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Report on
The Ionosphere, Skip Distances of
Radio Waves and the Propagation of Micro-Waves

by

E. C. Hulburt

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NAVY DEPARTMENT
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The Ionosphere, Skip Distances of
Radio Waves and the Propagation of Micro-Waves.

NAVAL RESEARCH LABORATORY
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E.O. Hulburt, Physicist.
Reviewed by: _____
A.H. Taylor, Supt., Radio Division
Approved by: _____
H.M. Cooley, Captain, USN, Director
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ABSTRACT

A detailed description of the ionosphere is given based on the recent measurements of The National Bureau of Standards and the Department of Terrestrial Magnetism of the Carnegie Institution.

From the ionosphere data the skip distances of radio waves are calculated for temperate and tropical zones, with the diurnal and seasonal changes. The values agree with the observed values as far as they are known. It is concluded that daylight short wave communication is controlled by the E region in summer and by the F₂ region in winter.

Theory indicates that the observed bending of micro-waves over the horizon, and hence the successful micro-ray communication to a distance of 200 km, is due to diffraction of the micro-waves over the bulge of the earth, and to temperature gradients in the lower atmosphere.

AUTHORIZATION

1. The report is submitted in connection with NRL Problem No. W3-2, "Study of Superfrequencies", authorized by Bureau of Engineering letter NPL4/NS (2-23-WS) of 1 March 1934.

CHAPTER I

INTRODUCTION

2. The ionized regions of the upper atmosphere, known as the "ionosphere", are important in the long distance propagation of radio waves, for the waves pass over the curve of the earth by successive reflections between the ionosphere and the surface of the earth. The skip distances of the shorter waves depend on the amount of ionization in the ionosphere and upon its height above the surface of the earth. Thus knowledge of the ionosphere leads to information about radio communication. It is only recently that extensive quantitative data of the ionosphere have become available.

3. A program of measurements by means of the radio echo method of Breit and Tuve¹ was entered upon by the Department of Terrestrial Magnetism of the Carnegie Institution in cooperation with the United States National Bureau of Standards, with stations at Washington, D.C., latitude 39° north, and at Huancayo, Peru, latitude 12° south. Results have appeared in a series of papers² which may be regarded as a first approach to a world wide survey of the ionosphere. The data cover three years' observations at Washington and one year at Huancayo.

4. In the present report the main features of the ionosphere are described. From the measured values of the ionization in the ionosphere the skip distances for Washington and Huancayo are calculated throughout the day and the season. The bending of waves below 10 meters over the bulge of the earth is discussed.

CHAPTER II.

THE IONOSPHERE

5. In any region of ionization the electron density, i.e. the number of electrons per cubic centimeter, increases with the height above sea level to a maximum value. At this point the height is denoted by z and the electron density by y ; z is termed the "height of the region above sea level" and y the "density of ionization of a region", although it is realized that the region of ionization may extend many kilometers above and below z . The radio echo method gives the "virtual", or optically equivalent, height z' of a region; this is always greater than the true height z of the region, but usually not very much greater. Although the exact value of $z' - z$ can not be determined from the experimental data, one can estimate whether it is large or small from the manner in which z' changes with the radio frequency of the echo.

6. During the day there are three main regions of ionization in the ionosphere and two at night. These are designated by E, F_1 and F_2 for day and by E and F for night, the daytime regions F_1 and F_2 coalescing to form the night F region.

7. The heights of the ionized regions. The observed virtual heights z' of all the regions are given in Plates 1 and 2 for Huancayo from November 1933 to August 1934 and for Washington from April 1933 to March 1934. z' is probably not more than 20 km greater than z for E, F_1 and F and not more than 50 km greater than z for F_2 . From the data of Plates 1 and 2 the following conclusions may be stated. The height of E above sea level is about 100 km and remains constant within 20 km for day, night, latitude and season. F_1 is at about 200 km above sea level and its height varies less than about 30 km with the latitude and season. The night F region is at about 250 km above sea level, any variance with latitude and season being less than about 30 km. The height of F_2 , however, exhibits pronounced changes with the time of day, the latitude and with the season in temperate latitudes. It increases to a maximum value at about noon at both Washington and Huancayo, the noon values at Washington being about 350 and 250 km for summer and winter, respectively; the height at Huancayo the year round was about the same as for summer conditions at Washington.

8. The density of ionization of the ionized regions. It may be stated without giving the details that experiment has shown that the ionization in F_1 , F_2 and F is predominately electronic as far as the refraction and absorption of radio waves is concerned. Whether E is electronic or ionic has not yet been determined; some experiments indicate mainly ions and some show the presence of electrons. However, for considerations of radio wave propagation, there is no error in treating the ionization in all regions as though it were electronic.

9. The observational data of y at Washington² are in the form of monthly averages of hourly values through the day and night over the year from April 1933 to March 1934, and at Huancayo² from November 1933 to August 1934. A portion of the measurements is given in Plates 3 to 7. The data show that y of E and F_1 increases during the day to a maximum value at about noon, being greater in summer than in winter for Washington; for Huancayo y of E and F_1 exhibited no marked variations with the season of the year.

Huancayo is so near the equator that large seasonal variations would not be expected. At night y of E decreases to values below 0.3×10^5 , which are too low to be measured within the range of the present radio echo equipment. Sudden and erratic increases were often observed in y of E at night which might persist for a few minutes or an hour or more.

10. The diurnal and seasonal variations in y of F_2 are complex. At Huancayo and at Washington in the summer y of F_2 has two maxima, a ragged and erratic maximum in the morning, a minimum near noon and a higher broader maximum in the afternoon. In winter at Washington y of F_2 is a maximum around noon. y of F_2 is at all times more variable than y of E or F_1 , its actual value at any particular time may vary as much as 40% from day to day. At Huancayo and for summer and equinox at Washington, y of F at night decreases through the night with occasional temporary increases of as much as 50%. For mid-winter nights at Washington y of F diminishes during the early part of the night, it then increases to a maximum between 2 and 4 A.M., and diminishes again until the rise at dawn.

11. General description of the ionosphere. From the data of Plates 1 to 7, we may describe the main world-wide features of the ionosphere as follows:

The E and F_1 regions are fairly simple, they lie at about 100 and 200 km levels, respectively. The density of ionization of each is a maximum directly under the sun, so that the E region fades away in the night and the F_1 region is swallowed up on the twilight meridian by the descending F_2 region. The F_2 region is more complicated. It bulges out toward the sun, being 300 to 400 km away from the surface of the earth at its most lofty point, and sinks back to a 250 km level in the twilight zone. Its density of ionization is always greater and more variable than that of the E and F_1 regions. In tropical latitudes its density of ionization has two maxima, an irregular one around 10 A.M. and a larger, smoother one near sunset; in temperate latitudes there is a single maximum in winter and in summer there are two maxima similar to the tropical case except that often the morning maximum is ill-defined. During the night, apart from irregular ups and downs, the F ionization density diminishes at all latitudes except for a recrudescence in the small hours of winter morning in temperate latitudes.

12. The ionosphere and solar activity. The data of Plates 1 to 7 were obtained during 1933 and 1934, an epoch of sunspot minimum and few magnetic disturbances. They therefore refer fairly well to the period of solar quiescence.

13. Maximum solar activity is expected to occur about 1938. The observed changes in the skip distances during a sunspot cycle and a few ionosphere measurements indicate that the values of y should increase by about 50% from 1933 to 1938.

14. Detailed investigation of the ionosphere during magnetic storms has not yet been carried out. A number of observations indicate that the ionized regions, particularly the upper ones, are much confused during strong magnetic disturbances.

CHAPTER III.

SKIP DISTANCES OF RADIO WAVES

15. Approximate formula for skip distance. The skip distance $2s$ of a radio wave of wavelength λ is related to y and z by the relation³

$$\frac{ye^2\lambda^2}{4\pi m} = 1 - \frac{\sin^2 s/r}{\sin^2 s/r + (1 + z/r - \cos s/r)^2} \quad (1)$$

where r is the radius of the earth, and e and m are the charge and mass of the electron; c.g.s.e.m. units are used. The skip distance varies with the state of polarization of the radio wave and with the direction of propagation with respect to the magnetic field of the earth. The amount of the variation is not large, being in most cases less than 15% of $2s$, and (1), which refers to the polarization or propagation such that the electric vector of the wave is parallel to the magnetic field of the earth, is a fair average among the possible variations. (1) is approximate in that it is based on the assumption that the waves experience reflection from the ionized region, as if the region were a mirror. The approximation has been shown to be valid³, although the waves probably are bent back to the earth by refraction in the region. In applying (1) to the case of several ionized regions, the assumption is made that the density of ionization between the regions is small; the assumption probably leads to no serious error.

16. Skip distances during minimum solar activity. The values of the skip distances were calculated by means of (1) with the values of y and z of Plates 1 to 7, and are plotted in the curves of Plates 8 to 11 for various times of day and seasons of the year 1933-1934. The period was one of minimum solar activity and it is of interest to compare the calculated skip distances with the average daytime temperate zone skip distances observed⁴ in 1923, also a period of minimum solar activity. The comparison is shown in Table 1; it is seen that the average of the last three columns, which are the calculated values taken from Plates 8, 9 and 10, agree well with the observed values in the second column.

TABLE 1.

Day Skip Distances.

	Observed 1923-24	From Plate 8. Jan. 1934	From Plate 9. March, 1934	From Plate 10. June, 1933
λ				
40 meters	400 km	400 km	500 km	400 km
30	700	800	800	700
20	1200	1400	1300	1200
16	2000	2300	2200	2200

17. It may be emphasized that the curves of Plates 8 to 11 offer a more complete world-wide survey of the skip distances than has heretofore been available. Plate 8 shows that the winter skip distances reach their

greatest lengths around midnight and then become shorter from 2 to 4 A.M. It is not certain that this effect has been observed. The effect is probably erratic, for the recrudescence of ionization in the small hours of winter night to which the effect is due, is erratic. It is a matter of general experience that the skip distances in the early morning hours are variable and ill-defined.

18. In Plates 8 to 10 no skip distance curves are given for the sunrise period between 3 A.M. and 9 A.M., because the ionosphere data for all regions are not sufficiently complete during these hours. The data indicate roughly that the average skip distances do not change much between 3 A.M. and sunrise, and that after sunrise they shorten rapidly.

19. Effect of the various regions of ionization on short wave propagation. Since there are several regions of ionization, the skip distances for each epoch were calculated for each region by the use of y and z for the region. The region which gave the shortest values of $2s$ was of course the region which controlled the skip distances for the epoch in question. In the curves of Plates 8 to 11 the region which controlled the skip distances is marked on each curve. From this certain new facts stand out. For example, it is seen from Plate 10 that at Washington in summer the skip distances during the day are controlled by the E region. This means that low angle rays, which are those of long distance propagation, are turned down by E and do not get through to F_1 or F_2 at all. Whereas in winter, Plate 8, the skip distances are controlled by F_2 , and hence low angle rays pierce through E and F_1 to be refracted by F_2 . Therefore long distance short wave communication in winter is by rays which experience less than half the number of earth and ionosphere reflections which they experience in summer, since F_2 is more than twice as high as E. Further, absorption of energy from the radio wave is greater in E than in F_2 , since the molecular density in E is greater than in F_2 . Thus we find an explanation of the well known fact that in general long distance short wave communication is better in winter than in summer.

20. The summer afternoon case, as shown by the 5 P.M. curve of June at Washington, Plate 10, presented the complexity that for waves from about 20 to 40 meters the skip distances were controlled by E, and for waves below 20 meters the skip distances were controlled by F_2 . One might conclude that better temperate zone summer afternoon short wave communication would be achieved by decreasing the wavelength until penetration of E was secured. However, such a conclusion is hardly safe in view of the fact that the values of y of Plates 3 to 7 are monthly average curves of ionization which fluctuated within fairly wide limits from day to day; and any conclusion, as the foregoing, which demands high accuracy of the ionization curves, is not dependable.

21. Other possibilities appear from the ionization curves. For example, a ray of waves of the correct wavelength and correct angle to the horizontal to pass through E transmitted southward from Washington might be refracted downward by F_1 or F_2 to E again over, say, Florida, and because of the increased y of E, due to the lower latitude, the ray might not penetrate E but be refracted upward again to F_1 or F_2 ; and so on, until the ray finally reached the latitude where it could get through E down to earth again. Such a ray would have an abnormally long skip. Similarly for east west

propagation, where the change in y of the regions of ionization with longitude at any specified instant of time might introduce various complicated effects.

22. The shortest wavelength useful for long distance communication. The skip distance curves of Plates 8 to 10 rise rapidly with decreasing wavelength and soon become imaginary. The value of λ at this point, denoted by λ_1 , is the shortest wavelength useful for long distance communication, since waves shorter than λ_1 are not refracted back to the earth again. λ_1 may be determined from the 2s, λ curves of Plates 8 to 11, or, what amounts to the same thing, may be calculated directly from the relation

$$\frac{ye^2\lambda_1^2}{4\pi} = 1 - \left[r/(r+z) \right]^2 \quad (2)$$

where λ_1 refers to the region of height z and ionization density y .

23. λ_1 is tabulated in Table 2. The values are open to considerable uncertainty, as much as 20%, for (2), being a limiting case of (1), depends on the same assumptions as (1), but is more sensitive than (1) to errors in the assumptions. Table 2 agrees in general with the observed values as far as they are known. A possible discrepancy is that according to the Table λ_1 for noon at Washington is slightly greater in June than in January, whereas qualitative experience appears to indicate the reverse.

TABLE 2.

Values of λ_1

	Washington, 1933-34			Huancayo, 1933-34
	January	March	June	Year average
6 A.M.	-	-	-	18
9 A.M.	15 m	19	17	13
Noon	14	17	16	13
3 P.M.	15	19	17	13
5 P.M.	19	17	16	10
9 P.M.	42	17	17	12
Midnight	42	32	28	13
3 A.M.	28	38	42	20

24. Skip distances, the shortest useful wavelengths and the sunspot cycle. The skip distances 2s of Plates 8 to 11 and the shortest useful wavelengths λ_1 of Table 2 refer to 1933 and 1934, a period of approximately sunspot minimum. Fragmentary data indicate that the ionization y of the regions of the ionosphere increases by about 50% from the minimum to the maximum of the sunspot cycle. From (1) and (2) 2s and λ_1 are roughly proportional to the reciprocal of the square root of y . Therefore at sunspot maximum in 1938 2s and λ_1 should be 20 to 30% less than the values of Plates 8 to 11 and Table 2. It will be of interest to calculate 2s and λ_1 each year as the ionosphere data of the year become avail-

able. Comparison will be possible between the calculated values for 1938 and the skip distances observed⁶ during 1927-28, the last epoqe of maximum solar activity.

CHAPTER IV.

THE BENDING OF MICRO-WAVES OVER THE HORIZON

25. Experiments have shown that radio waves below 10 meters in length, at the present time termed "micro-waves", may be received at moderate distances over the horizon from the transmitter. Available evidence indicates that the micro-rays are not sufficiently refracted by the ionosphere to turn them back to the earth again. Therefore to account for the wave energy over the bulge of the earth one must turn to other causes. Refraction of the waves in the lower atmosphere and diffraction are obvious causes which come to mind and, as shown in the following paragraphs, appear adequate to account for the observed effects.

26. Diffraction of micro-waves over the curve of the earth. A complete solution of the diffraction of electromagnetic waves over the curve of the earth is complicated. An approximate solution was obtained by Epstein⁷ for moderate distances neglecting effects of the atmosphere. Denote the distance of the transmitter from its horizon by b and the great circle distance from the transmitter to the receiver by x . For x not much greater than b the expression for the energy at the receiver involved a number of integrals and for x large with respect to b , and not too large, the energy E at the distance x was given by

$$E = E_0 r^2 / \pi^2 \lambda (x - b)^3 (x + b) x, \quad (3)$$

where E_0 is the energy at the transmitter, r is the radius of the earth and λ is the wavelength. Approximately (3) becomes

$$E = E_0 r^2 / \pi^2 \lambda r^5 \quad (4)$$

This yields a decline of the energy inversely as the fifth power of the distance.

27. Marconi⁸ transmitted 50 to 60 cm waves from an elevation of 750 meters and found that reception over water was usually good up to about 200 km and occasionally to 230 km. The distance b to the optical horizon was 98 km. Epstein evaluated the expression for E at various distances as given in Table 3, putting $E = 1$ at 98 km. From the table it is seen that at $x = 200$ km, or 102 km from the optical horizon of the transmitter, the energy was about 1/200 of the energy at the optical horizon. Such an intensity appeared to be detectable and Epstein concluded the experimental range of the waves did not materially exceed the expectations of a theory disregarding all atmospheric influences.

TABLE 3.

x	E	x	E
98 km	1.00	180 km	0.012
100	0.96	200	0.0052
120	0.22	220	0.0026
140	0.057	240	0.0014
160	0.020	250	0.0011

28. It is noted that (3) or (4) yields an energy inversely proportional to the wavelength. Therefore the intensity of longer waves bent over the horizon is less than that of shorter waves, although the rate of attenuation with the fifth power of the distance is the same for all wavelengths.

29. Refraction of electromagnetic waves in the lower atmosphere. If the refractive index of air decreases upward, electromagnetic rays passing horizontally through the air will be bent downward. In order for the rays to be bent with the curvature of the earth the refractive index μ must satisfy the relation

$$\frac{d\mu}{dr} = - \frac{\mu}{r} \quad (5)$$

where r is the radius of the earth, dr being positive away from the earth.

30. An upward decrease in μ may be caused by (a) an upward increase in temperature, (b) an upward decrease in water vapor, (c) an upward decrease in pressure and (d) an upward increase in ionization. Of these four possible causes it will be shown that geophysical conditions are such that probably (a) is the most important, (b) is doubtful and (c) and (d) are inappreciable.

31. The refractive index of air for waves longer than the infra red is $\mu = 1.00027$, and with $r = 6.36 \times 10^8$ cm (5) becomes

$$d\mu = - 1.57 \times 10^{-9} dr. \quad (6)$$

The change in μ with the temperature t is given by

$$d\mu = - 5.5 \times 10^{-7} dt. \quad (7)$$

Whence from (6) and (7)

$$\frac{dt}{dr} = 0.029^\circ \text{ Centigrade}. \quad (8)$$

Therefore t must increase upward 0.029° Centigrade per cm, or about 1° per 10 feet, in order that the rays be bent with the curvature of the earth. Temperature gradients of this magnitude due to warm and cold streaks in the air occur and would be expected to cause fading and strengthening of micro-ray signals.

32. The conclusion is in accord with the recent results of Hull⁹ in his 5 meter transmissions over a distance of 148 km, one terminal being 200 meters and the other 100 meters above sea level. In 239 days of communication schedules only 5 days were missed because of insufficient signal level. We may conclude that the reliable communication was due to diffraction. Further, the strongest signals were obtained when the temperature increased upward as observed in airplanes to an altitude of 2,000 meters. The highest signal levels were obtained on occasions when a warm tropical air was overrunning a cold polar air. This is in keeping with the temperature gradient refraction calculation.

33. The refraction calculation based on (5), (6) and (7) is independent of the wavelength; it is the same for all wavelengths from the infrared to the longest radio wave. It is similar to the calculation under-

lying the explanation of the twinkling of lights and stars. However, in considering radio waves one must keep in mind the relative size of the radio wave and the regions of the atmosphere where the temperature gradients exist. For example, a warm streak of air 30 feet across would be large enough to bend downward a 5 meter wave but would have no noticeable effect on a 100 meter wave.

34. The effect of water vapor, case (b), may be calculated from the dielectric constant 1.0072 for pure water vapor at 17°C and atmospheric pressure, measured by Zahn¹⁰ for frequencies of the order of 1 kilocycle, assuming that the same value is true for the frequencies of micro-waves. It turns out that to bend the rays downward with the curvature of the earth there is required a water vapor gradient such that there is saturated vapor at 20°C at one point and zero vapor at a point 1 km higher. Gradients of this amount, and greater, probably occur in the lower atmosphere. A priori the gradients might be either plus or minus, that is, the water vapor might increase or decrease upward, depending on the previous history of the atmosphere. Thus, the water vapor might bend the rays either up or down.

35. However, Hull⁹ found good agreement between the 5 meter reception and temperature inversion. We may conclude that in his experiments either the water vapor bending was usually small compared to the temperature inversion bending, or that the water vapor bending was usually in the same direction as the temperature inversion bending.

36. Referring to (c), in order for refraction due to an upward decrease in pressure to satisfy (6), the change in pressure p with r must be

$$\frac{dp}{dr} = 10.5 \text{ dynes/cm}, \quad (9)$$

which amounts to a decrease of 1050 dynes per meter. This is about 10 times the normal decrease in pressure with altitude in the lower atmosphere. Such large pressure gradients do not occur except in very abnormal meteorological conditions as tornadoes and water spouts. We may conclude that pressure gradients in the atmosphere are very rarely large enough to cause appreciable refraction of radio waves, long or short. Similar calculations led to the same conclusion for (d) gradients in the ionization of the lower atmosphere.

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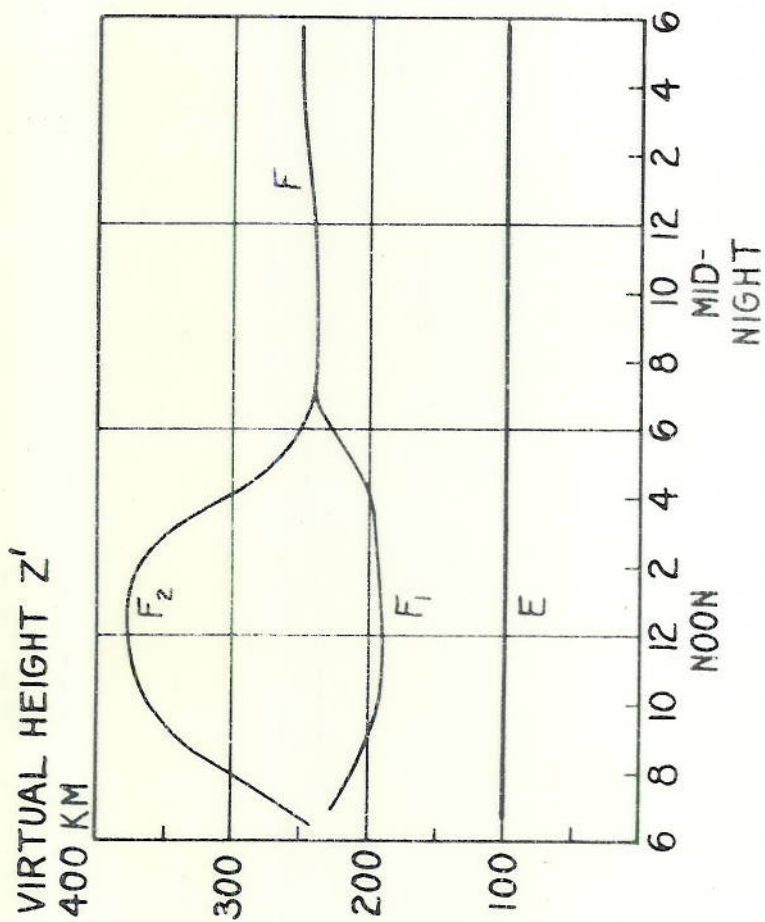


PLATE I. VIRTUAL HEIGHT OF THE IONIZED REGIONS
DURING 1933 AND 1934 AT HUANCAYO,
LATITUDE $12^{\circ} 3'$ SOUTH.

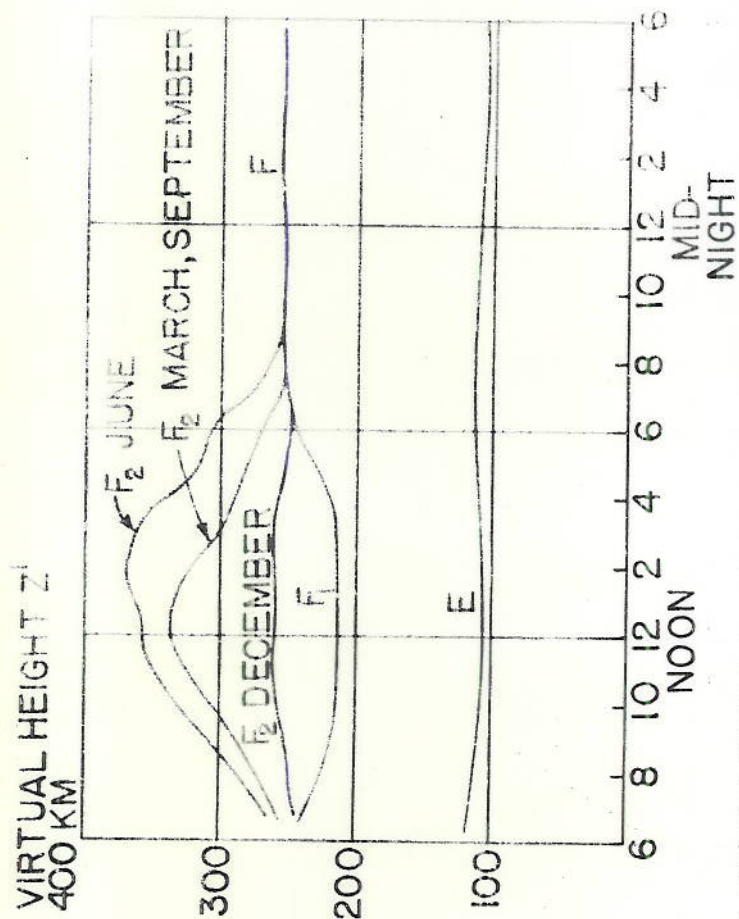


PLATE 2. VIRTUAL HEIGHT OF THE IONIZED REGIONS
DURING 1933 AND 1934 AT WASHINGTON,
LATITUDE $39^{\circ} 38'$ NORTH.

JUN 17 1935

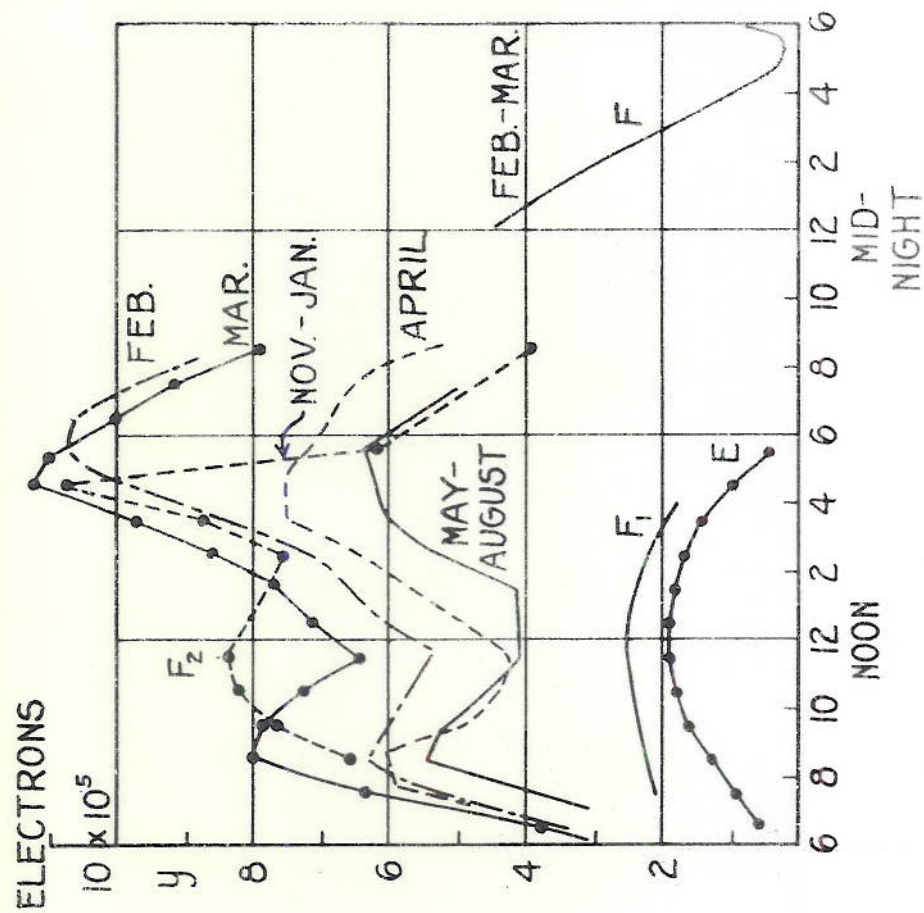


PLATE 3. THE IONOSPHERE AT HUANCAYO,
NOVEMBER 1933 TO AUGUST 1934.

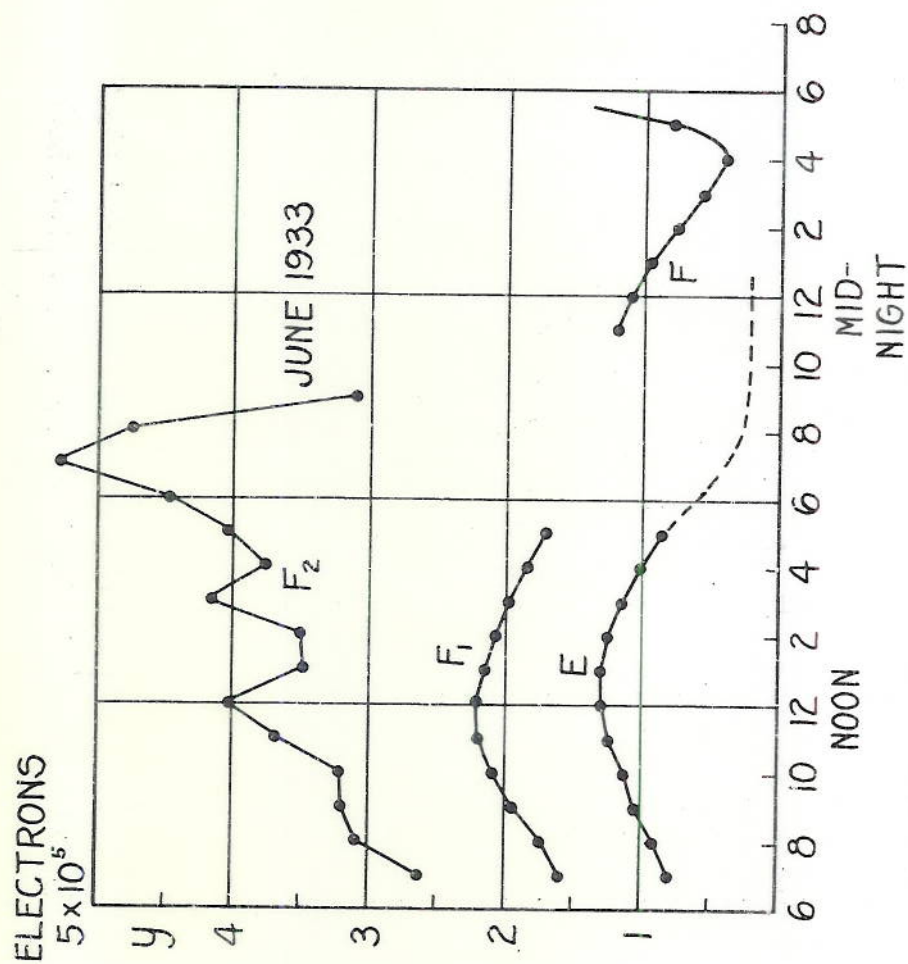


PLATE 4. THE IONOSPHERE AT WASHINGTON,
JUNE 1933.

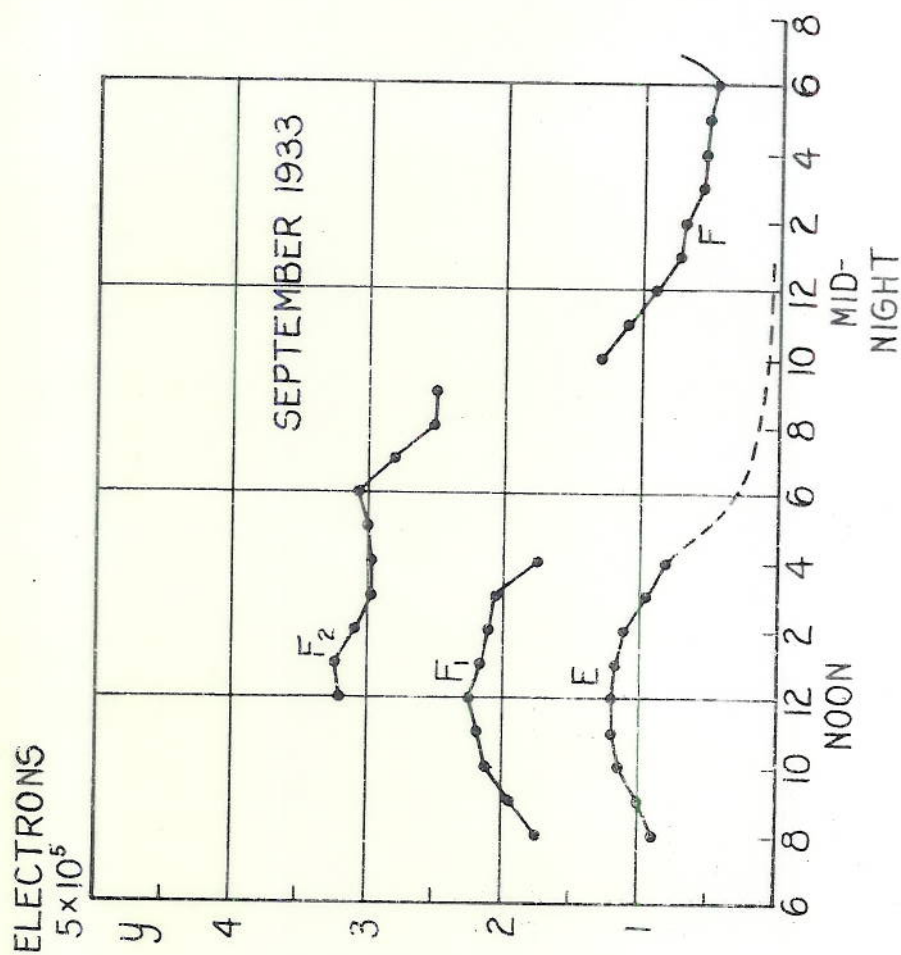


PLATE 5. THE IONOSPHERE AT WASHINGTON,
SEPTEMBER 1933

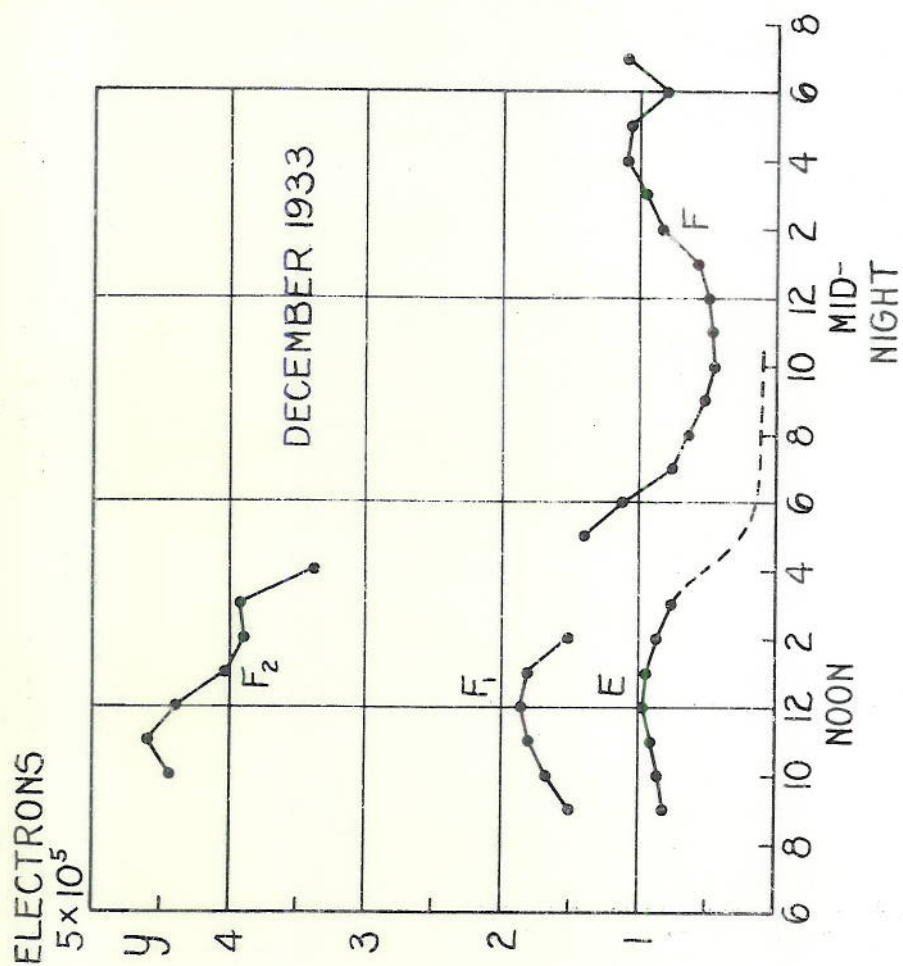


PLATE 6. THE IONOSPHERE AT WASHINGTON,
DECEMBER 1933.

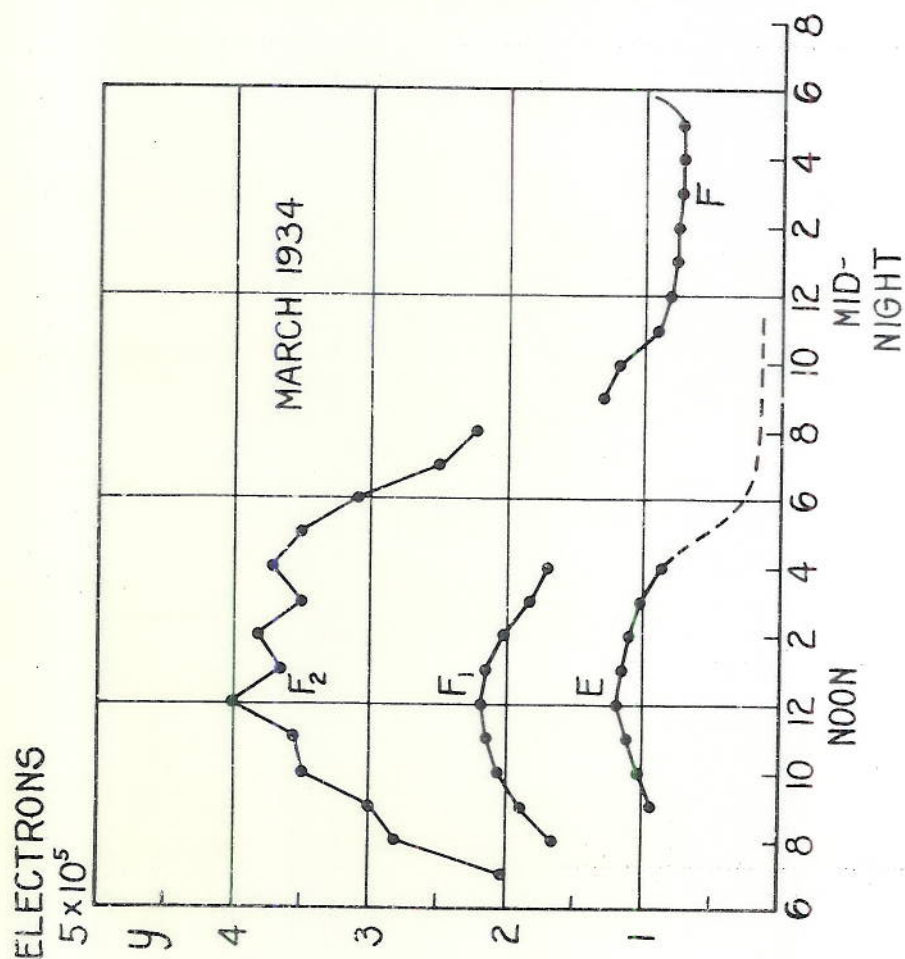


PLATE 7. THE IONOSPHERE AT WASHINGTON,
MARCH 1934.

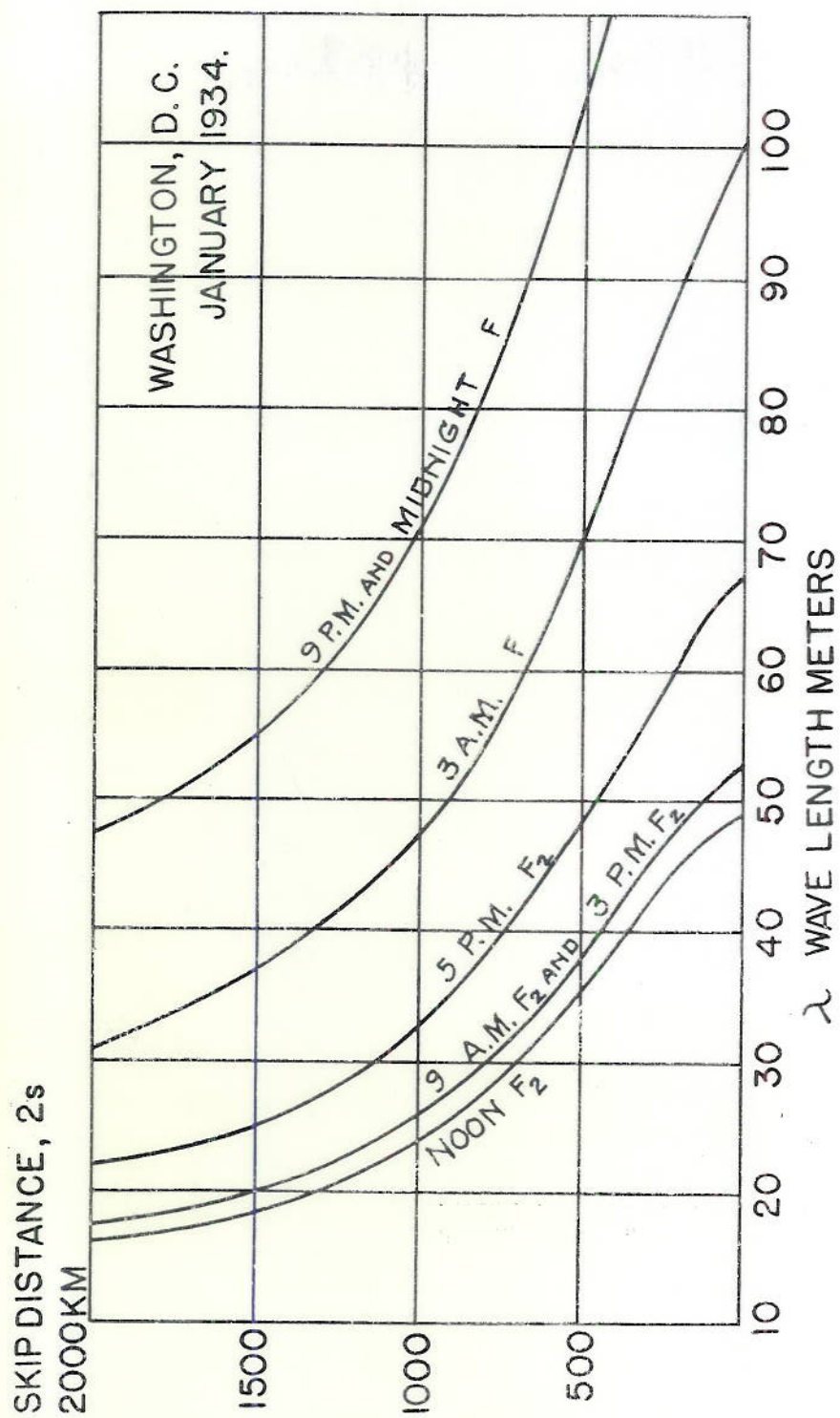


PLATE 8 - SKIP DISTANCES AT WASHINGTON,
JANUARY, 1934

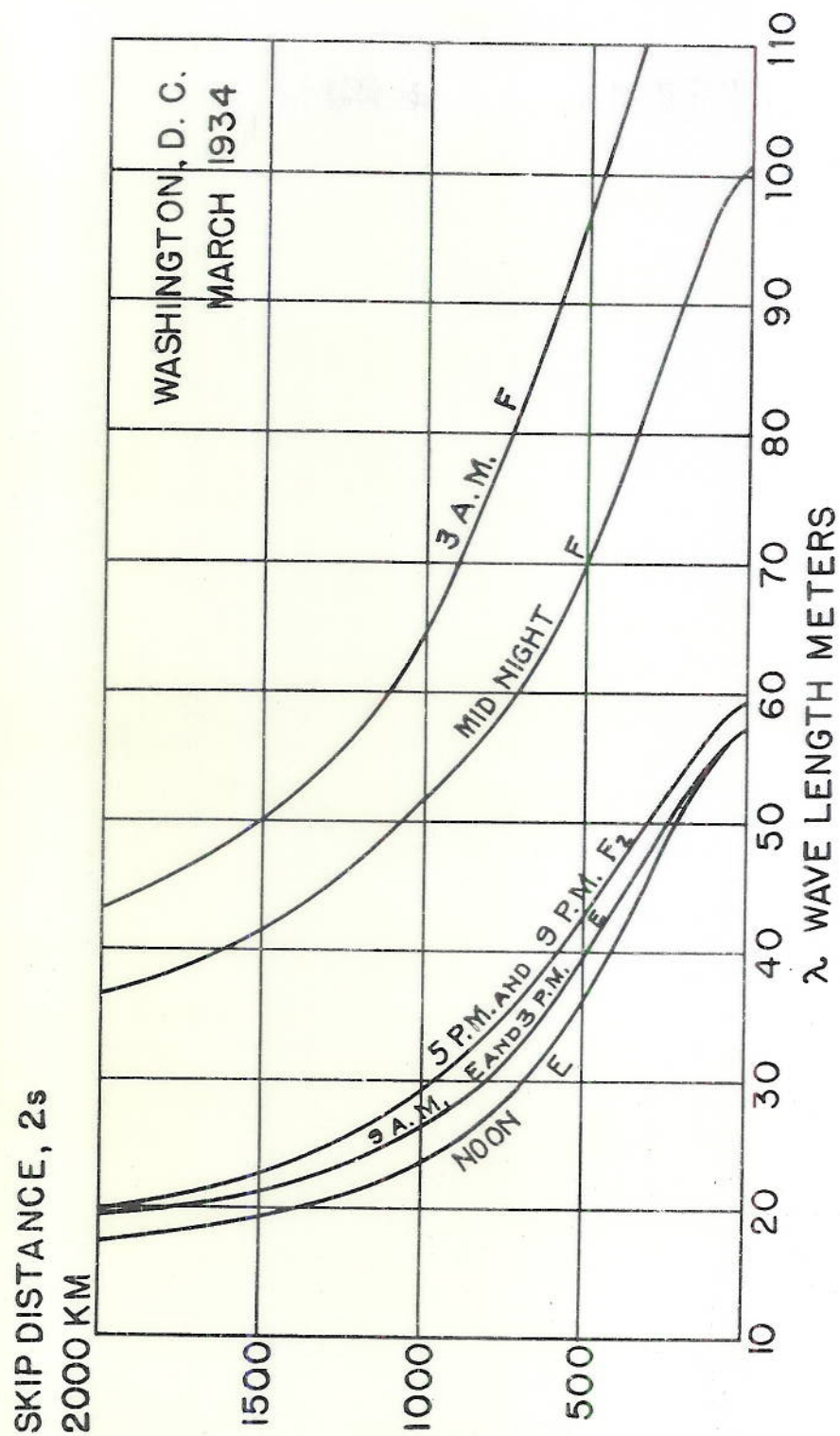


PLATE 9 - SKIP DISTANCES AT WASHINGTON,
MARCH, 1934.

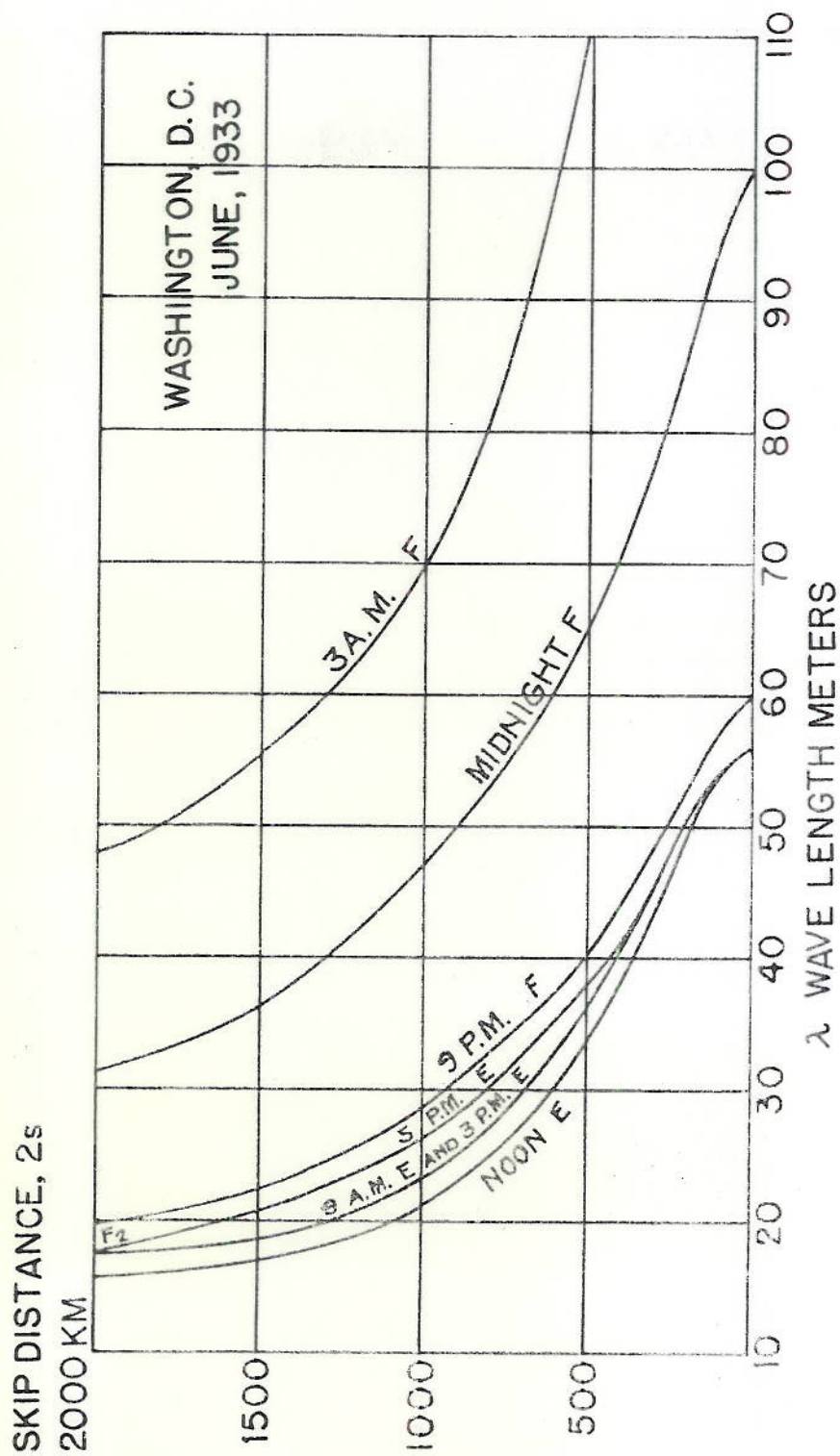


PLATE 10- SKIP DISTANCES AT WASHINGTON,
JUNE, 1933.

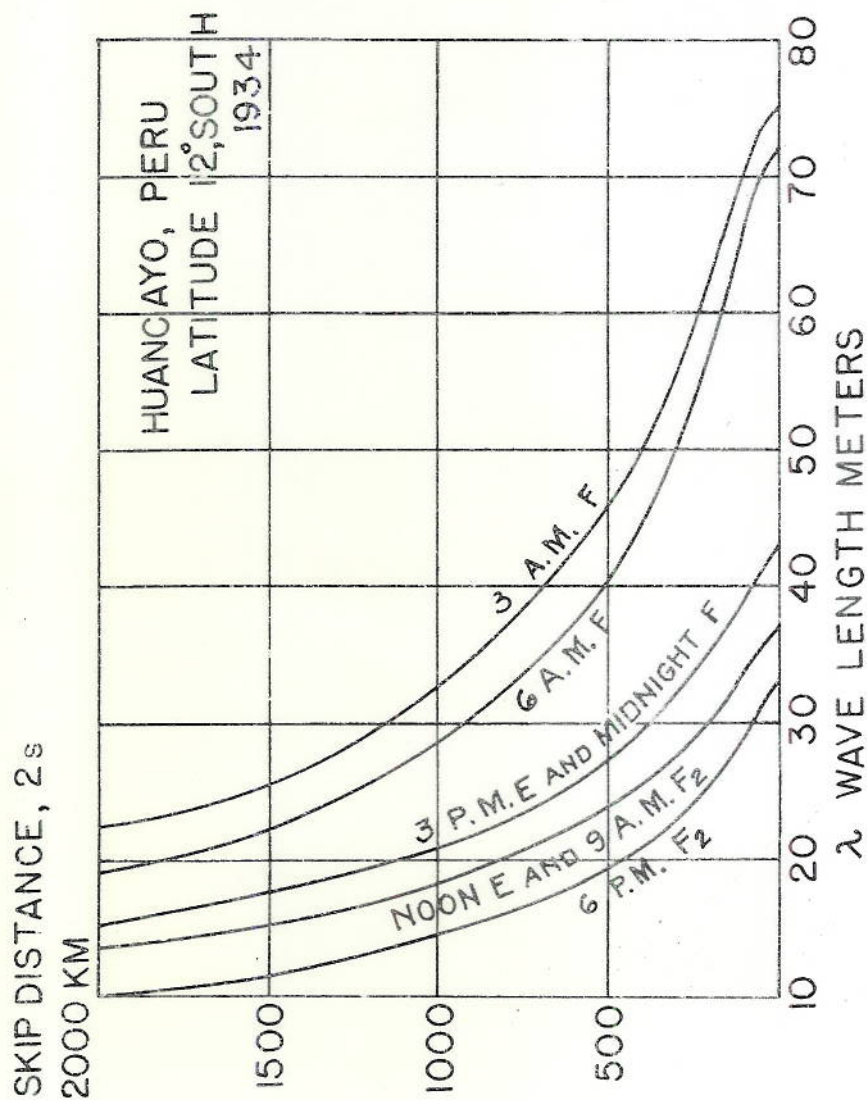


PLATE II - SKIP DISTANCES AT HUANCAYO,
1933-1934