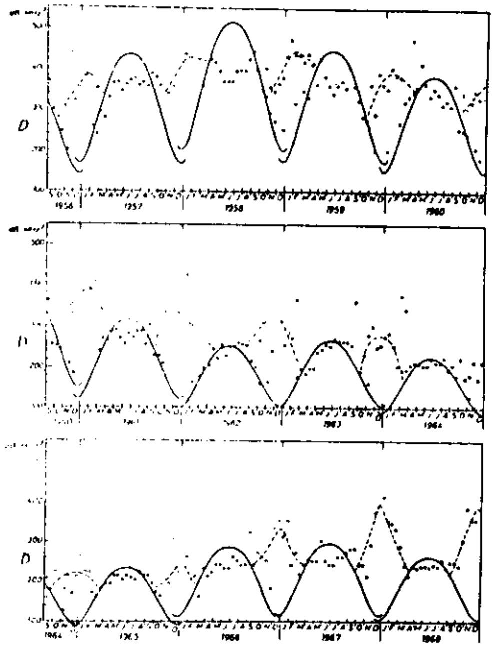


Figure 8 Half-monthly median noon values of absorption from 1956 through 1968, i.e. over more than one sunspot cycle; circuit Norddeich-Lindau. The curves indicate the function $D = D_0 \cos^{0.75}\chi$; D_0 was determined empirically from plots of log D vs. -log cos χ

SEASONAL VARIATION OF THE IONOSPHERIC ABSORPTION AT FIXED SOLAR ZENITH ANGLE

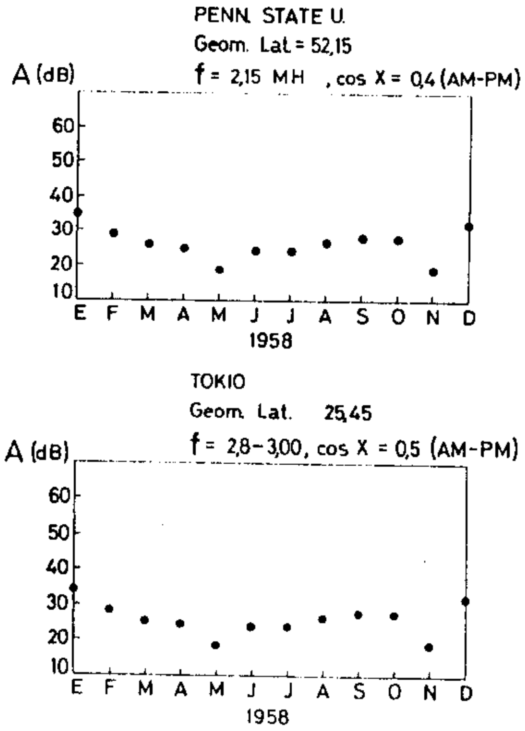


Figure 9

H. Schwentek, W. Elling and M. Peres

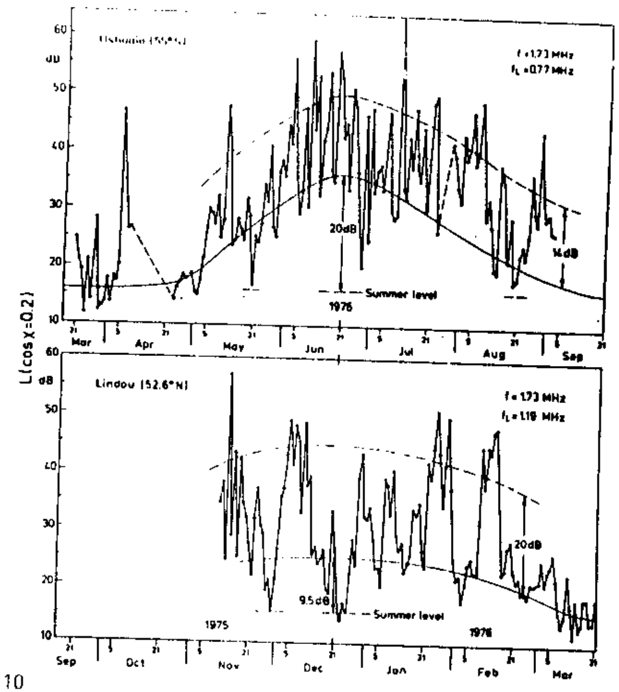


Figure 10

Absorption at a constant solar zenith angle $\chi = 78.5°$, $L(\cos \chi = 0.2)$ as a function of time, for a winter in the southern hemisphere (Ushuaia), and for a winter in the northern hemisphere (Lindau). Method A1; frequency 1.73 MHz. Sunspot minimum was in June 1976. All data were obtained from measurements of the diurnal variation of absorption. The curves showing the general trends are drawn tentatively in order to indicate approximately the 'normal winter anomaly' (solid lines) and the average enhancement in excess absorption (dashed lines); (Schwentek, 1971). At the equinoxes, the summer level is attained (Elling and Schwentek, 1977).

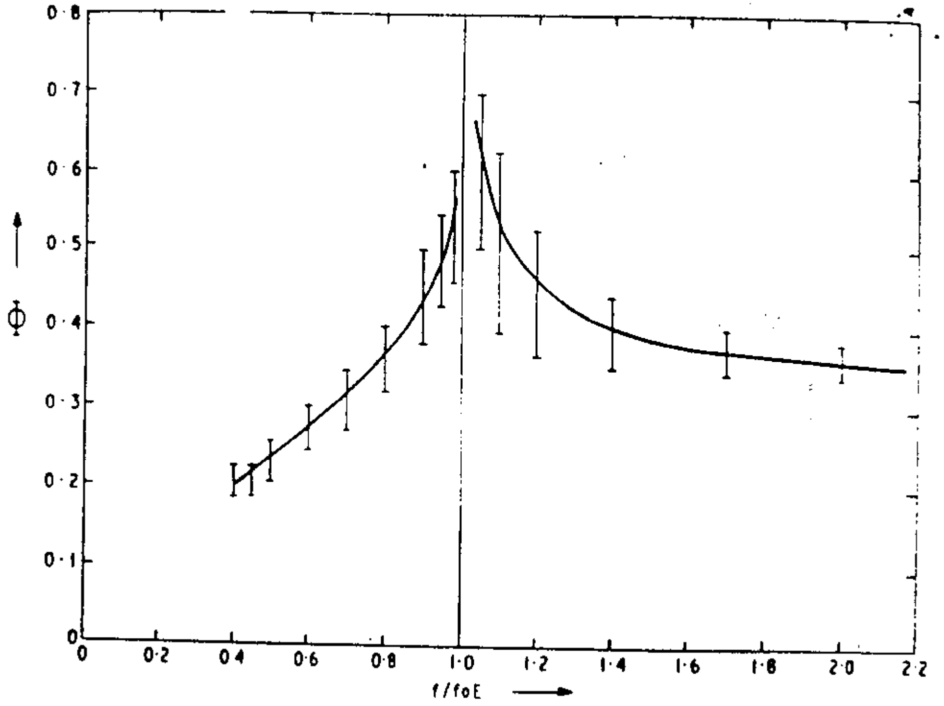


Figure 11 The mean function ϕ (f/foE) and associated limits (from George, 1975)

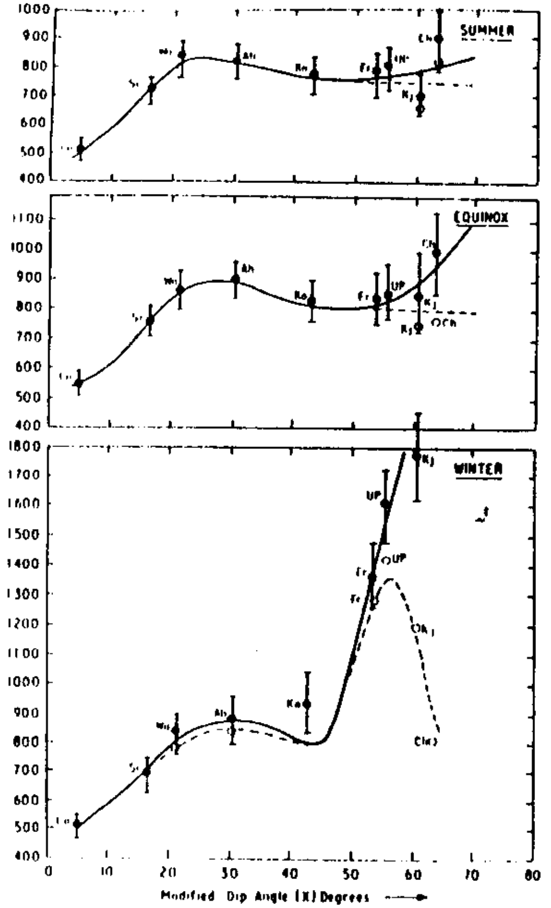


Figure 12 Variation of A_T with latitude and season for an overhead sun and smoothed sunspot number 200 (from George, 1965)

—— best fit with diurnal exponent of 2
- - - improved fit with variable diurnal exponent

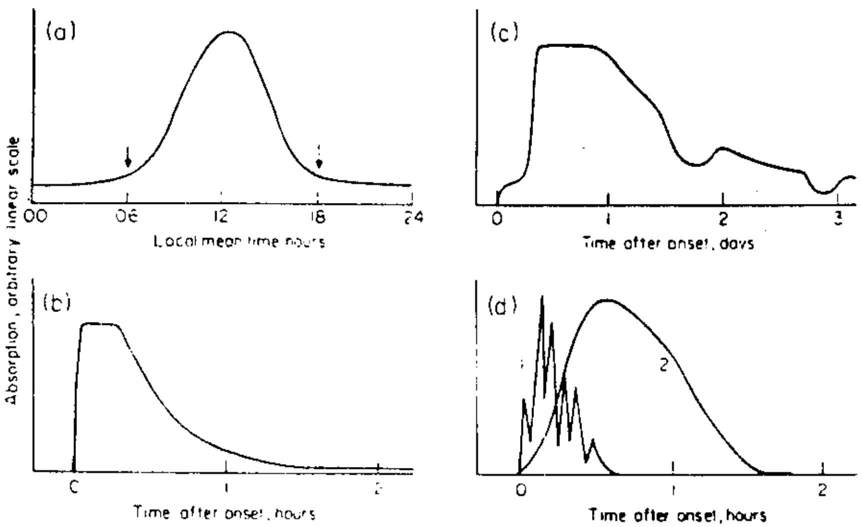


Figure 13 Idealised representations of different types of ionospheric absorption

(a) normal absorption with noon maximum
(b) short-wave fadeout
(c) polar cap absorption
(d) alternate forms of auroral absorption

Figure 14

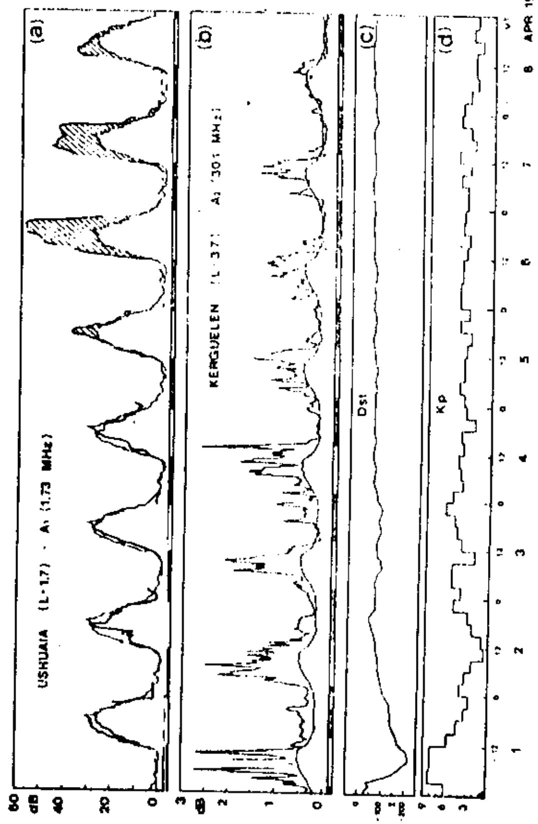


TABLE 1

Latitudinal Variation of Constant n (Equation 8) (A1 Technique)

Location	Dipole Latitude	Period of Observation	f (MHz)	n
Colombo	- 2.95	IGY/IQSY	2.0-2.85	.90
Waltair	7.82	June 51-Sept.62	2.0	.80
Ahmedabad	13.82	IGY	2.5	.73
Washington	49.93	1946	2.06	.82
Swansea	55.19	Oct.50-Aug.51	2.0	.82
Prince Rupert	58.62	1949-1950	2.0	.50
Churchill	68.71	IGY (summers)	2.0	.27
Baker Lake	73.81	IGY (summers)	2.0	.18
Resolute Bay	83.18	IGY (summers)	2.0	.07