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Solar-Terrestrial Predictions in regard to Ionospheric Absorption of Radio Waves

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The Al-ionospheric radiowave absorption, L_{dB}, measured on three different frequencies, viz. 1.8, 2.2 and 2.5 MHz at Ahmedabad (lat., 23°N; long., 72.6°E; mag. dip 34°N) during the 9-yr period (1972-1980) of the solar cycle 20-21 is studied for finding its relationship with solar activity at different times of the day or solar zenith angles (SZA) χ for each month of the year. It is found that the cos χ-index, n, for diurnal variation of absorption does not undergo much change with solar activity and it remains at a mean value of about 0.8 with a scatter of up to ± 0.3 depending on the season. The variation of absorption is more sensitive to solar activity at higher SZA both in respect of the time of the day and the season. The smoothed 12-monthly running average of L_{dB} and R_z show that the former increases by a factor of about $\sqrt{2}$ when the latter goes up to 110, beyond which the rate of increase of absorption slows down, finally stopping to increase any further. Two examples are given to illustrate the method of prediction of diurnal variation of absorption in different seasons for a specified solar activity, and application of these in practical radio communication. The predicted values are found to be in good agreement with the observed values of absorption.

1 Introduction

The ionospheric Al-absorption measurements of HF radio waves were regularly done every hour during the daytime at Ahmedabad, a tropical station (lat., 23°N; long., 72.6°E; mag. dip, 34°N), for the 9-yr period (Apr. 1972-Mar. 1981) covering minimum and maximum in the descent and ascent of solar cycle (R_z varying from 10 to 200). These data are used to study the solar cycle variation of absorption (L_{dB}) at constant solar zenith angle (SZA), χ, and at different times of the day for each month of the year and to obtain the relations for the solar-terrestrial predictions, viz. the diurnal and seasonal variation of absorption. Sunspot number (R_z or R_i, z for Zurich and i for international) and 10.7 cm solar radio flux ($S_{10.7}$ or $F_{10.7}$) are generally used as indices of solar activity. However, Rawer *et al.*[1] tried a new index of solar activity in terms of EUV flux measured by satellite for modelling of neutral atmosphere, but not with much success. Recently Kurian *et al.*[2] found Ca-plages (A_p) and photospheric faculae (A_F) as good indices of solar activity for the long-term variation in the ionization of E and F2 layers of the ionosphere. However, in the study of HF radiowave absorption, Kotadia *et al.*[3] found R_z or $S_{10.7}$ as a satisfactory index of solar activity.

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2 Monthly Variaton of L_{dB} at Constant SZA (1972-1980)

The diurnal variation of ionospheric absorption of radio waves shows departure from that expected according to the theoretical 3/2-power law of cos χ based on ideal Chapman-layer conditions. In general, this variation obeys the law

$$L = L_0 \cos^n \chi \qquad \text{... (1)}$$

where L_0 is total absorption when the sun is at the zenith or $\chi = 0$. From the plot of log L versus log (cos χ), and a straight line fit by least-square method through these points, the monthly median values of absorption at cos $\chi = 1.0$ (i.e. extrapolated to L_0) and at cos $\chi = 0.6$ (mean of forenoon and afternoon values) are found. A sequence of monthly median values of absorption on 2.2 MHz at cos $\chi = 1.0$ and 0.6 is shown in Fig. 1 for the period Apr. 1972-Dec. 1980 and compared with the monthly mean values of R_z. It is not a good practice to compare absorption at a fixed hour with R_z since that would involve an additional influence of changing cos χ in different months. Absorption at cos χ chosen because it is available for all months, at around midday in winter and at morning and evening hours in summer. It is seen that month-to-month variation in L_{dB} at constant cos χ shows good correspondence with sunspot number, but the variation and the average increase of absorption seem to become smaller when R_z increases beyond a certain value, say about 110, as during the year 1979-1980. The overall range of variation in a year is found to be about 20 dB (peak-to-peak, within the limits 30-50 dB and 20-40 dB for cos χ = 1.0 and 0.6, respectively) during the course of a solar cycle. This may include some amount of purely seasonal variation of absorption independent of cos χ and R_z with maxima in equinoxes and minima in winter and summer, a fact to be dealt with in a subsequent paper.

3 Smoothed Solar Cycle Variation of L_{dB}

To establish a relation between L_{dB} at constant SZA (cos $\chi = 1.0$ and 0.6 for all months taken together) and R_z, it is necessary to eliminate the seasonal influence in

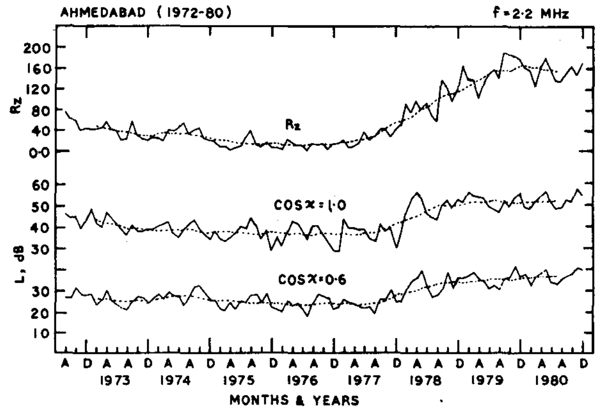

Fig. 1—Variation of monthly median value of ionospheric absorption L_{dB}, at Ahmedabad for cos $\chi = 1.0$ and 0.6 compared with changes in sunspot number R_z for the period 1972-1980 (Dotted curves through the plots show their respective 12-monthly running averages.)

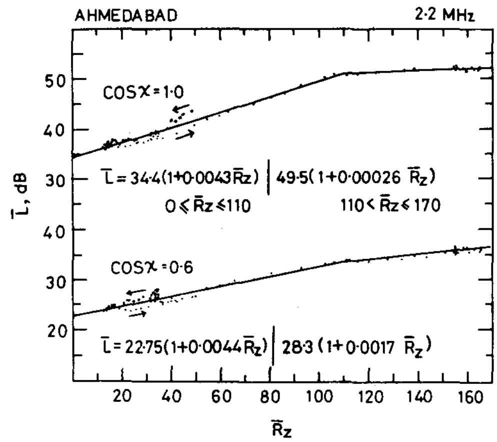

Fig. 2— Variation of 12-monthly running averages of L_{dB} at constant cos χ on 2.2 MHz with those of R_z [Points lying above the straight line fit are for descending part of the sunspot cycle (1972-1980) as indicated by the arrow, and vice-versa (1976-1980). Some points are very close to each other for ascent and descent.]

L_{dB}. This is done by taking 12-monthly running averages of L_{dB} and plotting it against those of R_z as shown in Fig. 2. The arrow marks show the descending (1972-1976) and ascending (1976-1980) parts of the sunspot cycle. It may be noticed that the rate of increase of L_{dB} slows down or flattens at values of $R_z > 110$. For this reason, the straight line fitting of L_{dB} is derived for two parts, one for R_z = 0-110 and the other for $R_z > 110$. Regression analysis is done to fit the straight line represented by the equation

$$L = a(1 + bR_z) \quad \ldots (2)$$

The empirical relations for L_{dB} and R_z so found are as follows.

$$L_{dB}\ (\cos\chi = 1.0) = 34.4\ (1 + 0.0043\ \bar{R}_z)\ \text{for}\ 0 \leq R_z \leq 110$$
$$= 49.5\ (1 + 0.00026\ \bar{R}_z) \quad \bar{R}_z > 110 \quad \ldots (3)$$

$$\bar{L}_{dB}\ (\cos\chi = 0.6) = 22.75\ (1 + 0.0044\ \bar{R}_z) \quad 0 \leq \bar{R}_z \leq 110$$
$$= 28.30\ (1 + 0.0017\ \bar{R}_z) \quad \bar{R}_z > 110 \quad \ldots (4)$$

From relations (3) and (4) it is clear that b, the rate of increase of absorption relative to the reference value of a (in dB) at $R_z = 0$ is higher for cos $\chi = 0.6$ ($b = 0.0017$) than that for cos $\chi = 1.0$ condition ($b = 0.00026$), showing absorption at cos $\chi = 0.6$ more sensitive to solar activity than that at cos $\chi = 1.0$ for R_z greater than 110. It is interesting to find that the value of b for cos $\chi = 1.0$ as well as for cos $\chi = 0.6$ remains almost same (0.0043) for $0 \leq R_z \leq 110$. The values of a and b found here tell us about the long term average variation of absorption with solar activity.

4 Dependence of the Solar Cycle Variation of L_{dB} on Time of the Day

A more detailed study is made to show the dependence of solar cycle variation of absorption on time of the day (0800-1700 hrs) for individual months considering the monthly median values of absorption on three frequencies, viz. 1.8, 2.2 and 2.5 MHz. Standard method was used to establish the linear relation between L_{dB} and R_z in the form $L = a(1 + bR_z)$, where a and b represent quantities already defined, by which, L_{dB} at any time of the day, season and stage of solar activity can be predicted. Values of a and b so obtained for the internationally recommended standard frequency, 2.2 MHz, for absorption measurements are given in Tables 1 and 2. The same is done for 1.8 and 2.5 MHz, but they are not presented here (These can be supplied on request). In Fig. 3 is shown the variation of annual mean value of b with time of the day on three frequencies. It is interesting to see that b is low around noontime and high in the morning and evening for all the three frequencies. Also

Table 1—Daytime Values of *a* in dB on 2.2 MHz for Different Months

Month	Time (hrs) 0800	0900	1000	1100	1200	1300	1400	1500	1600	1700
Jan.	—	15.6	19.7	23.8	27.5	28.8	25.7	20.6	16.9	10.9
Feb.	—	15.0	21.7	26.3	29.6	30.6	28.7	27.0	19.5	14.9
Mar.	13.4	18.5	24.9	29.6	35.1	36.0	33.1	28.1	22.4	15.3
Apr.	16.2	24.2	31.9	36.2	41.2	40.4	35.9	26.6	23.4	14.7
May	17.1	25.8	32.1	40.0	44.2	43.6	39.2	32.5	34.9	18.8
June	18.3	24.4	31.0	36.5	41.6	40.9	35.9	29.6	23.5	15.3
July	15.1	24.1	28.9	32.8	37.5	37.1	32.5	26.5	21.8	17.4
Aug.	16.1	22.1	29.8	34.3	37.9	38.0	32.9	26.9	22.4	20.5
Sep.	17.9	23.3	29.1	34.8	39.4	36.7	39.7	31.5	28.6	—
Oct.	16.8	23.6	27.3	32.3	34.8	31.2	30.6	26.3	21.2	14.7
Nov.	18.2	20.6	26.3	30.2	32.1	33.0	27.6	23.2	18.4	11.4
Dec.	—	16.1	18.5	22.0	22.7	23.9	24.2	21.0	15.3	10.0

Table 2—Daytime Values of *b* (10^{-3}) in Different Months for 2.2 MHz

Month	Time (hrs) 0800	0900	1000	1100	1200	1300	1400	1500	1600	1700
Jan.	—	5.0	4.6	4.0	3.1	2.1	2.4	3.7	4.1	6.3
Feb.	—	7.0	5.1	3.8	2.8	2.1	2.4	2.9	3.1	1.2
Mar.	7.1	6.4	5.6	4.9	3.0	2.8	3.4	3.9	4.5	3.4
Apr.	8.0	4.8	4.7	4.3	2.8	3.3	4.5	6.7	5.3	6.2
May	6.3	3.3	4.0	2.5	1.1	1.0	1.4	3.1	4.5	2.5
June	3.9	3.3	2.8	1.9	0.6	0.8	2.1	2.9	3.4	3.2
July	6.4	3.7	3.4	2.8	1.1	1.3	3.0	4.1	4.6	3.2
Aug.	5.7	4.5	3.8	2.8	1.8	1.9	3.7	5.4	6.0	3.0
Sep.	2.6	3.7	3.7	2.4	1.3	1.8	0.5	1.8	0.7	—
Oct.	3.6	2.4	3.0	2.9	2.2	4.4	3.1	4.0	3.1	4.6
Nov.	3.0	4.0	4.1	3.0	2.3	1.7	3.6	2.8	3.2	5.3
Dec.	—	3.5	4.8	5.7	5.4	4.2	3.2	3.3	3.5	4.7

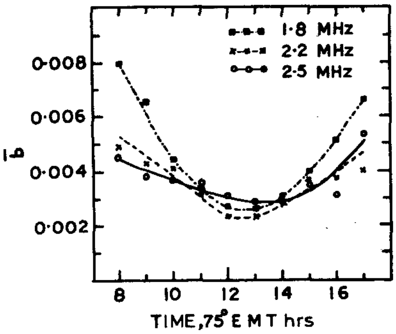

Fig. 3—Variation of annual mean of *b* with time for absorption on 1.8, 2.2 and 2.5 MHz

there is a large change in the value of *b* towards morning and evening hours, that for 1.8 MHz being the most. The diurnal variation of *b* shown in Fig. 3 indicates that the sensitivity of absorption to solar activity is more at higher SZA than at lower SZA.

5 Seasonal Variation of Constants *a* and *b* at Fixed SZA

The values of L_{dB} at $\cos\chi = 1.0$ and 0.6 plotted in Fig. 1 for 2.2 MHz were used to find the variation of L_{dB} with R_z for each month separately. In Fig. 4, the variation of L_{dB} at $\cos\chi = 0.6$ with R_z is shown for each month. The values of *a* and *b* in Eq. 2 were calculated by the usual standard method. The same was repeated for $\cos\chi = 1.0$. The results are summarized as follows: *a* shows maxima in equinoxial months with a variation of about 12 dB (27.6 to 39.8 dB) from minimum to maximum and about 6 dB (20.0 to 26.0 dB) with annual averages of 36.0 dB and 23.0 dB for $\cos\chi = 1.0$ and $\cos\chi = 0.6$ conditions, respectively, which very nearly agree with those obtained from the analysis of 12-monthly running averages (sec. 3) for R_z up to 110. As regards *b*, it varies from 0.0022 in June/September to 0.006 in December with an annual mean of 0.0032 at $\cos\chi = 1.0$, and from 0.002 in September to 0.0053 in March with an annual average of 0.0039 at $\cos\chi = 0.6$. The high value of *b* at $\cos\chi = 0.6$ in August seems to be somewhat unusual (see also Table 2) because of the paucity of data in that month. It is interesting to find that the value of *b* at $\cos\chi = 0.6$ is higher than that at $\cos\chi = 1.0$ for most part of the year, which fact further testifies our earlier conclusion that absorption is more

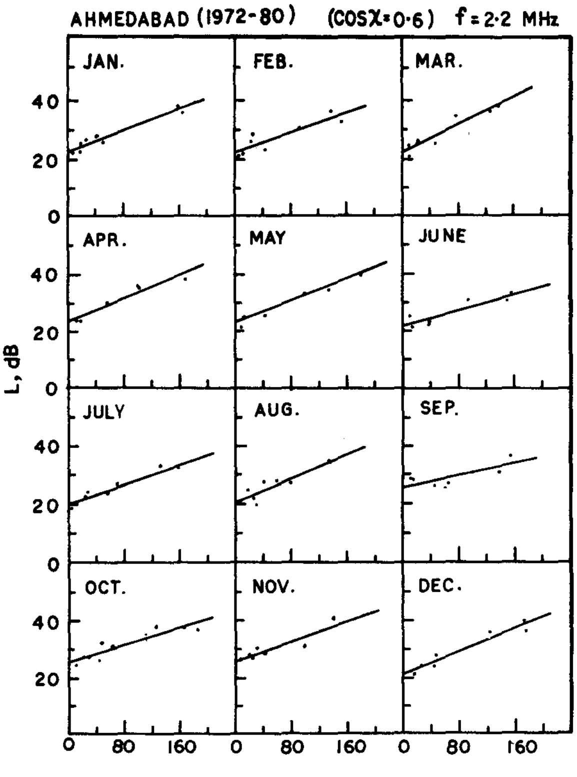

Fig. 4—Variation of L_{dB} at cos χ=0.6 on 2.2 MHz with R_z

sensitive to solar activity at higher SZA (Fig. 3). Appleton and Piggott[4] found that the value of b for noontime absorption on 4.0 MHz at Slough (lat., 51.6°N; long., 0.6°W) changed from 0.013 in summer to 0.007 in February with annual mean equal to 0.0095. Patel *et al.*[5] found the value of b on 1.725 MHz at Freiburg (lat., 48°N; long., 7.8°E) lower than that at Slough on 4.0 MHz frequency. They found it varying from 0.0018 in midwinter to 0.0048 in equinoxes with annual average of 0.0042. Thus the value of b depends on the frequency of the exploring wave, SZA and the latitude of the place of observations. The values of a and b at different places were reported earlier by Gnanalingam[6] and Kotadia *et al.*[3] Rawer[7] gave a general expression for prediction of ionospheric absorption along oblique path at midlatitude using the long series of data of Slough as

$$L=430\ (1+0.0035\ R_z)\cos^{0.75}\chi\ \sec i_D (f \pm f_L)^{-2} \quad \dots (5)$$

where f is oblique incidence radio frequency, i_D is the angle of incidence at the lower boundary of the D-layer and f_L is longitudinal component of electron gyromagnetic frequency.

6 Prediction of Diurnal Variation of Absorption

With the values of a and b obtained for different hours and months, we are now in a position to predict the diurnal variation of ionospheric absorption on a given frequency in any month and stage of solar activity using the empirical relation

$$L_{dB}=a_0\ (1+bR_z)\cos^n\chi \quad \dots (6)$$

and putting $a=a_0\cos^n\chi$ in the general form, where a_0 is absorption at $\chi=0$ and $R_z=0$. The average value of index n of cos χ for diurnal variation of absorption is found to be around 0.8 with some indication of a slight decrease at higher solar activity, and deviations of up to about ± 0.3 from the average value during the course of a year (see Table 3). The values of a and b for different months are taken from Tables 1 and 2 for 2.2 MHz. As an example for prediction, we have selected months of January, April, July and October representing four seasons to compute predicted values of L_{dB} on 2.2 MHz during a low solar activity year 1976 ($\bar{R}_z=13$) and moderately high activity year 1978 ($\bar{R}_z=93$). The values of n for diurnal variation of absorption calculated for different months at $R_z=0$ and 100 are given in Table 3. The predicted and actually observed values of absorption are shown in Fig. 5. It is clearly seen that the predicted absorption agrees reasonably well with the actually observed absorption within a limit not exceeding 4 dB, i.e. about 10% at the most, at some hours. These small discrepancies may be due to irregular day-to-day fluctuations in the observations and to some extent due to differences in sunspot number in the corresponding month from the fixed value taken here for all months. The cos χ index for diurnal variation of the quantity, $A_T(f)$, expressed in dB.MHz^2, which is proportional to $\int N\nu dh$ and representative of nondeviative absorption has also been studied for the entire 9-yr period, where N is electron density and ν is electron collision frequency. The results of this study will be reported in a separate paper. Similarly, with the knowledge of cos χ index for seasonal variation of absorption at given hours, we can predict seasonal variation of L_{dB} for any fixed value of R_z.

7 Radio Wave Absorption in Communications over Long Distances

In actual radio communication systems, one needs to know the ionospheric loss over the oblique path between the transmitter and the receiver, i.e. T and R terminal points. From the absorption measured at vertical incidence, it is easy to find by using Martyn's formula the absorption on equivalent frequency at oblique incidence over a path in the ionosphere for a given ground distance by way of reflection of the radio wave from the same height as that for vertical incidence. If L_v is absorption at vertical incidence frequency, f_v, at the place midway between the two terminal points for one-hop propagation, the

Table 3—Index n of $\cos\chi$ for Diurnal Variation of Absorption for Different Months at $R_z=0$ and $R_z=100$ for Different Frequencies

Month	Frequency = 1.8 MHz				Frequency = 2.2 MHz				Frequency = 2.5 MHz			
	$R_z=0$		$R_z=100$		$R_z=0$		$R_z=100$		$R_z=0$		$R_z=100$	
	L_0	n	L_{100}	n	L_0	n	L_{100}	n	L_0	n	L_{100}	n
Jan.	40.73	0.84	45.80	0.57	37.58	0.88	39.7	0.49	33.34	0.70	40.33	0.61
Feb.	40.33	0.91	49.35	0.68	34.72	0.81	43.87	0.69	33.11	0.80	40.95	0.62
Mar.	44.25	1.10	50.00	0.43	37.42	0.90	50.17	0.76	32.54	0.78	49.32	0.73
Apr.	49.38	0.85	52.20	0.44	40.67	1.08	55.05	0.86	36.34	0.98	51.39	0.76
May	45.74	0.92	50.41	0.56	42.28	1.17	49.87	0.81	37.58	0.90	46.45	0.72
June	37.67	1.03	44.53	0.66	39.41	1.24	45.03	0.84	33.97	0.99	41.75	0.79
July	39.03	0.94	47.96	0.88	36.03	1.23	44.63	0.83	32.67	1.01	42.05	0.87
Aug.	35.74	1.46	59.41	0.49	36.09	1.01	46.29	0.68	33.65	0.96	41.74	0.64
Sep.	39.87	0.75	48.96	0.73	38.67	0.74	45.32	0.62	34.08	0.77	44.27	0.68
Oct.	38.37	0.63	57.36	0.61	35.55	0.60	48.95	0.71	33.12	0.51	45.37	0.64
Nov.	44.20	0.93	55.29	0.65	40.76	0.84	48.44	0.62	33.07	0.57	43.31	0.58
Dec.	37.15	0.75	48.68	0.58	29.39	0.58	47.58	0.77	27.64	0.45	39.51	0.59

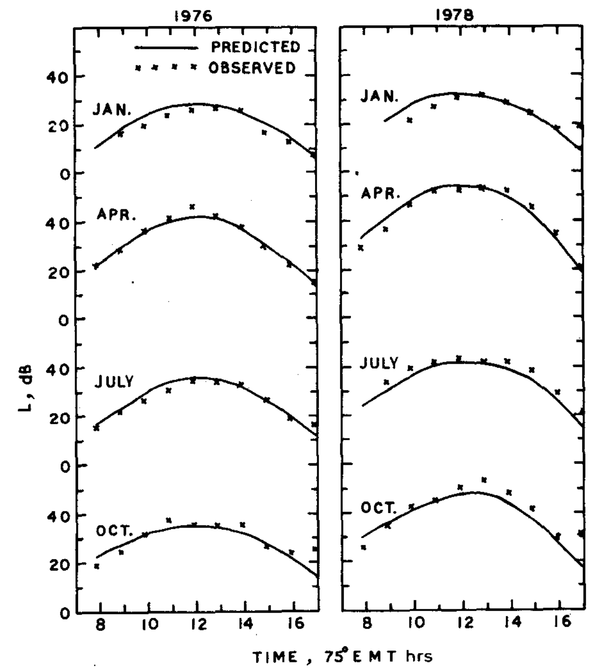

Fig. 5—Comparison of observed and predicted diurnal variation of absorption on 2.2 MHz (Discrepancy between them at some hours could be within a limit not exceeding 10% at the most.)

absorption L in dB at oblique incidence frequency, f_{ob}, is given by

$$L=L_v\cos i \quad \text{and} \quad f_{ob}=f_v\sec i \qquad \dots (7)$$

Assuming safely a thin ionized layer having scale-height of about 7 km and flat earth for small ground range, say up to 1500 km, as compared to the circumference of the earth, we may write

$$\sec i=(1+D^2/4h^2)^{1/2} \qquad \dots (8)$$

where D is the distance between T and R, h is height of reflection of the radio wave and i is the angle of incidence of the wave at the lower boundary of the ionized layer.

Fig. 6 shows plots of L_{dB} and f_{ob} corresponding to f_v of 1.8, 2.2 and 2.5 MHz around noontime against D for one-hop propagation via the E-layer over Ahmedabad under the conditions $R_z=0$ and $R_z=100$ in the months representing four seasons. Results of a detailed study on the frequency dependence of absorption at Ahmedabad have been reported earlier by Patel and Kotadia[8]. The value of D is chosen to range from 500 km to 1500 km and h is taken as mean height of reflection over 0800-1700 hrs of daytime. The departure of height during the course of a day from its mean value accounts for a change in absorption up to about $\pm 5\%$ of that calculated by the above formula using the same mean height for different hours (minus around noon and plus at higher SZA). From Fig. 6, it is convenient to read out the ionospheric loss and corresponding communication frequency over a given distance. Larger the distance, the difference in absorption at the equivalent high frequencies becomes smaller and smaller. Essentially, the absorption at lower frequency is higher, but one of the curves of L_{dB} may interchange with or overlap the other depending on season and solar activity. To given an example, in October, at $R_z=0$, L was about 8-10 dB in 31 m and 41 m bands and this increased by 2 to 3 dB only in high solar activity for coverage of 1000 km ground distance. This absorption is in addition to the spatial and other losses suffered in the path-length outside the ionosphere. It may be noted that the ionospheric absorption is higher in equinoxial months than in winter and summer for the same solar activity. Similar

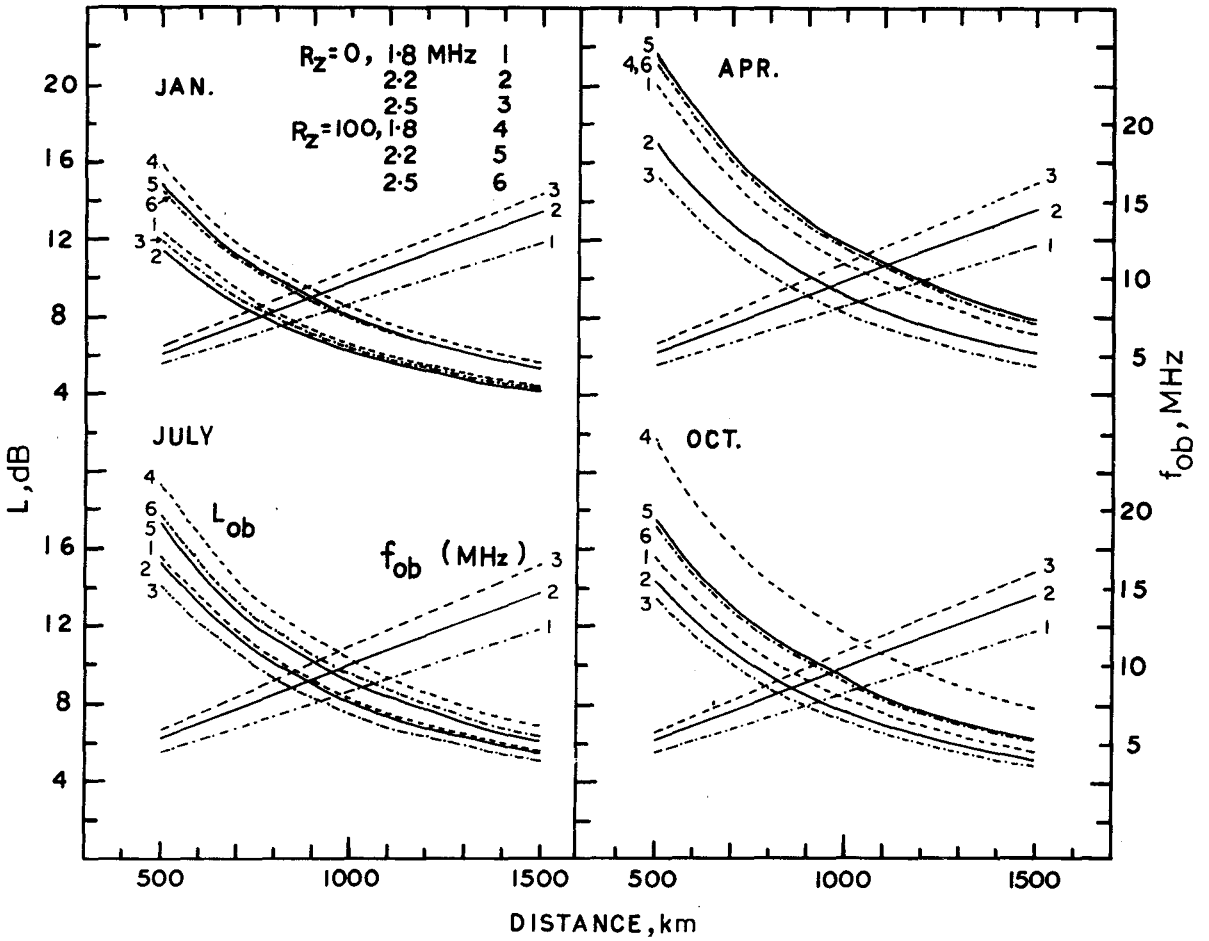

Fig. 6—Variation of L_{dB} and f_{ob} corresponding to equivalent f_v of 1.8, 2.2 and 2.5 MHz around noontime with distance between T and R for January, April, July and October at R_z = 00 and R_z = 100

plots can be prepared for the remaining months and any other fixed sunspot number using the values given in Tables 1 and 2 and the corresponding height data obtained from ionosonde measurements.

8 Discussion and Conclusions

The month-to-month variation in L_{dB} at constant cos·χ (or SZA) shows a good correspondence with sunspot number, but the range of variation and increase in L_{dB} become smaller when R_z increases above 110. The seasonal variation of absorption independent of SZA and R_z, with some model calculations, will be reported later.

The smoothed solar cycle variation of absorption shows that absorption is more sensitive to solar activity at higher SZA for $R_z > 110$. Some kind of saturation effect is found to set in absorption during high solar activity. This fact explains why some workers found the value of b small by treating the data obtained during the IGY-IGC periods (1957-1959) only. The annual average absorption increases by a factor of about 1.45 (or $\sqrt{2}$) at the most, from SS_{min} to SS_{max}. This result is in conformity with the increase by a factor of 2 in ionizing radiation flux, mainly Lyman-α (1215 Å) and 1108 Å responsible for the ionization of main gas species [NO] and O_2 ($^1\Delta_g$) in the D-region since the electron density is proportional to the square-root of electorn-ion production rate and hence to the square-root of ionizing radiation flux. The X-radiation, however, increases by a factor of about 200 when R_z becomes 110 or $S_{10.7}$ reaches 170 units, beyond which it remains at a steady value. It thus appears that the quiet-sun X-radiation is not so important as the UV radiation so far as the general long term variation of absorption in the D-region is concerned. Nevertheless, dense ionization by as much as 10 times the normal is produced in the lower region due to solar X-ray bursts as a result of which there is a complete fadeout or very high absorption of HF radio signal (SID and SWF). Very likely, the larger increase in the soft as well as hard (disturbed sun) X-ray flux causing abnormal effects ionizes other gases also in the height range 70-100 km besides those which account for the normal behaviour of D-region.

The variation of annual mean value of b in Eq. (2) with time shows that b is low around noontime and high in the morning and evening hours for all the three frequencies. Also the seasonal variation of b at constant cos χ shows that the value of b is higher at cos $\chi = 0.6$ than that at cos $\chi = 1.0$. This characteristic variation of b shows that the ionospheric absorption which reaches a stable value around midday is less affected by solar activity than that at other hours when the absorption is in the process of rising or falling. This is understandable because the height of ionized region at larger SZA is greater where the solar ionizing radiation is more effective.

With the values of a and b, evaluated for constant SZA and also at different hours for individual months, it is possible to predict diurnal and month-to-month variation of absorption on a given frequency of the radio wave in the lower ionosphere for any stage of the solar activity cycle.

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References

1 Rawer K, Emmenegger G & Schmidtke G, *Some features of EUV solar activity indices, Paper presented at XXI COSPAR conference held at Innsbruck, Austria*, 1978.

2 Kurian P P, Muralidharan V & Sampath S, *J Atmos & Terr Phys (GB)*, **45** (1983) 285.

3 Kotadia K M, Datta G & Chhipa G M, *Indian J Radio & Space Phys*, **10** (1981) 171.

4 Appleton E V & Piggott W R, *J Atmos & Terr Phys (GB)*, **5** (1954) 141.

5 Patel B M, Patel J C & Kotadia K M, *Indian J Radio & Space Phys*, **2** (1973) 219.

6 Gnanalingam S, *Review Report presented at the Third International Symposium on Equatorial Aeronomy held at Ahmedabad, India*, 1969.

7 Rawer K, *Wireless Engr (GB)*, **29** (1952) 289.

8 Patel D B & Kotadia K M, *Indian J Radio & Space Phys*, **13** (1984) 119.