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Absorption of Radio Waves Reflected at Vertical Incidence as a Function of the Sun's Zenith Angle

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The diurnal variation of ionospheric absorption is related to the sun's zenith angle. The absorption values for this study were obtained from the continuous automatic field-intensity recordings made at the Central Radio Propagation Laboratory on two frequencies. Because of proximity of the receiving station to the transmitting station, reflections are obtained at nearly normal incidence. An analysis of data covering a period of 3 years indicates that little error is introduced by assuming a linear dependence of absorption upon the cosine of the sun's zenith angle.

Maximum ionospheric absorption of radio waves per unit length of virtual path occurs at that height where the product of the electron density and the frequency of collisions with gas molecules is a maximum. This may be shown to be the lower part of the ionosphere for certain radio frequencies. Here the ionization is produced mainly by ultraviolet radiation from the sun. Various theories of the formation of the *E*-layer indicate that the absorption should be proportional to some power of cos X, where X is the sun's zenith angle.

The effect of this absorption is to diminish the field intensity of the reflected wave relative to what it would be in absence of absorption. Thus, if E_0 is the intensity of the wave without loss of energy through absorption, and E is the intensity of the wave as actually received, then

$$E = E_0 10^{-A}, \tag{1}$$

where A is the index of absorption.

The purpose of this report is to express the diurnal variation of this so-called nondeviative absorption, the absorption without appreciable refraction, as

$$A = A_0 \cos^n X, \tag{2}$$

in which X is the zenith angle of the sun and A_0 is the subsolar absorption on the frequency investigated.

In 1944 the Central Radio Propagation Laboratory began a program of recording continuous emissions at vertical incidence. For this purpose four frequencies, namely, 2,061, 4,272, 5,892, and 6,992 kc, were emitted from the radio-transmitting station at Beltsville, Md., and received at the laboratory at Sterling, Va. The base-line distance, about 60 km, is sufficiently short that the reflection can be considered to be at vertical incidence.

The recordings for 3 years, from March 1945 through February 1948, of the 2,061- and 4,272-kc frequencies were analyzed, and the results are presented in this paper. The two higher frequencies were above or near the critical frequency of the *F*2-layer for a considerable part of the time and have, therefore, been excluded from this study.

During the night when the absorption is negligible, the field intensity was assumed to be diminished only by the inverse distance attenuation. This field intensity is referred to as the unabsorbed field intensity. The absorption for any time can be found from the logarithm of the ratio of the received field intensity at that time to the unabsorbed field intensity. The recorded values are in logarithms of microvolts input to the receiver, thus the absorption for any value of cos X is the difference between unabsorbed field intensity and the field intensity received at the time for which that value of cos X obtains.

The median values of received field intensity in logarithms of microvolts input to receiver for each hour of the day were determined from the recordings. These data were grouped by seasons; summer—May, June, July, August; equinox—March, April, September, October; winter—

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TABLE 1. *Average values of absorption index on 2061-kc frequency at vertical incidence corresponding to the values of the cosine of the sun's zenith angle at the middle of the hour, calculated to the nearest 0.05*

The values in columns A are the average values of the absorption index and the values in columns N are the number of hours used to determine the average.

cos X	Apr., Sept., Oct., 1945		May, June, July, Aug., 1945		Nov., Dec., 1945; Jan., Feb., 1946		Mar., Apr., Sept., Oct., 1946		May, June, July, Aug., 1946		Nov., Dec., 1946; Jan., Feb., 1947		Mar., Apr., Sept., Oct., 1947		May, June, July, Aug., 1947		Nov., Dec., 1947 Jan., Feb., 1948	
	A	N	A	N	A	N	A	N	A	N	A	N	A	N	A	N	A	N
0.10	0.44	10	----	---	0.72	11	1.27	21	0.55	17	0.65	17	0.97	18	0.79	10	1.05	31
.15	.50	21	0.34	4	.72	36	0.59	23	.75	29	.84	49	.75	36	.64	42	1.03	78
.20	.50	38	.36	19	.79	73	.63	50	.51	43	.81	68	.76	56	.61	51	0.93	52
.25	.50	34	.46	40	.61	68	1.02	55	.73	40	1.09	64	.85	76	.80	39	1.00	67
.30	.58	41	.47	92	.95	65	1.11	55	.70	94	1.13	79	1.11	58	.92	85	1.23	112
.35	.56	53	.65	66	1.03	88	0.82	78	.90	62	1.23	93	1.09	93	.98	50	1.23	63
.40	.65	49	.56	35	1.14	123	.84	62	.77	40	1.44	123	1.11	61	1.02	37	1.39	134
.45	.80	53	.69	60	1.22	160	1.52	71	1.11	51	1.54	124	1.35	74	1.12	48	1.49	163
.50	.81	57	.73	94	1.32	120	1.17	79	1.00	94	1.60	152	1.43	77	1.31	80	1.52	130
.55	.93	56	.81	70	1.47	88	1.39	80	1.18	70	1.63	95	1.57	84	1.42	85	1.52	104
.60	1.05	72	.79	38	1.48	42	1.62	93	1.40	39	1.57	46	1.70	89	1.57	36	1.53	33
.65	1.12	90	.96	107	1.71	19	1.52	108	1.31	107	1.78	17	1.76	98	1.63	117	1.61	26
.70	1.20	75	1.12	88	----	---	1.67	101	1.54	63	----	---	1.79	96	1.61	54	----	----
.75	1.27	76	1.10	57	----	---	1.73	110	1.69	53	----	---	1.83	101	1.88	46	----	----
.80	1.24	73	1.24	146	----	---	1.61	102	1.64	134	----	---	1.92	90	1.93	130	----	----
.85	1.37	68	1.36	117	----	---	1.83	69	1.76	97	----	---	2.04	52	1.98	82	----	----
.90	1.54	24	1.44	226	----	---	1.93	26	1.96	213	----	---	2.06	25	2.01	183	----	----
.95	----	--	1.54	142	----	---	----	---	1.98	144	----	---	----	---	2.03	144	----	----

TABLE 2. *Average values of absorption index on 4,272 kc frequency at vertical incidence corresponding to the values of the cosine of the sun's zenith angle at the middle of the hour, calculated to the nearest 0.05*

The values in column A are the average values of the absorption index and the values in columns N are the number of hours used to determine the average

cos X	Mar., Apr., Sept., Oct., 1945		May, June, July, Aug., 1945		Nov., Dec., 1945 Jan., Feb., 1946		Mar., Apr., Sept., Oct., 1946		May, June, July, Aug., 1946		Nov., Dec., 1946 Jan., Feb., 1947		Mar., Apr., Sept., Oct., 1947		May, June, July, Aug., 1947		Nov., Dec., 1947 Jan., Feb., 1948	
	A	N	A	N	A	N	A	N	A	N	A	N	A	N	A	N	A	N
0.10	0.23	11	0.13	22	0.13	41	0.22	24	....	21	0.12	18	0.25	30	0.20	19	0.12	39
.15	.28	26	.21	48	.22	62	.17	46	0.27	41	.17	61	.22	45	.22	61	.18	62
.20	.22	60	.27	47	.30	84	.20	86	.29	44	.23	68	.25	61	.34	33	.22	83
.25	.22	60	.40	25	.30	63	.36	76	.42	28	.26	66	.22	69	.41	35	.24	69
.30	.35	50	.42	81	.34	84	.40	39	.51	73	.32	81	.37	58	.40	75	.34	78
.35	.35	62	.42	63	.42	68	.36	79	.57	64	.40	93	.37	73	.41	55	.35	86
.40	.37	59	.54	35	.45	125	.43	58	.61	24	.49	121	.44	59	.55	34	.50	122
.45	.45	72	.60	56	.56	164	.61	71	.68	40	.56	153	.50	99	.57	43	.59	167
.50	.53	76	.66	61	.60	128	.67	77	.71	73	.61	126	.63	77	.61	66	.65	126
.55	.60	61	.76	73	.74	91	.66	69	.73	55	.62	94	.67	90	.65	61	.67	94
.60	.64	66	.61	37	.71	39	.79	84	.83	27	.76	63	.80	59	.60	33	.64	43
.65	.72	99	.64	95	.84	22	.76	100	.79	78	----	---	.92	108	.64	65	.69	25
.70	.77	103	.92	86	----	---	.86	98	.91	67	----	---	.97	97	.93	71	----	----
.75	.81	102	.89	63	----	---	.98	99	1.03	47	----	---	1.10	103	1.15	40	----	----
.80	.91	91	.91	124	----	---	1.01	83	0.97	102	----	---	1.14	96	1.23	91	----	----
.85	1.00	65	.99	106	----	---	1.02	66	1.12	85	----	---	1.42	46	1.36	71	----	----
.90	0.91	25	1.00	211	----	---	1.09	22	1.18	186	----	---	1.47	19	1.50	125	----	----
.95	----	--	1.01	119	----	---	----	---	1.22	101	----	---	----	---	1.67	84	----	----

November, December, January, February. The cosine of the sun's zenith angle was calculated to the nearest five-hundredths for the middle of each hour. From these data the mean value of absorption corresponding to a particular position of the sun was determined. Corrections were made for the presence of the earth's magnetic field and for multiple reflections, so that the results are the average absorption index of the ordinary component of a single ray for each value of cos X for each season.

The values of absorption for the two lower frequencies (2,061 and 4,272 kc) are given in tables 1 and 2. The number of hours used to determine the mean value is also given. During the early morning hours, when the sun's zenith angle is great, the electron density of the *E*-layer is not high enough to reflect the 2,061-kc frequency. This accounts for the scarcity of data for these periods.

In figure 1 the values of the absorption index for the 2,061-kc frequency plotted against cos X are shown. A line was fitted to each set of points by visual adjustment and its slope determined. The

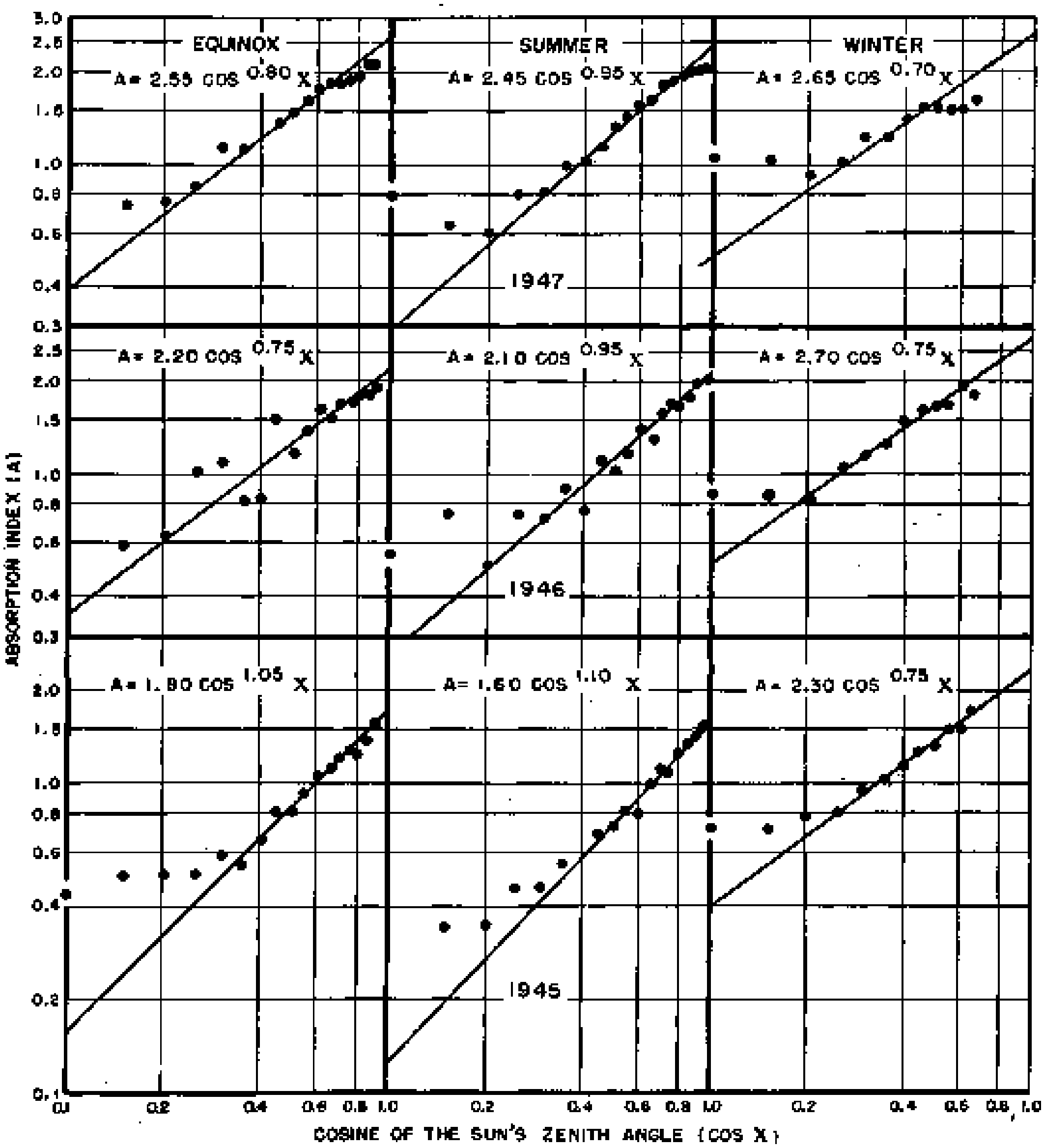

FIGURE 1. *Dependence of absorption at vertical incidence at 2,061 kc on cosine of sun's zenith angle.*

slope is the power of cos X and has a mean value of 0.87 for this frequency. The departures of the plotted points from a straight line for low values of cos X are perhaps due to the scarcity of data when the solar radiation angle is low, indicating inaccuracy of the law for periods near grazing incidence of solar radiation. In 1947 and 1948, the records show ground-wave rather than sky-wave propagation for several hours around noon. The recorded field-intensity values are higher than the sky-wave intensities, and the absorption values are greater than indicated. This was taken into account in fitting the lines to the data.

Figure 2 shows similar plots for the 4,272-kc frequency. The mean value of the slope is 1.07. Difficulty was encountered in analyzing these data, because the layer from which reflections are obtained appears to change during the day. Increases in absorption are attributed to increases in height of reflection. An appreciably greater change of log A with log cos X is noted during the equinox and summer of 1947 when the sunspot numbers were very high.

Table 3 gives the values of A_0, the absorption at cos X=1.00, for each season as obtained from the data for these two frequencies, and the mean sunspot number for the same period. Although the exact rate of change of A_0 with sunspot number

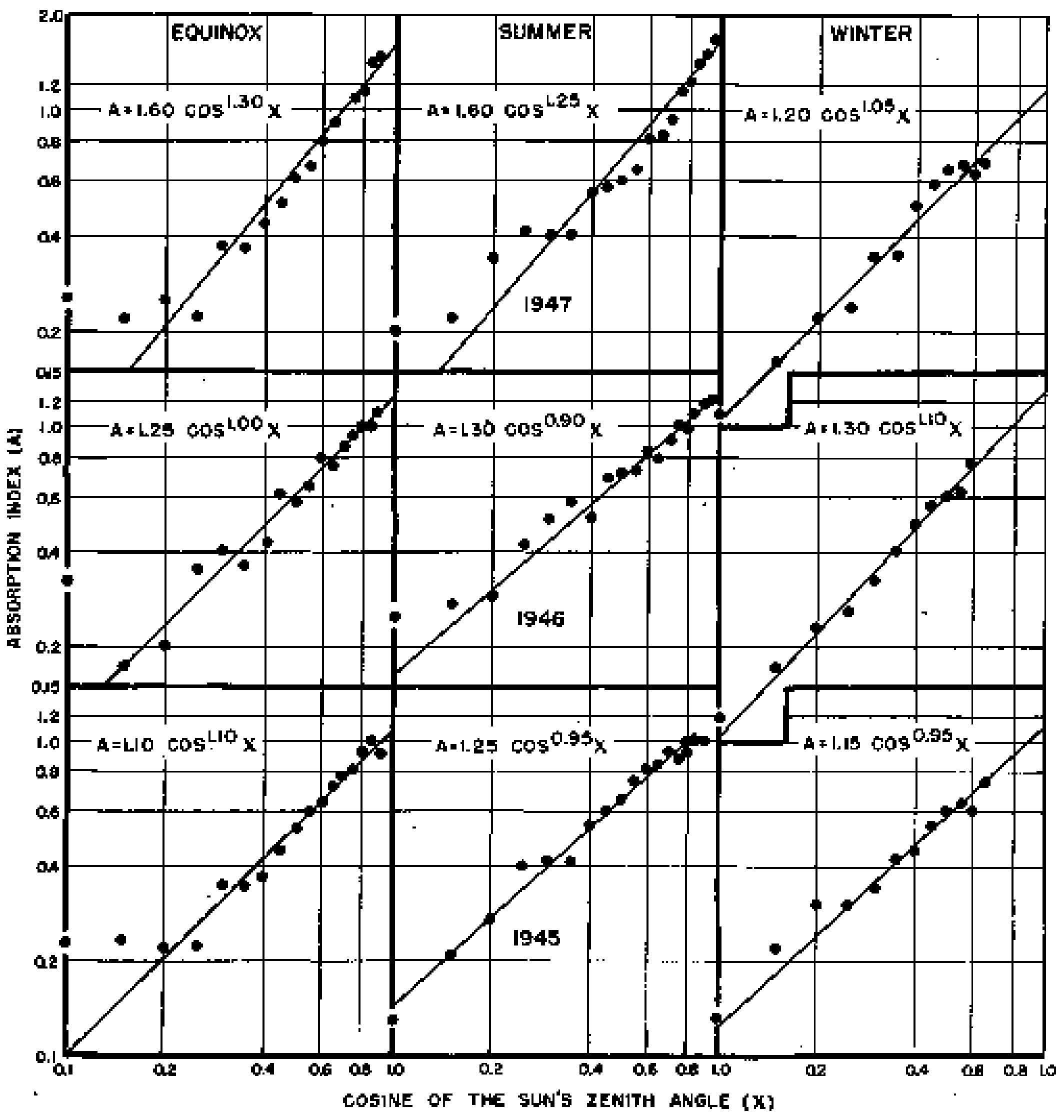

FIGURE 2. *Dependence of absorption at vertical incidence at 4,272 kc on cosine of sun's zenith angle.*

TABLE 3. *Intercepts (A_0) and slopes (n) of absorption equation $A = A_0 \cos^n X$ for 2,061 and 4,272 kc*

Year	Equinox					Summer					Winter				
	Sunspot number	2,061 kc		4,272 kc		Sunspot number	2,061 kc		4,272 kc		Sunspot number	2,061 kc		4,272 kc	
		A_0	n	A_0	n		A_0	n	A_0	n		A_0	n	A_0	n
1945	39	1.80	1.05	1.10	1.10	34	1.60	1.10	1.25	0.95	62	2.30	0.75	1.15	0.95
1946	87	2.20	0.75	1.25	1.00	95	2.10	0.95	1.30	.90	123	2.70	.75	1.30	1.10
1947	159	2.55	.80	1.60	1.30	185	2.45	.95	1.60	1.25	109	2.05	.70	1.20	1.05

has not been determined in this paper, the values show increases in absorption with increased sunspot numbers.

Although the slopes of the A—cos X curves are different for the two frequencies, the variations with season and sunspot number appear to be random. This slope, which represents the changes in absorption from one position of the sun to another, is the power to which cos X is raised in eq 2. The data analyzed in this paper indicate that the law of absorption is different for the two frequencies but constant with season and sunspot number. As the mean values of the slopes for both frequencies are close to unity, the first power of cosine X will express the diurnal variation of absorption sufficiently well for practical purposes.

It is concluded from this analysis that a linear dependence on cosine of the sun's zenith angle is a simple expression that will give the absorption to be expected on any particular frequency at vertical incidence in the daytime. Higher absorption than would be predicted by this law is observed when the sun's zenith angle is close to 90°. The absorption when the solar radiation is incident at other angles increases with increasing solar activity.

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