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ANALYSIS OF THE IONOSPHERIC ABSORPTION AT KOKUBUNJI

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ABSTRACT

The results of the ionospheric absorption measurements at Kokubunji (35°42.4'N, 139°29.3'E) by the pulse reflection method are analysed by the use of the data obtained in the three ranges of frequency (2.4 Mc/s, 2.8-3.0 Mc/s, and 4.2-4.8 Mc/s) for the period from January 1958 to February 1959. A radio wave absorption suffering from the *D*-region was deduced from the observational data of total absorption. For this purpose the absorption in the *E*-layer was calculated on the assumption of simple Chapman distribution of electron density.

Furthermore, a study was made of the reason why the total value of the absorption is not proportional to $(f+f_L)^{-2}$, where f and f_L are the wave frequency and the component of the gyro-frequency along the positive direction of propagation, respectively.

An investigation was also made of the deviative absorption in the *F*-layer.

Diurnal variation in characteristic of the absorption values in the *D*-region was studied and it was found that the dependence of $\cos^{3/2} \chi$ law holds in the morning, where χ is the solar zenith angle.

1. Introduction

The data of the ionospheric absorption measurement are classified into the non-deviative absorption in the *D*-region and the deviative absorption in the *E*-layer, when the waves are reflected from the *E*-layer, or into the non-deviative absorption in the *D*- and *E*-regions and the deviative absorption in the *F*-layer, when the waves are reflected from the *F*-layer. The main purpose of the ionospheric absorption measurement is to get the information on the ionization in the *D*-region, but it is difficult to distinguish the non-deviative absorption in the *D*-region from others, because it is much influenced by the occurrence of the *E_s* layer and the earth's magnetic field. So it remains unsolved how to use the data to get the necessary information about the *D*-region ionization.

The author attacked this problem by using the data obtained at Kokubunji on the three frequencies for the period of January 1958 to February 1959, and some principles are suggested for the use of the data.

2. Some Introductory Theories

The absorption of radio waves in the ionosphere depends upon the collision loss of energy of vibrating electrons with other particles in the presence of the electric field, and the rate of loss is proportional to the following quantities:

- (1) Electron density,
- (2) Electron collision frequency per unit volume per unit time, and
- (3) The reciprocal refractive index which is proportional to the duration of passage of the wave.

The fundamental index in calculating the absorption values is the coefficient κ per unit length along the wave path. In the presence of the earth's magnetic field a radio wave propagating through the ionosphere is separated into two independent component, the ordinary and the extraordinary waves, and according to the magneto-ionic theory developed by Appleton⁽¹⁾ and Hartree⁽²⁾, the complex index of refraction follows the next equation. The ordinary and extraordinary components correspond to the signs + and - respectively in the following:

$$\left(\mu - \frac{i\kappa c}{\omega}\right)^2 = 1 - \frac{X}{1 - iZ - \frac{Y_T^2}{2(1-X-iZ)} \pm \sqrt{\frac{Y_T^4}{4(1-X-iZ)^2} + Y_L^2}} \quad (1)$$

where μ : refractive index,
 κ : absorption coefficient per unit path length,
 c : light velocity in vacuo,
 ω : angular frequency in Mc/s.

The symbols mean the same as in Appleton's paper.⁽¹⁾ For the wave in the high frequency band on condition that $\omega \gg \nu$, the relation $Z \ll 1 - x$ is generally realized in regions above the height of the *E*-layer. Except in the neighborhood of the reflection point, if the relation $\mu \gg \frac{\kappa c}{\omega}$ is properly assumed, μ and κ in equation (1) can be expressed as follows:

$$\mu^2 = 1 - \frac{X}{1 + Q_1 Y_L} \quad (2)$$

$$\kappa = \frac{\omega}{2c} \frac{XZ(1 + 2Q_2 \cot^2 \theta)}{(1 + Q_1 Y_L)^2 \sqrt{1 - \frac{X}{1 + Q_1 Y_L}}} \quad (3)$$

where $Q_1 = \sqrt{1 + m^2} - m$

$$Q_2 = \frac{m^2}{\sqrt{1 + m^2}} \{\sqrt{1 + m^2} - m\}$$

with $m = \frac{Y_T^2}{2Y_L(1-X)} = \frac{Y_L \tan^2 \theta}{2(1-X)}$

Equations (2) and (3) and the parameters Q_1 and Q_2 were introduced by Whitehead⁽³⁾ and they are very useful for calculation of the absorption. Equation (3) can not be used in the vicinity of the reflection point, because the relation $\mu \gg \frac{\kappa c}{\omega}$ fails to hold there, but the total value of absorption integrated throughout the pass has an error less than 5% only.

When it is allowed to neglect the influence of the earth's magnetic field, μ and κ are expressed by the following well-known equations (see for example reference (4)):

$$\mu = \sqrt{1 - \frac{Ne^2}{\pi m f^2}} \quad (4)$$

$$\kappa = \frac{\nu}{2c} \frac{1 - \mu^2}{\mu} = \frac{\nu}{2c} \frac{Ne^2}{\pi m f^2} \frac{1}{\mu} \quad (5)$$

where

- N : electron density,
- e : charge of electrons (e.s.u.),
- m : mass of electrons;
- f : wave frequency,
- ν : mean collision frequency of electrons with other particles of gas per unit time.

3. Effective Collision Frequency of Electrons

Although many attempts were made theoretically or experimentally to obtain the effective collision frequency at various heights, certain values are not yet known.

The main experimental methods of measurement of collision frequencies will use (i) the phenomenon of interaction of radio waves or (ii) the measurement of refraction coefficient and $h'f$ curves. Another method is based on the measurement of the ionospheric absorption, but in this case the values are the product of the collision frequency and the scale height. The values obtained experimentally from these measurements are plotted in Fig. 1. Now, we will attempt to group the values in Fig. 1 according to the methods by which those values were obtained. The values by Fejer⁽⁵⁾ were obtained by the first method mentioned above and they are almost in agreement with the results obtained by Crompton, et al.⁽⁶⁾ who calculated the collision frequencies with the empirical formula deduced from their laboratory experiments, applying the pressure value given by rockets by Havens, Koll and LaGow. Furthermore, we can see in Fig. 1 that the values given by Schaw⁽⁷⁾ after the first method are in agreement with the results by others. Thus, we will use these values for a height below 90 km.

On the other hand, at a height above 100 km, the measured values can be obtained mainly by the second method, although a part of the values due to Briggs⁽⁸⁾ were obtained from the reflection coefficient of the E_s layer which was assumed as the thin horizontally-stratified layer. Schlapp's values⁽⁹⁾⁽¹⁰⁾ obtained

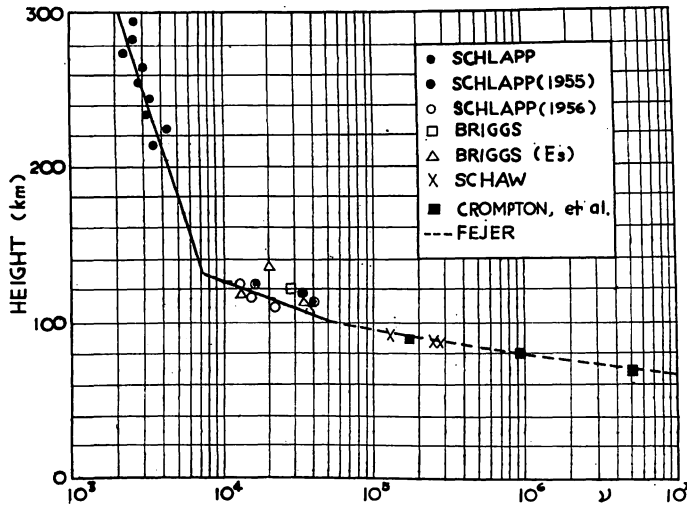


Fig. 1. Collision frequency of electrons at various heights

by the apparatus due to Briggs⁽¹¹⁾ under the second method are useful since the height for each value is indicated by the true height. As to the *F*-region, many experiments have been made since Appleton's measurement⁽¹²⁾ in the year 1935, and it is believed that at a height of 250 km the collision frequency is less than 3×10^3 , although the exact value is still unknown.

Nicole⁽¹³⁾⁽¹⁴⁾ deduced empirical formulae from the laboratory work in 1953 and 1958 and it is concluded that the values given by the first method are consistent with the value obtained by his empirical formula above the 85 km level, if we use the formula obtained in 1958 rather than the one obtained in 1953. In Fig. 1, the three linear lines are drawn for heights below 100 km, of 100–130 km, and above 130 km, to fit with the observational point for each region. Although the measured values are scattered over heights of 100–130 km, the line is drawn on the basis of values obtained by Schlapp in 1955, so that it may continue to the line in the region below 100 km.

A brief discussion will be added on the relationship between the mean collision frequency and the component of the air. Crompton, et al.⁽⁶⁾ considered that the molecular nitrogen would play an important role in the mean collision frequency, and Nicolet⁽¹³⁾⁽¹⁴⁾ gave the same conclusion, but he also recognized the contribution from the molecular oxygen. Their result agrees with the measured values below the 100 km level where the molecular oxygen and nitrogen do not dissociate into atoms. But, above the 100 km level, the measured values are usually higher than those calculated from their empirical formulae, and at the *F*-regional level the result of calculation does not explain the collision frequency at all. In this case it is supposed that atomic oxygen will play an important role⁽¹⁵⁾, but it may be rather difficult to find out the amount of contribution from the atomic oxygen on the collision frequency, and, therefore, the relationship between the collision frequency and the component of the air can not be determined.

4. Electron Density Distribution

The information on electron density distribution in the normal E -layer was obtained by ionosonde. It is known that the electron density of the E -layer shows the diurnal variation proportional to $\sqrt{\cos \chi}$ during the daytime as the first approximation, and the electron density distribution with a true height well approximates the Chapman function in regions below the height of the maximum electron density, particularly where the electron density has a small value.

In the upper part of the layer observed by rockets recently, the electron distribution is fairly complicated, as shown in the examples of the distribution obtained at White Sands⁽¹⁶⁾, Ft. Churchill⁽¹⁷⁾ and Akita,⁽¹⁸⁾ Japan, respectively. The ionospheric absorption, however, occurs mainly in the lower part of the layer, and the error would be slight if we calculate the absorption on the assumption of Chapman's electron density distribution. Another important information on these measurements is the height of maximum electron density which exists at about 105–110 km in the daytime. The height of maximum electron density in these measurements is not constant in the daytime, and it may be difficult to obtain more precise information about the height by the recent rocket techniques. Since the change in height of the maximum electron density with the solar zenith angle is very small during the daytime in summer⁽¹⁵⁾, the height of maximum electron density when $\cos \chi = 1$ will be estimated at approximately 107 km as average.

If it is assumed that the E -layer is produced according to the Chapman theory, the formation of the layer will be under the process of absorption of the solar radiation by the air component (molecular oxygen) as studied, for example, by Watanabe, et al.⁽¹⁹⁾ and the decay process will be under action of recombination. On this assumption, the electron density distribution of the E -layer will depend upon the density of molecular oxygen, whose distribution depends upon the scale height for molecular oxygen. Some considerations from this point of view will be given later again.

5. Influence of the E_s Layer

At night when the normal E - and D -layers disappear, the reflection and transmission coefficients of the E_s -layer in the high frequency band can be measured, and the reflection coefficient is sometimes nearly unity, but very small at some other times.

Generally speaking, the relation between $f_o E_s$ and the reflection coefficient is not clear. Then, it is difficult to clarify the effect of the E_s -layer on the absorption value, particularly in the daytime when the E_s -layer is embedded in the normal E -layer.

Bibl, et al.⁽²⁰⁾ studied this problem and calculated the chart of absorption in the E -layer by using parameters such as $f_o E$, cusp frequency f_c , and wave frequency f . In this calculation the deviative absorption in the E -layer is integrated below the E_s layer on the assumption of the parabolic density distribution of the normal E -layer, but the effect of the reflection coefficient of the E_s -layer is

neglected.

The author tried to clarify the effect of the E_s -layer on the absorption value measured at Kokubunji. Actually, the relation of the absorption values to $h'E_s$ and types of E_s at each time was studied, but it was difficult to find out the distinct relation between them. Perhaps this will be due to lack of record of the lower part of frequency on ionogram and lack of knowledge of the structure of the E_s -layer.

Besides, the author tried to clarify the effect of the E_s -layer on the absorption value measured at Freiburg⁽²¹⁾ on the four frequencies, 1.725 Mc/s, 2.05 Mc/s, 2.44 Mc/s and 2.90 Mc/s. Although the statistics of occurrence of the E_s -layer at Freiburg are different from those at Kokubunji, analogous information may be obtained from the analysis of data at Freiburg, since Kokubunji and Freiburg are not appreciably different from each other in latitudes.

Tables 1 to 3 show L at noon measured at Freiburg in the selected months in which the number of days having the E -layer reflected echo and the E_s -layer reflected echo is not much different and each group of days is not concentrated in any part of the month. Table 2 is constructed of the data on the E -layer reflected echo only and Table 3 is of those from the E_s -layer, while Table 1 is of those from both the E - and E_s -layers. The amount of contribution from the E_s -layer may be obtained from these tables by analyzing the data as follows:

Table 4 was made up by subtracting the values on Table 3 from the corresponding values on Table 1. Table 5 was made up by the values of difference between Tables 3 and 2 in the same way. On examination of the values in Table 4 it may be said that the difference is the smallest and about 2.5 db on the frequency 2.44 Mc/s and it becomes larger as the frequency increases. The values in Table 5 will bring about similar conclusions and the difference is about 4 db. On the above-mentioned analysis, the effect of the E_s -layer may be said to be the smallest on the frequency 2.4 Mc/s at Kokubunji.

When the frequency of wave reflected from the F -region is used, both the E_s and F reflection coefficient can be measured in the existence of the E_s -layer, and by comparison of the values of reflection coefficient we can find whether the E_s -layer masks the F -layer completely or not. Absorption values of waves on 4.8 Mc/s are shown in Table 6 for the period of 3 months. Of course, the absorption value changes daily with the solar activity, but the median values for the period of 3 months will be useful for comparison. In this table we can see that the value obtained from the F -layer echo is 5 db larger than that from the E_s -layer echo, and it should be noted that the difference is the summation of the non-deviative absorption in the E -layer above the E_s -layer level and the deviative absorption in the F -layer, because the reflection coefficient of the E_s -layer will be nearly unity when the E_s -layer masks the F -layer.

Table 1. Median value of L at noon obtained from the E - and E_s -layer reflected echo over Freiburg (Except the value of B)

	1. 725 (Mc/s)		2. 05 (Mc/s)		2. 44 (Mc/s)		2. 90 (Mc/s)	
	Median Count	Median value (db)	Median Count	Median value (db)	Median Count	Median value (db)	Median Count	Median value (db)
March 1958	52	51.3	53	48.5	57	38.6	58	34.8
April	55	52	56	49	57	42.5	57	36.8
Oct.	58	43.2	58	35.3	58	31.4	58	27.2
Feb. 1959	54	49.2	54	42.4	54	35.2	54	32.2
April	54	49.4	55	46.9	55	41.6	55	36.7

Table 2. Median value of L at noon obtained from the E -layer reflected echo over Freiburg (Except the value of B)

	1. 725 (Mc/s)		2. 05 (Mc/s)		2. 44 (Mc/s)		2. 90 (Mc/s)	
	Median Count	Median value (db)	Median Count	Median value (db)	Median Count	Median value (db)	Median Count	Median value (db)
March 1958	41	52.5	37	50.0	38	39.6	36	38.5
April	45	52.0	47	49.5	46	43.0	37	38.8
Oct.	28	46.2	36	38.3	31	33.1	13	35.2
Feb. 1959	36	53.4	41	43.8	28	39.1	21	40.6
April	40	50.4	29	49.6	34	43.7	24	41.8

Table 3. Median value of L at noon obtained from the E_s -layer reflected echo over Freiburg (Except the value of B)

	1. 725 (Mc/s)		2. 05 (Mc/s)		2. 44 (Mc/s)		2. 90 (Mc/s)	
	Median Count	Median value (db)	Median Count	Median value (db)	Median Count	Median value (db)	Median Count	Median value (db)
March 1958	11	44.4	16	42.5	19	35.7	22	29.5
April	10	53	9	42	11	41.5	20	35
Oct.	30	38	22	32	27	29.8	45	24.4
Feb. 1959	18	49	13	37.2	26	31.1	33	29.7
April	14	46.8	26	43.9	21	38.1	31	35.7

Table 4. Value of difference between L on Table 1 and L on Table 3.

	1. 725 (Mc/s)	2. 05 (Mc/s)	2. 44 (Mc/s)	2. 90 (Mc/s)
March 1958	6. 9	6	2. 9	5. 3
April	-1	7	1	1. 8
Oct.	5. 2	3. 3	1. 6	2. 8
Feb. 1959	0. 2	5. 2	4. 1	2. 5
April	2. 6	3	3. 5	1

Table 5. Value of difference between L on Table 2 and L on Table 3.

	1. 725 (Mc/s)	2. 05 (Mc/s)	2. 44 (Mc/s)	2. 90 (Mc/s)
March 1958	8. 1	7. 5	3. 9	9. 0
April	-1	7. 5	1. 5	3. 8
Oct.	8. 2	6. 3	3. 3	10. 8
Feb. 1959	4. 4	6. 6	8. 0	10. 9
April	3. 6	5. 7	5. 6	6. 1

Table 6. Absorption values of radio waves reflected from the E_s - or F -layer on the frequency 4.8 Mc/s

AT noon

Date	E_s		F	
	Median value (db)	Median count	Median value (db)	Median count
May 1958	22	17	27	9
June	28	17	32	3
July	25. 5	18	30	1
Total	25	52	30	13

$\cos \chi = 0.5$ in the morning

Date	E_s		F	
	Median value (db)	Median count	Median value (db)	Median count
May 1958	9	9	13	9
June	3	7	16	11
July	13.5	8	17	8
Total	10.5	24	15.5	20

6. Influence of the Earth's Magnetic Field

At Kokubunji the gyro-frequency is $f_H = 1.23$ Mc/s at a height of 100 km above sea-level, and the angle between the direction of the earth's field and the direction of propagation is $\theta = 41^\circ 16'$. Therefore, the ionospheric absorption is calculated by equation (3) using these numerical values.

We first calculate the absorption in the E -layer, and by subtracting it from the total absorption value we may obtain the absorption in the D -region. In this calculation the model of Chapman distribution of electron density is used.

Neglecting the influence of the earth's magnetic field, Jaeger⁽²²⁾ calculated the total absorption in the case of deviative or of non-deviative absorption, and the result was tabulated. In his calculation the mean collision frequency distribution vs. the height is given in the form of $\nu_0 e^{-z}$, where z is the reduced height in terms of constant scale height H . The scale height is evaluated on the basis of rocket data by many workers. For instance, Yonezawa⁽²³⁾ obtained the value of 6.7 or 10 km in the scale height for a height of 100 or 110 km.

On the other hand, the scale height at these levels is calculated at 16 km from the collision frequency data in Fig. 1, and this is much less than what was given by the rocket measurements. As mentioned above, in the region below 100 km where the composition of the air is very similar to the air on the ground, the empirical formulae deduced from the laboratory experiments give the value of collision frequency in good agreement with the observational values as indicated in Fig. 1, while in regions above 100 km, it will be difficult to deduce the collision frequency from the composition of gas, since there is a difference between the value in the laboratory work and the observational value.

In Chapman's theory a scale height should be taken as that for O_2 in the E -layer as mentioned in section 4, and it may be 7 km at a height of 107 km as was calculated by Yonezawa and the mean collision frequency will be smaller in the lower part of the E -layer if we take the scale height of 7 km in the function $\nu_0 e^{-z}$. Therefore, it may naturally be supposed that the total absorption calculated by Jaeger's Table will be larger than the actual one, since the absorption may occur mainly in the lower part of ionosphere where $Z < 0$, particularly in case of deviative absorption. Figs. 2 and 3 show the $\kappa/\nu_0 - Z$ curves for non-deviative and deviative absorptions, respectively.

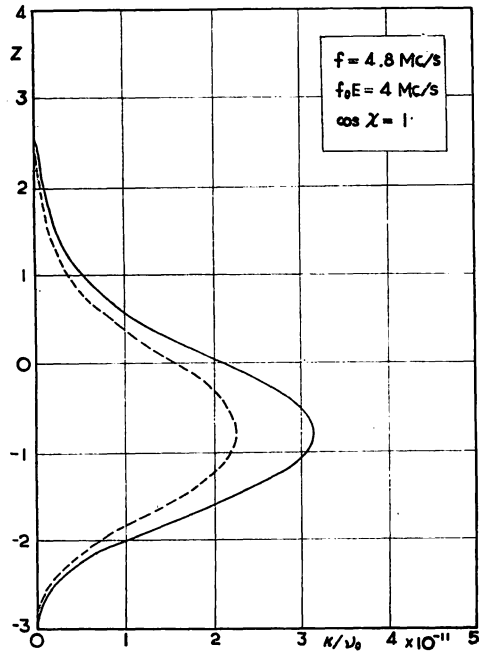


Fig. 2. Non-deviative absorption of the waves passing through Chapman layer at Kokubunji. The full line shows the absorption when the earth's magnetic field is neglected.

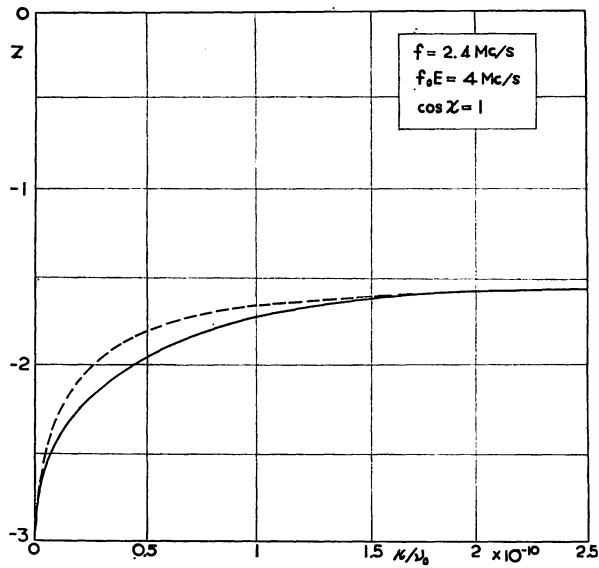


Fig. 3. Deviative absorption of the waves reflected from Champan layer at Kokubunji. The full line shows the absorption when the earth's magnetic field is neglected. In regions above the reflection height, $Z = -1.52$, the value of κ/ν_0 is zero.

It may be important to compare the present result of $\nu_o H$ which is the product of $3.2 \times 10^4 \text{ sec}^{-1}$ and 7 km with $\nu_o H$ obtained by Whitehead⁽²⁴⁾ from the absorption value of the reflected echo from the E -layer, that is,

$$\nu_o H = (1.9 \pm 0.1) \times 10^5 \text{ km/sec.} \quad (6)$$

On the other hand, the result of the present study gives

$$\nu_o H = 2.24 \times 10^5 \text{ km/sec.} \quad (7)$$

Both values do not differ greatly from each other and the difference may become less if we consider that Whitehead's value was obtained from the absorption in the lower part of the E -layer on the frequency 2 or 2.4 Mc/s, so giving a smaller value of H in equation (6).

When we consider the influence of the earth's magnetic field, κ in equation (3) should be integrated instead of equation (5). However, it may be difficult to tabulate generally the result, because the absorption is a complicated function of f_H , θ , f , $f_o E$, $\sec \chi$ in this case. In Fig. 4, the values of absorption at Kokubunji

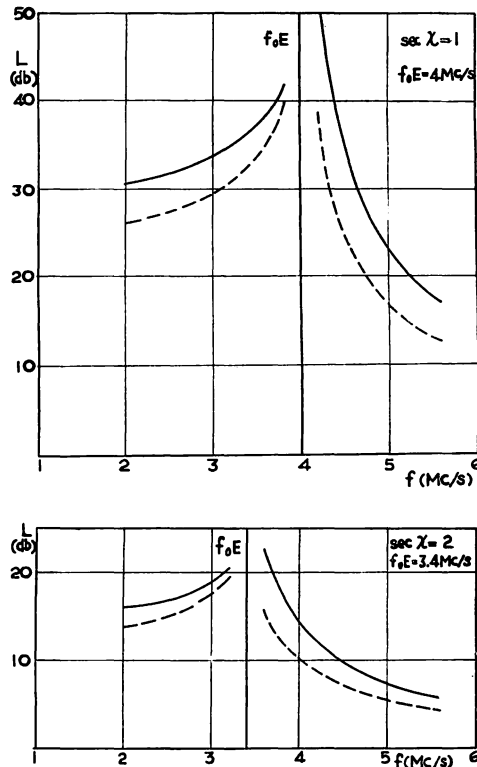


Fig. 4. Calculated values of L in Chapman layer at Kokubunji. The full line shows the absorption when the earth's magnetic field is neglected and the broken line shows it in consideration of the presence of the field.

($f_H=1.23$ Mc/s, $\theta=41.3^\circ$) are shown for the period of sunspot maximum in two cases of $\sec \chi=1$, $f_oE=4$ Mc/s and $\sec \chi=2$, $f_oE=3.4$ Mc/s. These two values of f_oE are taken reasonably to correspond to the value of χ in each case.* The effect of the earth's magnetic field appearing in Fig. 4 is summarized as follows. The total absorption is generally smaller with the earth's magnetic field than without it, and the reduction ratio will be given as 0.725 without a gross error in the case of non-deviative absorption and as 0.9 in the case of deviative absorption.

Thus, the author will give the approximate values of absorption with the earth's magnetic field by multiplying the ratio to the absorption values obtained from Jaeger's table hereinafter.

Table 7. Absorption value on 2.4 Mc/s at noon (Kokubunji)

		f_oE	L_{2F} $= \frac{8.69 \nu_o H}{c \sec \chi} F_1(f/f_oE)$	L	L_{2F} (Mag.) including the effect of the earth's magnetic field	L_{1D} difference value of L from L_{2F} (Mag.)
		(Mc/s)	(db)	(db)	(db)	(db)
1958	Jan.	3.80	17.4	44.5	17.3	23.4
	Feb.	3.85	21.1	37		
	Mar.	3.90	25.0	48.5	24.0	24.3
	Apr.	4.05	28.2	48		
	May	4.05	30.0	45	27.3	22.2
	June	4.10	30.6	50.5		
	July	4.15	30.4	53		
	Aug.	4.20	29.0	49		
	Sept.	4.05	26.5	50	22.2	21.8
	Oct.	3.85	22.8	38		
1959	Nov.	3.65	18.8	26	16.6	21.6
	Dec.	3.65	16.5	40		
	Jan.	3.80	17.4	48		
	Feb.	3.80	21.1	39		

Suffixes 1 and 2 mean 'non-deviative' and 'deviative', respectively, which D , E and F represent the D -, E - and F -layer, respectively.

* Deviative absorption values in this figure are not calculate from equation (3) since errors will be fairly large, but from more appropriate other formula whose introduction is given in Appendix I.

Table 8. Absorption value on 2.8 or 3.0 Mc/s at noon (Kokubunji)

		f (Mc/s)	L_{2F} $= \frac{8.69 \nu_0 H}{c \sec \chi} F_1(f/f_0 E)$ (db)	L (db)	L_{2F} (Mag.) including the effect of the earth's magne- tic field (db)	L_{1D} difference value of L from L_{2F} (Mag.) (db)	$L_{1D} \leftarrow 2.4$ calculated from L_{1D} on 2.4 Mc/s (db)
1958	Jan.	2.8	18.2	34	18.1	15.4	18.7
	Feb.	"	22.0	33			
	March	2.8	26.1	38	24.9	15.8	19.4
	April	"	29.3	43.5			
	May	3.0	32.0	40	29.0	13.5	15.9
	June	"	32.5	43			
	July	"	32.2	44.5			
1959	Aug.	3.0	30.7	44			
	Sept.	3.0	28.2	41	23.7	12.6	15.7
	Oct.	"	24.4	31.5			
	Nov.	2.8	19.7	20	17.4	15.1	17.3
	Dec.	"	17.4	35			
	Jan.	"	18.2	41			
	Feb.	"	22.1	34			

Suffixes 1 and 2 mean 'noon-deviative' and 'deviative' respectively,
while D , E and F represent the D -, E - and F -layer, respectively.

Table 9. Absorption value on 4.2-4.8 Mc/s at noon (Kokubunji)

		f (Mc/s)	L_{1F} $= \frac{8.69 \nu_0 H}{c \sec \chi} F(f_0 E/f)$ (db)	L (db)	L_{1F} (Mag.) including the effect of the earth's magne- tic field (db)	$L_{1D} \leftarrow 2.4$ calculated from L_{1D} on 2.4 Mc/s (db)	L_{2F} difference value of L from L_{1F} (Mag.) & $L_{1D} \leftarrow 2.4$ (db)
1958	Jan.	4.2	19.8	32.5	16.4	9.9	4.0
	Feb.	"	25.3	28			
	March	4.8	19.4	26	16.1	8.2	2.2
	April	"	25.0	27			
	May	4.8	26.6	27	20.4	7.5	1.5
	June	"	28.2	32			
	July	"	29.9	29			
1959	Aug.	4.8	—	—			
	Sept.	4.5	23.4	27	16.0	8.2	0.8
	Oct.	"	20.8	23			
	Nov.	4.5	14.2	12	11.0	8.1	1.4
	Dec.	"	12.5	22			
	Jan.	"	15.2	25			
	Feb.	"	18.4	23			

Suffixes 1 and 2 mean 'non-deviative' and 'deviative' respectively,
while D , E and F represent the D -, E - and F -layer, respectively.

7. Analysis of the Absorption Values for Three Frequencies

As mentioned in section 5, the radio wave on 2.4 Mc/s is affected by the presence of the E_s -layer to the slightest degree among the three frequencies at Kokubunji. If we do not consider the effect of the E_s -layer and assume that the absorption of the wave on 2.4 Mc/s in the E -region is only the deviative absorption, the non-deviative absorption in the D -region will be obtained as the difference between the total measured absorption and the calculated deviative absorption in the E -layer. Now, we can reduce the non-deviative absorption in the D -region on the two other frequencies from that on 2.4 Mc/s, since it is known that the non-deviative absorption is theoretically proportional to $(f+f_L)^{-2}$.

In Tables 7 to 9 the measured values of absorption L are shown for the three frequencies. The absorption values in various regions are calculated by the use of the above-mentioned non-deviative absorption in the D -region and are included in the Tables. L_{1D} and L_{1E} represent the non-deviative absorption in the D - and E -regions, respectively, while L_{2E} and L_{2F} represent the deviative absorption in the E - and F -regions, respectively. The calculated values are obtained in the two cases with and without the earth's magnetic field.

On the frequencies 2.8-3.0 Mc/s, provided that the measured value of absorption is composed of the deviative absorption in the E -layer and the non-deviative absorption in the D -region, the latter should be connected by the $(f+f_L)^{-2}$ law with the non-deviative absorption calculated on the wave frequency 2.4 Mc/s. Actually, however, there is a difference of about 3 db between them, and it is supposed that the E_s -layer affects the absorption value more remarkably at higher frequencies. So it is generally said that the non-deviative absorption deduced on lower frequencies gives more precise values.

On the radio wave reflected from the F -layer on the frequencies 4.2-4.8 Mc/s, absorption values are divided into the following three parts, i.e., the non-deviative absorption in the D -region, which can be calculated from the value deduced on 2.4 Mc/s, the non-deviative absorption in the E -layer, which can be calculated on the assumption of Chapman distribution, and the deviative absorption in the F -layer, which is the rest of the total absorption. As is seen in Table 9, the deviative absorption in the F -layer is about 2-3 db.

Further investigation was made theoretically of the deviative absorption in the F -layer. The electron density height distribution will be obtained from ionograms by the study of $N(h)$ curves and these curves show that the reflecting points of the waves on 4.2-4.8 Mc/s in the F -layer are usually at a height of one hundred and several ten kilometers in the daytime. Examples of $N(h)$ curves are given by many stations⁽²⁵⁾⁽²⁶⁾, and these heights are almost the same as obtained by rockets⁽¹⁶⁾.

In order to calculate the deviative absorption of waves reflected in the F -layer, it will be better to use the parabolic distribution of electron density in the F -layer instead of Chapman's distribution, since the former gives a simpler distribution than the latter and the semi-thickness of the F -layer can be defined in a simple form. Now, assume the electron density N in the layer in the following form:

$$N = \frac{\pi m}{e^2} f_c^2 (2x - x^2) \quad (8)$$

where
$$x = \frac{h - h_*}{Z_d} \quad (9)$$

h : height in km above sea-level of any point in the layer,
 h_* : height in km above sea-level of the lowest point in the layer,
 Z_d : semi-thickness in km of the layer,
 f_c : critical frequency of the layer.

The deviative absorption value of the wave reflected in this layer is indicated as follows:

$$L = \frac{Z_d \nu_c}{10^5} A \quad (\text{db}) \quad (10)$$

where ν_c is the collision frequency at a height of the reflection point and A is given by equation (A. 5) in Appendix II. The value of A is illustrated in Fig. 5 as a function of $p = f_c/f$.

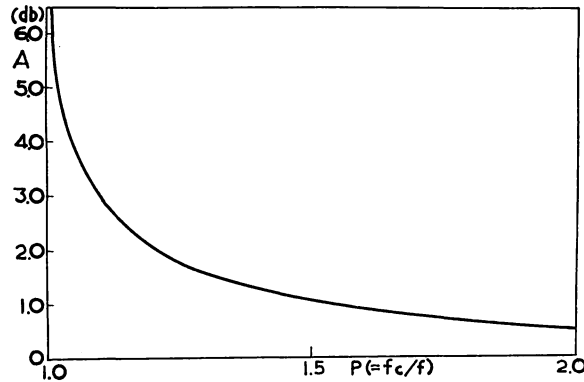


Fig. 5. Values of A as a function of p .

Universally, by equation (10) and Fig. 5 we can calculate easily the deviative absorption L in the layer of the parabolic electron distribution. As examples of calculation of the deviative absorption on 4.2–4.8 Mc/s (not far from f_oE) suffering from the F -layer in the daytime, on the assumption that the greater part of absorption occurs at a height of 160 km, we get the following:

$$L = \frac{50 \times 6 \times 10^8}{10^5} \times 1.6 = 4.8 \text{ db} \quad (11 \text{ a})$$

for the F_1 -layer ($Z_d = 50$ km, $\nu_c = 6 \times 10^8 \text{ sec}^{-1}$ and $p = 1.3$) and

$$L = \frac{100 \times 6 \times 10^8}{10^5} \times 0.5 = 3 \text{ db} \quad (11 \text{ b})$$

for the F_2 -layer ($Z_d=100 \text{ km}$, $\nu_e=6 \times 10^8 \text{ sec}^{-1}$ and $p=2$).

These values are greater than those obtained in Table 4 by 1-2 db. It may be supposed that the difference originates in the fact that the deviative absorption in the F -layer given in Table 9 is the difference between the measured total absorption and the calculated non-deviative absorption in the E -layer, which will be larger than the actual value, since in the calculation of absorption in the E -layer the collisional frequency will be larger than the actual one as was explained in section 6.

The author reexamined⁽²⁷⁾ whether the total absorption of the wave reflected from the E - and F -layers is proportional to $(f+f_L)^{-2}$, although it is known⁽²⁸⁾⁽²⁹⁾ that the $(f+f_L)^{-2}$ law holds rather well for the total absorption in Central and North Europe. However, it was found at Kokubunji that the $(f+f_L)^{-1}$ law was better than the $(f+f_L)^{-2}$ law. For the wave reflected from the E -layer, this may well be explained by the fact that the deviative absorption reaches about half of the total absorption at Kokubunji and that in regions below f_oE the deviative absorption increases in value as the frequency increases, although the non-deviative absorption rapidly decreases in value according to the $(f+f_L)^{-2}$ law.

8. Diurnal Variation in L_{1D}

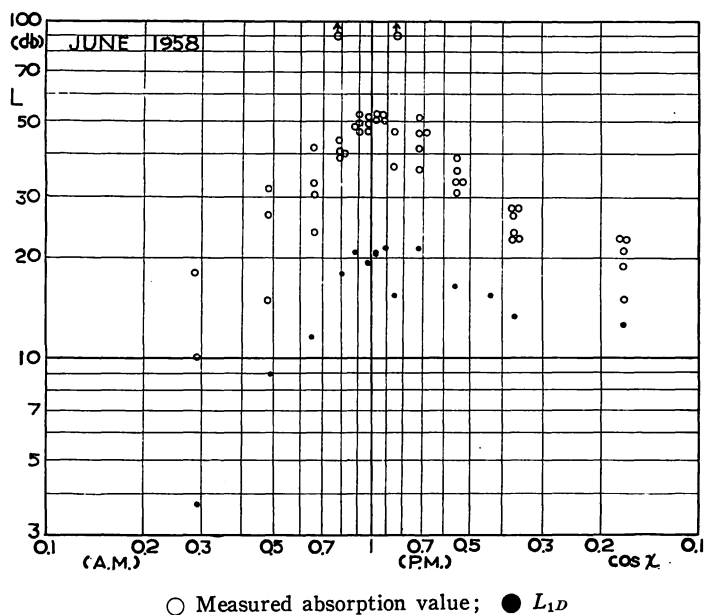
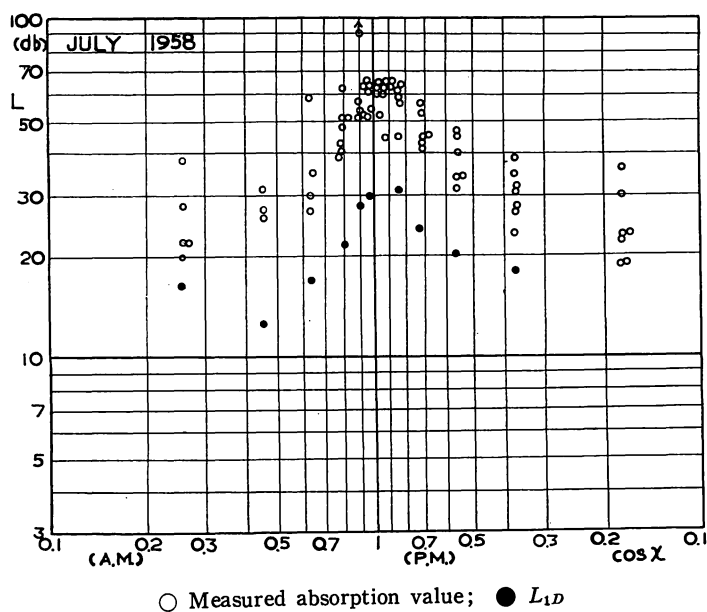
The author already studied the diurnal variation in values of absorption at three frequencies over Kokubunji in each season of the IGY⁽³⁰⁾ and obtained the result that the value of absorption on 2.4 Mc/s was proportional to $\cos \chi$ in the case of $\cos \chi > 0.25$ in the morning and to $\cos^n \chi$ in the case of $\cos \chi > 0.2$ in the afternoon, where n was much smaller than unity.

In the present study, analysis is made of the relation between L_{1D} and $\cos \chi$. The result is shown as the logarithmic plots of L_{1D} and $\cos \chi$ in Figs. 6 to 9. The former two indicate both the measured total values of absorption and L_{1D} in some particular months, while the latter two give the plots of L_{1D} only in 2 or 3 months. In these figures, we can estimate the value of n . The result is that n is 1.53 in Fig. 8 and 1.20 in Fig. 9 for $\cos \chi > 0.4$. These values are very close to 1.5 obtained by, for example, Jaeger⁽²²⁾ theoretically on condition that the wave frequency was much larger than the penetration frequency of the layer in the simple Chapman distribution.

9. Electron Density in the D -region Deduced from L_{1D}

To obtain information on the electron density in the D -region, the author deduced L_{1D} from L . Therefore, it was necessary to estimate the electron density at Kokubunji.

From the relation of (5), the value of absorption is expressed as follows:

Fig. 6. Logarithmic plots of L_{1D} and $\cos \chi$ on the frequency 2.4 Mc/sFig. 7. Logarithmic plots of L_{1D} and $\cos \chi$ on the frequency 2.4 Mc/s

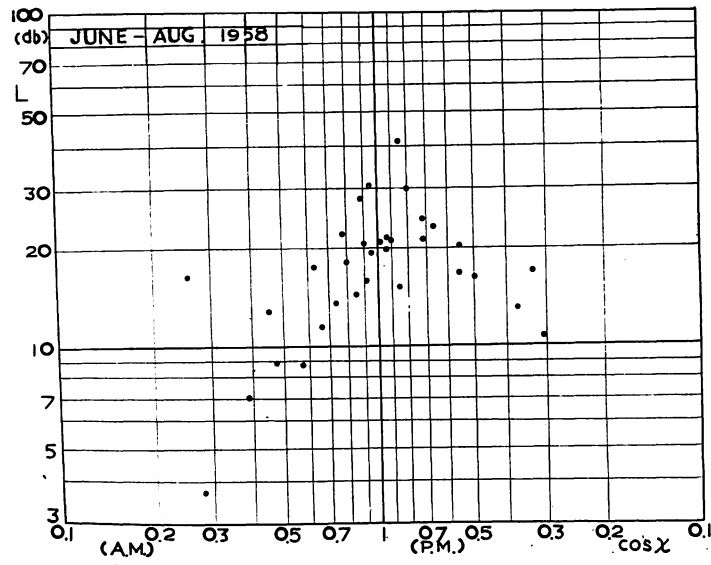


Fig. 8. Logarithmic plots of L_{1D} and $\cos \chi$ on the frequency 2.4 Mc/s

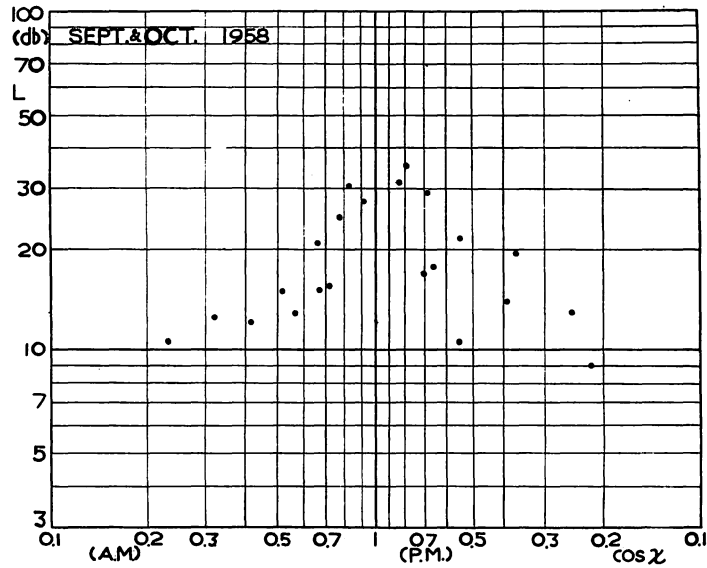


Fig. 9. Logarithmic plots of L_{1D} and $\cos \chi$ on the frequency 2.4 Mc/s

$$L = 8.69 \int_{\text{total path}} \kappa dh = 8.69 \int_{\text{total path}} \frac{\nu}{2c} \frac{Ne^2}{\pi m f^2} \frac{1}{\mu} dh \quad (\text{db}) \quad (12)$$

where the numerical factor 8.69 is the transformation factor from neper to decibel.

In the case of the non-deviative absorption, $\mu=1$, and if we represent ν by the constant value ν_d within the layer whose thickness is Z_d and, since the wave passes through the path twice,

$$L_{1D} = \frac{8.69 N e^2 \nu_d Z_d}{c \pi m f^2} \quad (\text{db}) \quad (13)$$

$$= 4.054 \times 10^{-15} \times N \nu_d Z_d \quad (\text{db}): \text{ for } 2.4 \text{ Mc/s} \quad (14)$$

ν will be regarded as 10^8 sec^{-1} at a height of 80 km and $5 \times 10^8 \text{ sec}^{-1}$ at 70 km in Fig. 1. If we represent ν_d by the value at 80 km when $\cos \chi = 0.5$ (for example, about noon in winter) and by the value at 70 km at noon in spring, summer and autumn, Table 10 may be obtained over Kokubunji on the assumption that the thickness of the layer is 10 km and the electron density distribution is rectangular (the same density from the bottom to the topside). Deduction of L_{1D} in these tables shows the same value as that of L_{1D} in the Table 7. Therefore, it can be said that the image on the D -layer is given by the author.

Table 10. Electron density in the D -region at Kokubunji on the assumption of the layer 10 km in thickness

$\cos \chi = 0.5$,

Assumed height of the layer: 80 km.

	L_{1D} (db)	$N \times 10^8 \text{elec./cc}$
1958 Jan. Feb.	20.5	5.1
Mar. Apr.	14.8	3.7
May—Aug.	10.2	2.5
Sept. Oct.	13.5	3.3
Nov. Dec.	20.4	5.0
1959 Jan. Feb.		

Noon

Assumed height of the layer: 70 km.

	L_{1D} (db)	$N \times 10^8 \text{elec./cc}$
1958 Mar. Apr.	24.3	1.2
May—July	22.2	1.1
Sept. Oct.	21.8	1.1

The values shown in the tables above may be compared with those obtained by Fejer and Vice⁽⁸¹⁾ and by Houston⁽⁸²⁾. The former was obtained from the rate

of change of integrated differential absorption and the latter from the modified Chapman theory of ionization production. Fejer and Vice gave the electron density at a height of 80 km as 3×10^8 elec./cc when $\cos \chi = 1$, and Houston's value of electron density was about 10^8 elec./cc when $0.5 \leq \cos \chi \leq 1$. The values in Table 10 are almost the same as the results of studies and when $\cos \chi = 0.5$ they are higher in winter than in spring and autumn. It may be difficult to say that the increase depends upon the solar activity. The author thinks⁽³⁰⁾ that the large absorption in winter will depend upon the abnormal partial reflection layer in the *D*-region, and it will not be possible to estimate the electron density from L_{1D} in winter.

10. Conclusions

The conclusions of the present paper may be summarized as follows:

- (1) The non-deviative absorption values in the *D*-region calculated from the absorption values on 2.4 Mc/s at Kokubunji are fairly reliable, if the *E*-layer is assumed to be of Chapman's electron density distribution with the scale height of $H = 7$ km at $h_o = 107$ km and ν_o is assumed as 3.2×10^4 sec⁻¹.
- (2) It is believed that for the total absorption of waves reflected from the *E*- and *F*-layers the $(f + f_L)^{-2}$ law is substantiated approximately, but it is shown that this can not be applied to waves reflected from the *E* layer, since the deviative absorption reaches about half of the total absorption at Kokubunji.
- (3) The $(f + f_L)^{-2}$ law can not also be applied to the *F* layer in the daytime when the wave frequency is not far from f_oE , since the deviative absorption value of waves reflected from the *F* layer will reach 3-4 db.
The above two items (2) and (3) will explain the empirical fact in the author's previous paper that the $(f + f_L)^{-1}$ law holds rather well with the measured absorption values than the $(f + f_L)^{-2}$ law.
- (4) The non-deviative absorption value in the *D*-region is shown to be in good agreement with that calculated from the $\cos^{3/2} \chi$ law in the morning.
- (5) The electron density in the *D*-region is estimated by L_{1D} at Kokubunji.

Although further investigation should be made on the structure of the *E_s* layer and on the mean collision frequency before arrival at final conclusion, it may be said that fairly good explanation of measured absorption values is obtained by the present study.

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References

- (1) Appleton, E. V., *J. Inst. Elect. Engrs*, **71**, 642 (1932).
- (2) Hartree, D. R., *Proc. Camb. Phil. Soc.*, **27**, 143 (1931).
- (3) Whitehead, J. D., *J. Atmos. Terr. Phys.*, **9**, 276 (1956).
- (4) Mitra, S. K., *The Upper Atmosphere*, Chap. VI, The Asiatic Society (1952).
- (5) Fejer, J. A., *J. Atmos. Terr. Phys.*, **7**, 322 (1955).
- (6) Crompton, R. W., Huxley, L. G. H. and Sutton, D. J., *Proc. Roy. Soc.*, **218**, 507 (1953).
- (7) Schaw, I. J., *Proc. Phys. Soc.*, **B64**, 1 (1951).
- (8) Briggs, B. H., *J. Atmos. Terr. Phys.*, **1**, 345 (1951).
- (9) Schlapp, D. M., *J. Atmos. Terr. Phys.*, **16**, 340 (1959).
- (10) Schlapp, D. M., *J. Atmos. Terr. Phys.*, **17**, 246 (1960).
- (11) Briggs, B. H., *Proc. Phys. Soc.*, **64**, 255 (1951).
- (12) Appleton, E. V., *Nature*, **135**, 618 (1935).
- (13) Nicolet, M., *J. Atmos. Terr. Phys.*, **3**, 200 (1953).
- (14) Nicolet, M., *Sci. Rep. No. 102*, Ionos. Res. Lab., State College, Penna (1958).
- (15) Ratcliffe, J. A. and Weekes, K., *Physics of the Upper Atmosphere*, Chapt. 9, p. 445, Academic Press (1960).
- (16) Seddon, J. C. and Jackson, J. E., *IGY Rocket Report Series*, No. 1, 149 (1958).
- (17) Jones, L. M., Fischbach, F. F. and Peterson, J. W., *IGY Rocket Report Series*, No. 1, 47 (1958).
- (18) Aono, Y., Hirao, K. and Miyazaki, S., *J. Radio Res. Labs.*, **8**, 441 (1961).
- (19) Watanabe, K. and Hinteregger, H. E., *J. Geophys. Res.*, **67**, 999 (1962).
- (20) Bibl, K., Paul, A. and Rawer, K., *J. Atmos. Terr. Phys.*, **16**, 324 (1959).
- (21) *Ionosphären-daten, Absorptions-messungen*, Freiburg.
- (22) Jaeger, J. C., *Proc. Phys. Soc.*, **59**, 87 (1947).
- (23) Yonezawa, T., *J. Radio Res. Labs.*, **7**, 69 (1960).
- (24) Whitehead, J. D., *J. Atmos. Terr. Phys.*, **16**, 283 (1959).
- (25) Thomas, J. O., Haselgrove, J. and Robbins, A. R., *Tables of Ionospheric Electron Density—Series B* (Slough, Watheroo, Maui and Huancayo), Cavendish Lab., Cambridge.
- (26) Schmering, E. R., *Ionospheric Electron Density for Washington, D. C., Panama, Talara and Huancayo*, *Sci. Rep., Ionos. Res. Lab., State College, Penna.*
- (27) Yasuda, J., *J. Radio Res. Labs.*, **9**, 325 (1962).
- (28) Appleton, E. V. and Piggott, W. R., *J. Atmos. Terr. Phys.*, **5**, 141 (1954).
- (29) Piggott, W. R., *Proc. Inst. Elect. Engrs.*, III, **100**, 61 (1953).
- (30) Yasuda, J. and Sugiuchi, H., *J. Radio Res. Labs.*, **7**, 551 (1960).
- (31) Fejer, J. A. and Vice, R. W., *J. Atmos. Terr. Phys.*, **16**, 291 (1959).
- (32) Houston, R. E., *Sci. Rep., No. 95*, Ionos. Res. Lab., State College, Penna (1953).

APPENDIX I

In the following equation,

$$\left(\mu - \frac{i\kappa c}{\omega}\right)^2 = 1 - \frac{X}{1 - iZ - \frac{Y_T^2}{2(1-X-iZ)} + \sqrt{\frac{Y_T^4}{4(1-X-iZ)^2} + Y_L^2}}$$

the same equation as (1) in the main text.

Assuming $Z \ll 1-X$, Whitehead⁽³⁾ got the approximate equation as shown below:

$$\mu - \frac{i\kappa c}{\omega} \div \sqrt{1 - \frac{X}{(1+Q_1 Y_L)^2} [1 + Q_1 Y_L + iZ(1 + 2Q_2 \cot^2 \theta)]}$$

We separate this equation into its real and imaginary parts, then

$$\begin{aligned} \mu &= \sqrt{\frac{1}{2} \left\{ 1 - \frac{X}{1+Q_1 Y_L} + \sqrt{\left(1 - \frac{X}{1+Q_1 Y_L}\right)^2 + \frac{Z^2 X^2 (1+2Q_2 \cot^2 \theta)^2}{(1+Q_1 Y_L)^4}} \right\}} \\ \kappa &= \frac{\omega}{c} \sqrt{\frac{1}{2} \left\{ -1 + \frac{X}{1+Q_1 Y_L} + \sqrt{\left(1 - \frac{X}{1+Q_1 Y_L}\right)^2 + \frac{Z^2 X^2 (1+2Q_2 \cot^2 \theta)^2}{(1+Q_1 Y_L)^4}} \right\}} \quad (\text{A. 1}) \end{aligned}$$

These equations are obtained without assumption $\mu \gg \frac{\kappa c}{\omega}$, which was assumed for equations (2) and (3) in the paper. In Fig. 4 the total deviative absorption calculated from (3) will reach 5% and this amount of error is too large to get the smooth curve of L . In the vicinity of the critical frequency of the layer the error will become much larger.

APPENDIX II

According to Snell's law, using the symbols as shown in Fig. A. 1,

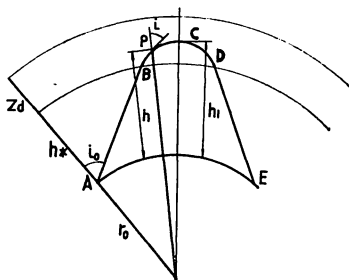


Fig. A. 1

$$r_0 \sin i_0 = \mu (r_0 + h) \sin i. \quad (\text{A. 2})$$

Using the relation of (5), the total absorption in the ionosphere will be expressed as follows:

$$\begin{aligned} L &= 8.69 \times 2 \int_{h^*}^{h_1} \frac{\kappa}{\cos i} dh \\ &= 8.69 \times \int_{h^*}^{h_1} \frac{\nu N e^2}{c \pi m f^2} \frac{1}{\mu} \frac{dh}{\cos i} \quad (\text{db}) \end{aligned} \quad (\text{A. 3})$$

If we replace the function N , μ in equation (A.3) by the relations of (4), (8) and (9) using the relation of (A.2), we get

$$L = \frac{8.69p}{c} Z_d \int_0^{x_1} \frac{\nu \{1 - (1-x)^2\}}{\sqrt{(1-x)^2 + B - 1}} dx$$

where x_1 is the value of x at the reflection point and

$$B = \frac{1 - \left(\frac{r_0}{r_0 + h_1} \sin i_0 \right)^2}{p^2}$$

At the reflection point C , $\cos i = 0$ and κ becomes predominant over the total integral value, so ν may be represented by the constant value ν_c at the height of the reflection point.

Then

$$L = \frac{8.69p}{2c} Z_d \nu_c \left\{ \frac{1 + 2x_1 - x_1^2}{2} \log \frac{1 + \sqrt{2x_1 - x_1^2}}{1 - \sqrt{2x_1 - x_1^2}} - \sqrt{2x_1 - x_1^2} \right\}$$

At the reflection point μ become 0, then

$$2x_1 - x_1^2 = \frac{1}{p^2}$$

and

$$L = \frac{8.69p}{2 \times 3} \left\{ \frac{1}{2} \left(1 + \frac{1}{p^2} \right) \log_e \frac{1 + \frac{1}{p}}{1 - \frac{1}{p}} - \frac{1}{p} \right\} \frac{Z_d \nu_c}{10^3} \quad (\text{A. 4})$$

Now, if we put

$$A = \frac{8.69}{6} \left\{ \frac{1}{2} \left(1 + \frac{1}{p^2} \right) \log_e \frac{1 + \frac{1}{p}}{1 - \frac{1}{p}} - \frac{1}{p} \right\} \quad (\text{A. 5})$$

(A.4) becomes (8) in the paper, and the calculated value of A is shown in Fig. 5.