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EXPERIMENTAL STUDIES OF IONOSPHERIC PROPAGATION AS APPLIED TO THE LORAN SYSTEM

ISSUED

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Contents

(over)

I. Introduction

The Loran system, as an aid to navigation, depends upon the determination of the difference in the great-circle distances between the point of observation and two points of known latitude and longitude. By expressing these distances in units of time (microseconds) required for the ground wave to travel from each of two synchronized radio-frequency pulse transmitters to the point of observation, the difference in the distances may be determined by measuring the difference in the time of arrival of the two sets of ground-wave pulses. The Loran system is thus fundamentally a ground-wave system. The difference in the time of arrival of the ground-wave pulses, from the two Loran transmitting stations, is known as the "ground-wave time difference".

The direct determination of ground-wave time differences is limited to the area in which the ground wave from both Loran transmitters can be received sufficiently well to permit time-difference measurements. Pulses reflected from the ionosphere, or "sky-wave" pulses, may be received at distances considerably in excess of the ground-wave range. This condition provides a method by which the usefulness of the system can be extended, under favorable conditions, to distances of approximately 1,400 nautical miles from the farthest transmitting station.

Two types of sky-wave time-difference measurements are practical: (a) the difference in the time of arrival of the first sky wave from one station and the ground wave from the other, and (b) the difference in the time of arrival of the first sky wave from each station.

The time required for a sky wave to travel from the transmitting station up to the ionosphere and back down to the receiving point is greater than that required for a ground wave to travel between the same points. The difference in the time of arrival of the sky-wave pulse and the ground-wave pulse from a single Loran transmitting station is known as the "sky-wave delay." The magnitude of the sky-wave delay is a function of the distance between the transmitting and receiving points and conditions existing in the ionosphere.

In order to represent the difference in the great-circle distance between the Loran transmitting stations and the receiving point, all time-difference measurements involving sky waves must be converted into equivalent ground-wave time differences. The correction necessary for a time-difference measurement between a ground wave and a sky wave is simply the sky-wave delay. The correction for a time-difference measurement between two sky waves is the difference between the two sky-wave delays. These corrections are more fully explained in connection with the use of the sky-wave delay curves.

The purpose of these studies was to determine:

(a) The reliability with which sky waves, suitable for Loran measurements, can be received at various distances.

(b) The effective layer heights.

(c) Reasonable correction values to be applied to time-difference measurements involving sky waves in order to convert them into equivalent ground-wave time differences.

(d) The variation in sky-wave corrections that may reasonably be expected as a result of changing ionosphere conditions.

(e) The effect of frequency upon sky-wave Loran propagation.

II. Program of Observations

The program consisted of time-difference measurements, from pulse transmissions, involving ground and sky waves at both vertical and oblique incidence. Most of the measurements were made at the IRPL receiving station at Sterling, Va., near Washington, D.C. Many were made at a temporary observing location at Longport, N.J. A total of 13,774 observations were made during the months of October, November, and December, 1943, and January, 1944. A standard Loran receiver and indicator was used for the reception and measurement of the pulse signals.

Three types of observations were made: (a) low-frequency oblique incidence (660 kc at 387 kilometers); (b) regular Loran-frequency oblique incidence at various distances up to 1500 kilometers, (c) regular Loran-frequency vertical incidence.

Low-frequency (660 kc) observations were made on pulse transmissions from WEAF during October and November, 1943. Special pulsing equipment was furnished to station WEAF by the IRPL for this purpose. The transmissions were made during the first ten minutes of each half hour, beginning at 0030 and ending at 0410 local time. This phase of the program involved measurements of the difference in the time of arrival of the first sky wave and the ground wave. The distance between the transmitting and receiving points was 387 kilometers.

Pulse transmissions were also observed from WLW (700 kc, 591 km) and WQXR (1560 kc, 378 km), using pulse equipment furnished by IRPL for the purpose. However, satisfactory reception of transmissions from WLW was found to be impractical because of interference on adjacent radio frequencies. Excellent reception of sky-wave pulses was obtained from WQXR but the amplitude of the ground-wave pulse, at Sterling, Va., was too small to permit direct measurement of sky-wave delay values.

Extensive time-difference measurements were made on pulse transmissions from regular Loran stations (1,950 kc) during December, 1943, and January, 1944, at distances ranging from 104 kilometers to 1514 kilometers. All observations have been included in the tabulations and graphs, regardless of the deviation of any single observation from mean or median values.

Three kinds of observations were made on Loran stations: (a) ground-wave observations, (b) ground-sky-wave observations, (c) sky-sky-wave observations.

A ground-wave observation represents the measurement of the difference in time of arrival of the ground wave from each of two Loran stations. These measurements are useful for comparison with the calculated time differences. All ground-wave time-difference measurements were made from the leading edge of one ground-wave pulse to the leading edge of the other.

A ground-sky-wave observation represents the measurement of the difference in the time of arrival of the ground wave from one Loran station and the first sky wave from the other. The sky-wave delay is the difference between this measurement and the ground-wave time difference. All ground-sky-wave time-difference measurements were made from the leading edge of the ground-wave pulse of one station to the leading edge of the first sky-wave pulse of the other station.

A sky-sky-wave observation represents the difference in the time of arrival of the first sky wave from each of two Loran transmitting stations. The difference between this measurement and the ground-wave time difference is known as the "sky-wave correction" and is the difference between the sky-wave delays of the two signals. All sky-sky-wave time-difference measurements were made from the leading edge of the first sky-wave pulse of one station to the leading edge of the first sky-wave pulse of the other station.

Random measurements, of the types mentioned above, were made on three pairs of Loran stations, as follows:

Station	Distance in km	Pair Number
A	218	0 (A–B)
B	689	1 (B–C)
C	1123	2 (C–D)
D	1514	

These observations were made at the IRPL receiving station, Sterling, Va., between 0830 and 1530 local time.

Two sets of continuous ground-sky-wave observations were maintained, at the rate of one measurement per minute, over a 24-hour period, for each of three distances as follows:

Receiving Location	Distance to Transmitting Station in km	Date
Sterling, Va.	689	28-29 Dec., 1943
" "	689	29-30 Dec., 1943
Longport, N.J.	442	18-19 Jan., 1944
" "	442	20-21 Jan., 1944
" "	885	19-20 Jan., 1944
" "	885	21-22 Jan., 1944

Random ground-wave observations were made at Longport, N.J., for comparison with calculated time differences.

Measurements of sky-wave delay (1,950 kc) at vertical incidence were made at the National Bureau of Standards radio receiving station, Sterling, Va., during December, 1943.

III. Discussion of Results

A. Low-Frequency Oblique-Incidence

Low-frequency pulse transmissions (660 kc) from WEAF were received, at Sterling, twenty-four nights during October and November, 1943. Sky waves were present at all times during the observational period, 0030 to 0410 local time.

A typical pulse pattern, as observed during this program, is illustrated in Fig. 1.

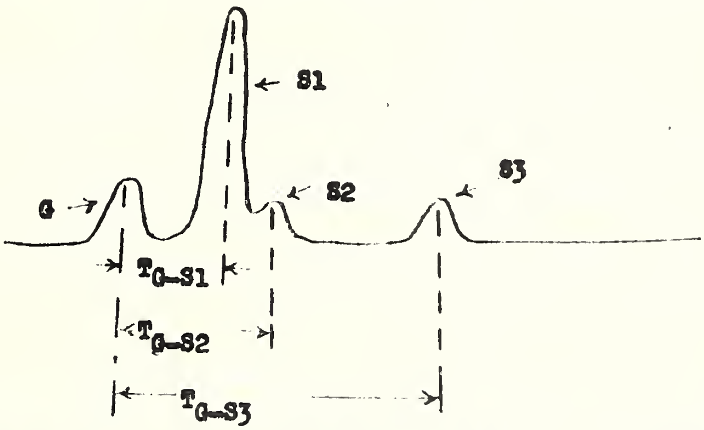


Fig. 1. Typical pulse pattern received from WEAF.

The ground-wave pulse is designated "G". S1, S2, and S3 represent the first, second, and third sky waves. T_{G-S1} represents the difference in the time of arrival of the ground wave and the first sky wave, T_{G-S2} the time difference between the ground wave and the second sky wave and T_{G-S3} the time difference between the ground wave and the third sky wave. An example of typical time differences (measured values at 0135-0136 local time, 11 November, 1943) follows:

T_{G-S1}:	140	microseconds
T_{G-S2}:	227	"
T_{G-S3}:	527	"

Equivalent reflection heights for these time differences, with an assumed sky-wave velocity of 3×10^8 meters/second over a triangular path, are as follows:

First sky wave:	89.7	kilometers
Second sky wave:	116.8	"
Third sky wave:	189.1	"

The number of sky-wave pulses received varied from one to six, with three the number most often observed. The amplitude of the first sky wave was almost invariably the largest, usually much larger than the ground wave. Most time-difference measurements were made on the first sky wave, with reference to the ground wave.

A rough correlation was observed between the amplitude of the first sky wave and its sky-wave delay. Low sky-wave field intensities were accompanied by small values of sky-wave delay, indicating low equivalent reflection heights.

The distribution of sky-wave delay observations (number of observations vs sky-wave delay) for all measurements of the first sky wave from WEAF (660 kc) is illustrated in Fig. 2. A scale of equivalent reflection height for a triangular path with a constant velocity of 3×10^8 meters/second is indicated below the sky-wave delay scale.

Fig. 3 shows the average and extreme values of equivalent reflection height for the first ten minutes of each half hour for the observational period 0030 to 0410 local time.

The probable error in the measurement of a single observation is estimated to be within ± 3 microseconds. The wide range of sky-wave delay values (107 to 177 microseconds) represents changes in the ionosphere.

B. Regular Loran-Frequency Oblique Incidence

A summary of the ground-wave observations made at Sterling, Va., between 8 December 1943 and 14 January 1944 is shown in Table 1.

The first number in the Loran reading identifies the Loran stations from which the measurement is made. All ground-wave observations at Sterling were made from the "0" pair of transmitting stations. Most of the observations within the range of 01216 to 01221 were obtained during the period between 4 January 1944 and 11 January 1944. These deviations from the calculated value are believed to represent errors in synchronization of the Loran stations or errors in measurement at the receiving point. The median value, 01211, is believed to be nearer the correct ground-wave time-difference than the average. Calculated values are obtained from the difference in the distances to the transmitting stations.

Summaries of ground-wave observations made at Longport, N.J., between 18 January 1944 and 22 January 1944 are shown in Tables 2 and 3.

Table 1. Ground-Wave Observations, Sterling, Va.

Loran Ground-Wave Reading in Microseconds	Number of Observations
01202	2
01203	2
01206	4
01207	4
01208	13
01209	52
01210	138
01211	178
01212	114
01213	51
01214	38
01215	26
01216	11
01217	22
01218	23
01219	38
01220	19
01221	6
01222	2
	743

Average ground-wave time difference, 01212.3.
Median ground-wave time difference, 01211.
Calculated ground-wave time difference, 01210.6.

Table 2. Ground-Wave Observations, Longport, N.J.

Loran Ground-Wave Reading in Microseconds	Number of Observations
01642	2
01645	13
01646	5
01647	25
01648	127
01649	281
01650	205
01651	64
01652	15
01653	2
01654	1
	740

Average ground-wave time difference, 01649.2
Median ground-wave time difference, 01649
Calculated ground-wave time difference, 01647.8

Table 3. Ground-Wave Observations, Longport, N.J.

Loran Ground-Wave Reading in Microseconds	Number of Observations
13901	1
13902	3
13904	1
13905	1
13907	2
13908	10
13909	23
13910	54
13911	60
13912	29
13913	14
13914	6
13915	4
13916	1
13917	3
13918	2
13919	2
13920	1
	217

Average ground-wave time difference, 13910.8
Median ground-wave time difference, 13911
Calculated ground-wave time difference, 13911.0

The small amount of scatter in the ground-wave measurements as shown in Table 2, relative to the other two groups, is believed to be due to more favorable ground-wave field intensities obtained for these observations.

On the basis of the distribution of ground-wave observations, it is believed that ± 2 microseconds is a reasonable probable error for a single observation, and ± 15 microseconds is a reasonable maximum error to be expected from a single observation as a result of errors in synchronization at the transmitting stations and measurement at the receiving point.

Loran sky-wave observations were made on 1,950 kilocycles during December 1943 and January 1944, at all hours of the day and night and at distances of 104, 218, 442, 689, 885, 1123, and 1514 kilometers from the transmitting stations.

The amplitude of the sky waves was much greater at night, regardless of distance, than during the day. The weakest sky waves were usually observed during the middle of the day. Wide changes in amplitude and shape of the sky waves were observed from minute to minute, particularly at night, and from one day to the next. Low sky-wave delay values, representing low equivalent reflection heights, were characteristic of low sky-wave amplitudes, as was noted during the WEAF observations.

During the day the Loran sky-wave pulse patterns normally represented only one reflection. However, at night the sky-wave patterns were very complex, changing rapidly in shape and amplitude. It was often impossible to distinguish the point at which the first sky wave ended and the second began. A train of sky waves, consisting of dozens of components, covering a sky-wave delay range up to 10,000 microseconds, was not at all unusual. The complexity of the sky-wave patterns appeared to vary inversely with the distance from the transmitting stations.

Sky waves from the Loran station located 689 kilometers from the point of observation were always present, regardless of the time of day. Sky waves from the stations located 218, 442, 885, and 1123 kilometers from the point of observation were normally present at all hours of the day. Sky waves from the station located 1514 kilometers from the point of observation were always present at night and about fifty percent of the time at all hours of the day.

Three sets of continuous sky-wave delay observations were made, at the rate of one time-difference measurement per minute, over two 24-hour periods each, at distances of 442, 689, and 885 kilometers, for the purpose of observing any diurnal change in sky-wave delay. The average and extreme values, for each 20-minute period, obtained from this program are shown in Figs. 4 to 9. The sky-wave delay for each observation, plotted against local time, is shown in Figs. 10 to 33.

It will be observed that the sky-wave delay was normally less during the day than at night. However, on 29 December 1943, from 0440 to 0620 (Fig. 4), and on 21 January 1944, from 0040 to 0140 (Fig. 8), sky-wave delay values were obtained comparable to those normally measured during the daytime. An abrupt increase in sky-wave delay at or near sunrise was observed on four of the six days of continuous observation.

The values obtained from the continuous observational program have been divided into four groups, based upon the time of observation, as follows:

(a) Daytime observations, covering the period 0900 to 1500 local time.

(b) Sunset observations, covering the period 1500 to 2100 local time.

(c) Nighttime observations, covering the period 2100 to 0300 local time.

(d) Sunrise observations, covering the period 0300 to 0900 local time.

The distribution of sky-wave delay observations (number of observations vs sky-wave delay) for each of the above time periods is shown in Figs. 34 to 36.

The distribution of sky-wave delay measurements, made at random during the day, between 8 December 1943 and 14 January 1944 are shown in Figs. 37 and 38. These measurements were made at distances of 218, 689, and 1123 kilometers from the transmitting stations.

The distribution of sky-wave correction observations, made at random during the day, from 8 December 1943 to 14 January 1944, is shown in Fig. 40. These observations represent time-difference measurements involving only sky waves. The sky-wave correction is the difference between the sky-wave delay of each signal and therefore involves the distance from each transmitting station.

The sky-wave delay curve represents the sky-wave delay as a function of distance from the transmitting station. Points, by which this curve may be determined graphically, are obtained from sky-wave delay measurements which represent the height of the delay curve at each observational distance. The daytime delay curve, illustrated in Fig. 39, was derived in this manner from the average and median values of all daytime sky-wave delay measurements.

A sky-wave correction is the difference between the sky-wave delays from two transmitting stations and therefore represents the average slope of the delay curve between the two distances. The sky-wave delay curve may thus be extended, beyond distances at which the sky-wave delay can be directly measured, by use of sky-wave correction observations.

Fig. 41 contains the daytime sky-wave delay curve, previously described, with points representing the mean and median of all sky-wave corrections observed at distances of 218-689, 689-1123, and 1123-1514 kilometers from transmitting stations.

Fig. 42 contains the sky-wave delay curve, derived by the Bureau of Ships, Navy Dept., for determination of Loran sky-wave corrections. The mean, median, and extreme values of nighttime sky-wave delay obtained from the continuous observational program are also shown in this Fig. The ranges of observed values are shown by the three vertical lines. As shown, the mean and median observed nighttime values agree well with this curve. (For daytime values see Fig. 39). Fig. 42 is believed to represent values of sky-wave delay that may reasonably be expected under nighttime ionosphere conditions.

The purpose of the sky-wave delay curve is to enable the observer to convert a Loran time-difference measurement, involving sky waves, into an equivalent ground-wave time difference. The method by which this may be accomplished will be briefly explained.

Consider a ground-wave measurement as illustrated in Fig. 43.

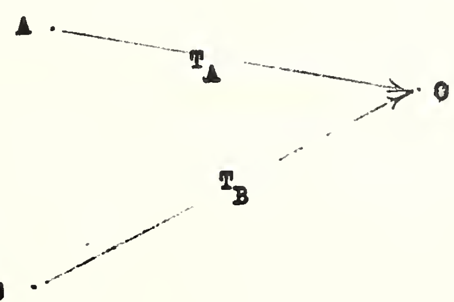


Fig. 43.

"A" and "B" represent two Loran transmitting stations and "O" the point of observation. T_A represents the time, in microseconds required for a ground-wave pulse to travel from A to O and T_B the time, in microseconds, for the ground-wave pulse to travel from B to O. If the transmitting stations are so synchronized that the pulses from B are transmitted exactly β microseconds later than those from station A, the measured ground-wave time difference (T_{AG-BG}) will be as follows:

$$T_{AG-BG} = \beta + T_B - T_A$$

This relation, for ground-wave time differences, holds regardless of the position of O with respect to A and B and therefore regardless of the relative magnitudes of T_A and T_B.

Sky-wave time-difference measurements are illustrated in Fig. 44.

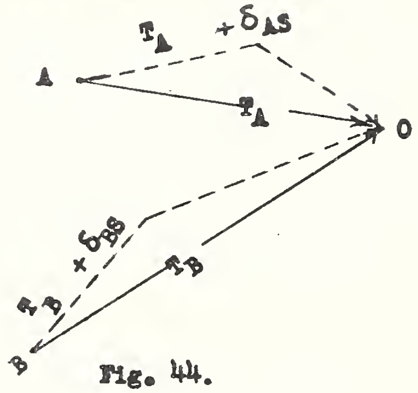


Fig. 44.

$T_A + \delta_{AS}$ represents the time required for the sky-wave pulse to travel from station A to O. Thus δ_{AS} is the sky-wave delay from station A. $T_B + \delta_{BS}$ represents the time required for the sky-wave pulse from station B to travel to O, and δ_{BS} is the sky-wave delay from station B.

The three sky-wave measurements possible under this condition are:

(a) T_{AG-BS}, which represents the difference in the time of arrival of the ground wave from station A and the sky wave from station B. The measured value at O will be:

$$T_{AG-BS} = \beta + (T_B + \delta_{BS}) - T_A$$
$$= (\beta + T_B - T_A) + \delta_{BS}$$
$$= T_{AG-BG} + \delta_{BS}$$

(b) T_{AS-BG}, which represents the difference in the time of arrival of the ground-wave from station B and the sky wave from station A. The measured value at O will be:

$$T_{AS-BG} = \beta + T_B - (T_A + \delta_{AS})$$
$$= (\beta + T_B - T_A) - \delta_{AS}$$
$$= T_{AG-BG} - \delta_{AS}$$

(c) T_{AS-BS}, which represents the difference in the sky waves from each station. The measured value at O will be :

$$T_{AS-BS} = \beta + (T_B + \delta_{BS}) - (T_A + \delta_{AS})$$
$$= (\beta + T_B - T_A) + (\delta_{BS} - \delta_{AS})$$
$$= T_{AG-BG} + (\delta_{BS} - \delta_{AS})$$

It will be observed that the magnitude of the correction applicable in cases (a) and (b), in order to obtain an equivalent ground-wave time difference, is the sky-wave delay. This value is obtained directly from the sky-wave delay curve and is a function of distance from the transmitting station. The sign of this type correction depends upon the relative distances from the transmitting stations.

The magnitude of the correction applicable in case (c) is the difference between the sky-wave delays of stations A and B. These values may also be obtained from the sky-wave delay curve. As in the previous cases, the sign of this correction depends upon the relative distances from the transmitting stations. It is believed that this is the only type sky-wave observation that is being used in the Loran system, at the present time. It will therefore be termed the "sky-wave correction".

The sky-wave delay, as obtained from the sky-wave delay curves, must be considered only as a reasonable value. In practice wide variations in sky-wave delay are observed. An estimate of the variation that may reasonably be expected can be obtained from the distribution of sky-wave delay observations illustrated in Figs. 34 to 36 and from Tables 4, 5, and 6.

Table 4. Daytime Continuous Sky-Wave Delay Observations

Distance from transmitting station, in kilometers	442	689	885
Sky-wave delay obtained from delay curve, in microseconds	118	78	66
Range of 50% of observations in microseconds	109 to 122	81 to 82	61 to 68
Total range of observations in microseconds	90 to 138	71 to 91	49 to 75

Table 5. Daytime Random Sky-Wave Delay Observations

Distance from transmitting station in kilometers	218	689	1,123
Sky-wave delay obtained from delay curve, in microseconds	243	78	59
Range of 50% of observations in microseconds	226 to 256	62 to 81	50 to 67
Total range of observations in microseconds	145 to 314	41 to 99	19 to 105

Table 6. Nighttime Continuous Sky-Wave Delay Observations

Distance from transmitting station, in kilometers	442	689	885
Sky-wave delay obtained from delay curve, in microseconds	144	96	80
Range of 50% of observations, in microseconds	141 to 150	91 to 101	79 to 86
Total range of observations, in microseconds	109 to 181	73 to 113	71 to 98

If the sky-wave delay from one Loran station varies independently from the sky-wave delay of the other, somewhat wider variations in the sky-wave correction would be expected for a Loran time-difference measurement between two sky waves than for either of the sky-wave delays separately. However, the observed sky-wave correction values, made during the daytime, have approximately the same range of values as the corresponding sky-wave delay measurements made during the same period.

The distribution of sky-wave correction values obtained from daytime sky-wave time-difference measurements, for three pairs of Loran stations, is shown in Fig. 40.

Alternate measurements of sky-wave delay were made, for short periods, on stations at distances of 104 and 442 kilometers and at 442 and 885 kilometers. Equivalent reflection heights were determined from the sky-wave delay values and plotted against time of day. Figs. 45 and 46 contain this information.

Fig. 47 shows the daytime equivalent reflection height for a triangular sky-wave path and an assumed velocity of 3×10^8 meters per second, at distances of 150 to 1300 kilometers between transmitting and receiving points. These are the equivalent reflection heights for the daytime sky-wave delay values of Fig. 39.

The nighttime equivalent reflection height, for distances of 400 to 1300 kilometers between transmitting and receiving points, which correspond with the nighttime sky-wave delay values of Fig. 42, are shown in Fig. 48.

C. Regular Loran-Frequency Vertical Incidence

Measurements of vertical-incidence pulse transmissions were made at a frequency of 1,950 kc. The virtual heights obtained ranged between 98 and 130 kilometers and were in substantial agreement with the regular vertical-incidence ionosphere records made during the same period at Sterling.

A thorough discussion of the relationship between vertical-incidence ionosphere measurements and oblique-incidence sky-wave transmission is contained in the paper, The relation of radio sky-wave transmission to ionosphere measurements, by N. Smith, Proc.I.R.E. 27, 332; May 1939. On the basis of simple theory, it is shown that the virtual height of reflection, measured at vertical incidence, for a radio frequency f, is equal to the height of the equivalent triangular path for a higher frequency f', at oblique incidence. An approximate relation between these frequencies, corrected for the curvature of the earth, is given as follows:

$$f = f' \cos \phi_o \left[1 - \frac{Z'_v - Z_o}{R + h} \tan^2 \phi_o \right]$$

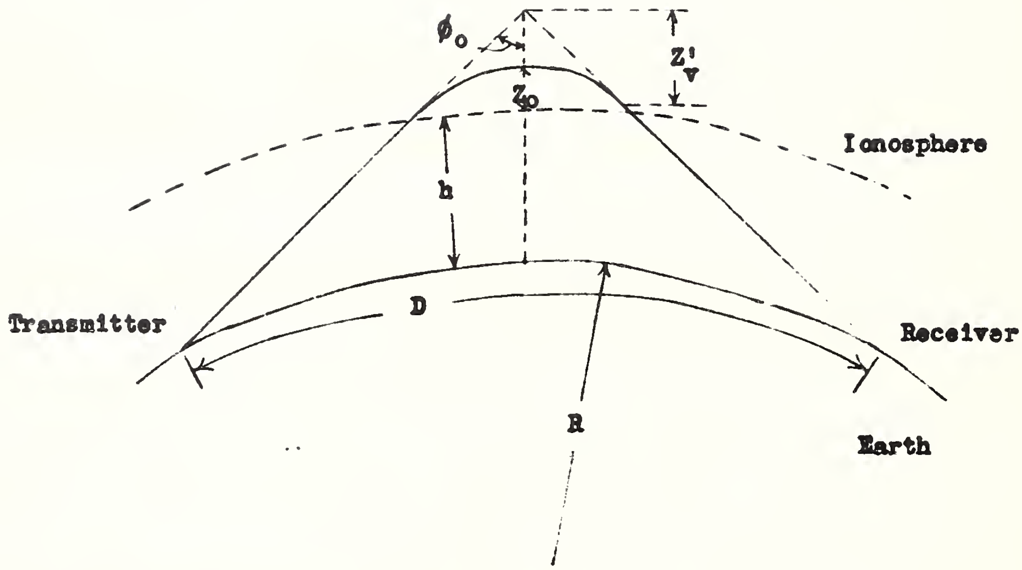
Where: the angle ϕ_o and distances R, h, Z'_v, and Z_o are those indicated in Fig. 49.

This approximation leads to results good to 1 percent or better for E-layer transmission, where Z_o is less than 50 kilometers.

Equivalent vertical-incidence frequencies, calculated from this relationship, for the daytime oblique-incidence observations made on 1,950 kc are shown in Table 7.

Equivalent vertical-incidence frequencies, calculated from the nighttime oblique-incidence data, are shown in Table 8.

The equivalent reflection heights are plotted against equivalent vertical-incidence frequency, for day and night conditions, in Figs. 50 and 51.



D = distance of transmission, R = radius of the earth, Z'_v = height of equivalent triangular path in the ionosphere, Z_o = true height of reflection in the ionosphere, h = minimum height of ionosphere above the earth, ϕ_o = one half-vertex angle of the equivalent triangular path.

Fig. 49.

Table 7. Daytime Equivalent Vertical-Incidence Frequency for 1950-kc Oblique-Incidence Transmissions.

Distance between Receiving and Transmitting Points, Kilometers		Total Height of Equivalent Triangular Path in Kilometers $(h + Z'_v)$	Equivalent Vertical-Incidence Frequency, kc
		Continuous Observations	
442	average	85.6	721
442	median	86.5	727
689	average	84.1	498
689	median	83.5	495
885	average	79.8	397
885	median	80.5	399
		Random Observations	
219	average	94.8	1279
219	median	96.1	1289
689	average	78.5	474
689	median	78.8	476
1123	average	78.8	340
1123	median	78.8	340

Table 8. Nighttime Equivalent Vertical-Incidence Frequency for 1950-kc Oblique-Incidence Transmissions.

Distance between Receiving and Transmitting Points, Kilometers		Total Height of Equivalent Triangular Path in Kilometers $(h + Z_v')$	Equivalent Vertical-Incidence Frequency, kc
442	average	97.6	806
442	median	97.9	807
689	average	91.4	537
689	median	91.4	537
885	average	91.6	445
885	median	90.5	441

The equivalent vertical-incidence frequency for the WEAF observations, on 660 kc, is 286 kc and the equivalent reflection height is 90.5 kilometers. These values represent the mean of all observations on 660 kc.

Vertical-incidence ionosphere measurements, in the range of 250 to 800 kc, are not, as yet, available for checking the virtual height of the equivalent vertical-incidence frequencies.

IV. Conclusions

Sky-wave propagation, with equivalent reflection layer heights between 60 and 110 kilometers, may be expected from the present Loran transmitting stations on 1,950 kc, at all times of the night, and approximately fifty percent of the time during the day, at distances of 400 to 1,500 kilometers. The maximum night distance is probably around 2,500 kilometers.

Data on the ionosphere layer heights effective in Loran propagation under various conditions and at various times of day are given in the attached Figs.

Correction values for Loran sky-wave observations, as a function of distance from the transmitting stations, may be obtained from the sky-wave delay curves of Figs. 39 and 42, which correspond to the equivalent reflection heights of Figs. 47 and 48.

Wide variations in sky-wave correction values, from those recommended, may be expected in practice. The most consistent sky-wave delay, or correction, values will be obtained between the hours of 2100 and 0300 local time, and the most erratic will be at or near sunrise and sunset.

Deviations from the recommended sky-wave delay values up to ± 10 microseconds may be expected at distances from the transmitting stations of 500 kilometers or greater, but the probability of a single Loran sky-wave measurement falling within this range is dependent upon the time of day and the particular day on which the observation is made as well as the distance from the transmitting stations. Under unusual ionospheric conditions, the recommended sky-wave delay values may be in error by as much as 50 microseconds.

It appears that substantial advantages can be gained by the use of lower radio frequencies than 1,950 kc, because of simpler sky-wave pulse forms, less variation in sky-wave correction values, and greater ground-wave distance range.

V. Further Work Needed

The following subjects, in approximate order of urgency, should be studied. They will be pursued as fully as practicable.

(a) Diurnal variation in sky-wave correction values. This will involve continuous measurements, over at least 24-hour periods, of the time difference between sky waves from both stations in a Loran pair.

(b) Alternate measurements of the sky-wave delay from two Loran stations. This information will show the extent to which the equivalent reflection height of the two sky-wave paths vary independently.

(c) Periodic continuous measurements of sky-wave delay, for the purpose of determining any seasonal trend in equivalent reflection height.

(d) Measurement of virtual height at equivalent vertical-incidence frequencies. If these measurements check the values indicated by the Loran oblique-incidence measurements, a multi-frequency automatic recording equipment, covering the range of 200 to 600 kilocycles could be used in connection with suitable transmission curves to obtain oblique-incidence transmission information at a minimum of time and expense. If the equivalent vertical-incidence measurements do not check the values indicated by the Loran measurements, oblique-incidence measurements may be made at higher frequencies than 1,950 kc in order to check the accuracy of the transmission curves now being used.

(e) Measurement of sky-wave delay for an east and west path and for a north and south path, in order to determine the effect of the magnetic field of the earth upon low-layer sky-wave transmission.

(f) Determination of sky-wave field intensities, for correlation with equivalent reflection heights.

(g) Determination of sky-wave delay at latitudes other than that of Washington.

9 MAR 1944

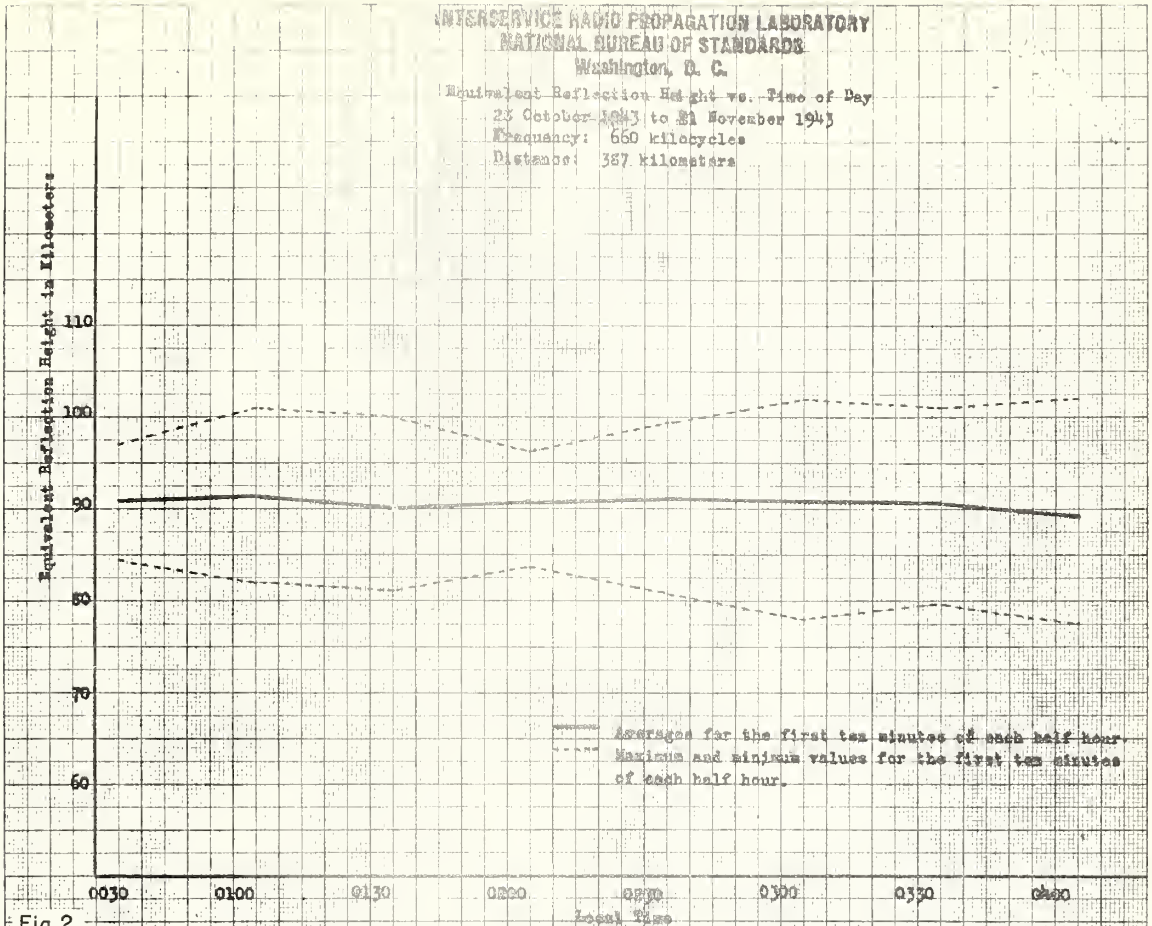


Fig. 2

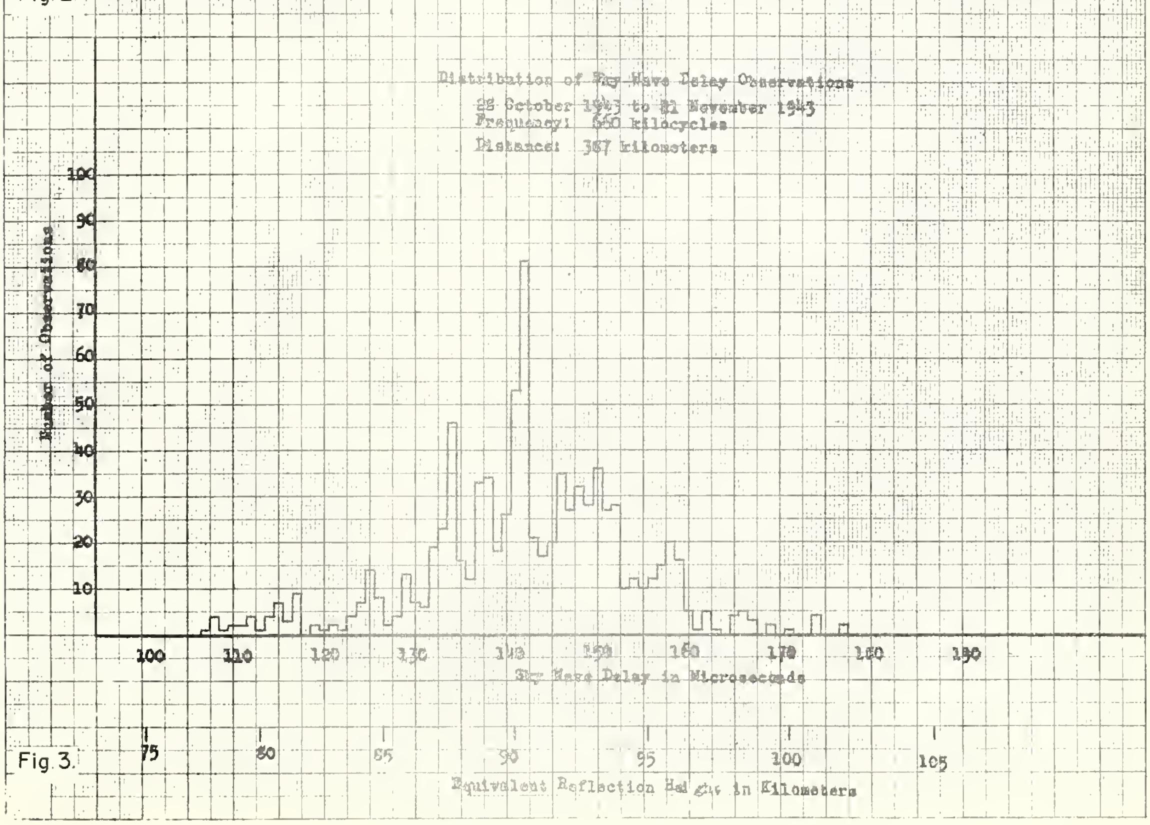


Fig. 3

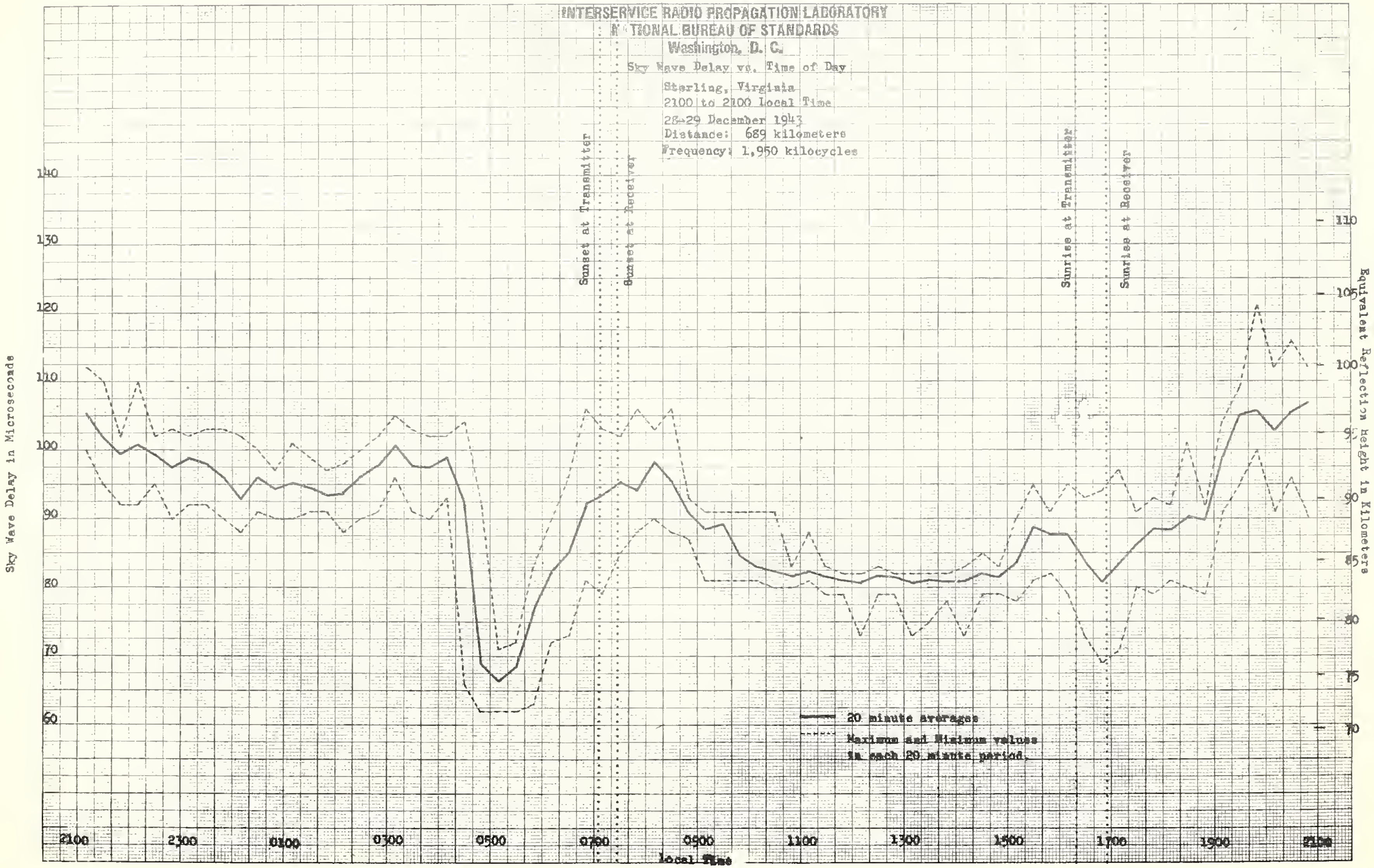

INTERSERVICE RADIO PROPAGATION LABORATORY
NATIONAL BUREAU OF STANDARDS
Washington, D. C.
Sky Wave Delay vs. Time of Day
Sterling, Virginia
2100 to 2100 Local Time
28-29 December 1943
Distance: 689 kilometers
Frequency: 1,950 kilocycles
Sunset at Transmitter
Sunset at Receiver
Sunrise at Transmitter
Sunrise at Receiver
Sky Wave Delay in Microseconds
140
130
120
110
100
90
80
70
60
Equivalent Reflection Height in Kilometers
110
105
100
95
90
85
80
75
70
20 minute averages
Maximum and Minimum values in each 20 minute period.
2100
2300
0100
0300
0500
0700
0900
1100
1300
1500
1700
1900
2100
Local Time

Fig. 4.

7 MAR 1944

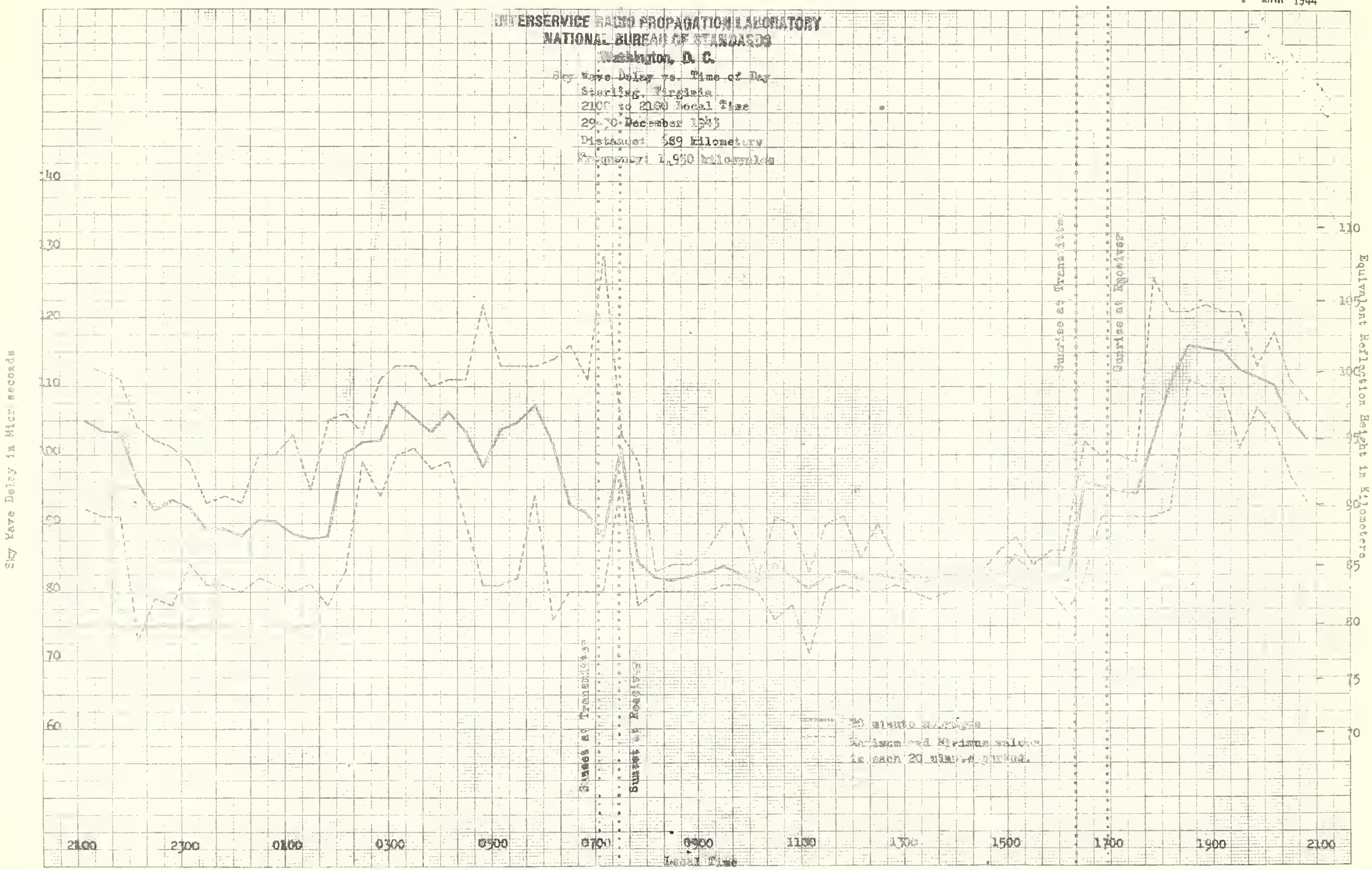
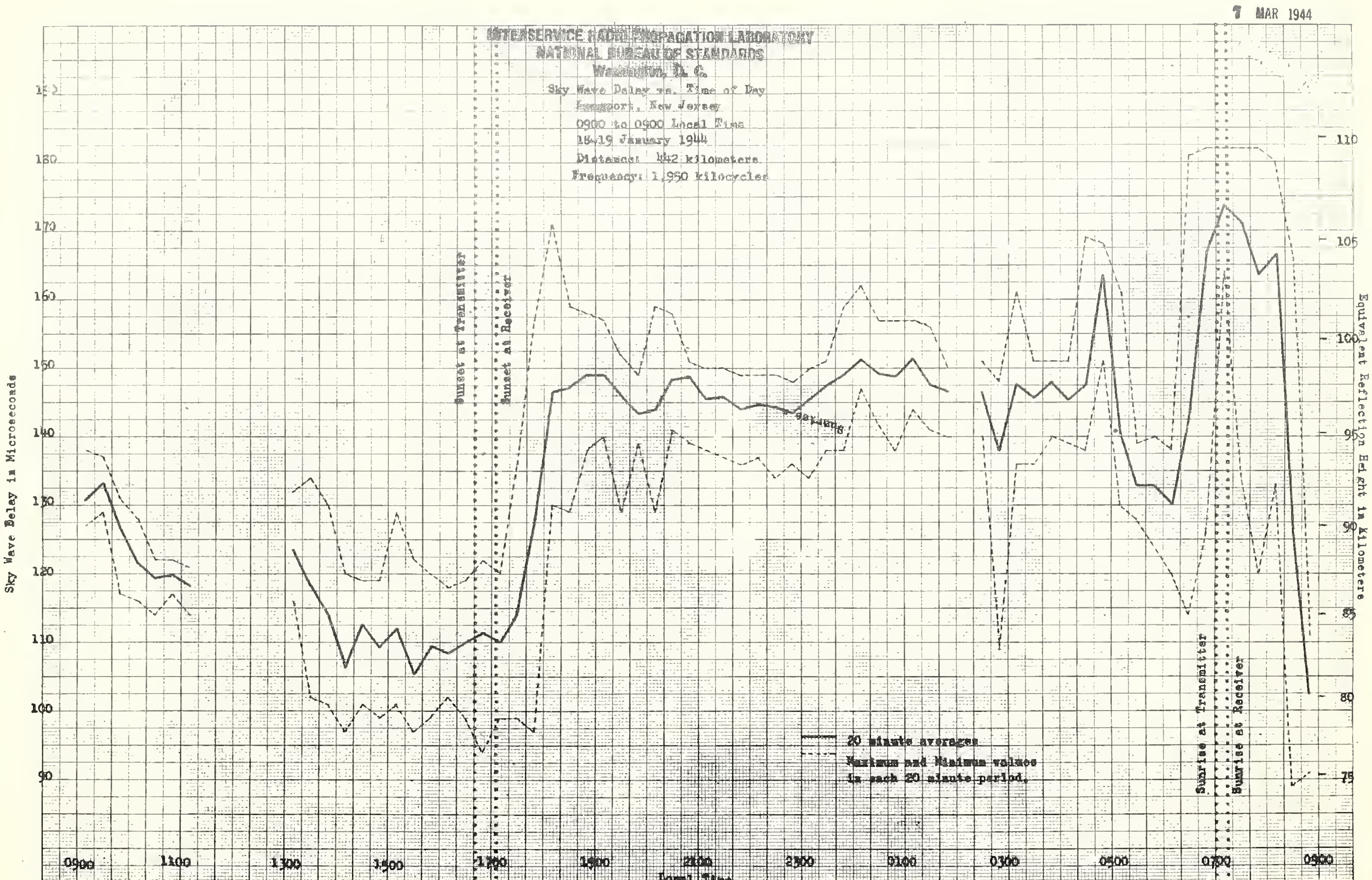


Fig.5



7 MAR 1944
INTERSERVICE RADIO PROPAGATION LABORATORY
NATIONAL BUREAU OF STANDARDS
Washington, D. C.
Sky Wave Delay vs. Time of Day
Freeport, New Jersey
0900 to 0900 Local Time
18-19 January 1944
Distance: 442 kilometers
Frequency: 1,950 kilocycles
Sky Wave Delay in Microseconds
Equivalent Reflection Height in Kilometers
Local Time
Sunset at Transmitter
Sunset at Receiver
Sunrise at Transmitter
Sunrise at Receiver
20 minute averages
Maximum and Minimum values in each 20 minute period.

Fig.6.

7 MAR 1944

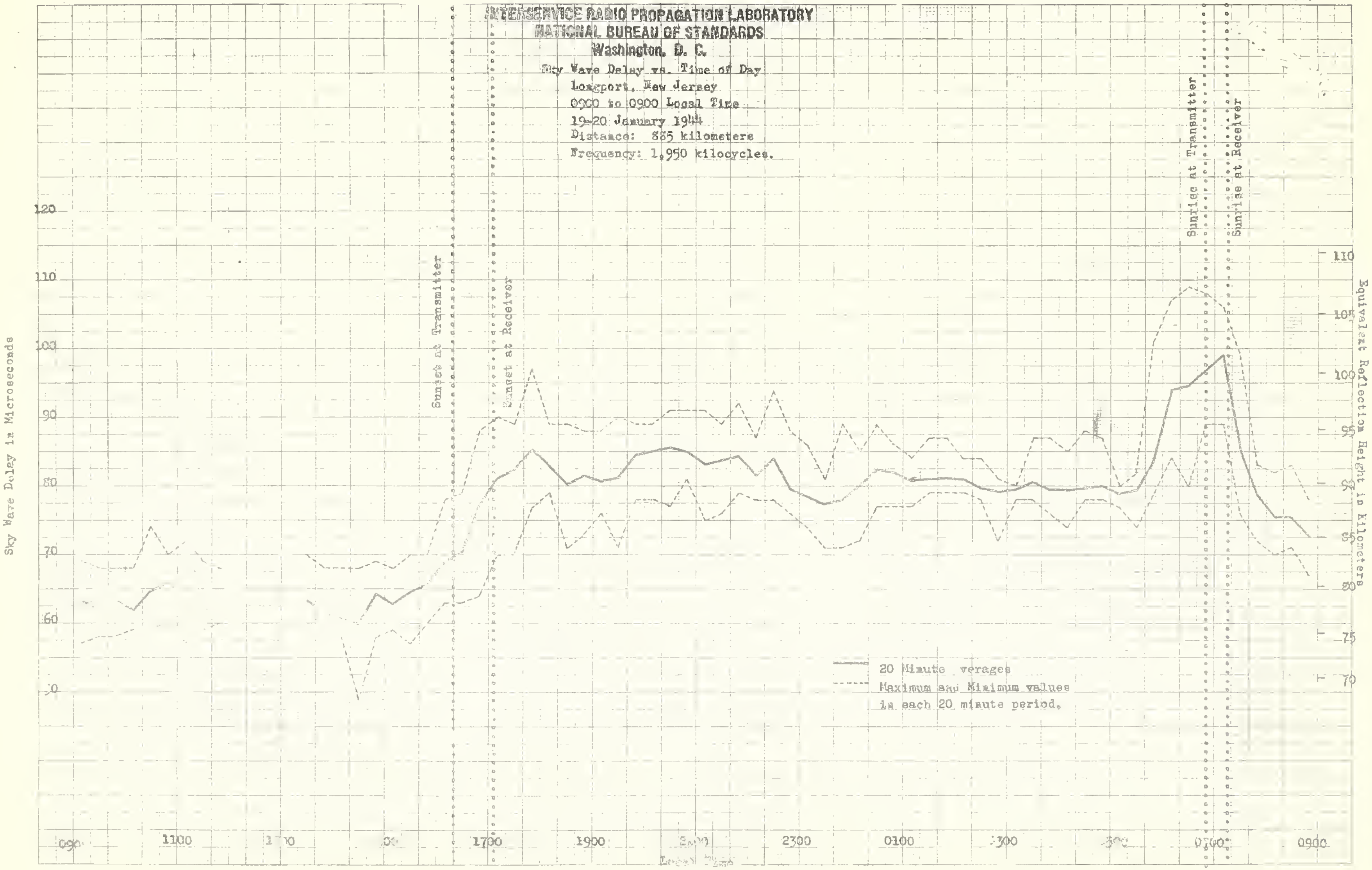


Fig.7

7 MAR 1944

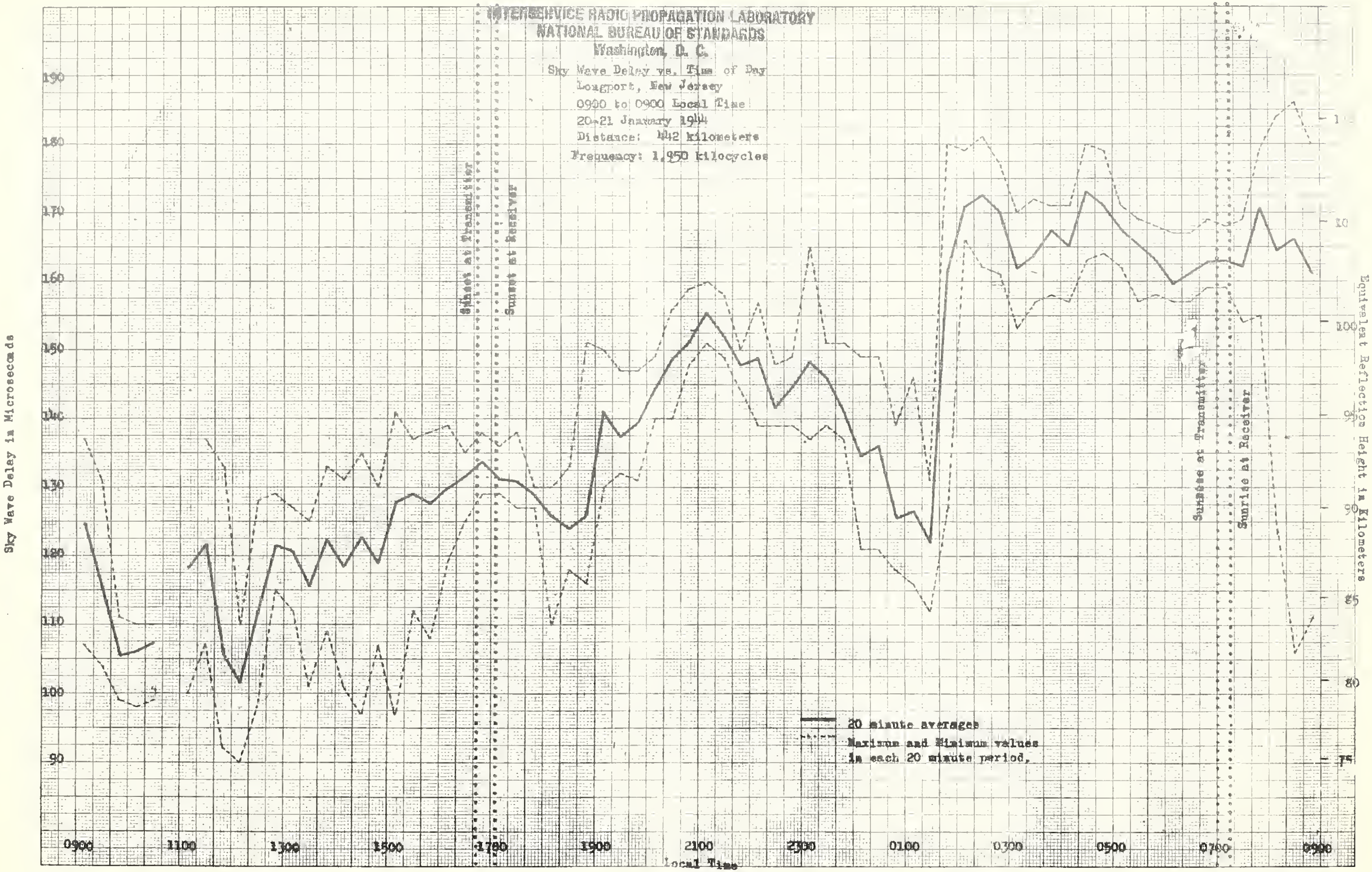


Fig 8.

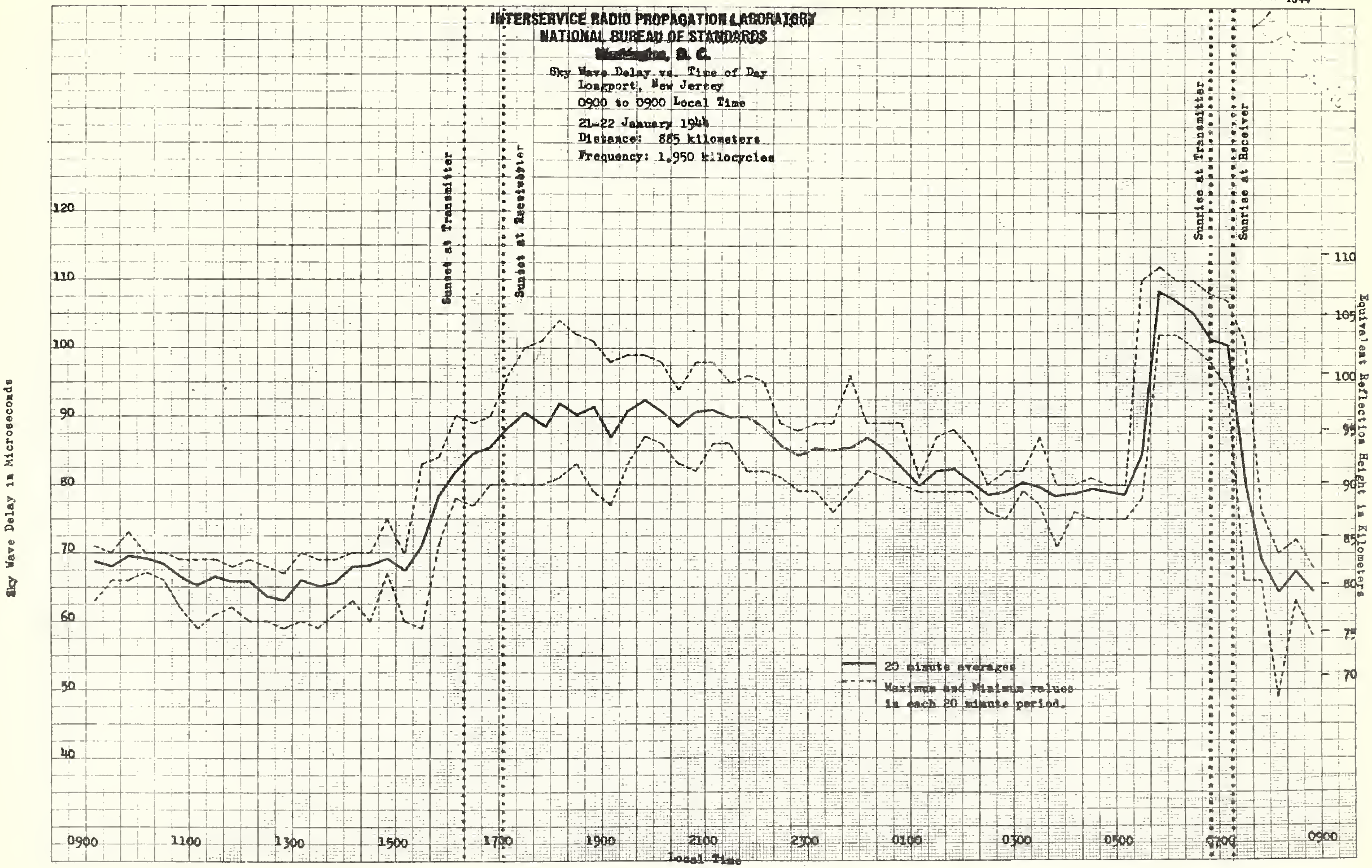

INTERSERVICE RADIO PROPAGATION LABORATORY
NATIONAL BUREAU OF STANDARDS
Washington, D. C.
Sky Wave Delay vs. Time of Day
Loagport, New Jersey
0900 to 0900 Local Time
21-22 January 1944
Distance: 885 kilometers
Frequency: 1,950 kilocycles
Sunset at Transmitter
Sunset at Receiver
Sunrise at Transmitter
Sunrise at Receiver
20 minute averages
Maximum and Minimum values in each 20 minute period.
Sky Wave Delay in Microseconds
Equivalent Reflection Height in Kilometers
Local Time
0900
1100
1300
1500
1700
1900
2100
2300
0100
0300
0500
0700
0900
120
110
100
90
80
70
60
50
40
110
105
100
95
90
85
80
75
70

Fig.9.

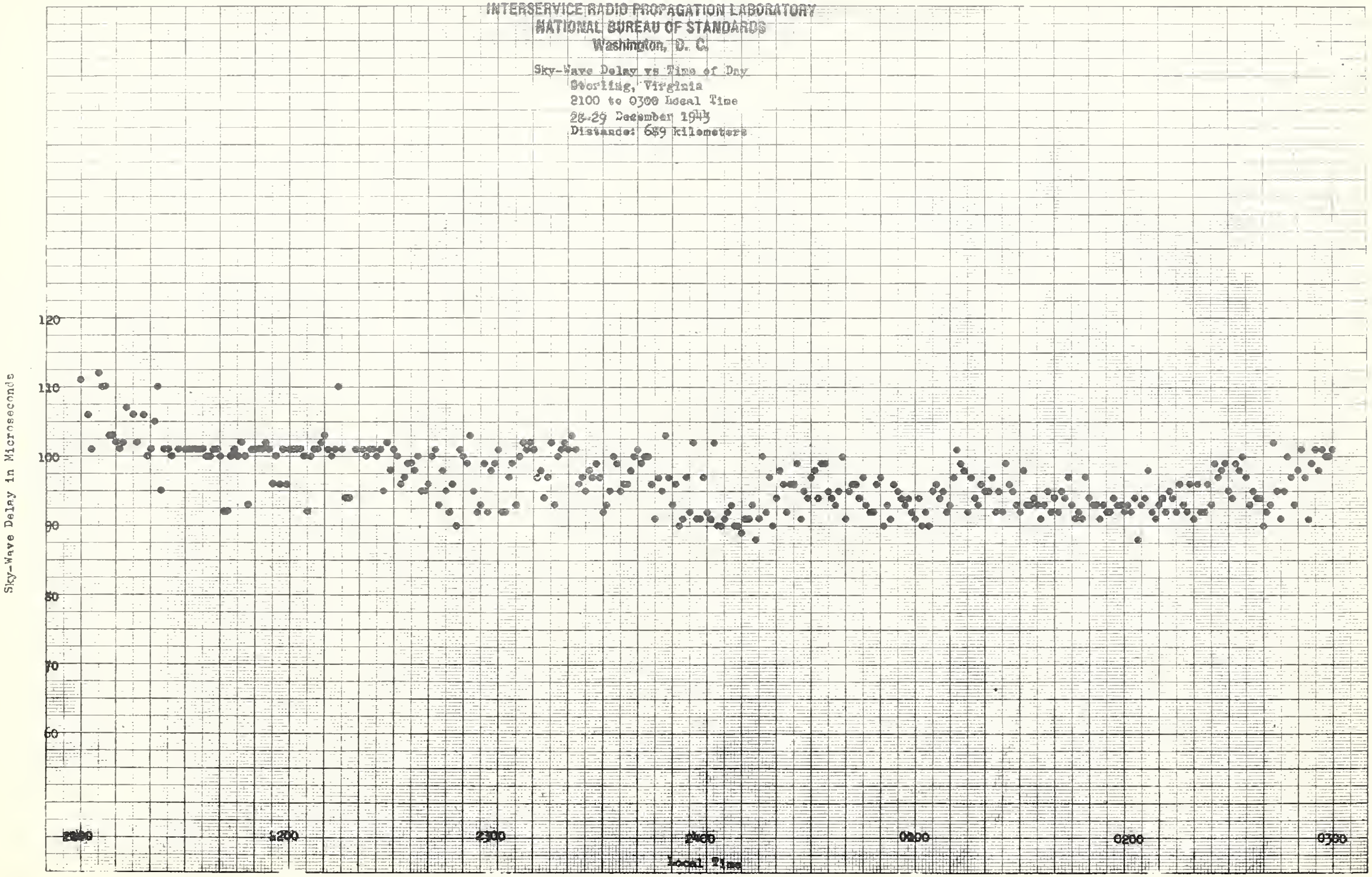

INTERSERVICE RADIO PROPAGATION LABORATORY
NATIONAL BUREAU OF STANDARDS
Washington, D. C.
Sky-Wave Delay vs Time of Day
Sterling, Virginia
2100 to 0300 Local Time
28-29 December 1943
Distance: 689 kilometers
Sky-Wave Delay in Microseconds
120
110
100
90
80
70
60
2100
2200
2300
2400
0100
0200
0300
Local Time

Fig.10.

12 FEB 1944

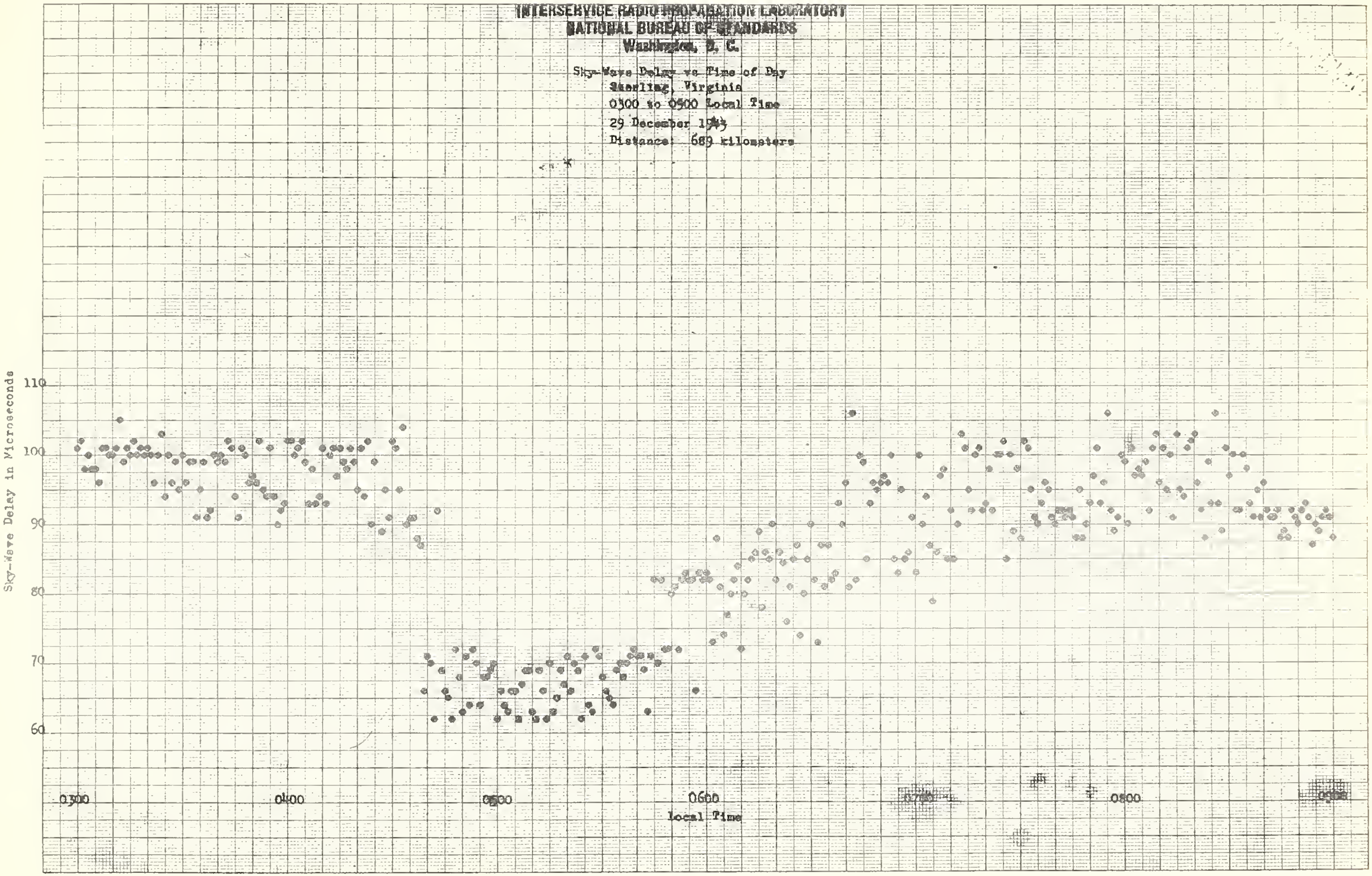
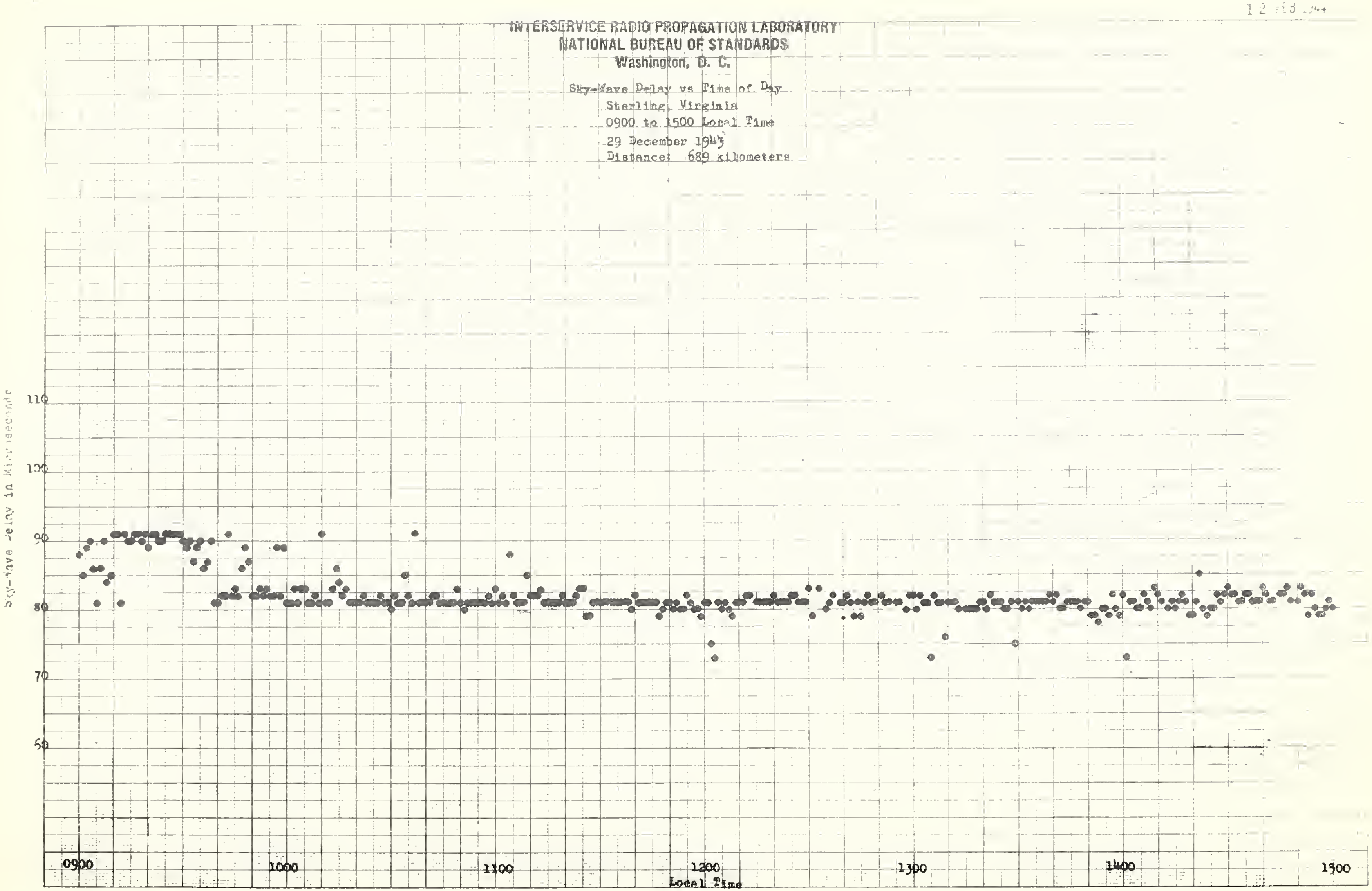


Fig.11.



INTERSERVICE RADIO PROPAGATION LABORATORY
NATIONAL BUREAU OF STANDARDS
Washington, D. C.
Sky-Wave Delay vs Time of Day
Sterling, Virginia
0900 to 1500 Local Time
29 December 1943
Distance: 689 kilometers
110
100
90
80
70
60
0900
1000
1100
1200
1300
1400
1500
Local Time

Fig.12.

12 FEB 1944

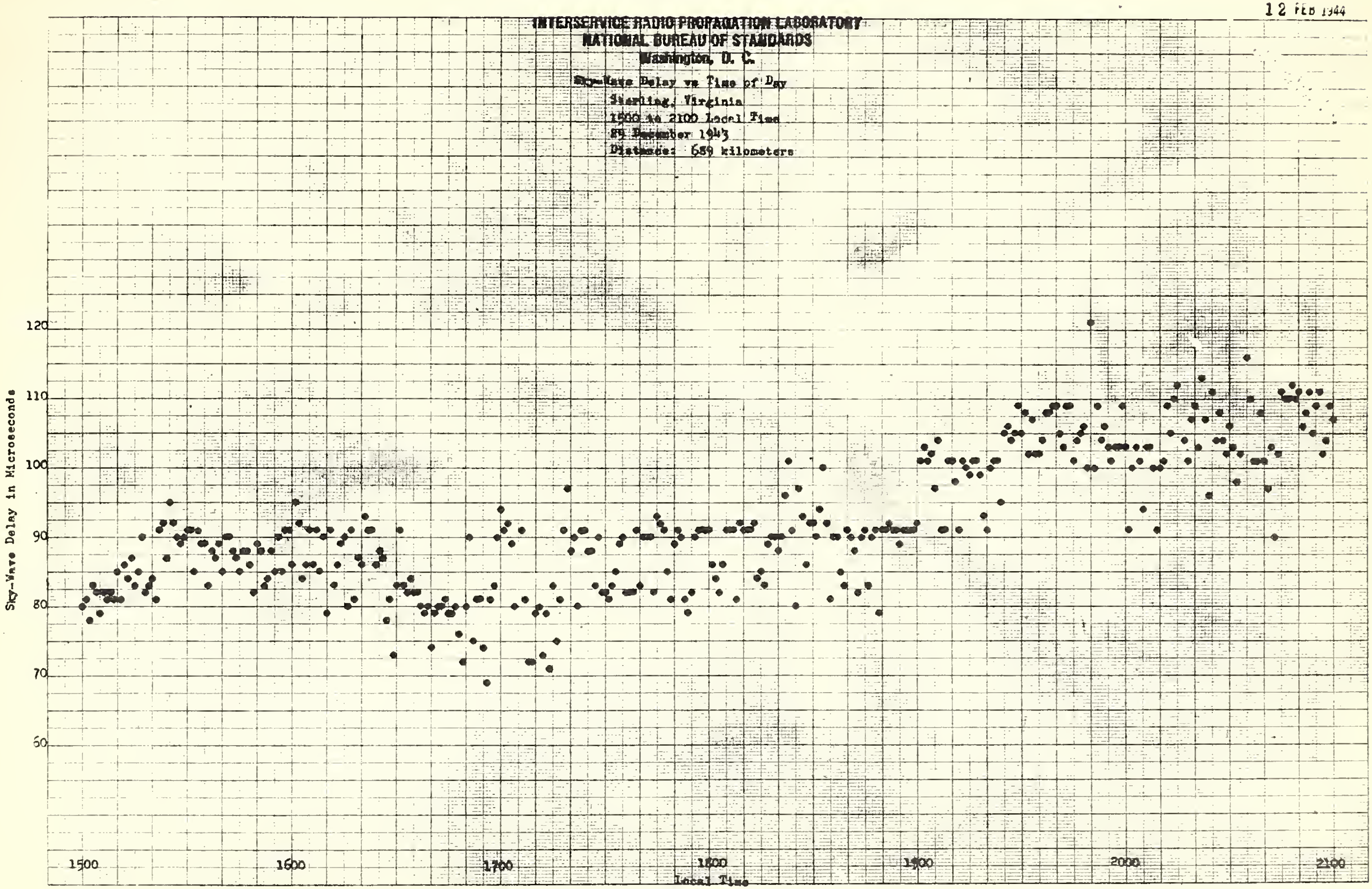
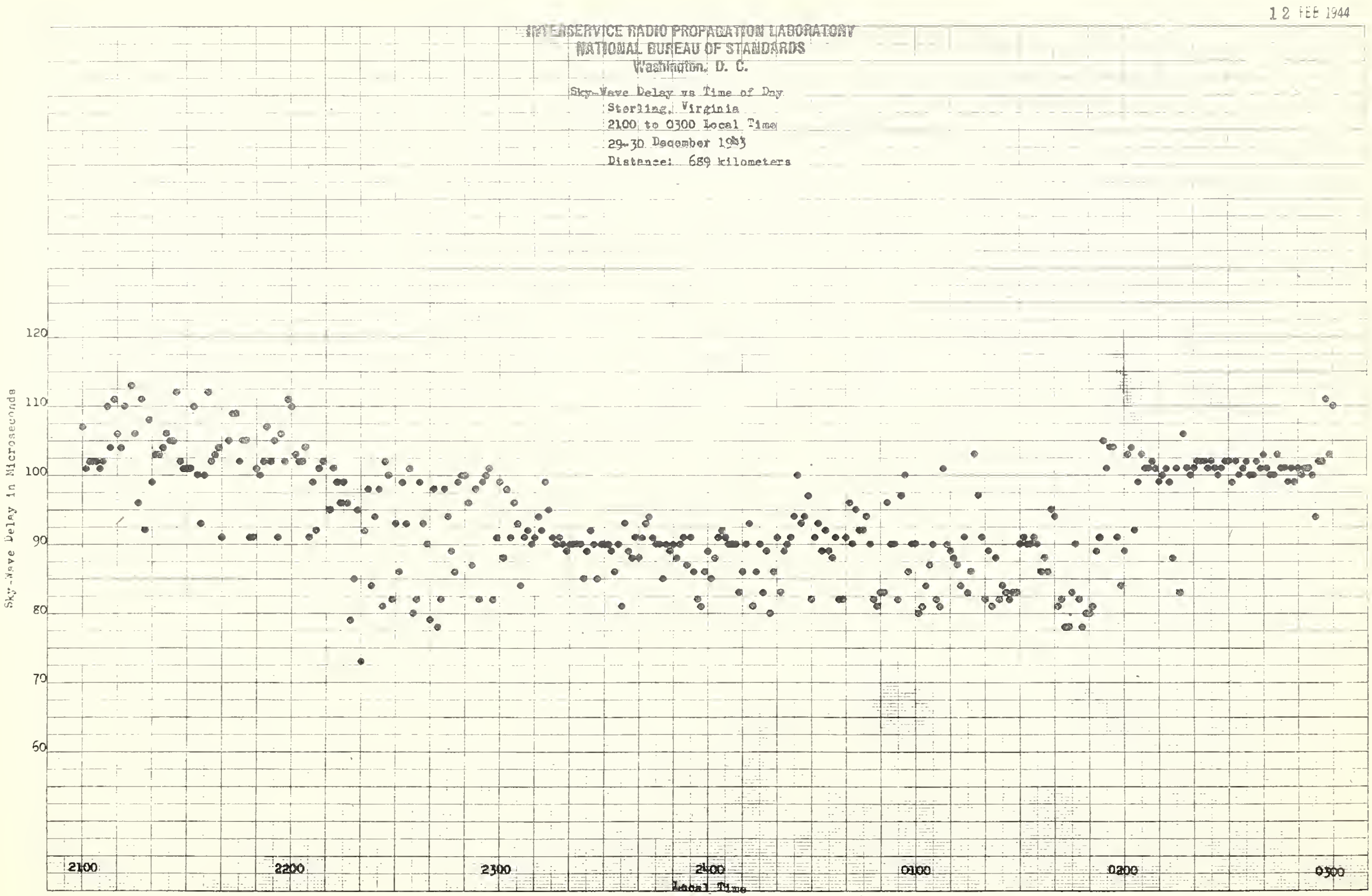


Fig.13.



12 FEB 1944
INTERSERVICE RADIO PROPAGATION LABORATORY
NATIONAL BUREAU OF STANDARDS
Washington, D. C.
Sky-Wave Delay vs Time of Day
Sterling, Virginia
2100 to 0300 Local Time
29-30 December 1943
Distance: 689 kilometers
Sky-Wave Delay in Microseconds
120
110
100
90
80
70
60
2100
2200
2300
2400
0100
0200
0300
Local Time

Fig.14.

12 FEB 1944

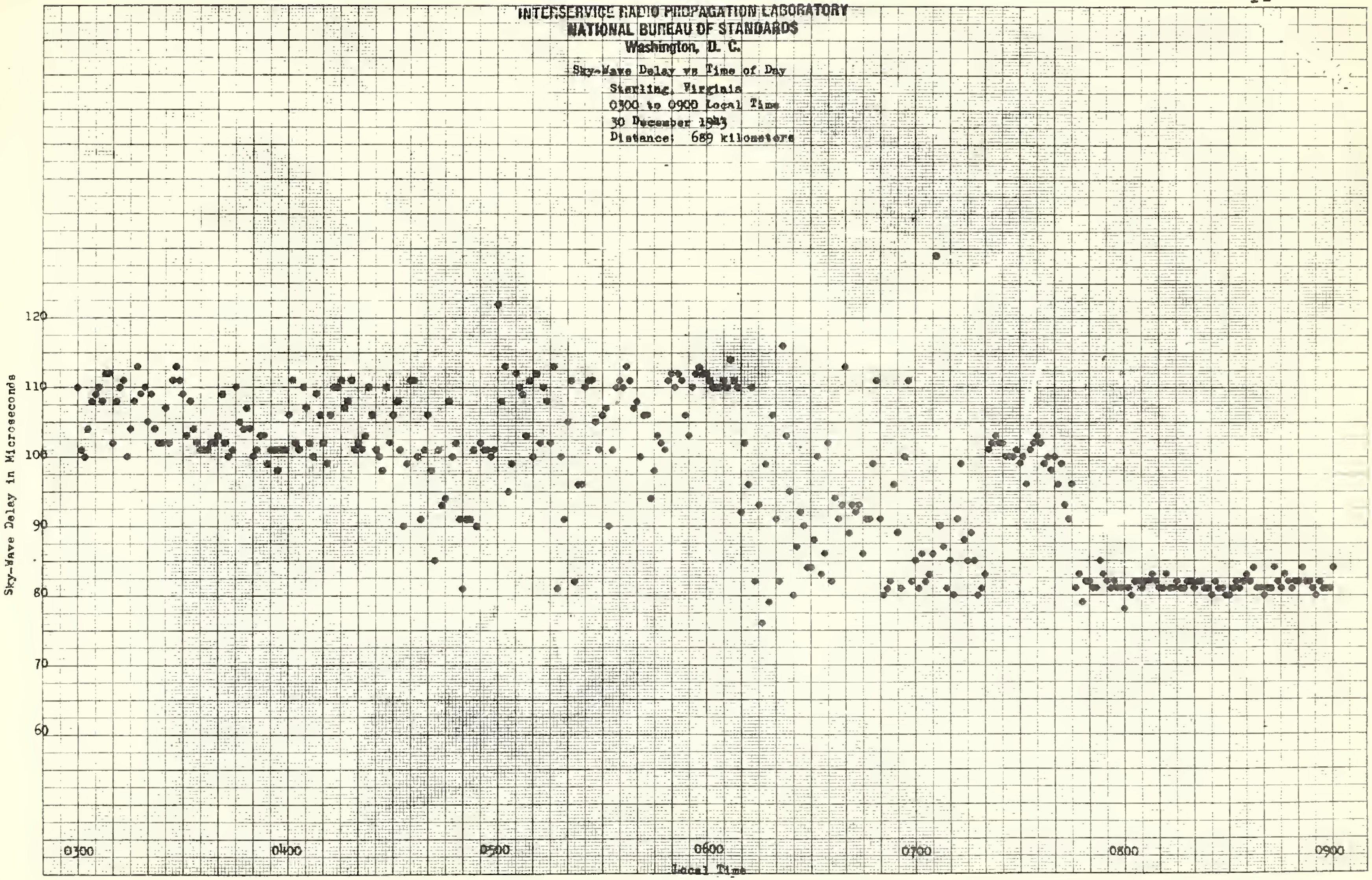
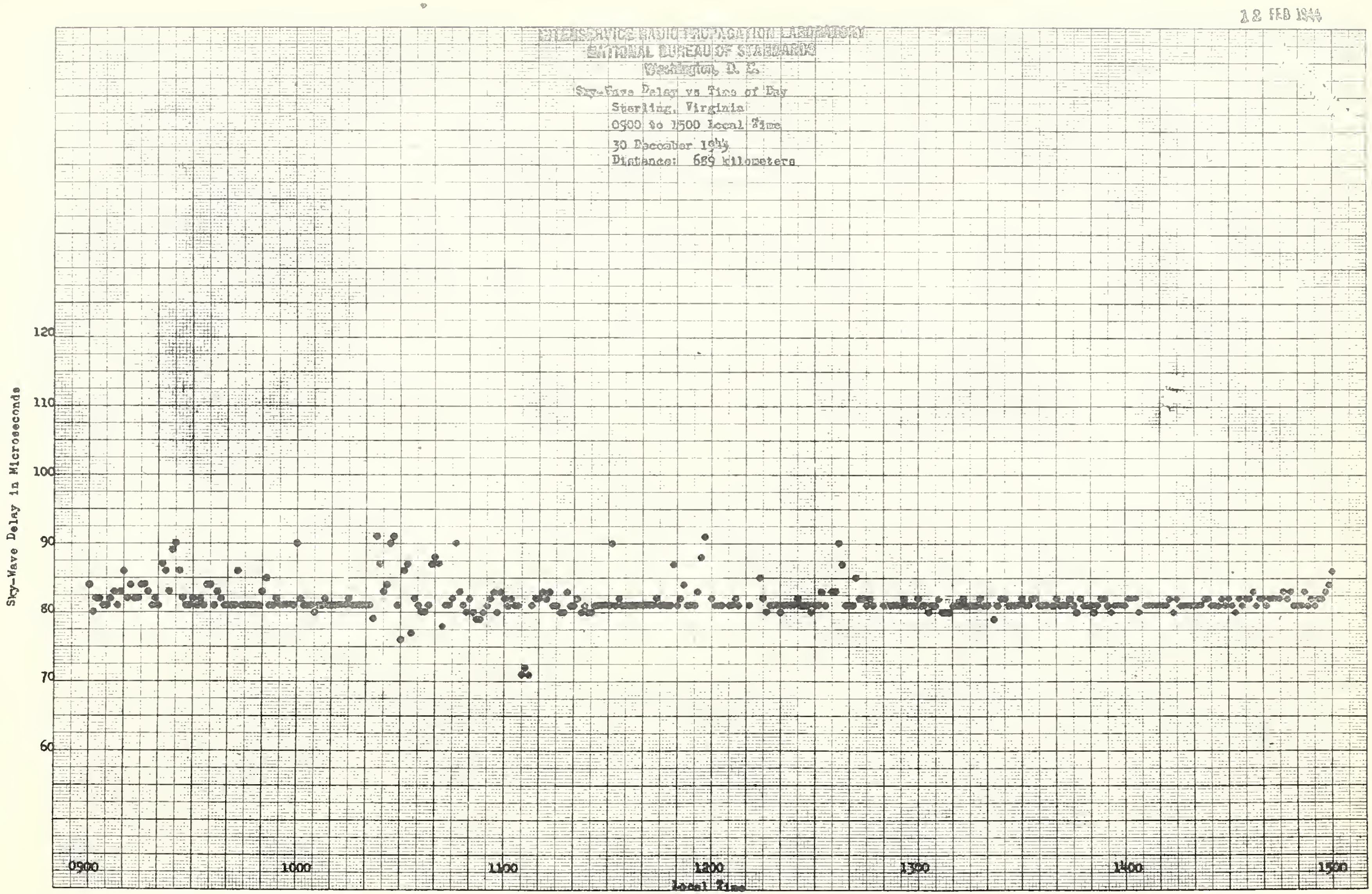
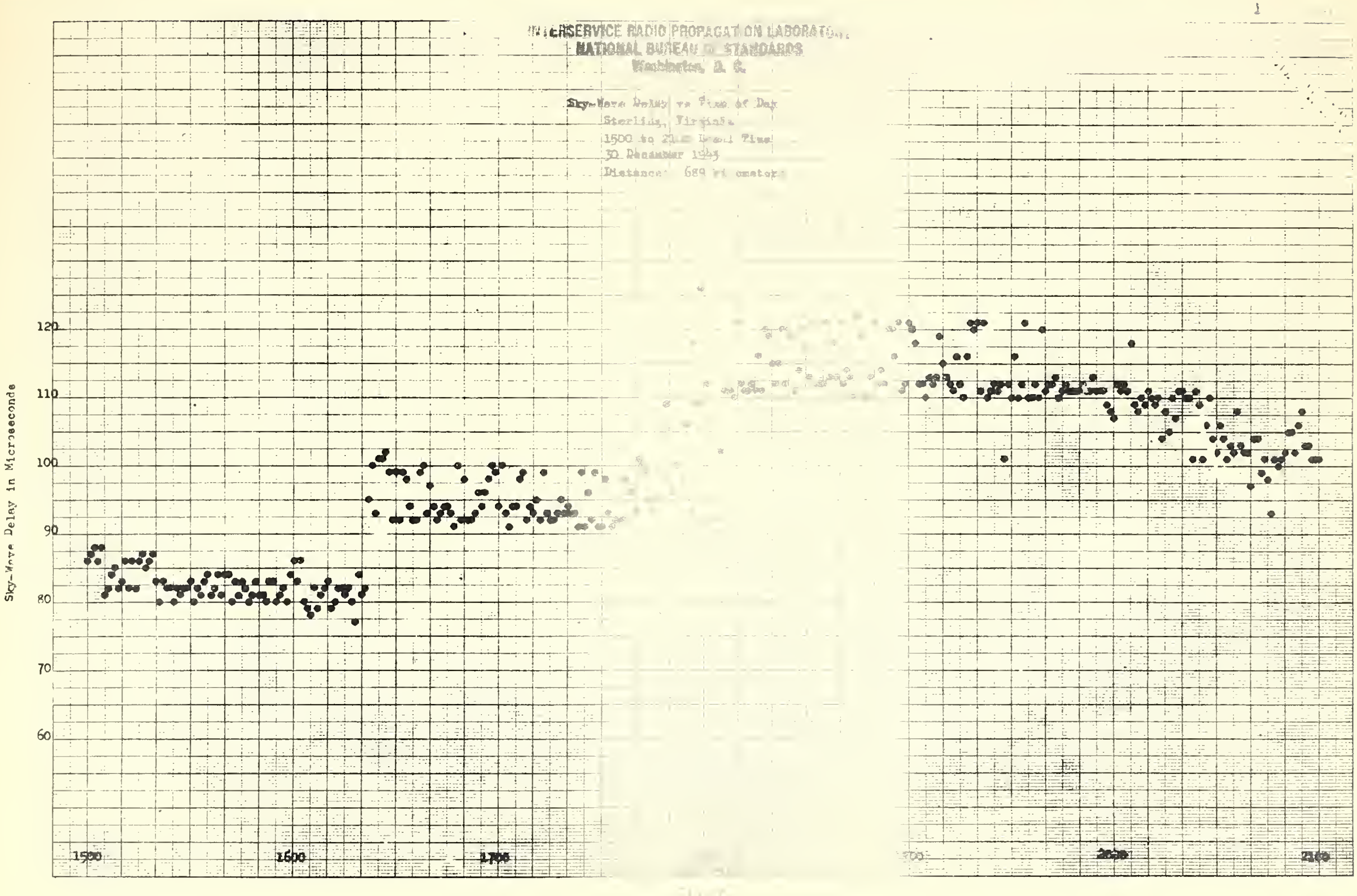


Fig.15


12 FEB 1944
INTERSERVICE RADIO PROPAGATION LABORATORY
NATIONAL BUREAU OF STANDARDS
Washington, D. C.
Sky-Wave Delay vs Time of Day
Sterling, Virginia
0900 to 1500 Local Time
30 December 1943
Distance: 689 kilometers
Sky-Wave Delay in Microseconds
120
110
100
90
80
70
60
0900
1000
1100
1200
1300
1400
1500
Local Time
Fig.16.


NATIONAL BUREAU OF STANDARDS
Washington, D. C.
Sky-Wave Delay vs Time of Day
Sterling, Virginia
30 December
Sky-Wave Delay in Microseconds
120
110
100
90
80
70
60
1500
1600
1700
2000
2100

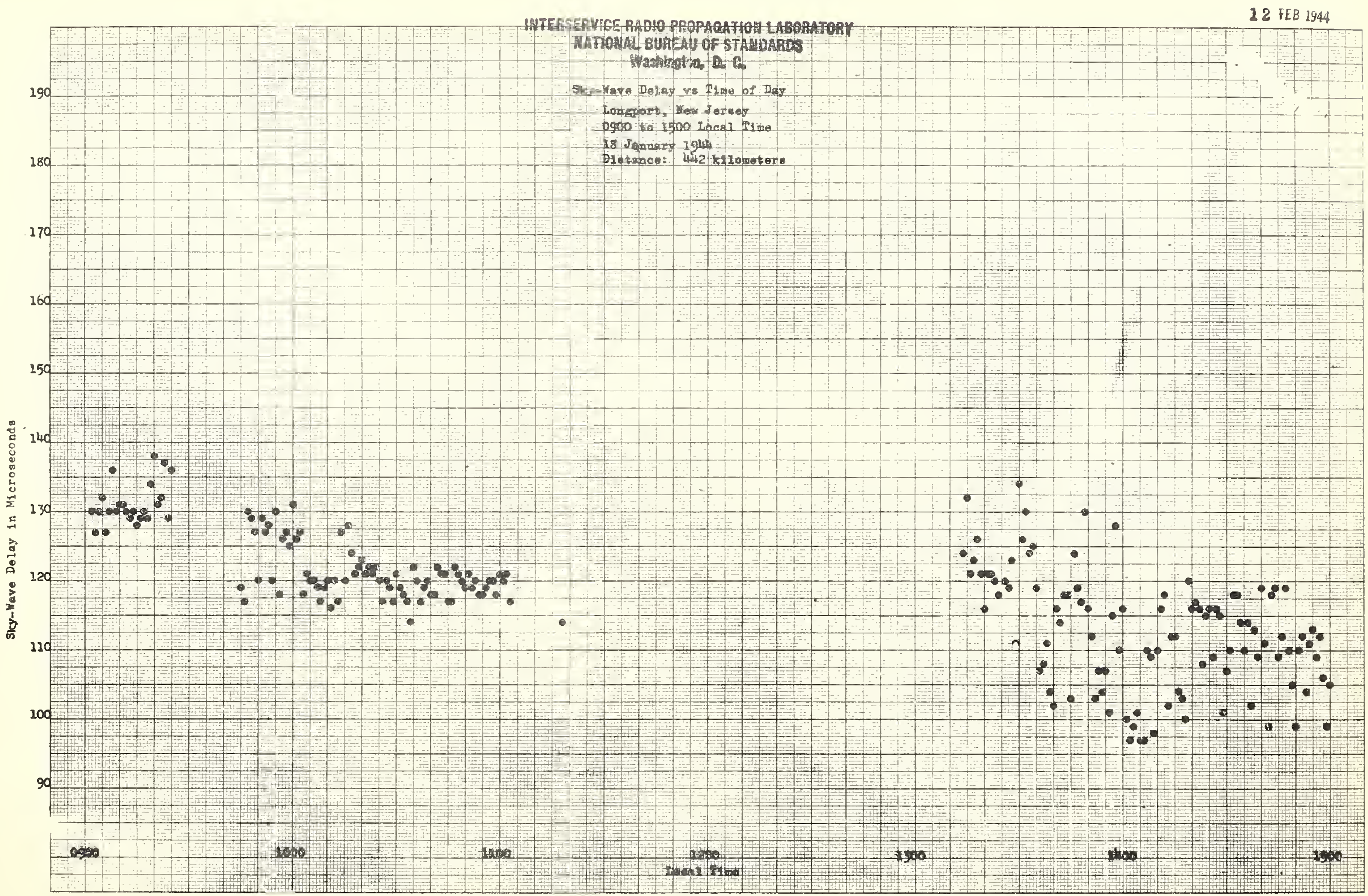
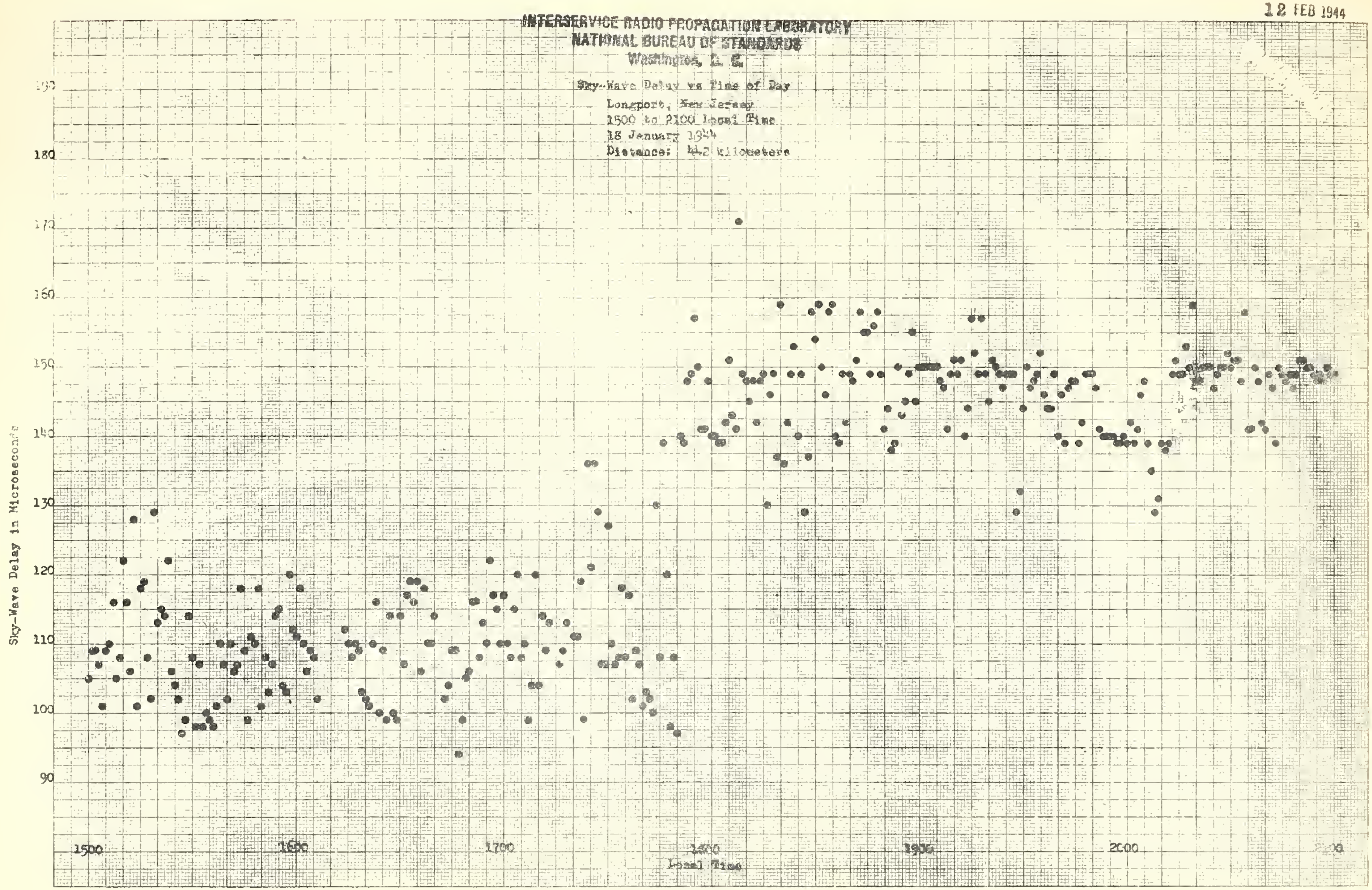

12 FEB 1944
INTERSERVICE RADIO PROPAGATION LABORATORY
NATIONAL BUREAU OF STANDARDS
Washington, D. C.
Sky-Wave Delay vs Time of Day
Longport, New Jersey
0900 to 1500 Local Time
13 January 1944
Distance: 442 kilometers
Sky-Wave Delay in Microseconds
190
180
170
160
150
140
130
120
110
100
90
0900
1000
1100
1200
1300
1400
1500
Local Time

Fig.18.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INTERSERVICE RADIO PROPAGATION LABORATORY
NATIONAL BUREAU OF STANDARDS
Washington, D. C.
Sky-Wave Delay vs Time of Day
Longport, New Jersey
1500 to 2100 Local Time
18 January 1944
Distance: 142 kilometers
180
170
160
150
140
130
120
110
100
90
Sky-Wave Delay in Microseconds
1500
1600
1700
1800
1900
2000
2100
Local Time

Fig.19.

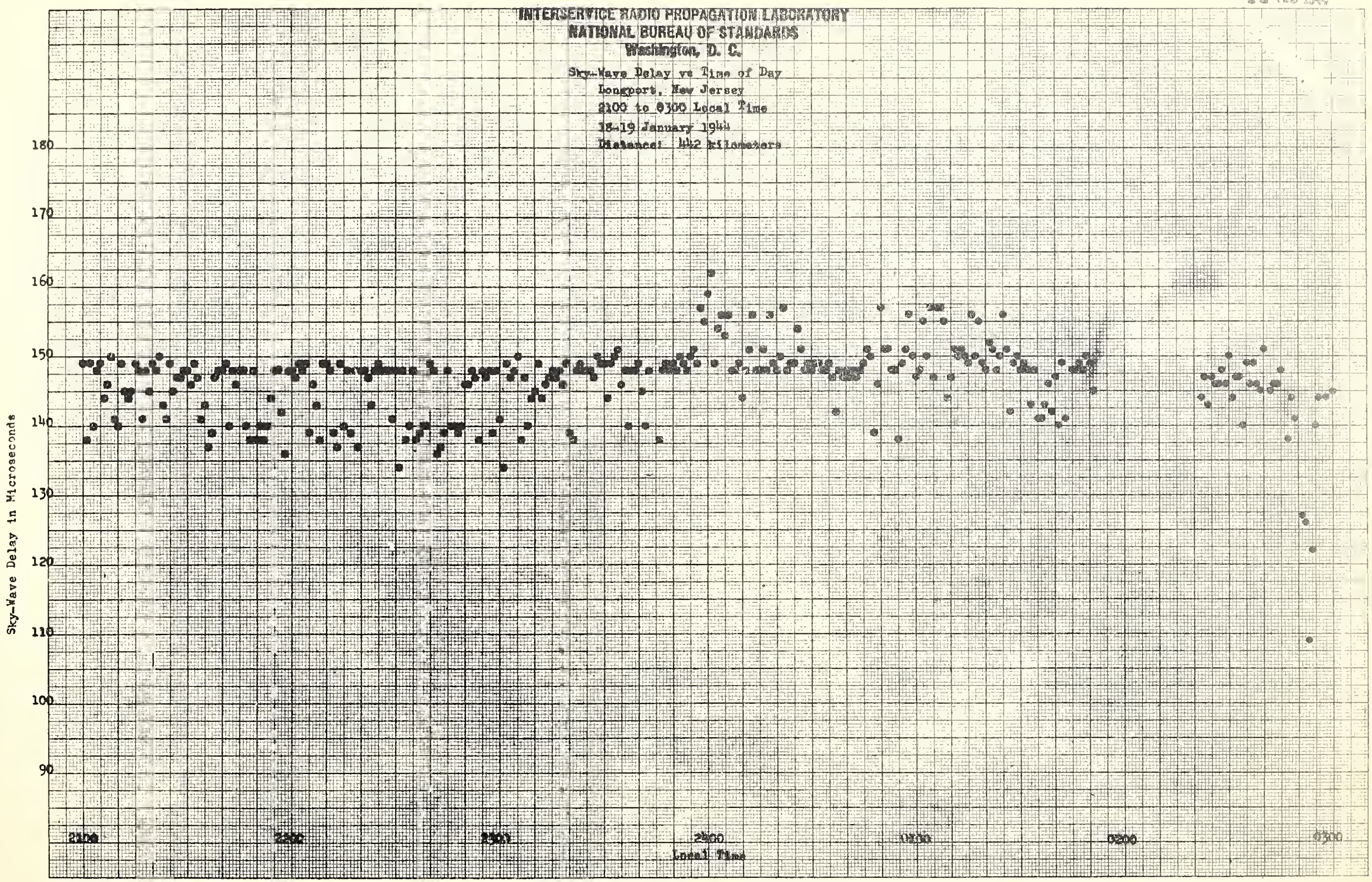

INTERSERVICE RADIO PROPAGATION LABORATORY
NATIONAL BUREAU OF STANDARDS
Washington, D. C.
Sky-Wave Delay vs Time of Day
Longport, New Jersey
2100 to 0300 Local Time
18-19 January 1944
Distance: 442 Kilometers
Sky-Wave Delay in Microseconds
180
170
160
150
140
130
120
110
100
90
2100
2200
2300
2400
0100
0200
0300
Local Time

Fig.20.

12 FEB 1944

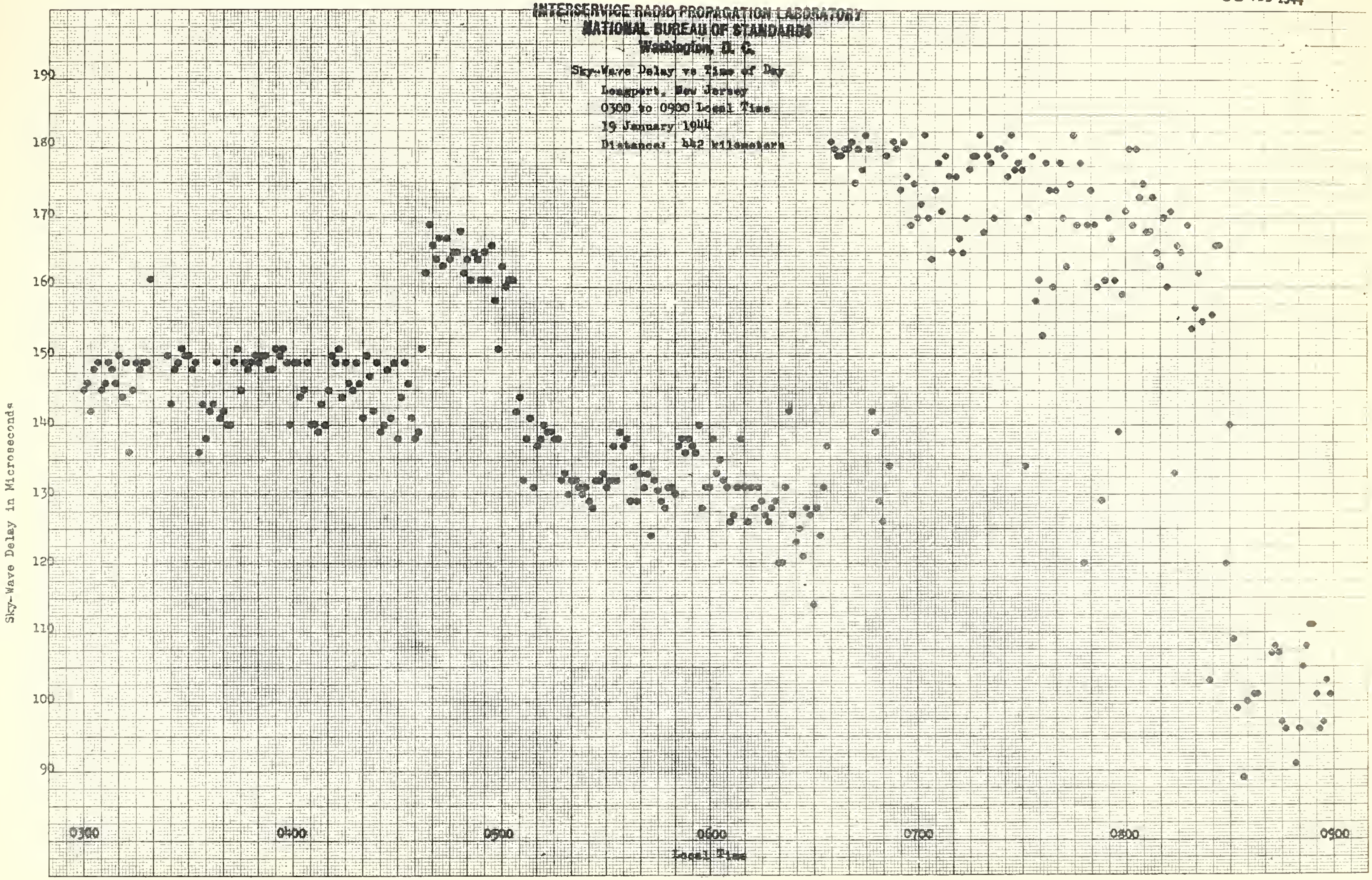


Fig. 21.

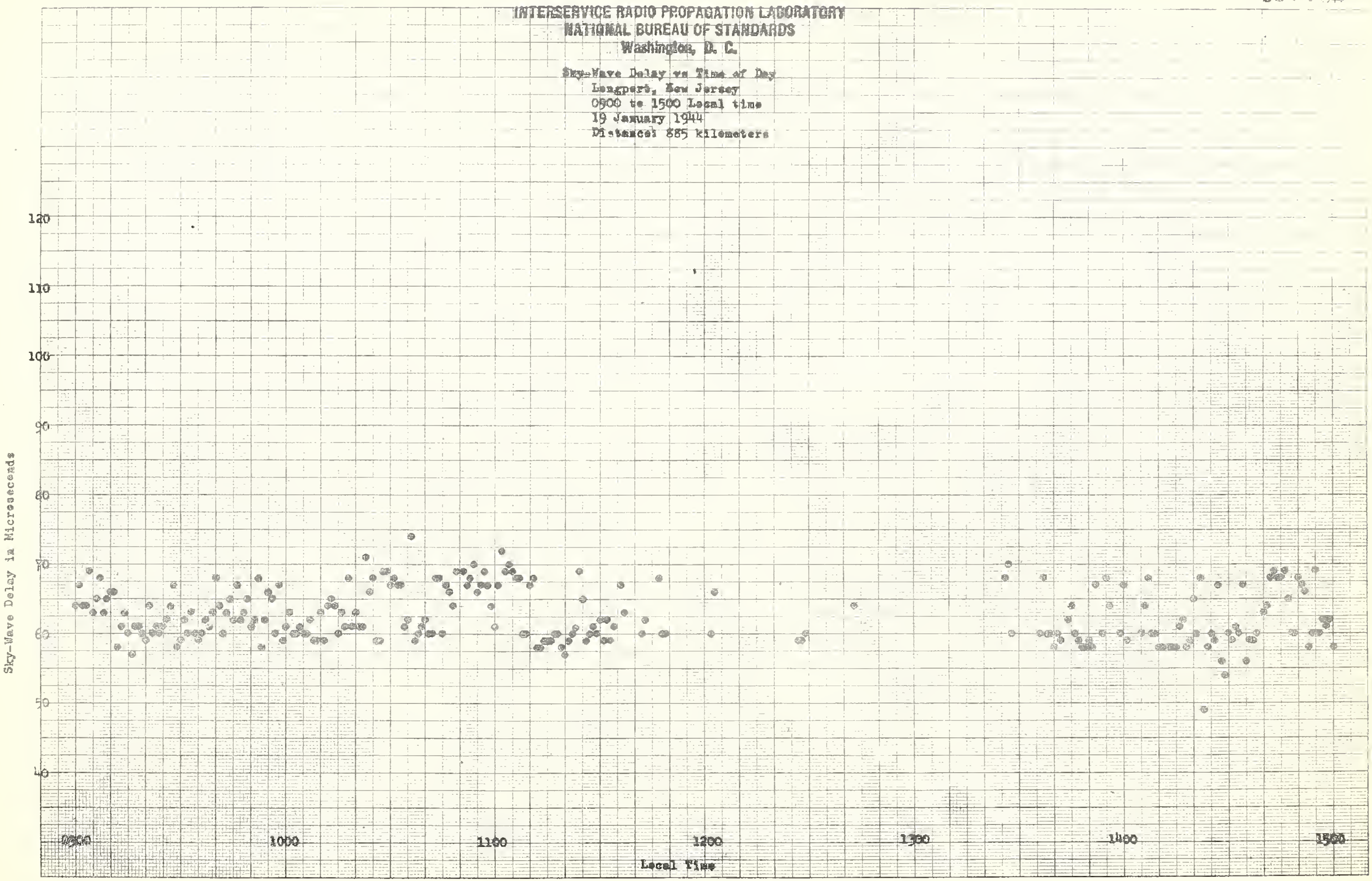
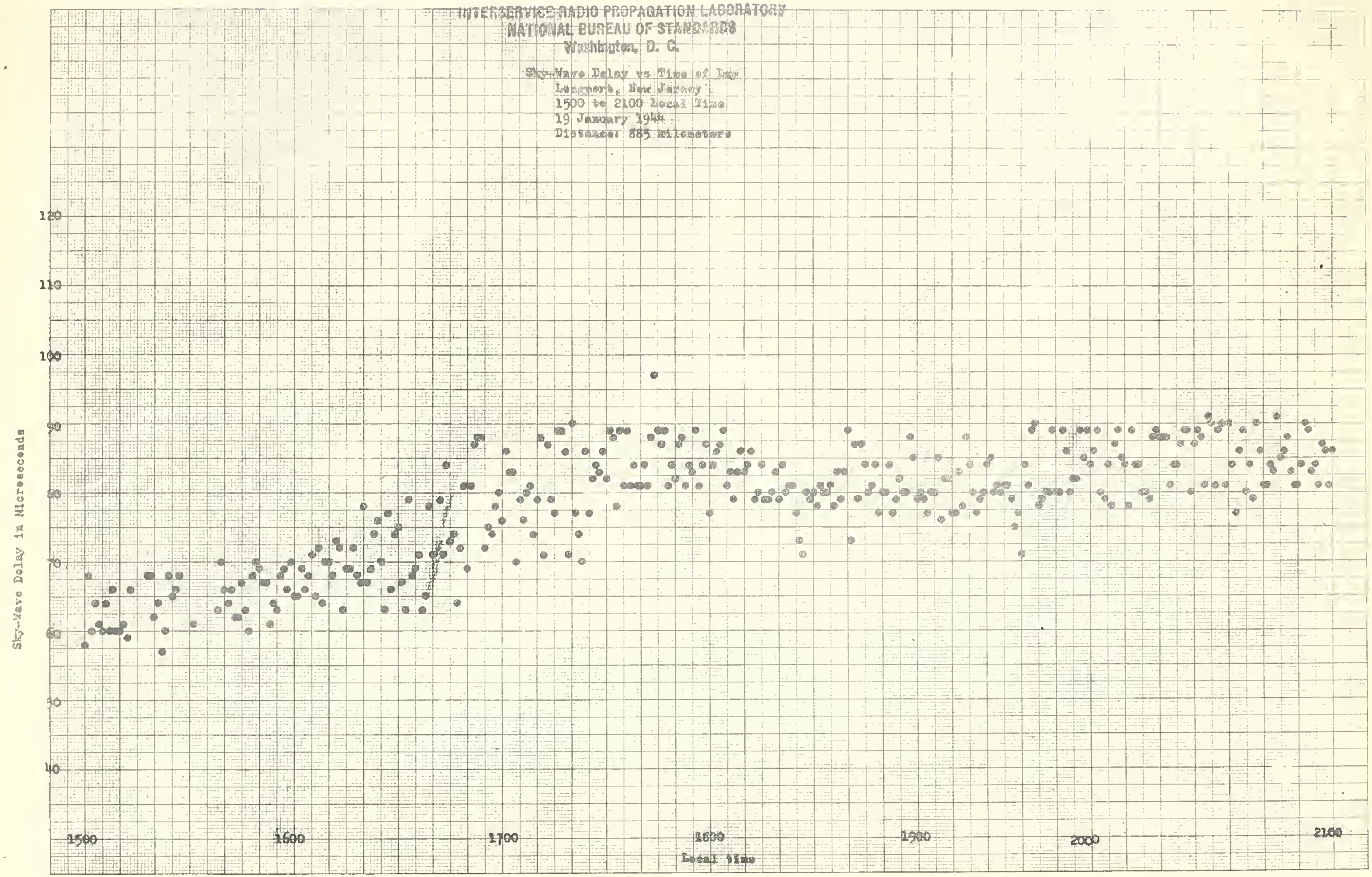

INTERSERVICE RADIO PROPAGATION LABORATORY
NATIONAL BUREAU OF STANDARDS
Washington, D. C.
Sky-Wave Delay vs Time of Day
Longport, New Jersey
0900 to 1500 Local time
19 January 1944
Distance: 885 kilometers
Sky-Wave Delay in Microseconds
120
110
100
90
80
70
60
50
40
0900
1000
1100
1200
1300
1400
1500
Local Time

Fig.22.


INTERSERVICE RADIO PROPAGATION LABORATORY
NATIONAL BUREAU OF STANDARDS
Washington, D. C.
Sky-Wave Delay vs Time of Day
Longport, New Jersey
1500 to 2100 Local Time
19 January 1944
Distance: 885 kilometers
Sky-Wave Delay in Microseconds
120
110
100
90
80
70
60
50
40
1500
1600
1700
1800
1900
2000
2100
Local Time
Fig.23.

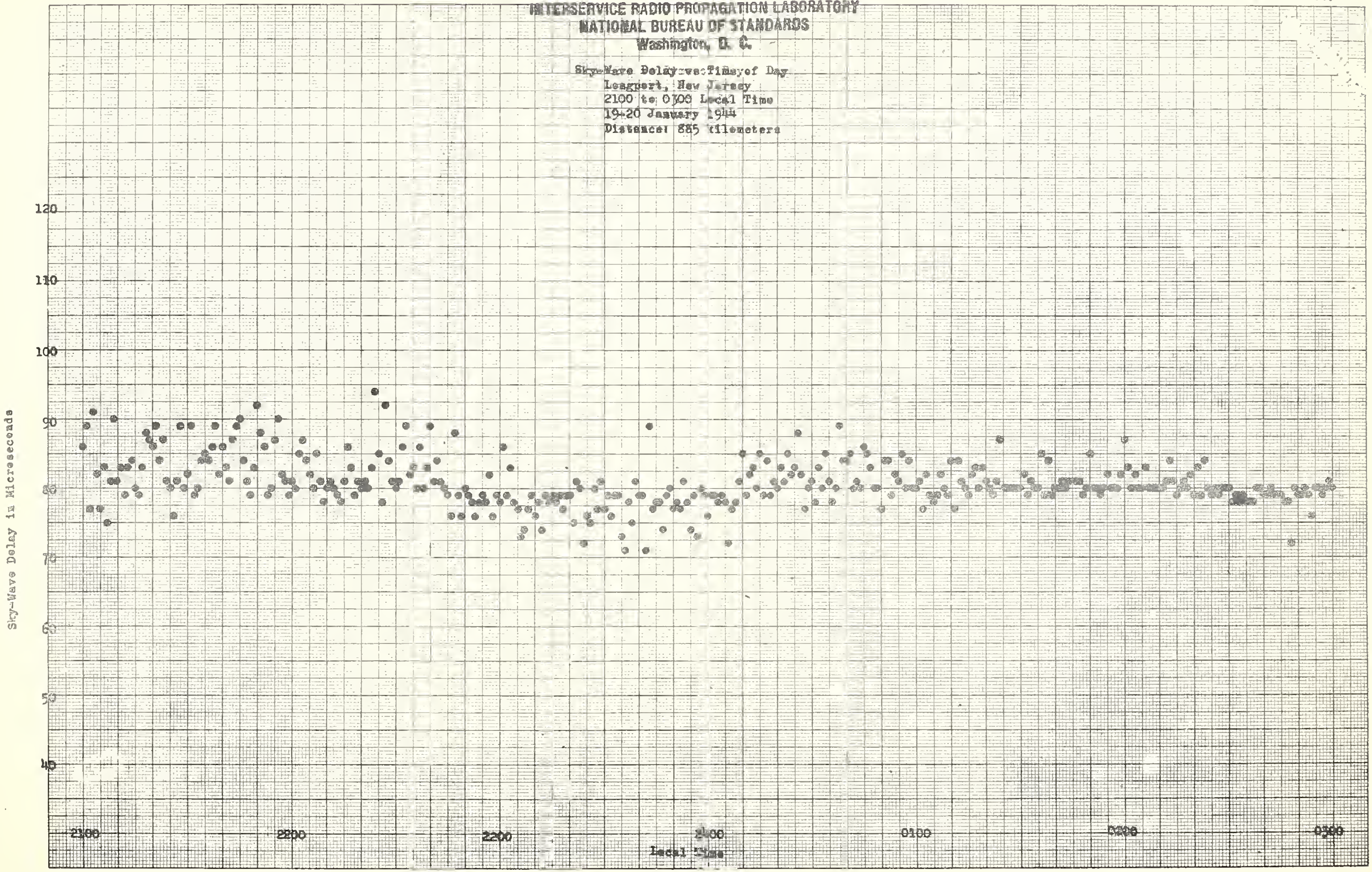

INTERSERVICE RADIO PROPAGATION LABORATORY
NATIONAL BUREAU OF STANDARDS
Washington, D. C.
Sky-Wave Delay vs. Time of Day
Leagport, New Jersey
2100 to 0300 Local Time
19-20 January 1944
Distance: 885 kilometers
120
110
100
90
80
70
60
50
40
Sky-Wave Delay in Microseconds
2100
2200
2200
2400
0100
0200
0300
Local Time

Fig.24

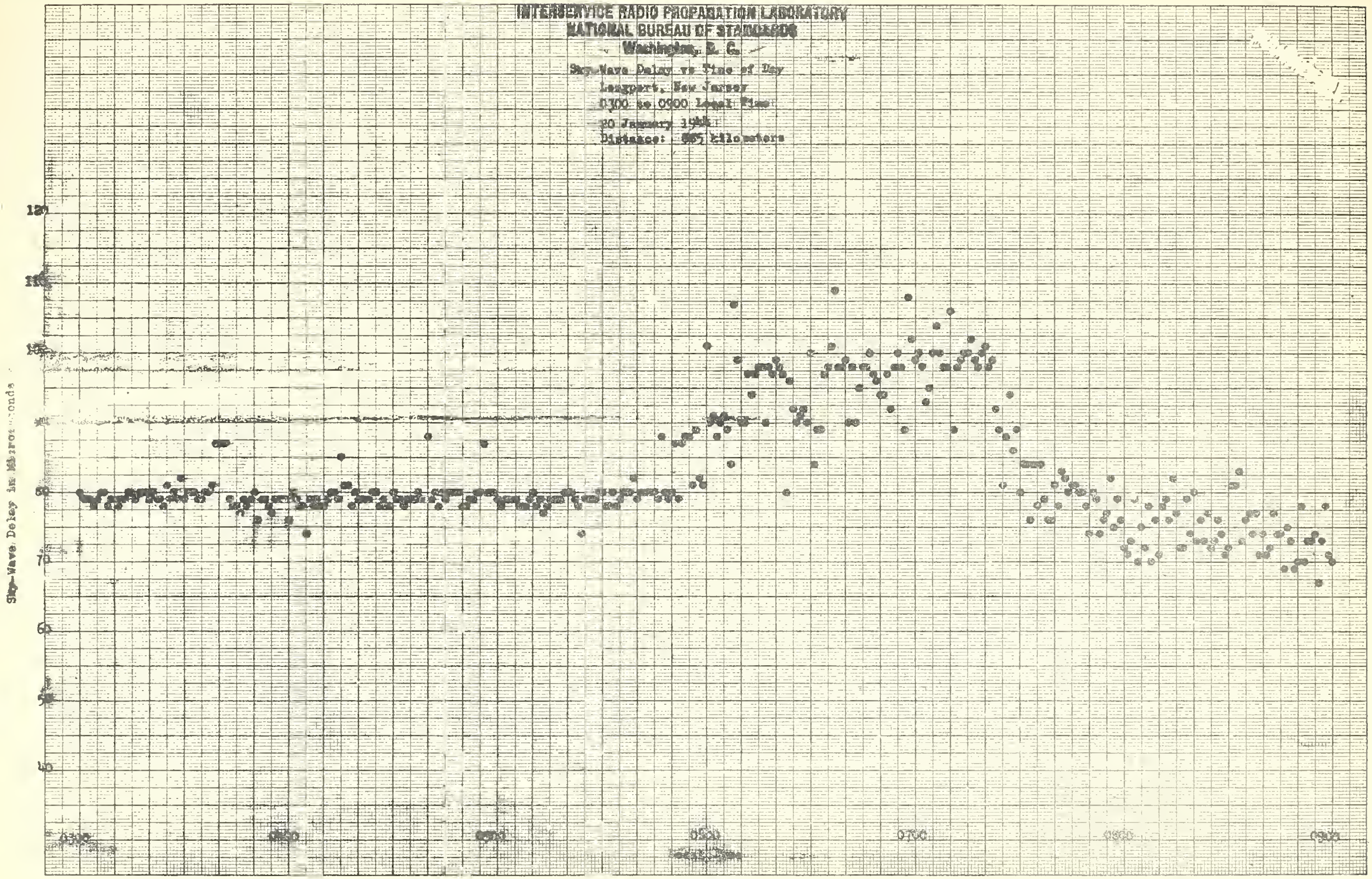

INTERSERVICE RADIO PROPAGATION LABORATORY
NATIONAL BUREAU OF STANDARDS
Washington, D. C.
Sky-Wave Delay vs Time of Day
Lakehurst, New Jersey
0300 to 0900 Local Time
20 January
Distance: Kilometers
Sky-Wave Delay in Microseconds
120
110
100
90
80
70
60
50
40
0300
0400
0500
0600
0700
0800
0900
Local Time

Fig. 25.

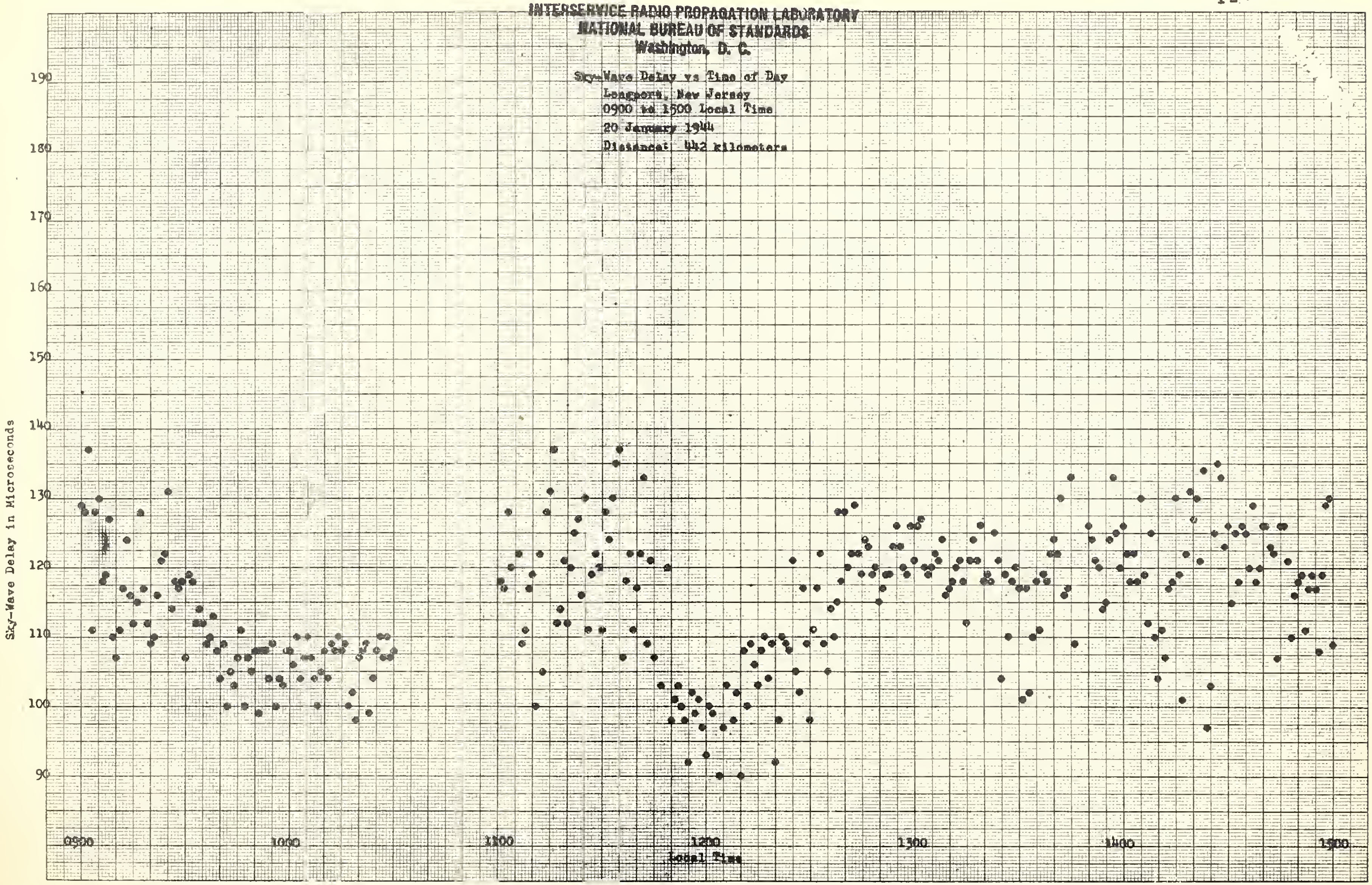

INTERSERVICE RADIO PROPAGATION LABORATORY
NATIONAL BUREAU OF STANDARDS
Washington, D. C.
Sky-Wave Delay vs Time of Day
Longport, New Jersey
0900 to 1500 Local Time
20 January 1944
Distance: 442 kilometers
Sky-Wave Delay in Microseconds
190
180
170
160
150
140
130
120
110
100
90
0900
1000
1100
1200
1300
1400
1500
Local Time

Fig.26.

12 FEB 1944

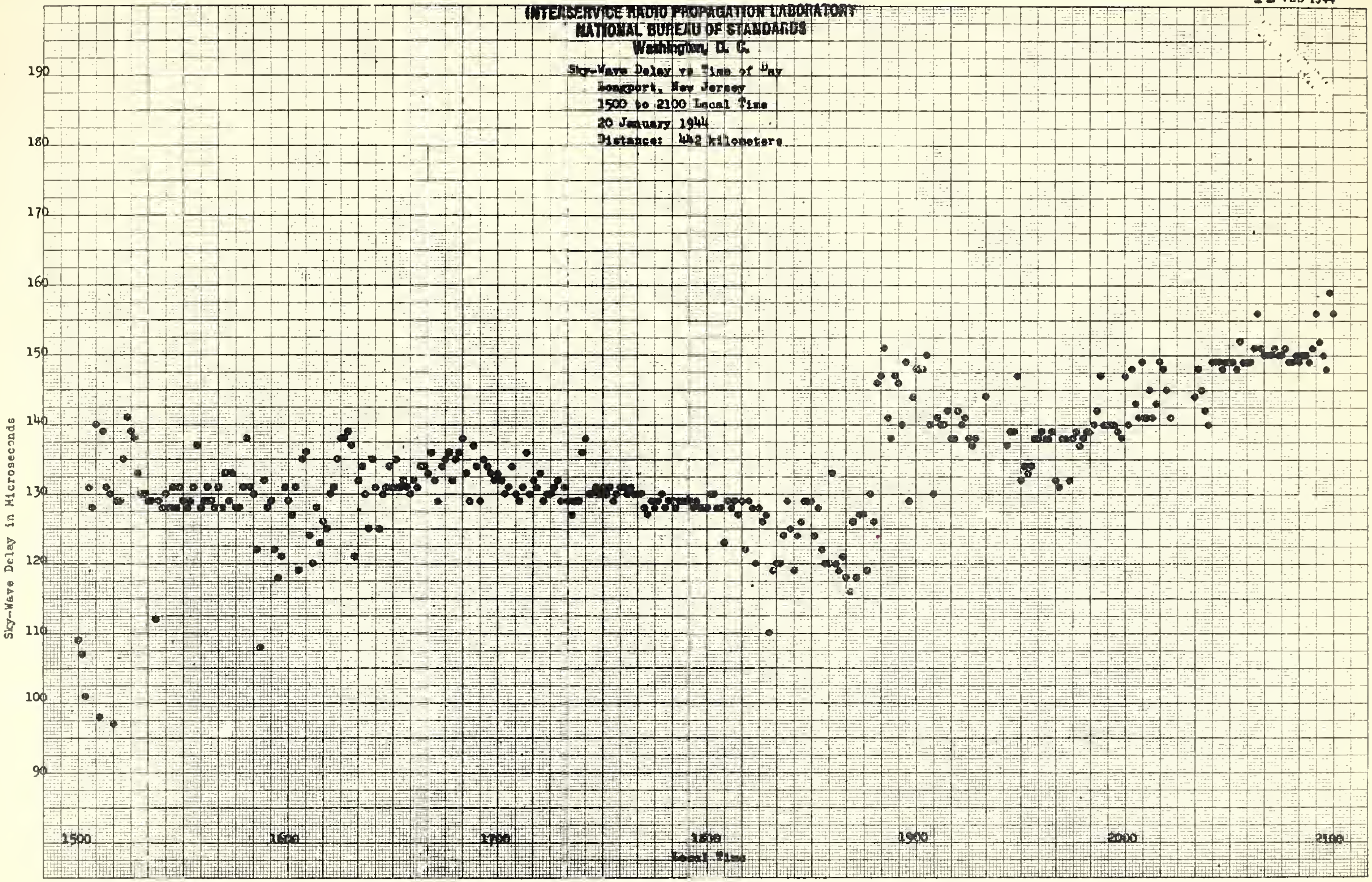


Fig.27.

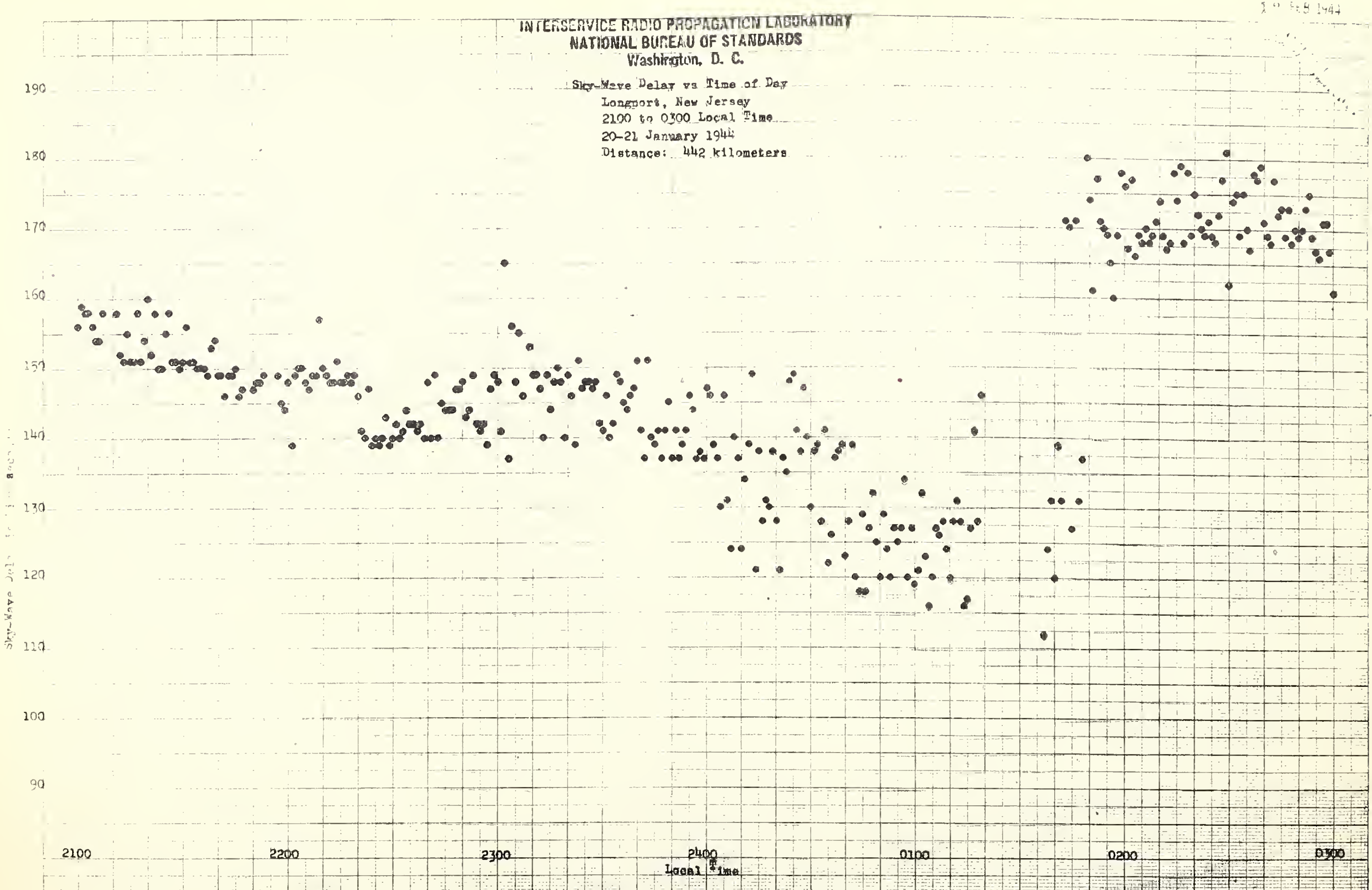

INTERSERVICE RADIO PROPAGATION LABORATORY
NATIONAL BUREAU OF STANDARDS
Washington, D. C.
Sky-Wave Delay vs Time of Day
Longport, New Jersey
2100 to 0300 Local Time
20-21 January 1944
Distance: 442 kilometers
190
180
170
160
150
140
130
120
110
100
90
2100
2200
2300
2400
0100
0200
0300
Local Time

Fig. 28.

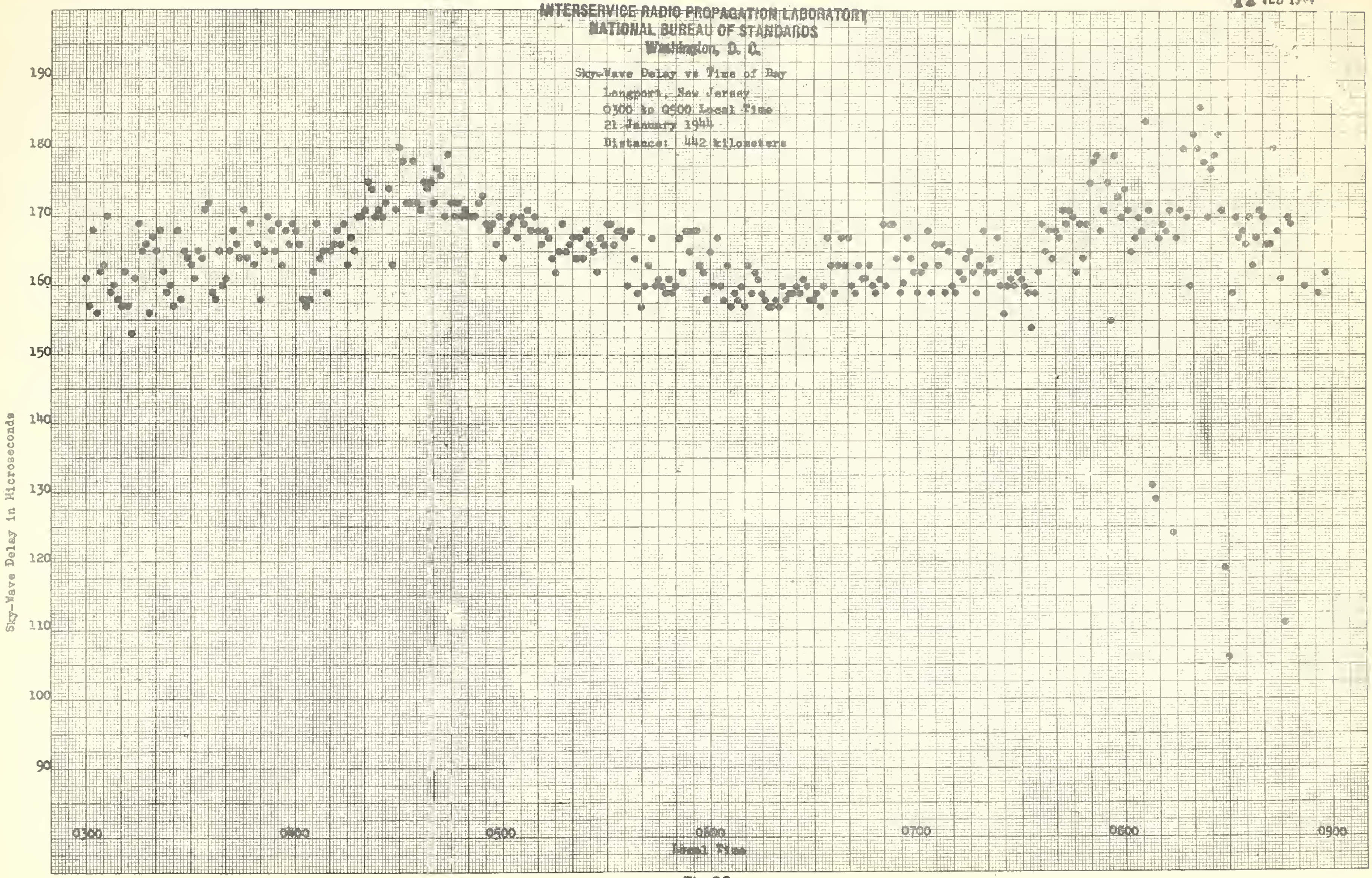

INTERSERVICE RADIO PROPAGATION LABORATORY
NATIONAL BUREAU OF STANDARDS
Washington, D. C.
Sky-Wave Delay vs Time of Day
Longport, New Jersey
0300 to 0900 Local Time
21 January 1944
Distance: 442 kilometers
Sky-Wave Delay in Microseconds
190
180
170
160
150
140
130
120
110
100
90
0300
0500
0700
0900
Local Time

Fig.29.

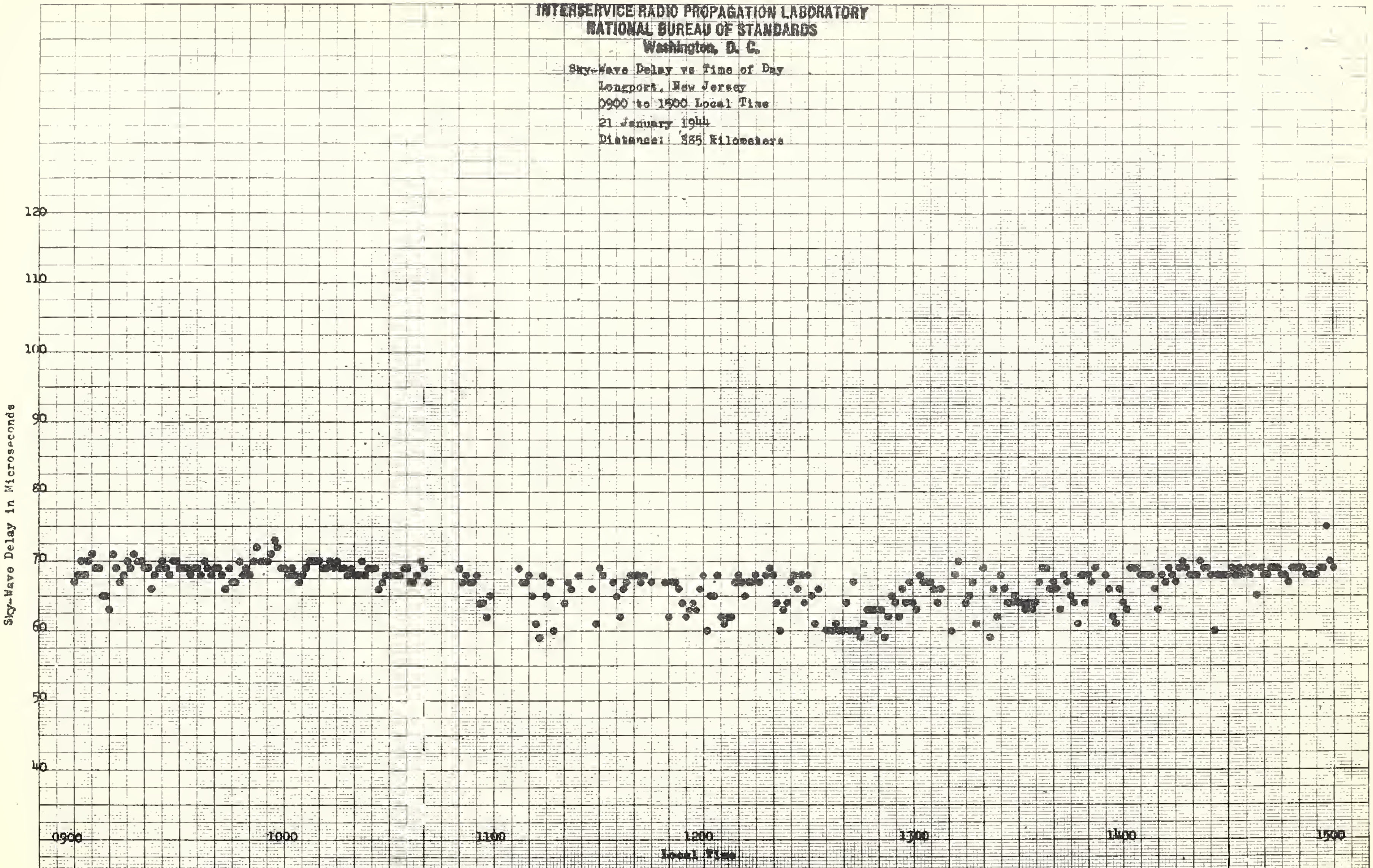

INTERSERVICE RADIO PROPAGATION LABORATORY
NATIONAL BUREAU OF STANDARDS
Washington, D. C.
Sky-Wave Delay vs Time of Day
Longport, New Jersey
0900 to 1500 Local Time
21 January 1944
Distance: 385 Kilometers
120
110
100
90
80
70
60
50
40
Sky-Wave Delay in Microseconds
0900
1000
1100
1200
1300
1400
1500
Local Time

Fig. 30.

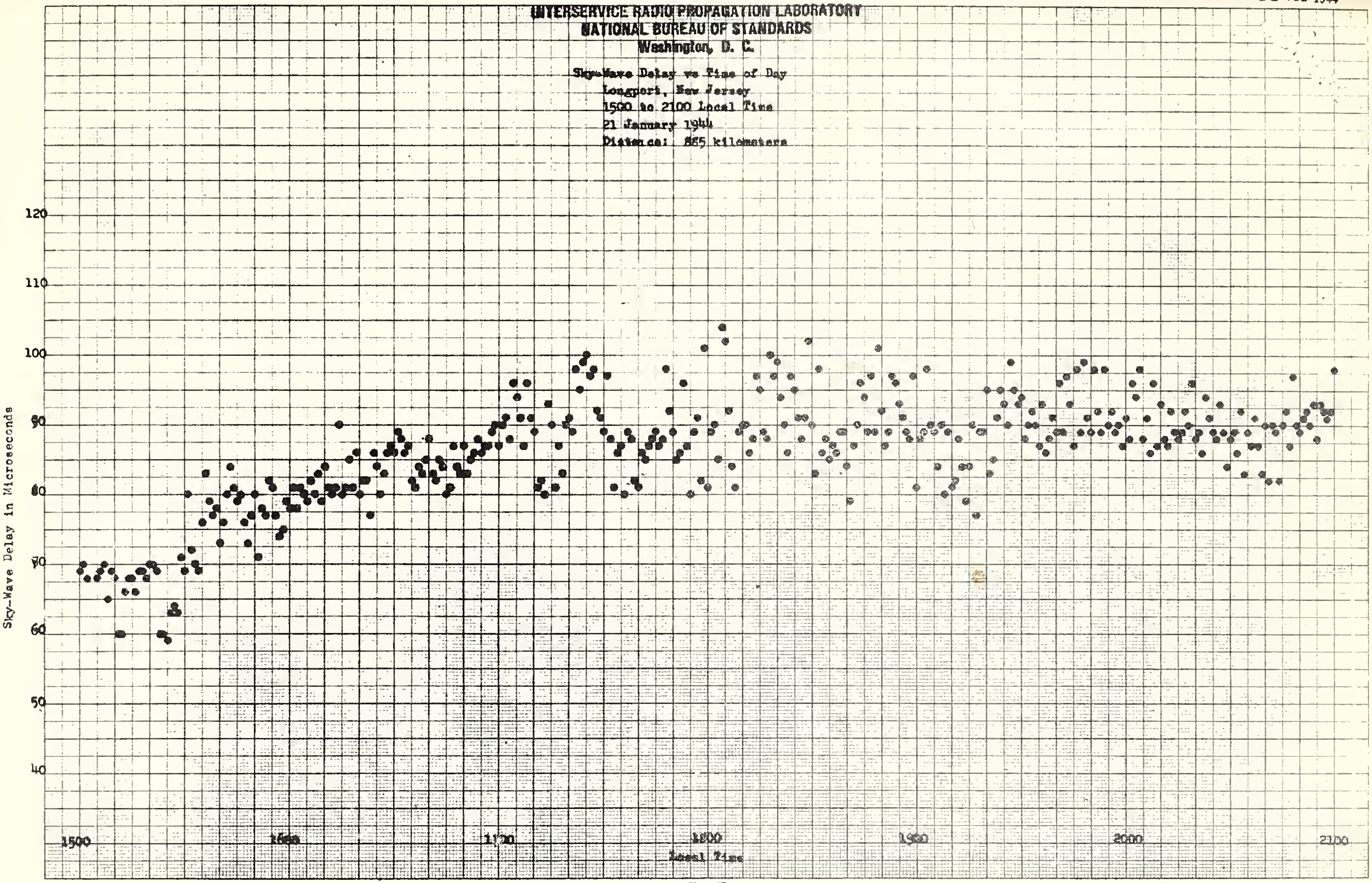

INTERSERVICE RADIO PROPAGATION LABORATORY
NATIONAL BUREAU OF STANDARDS
Washington, D. C.
Sky-Wave Delay vs Time of Day
Longport, New Jersey
1500 to 2100 Local Time
21 January 1944
Distance: 865 kilometers
120
110
100
90
80
70
60
50
40
Sky-Wave Delay in Microseconds
1500
1600
1700
1800
1900
2000
2100
Local Time

Fig. 31.

12 FEB 14

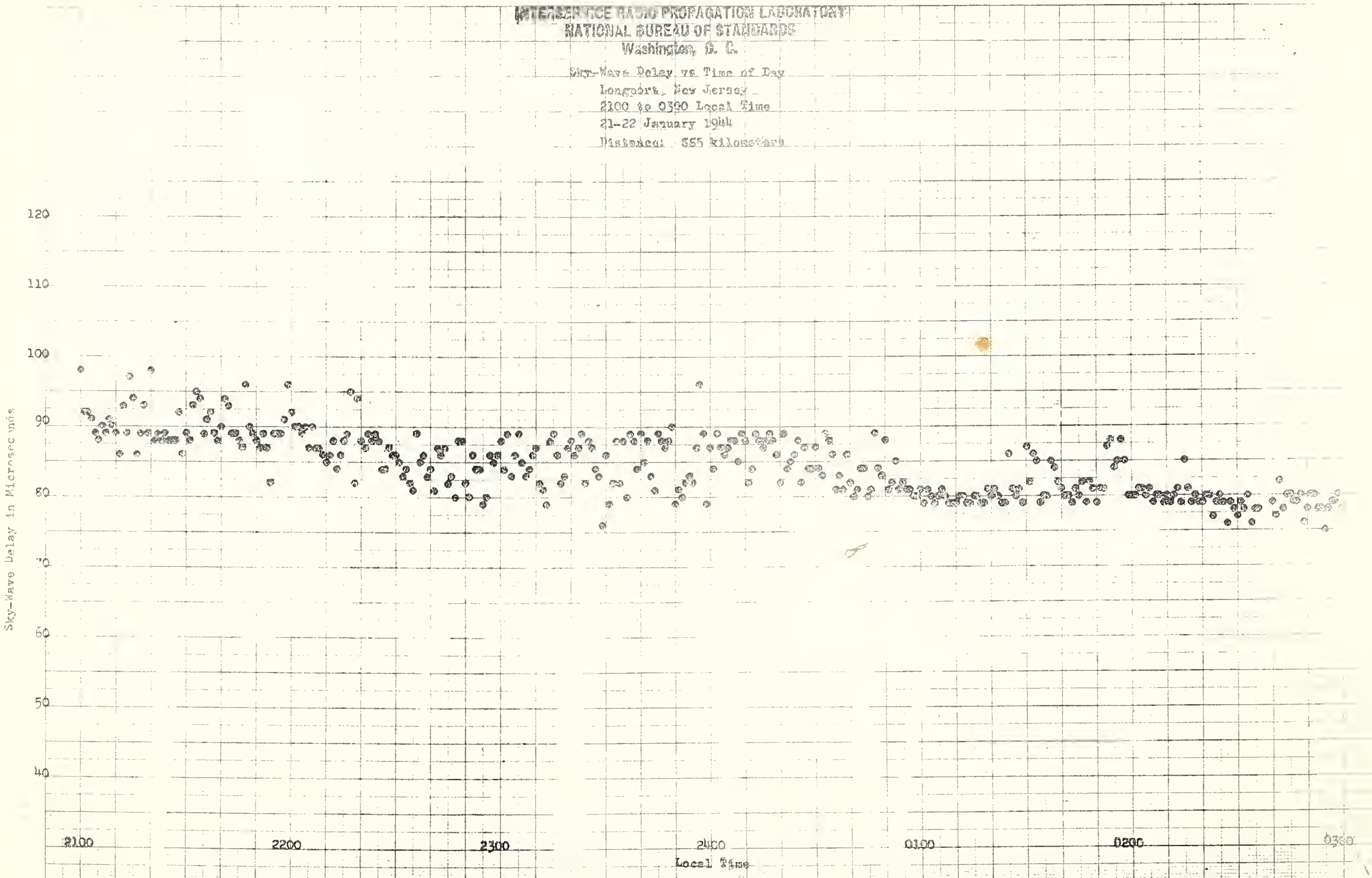


Fig. 32.

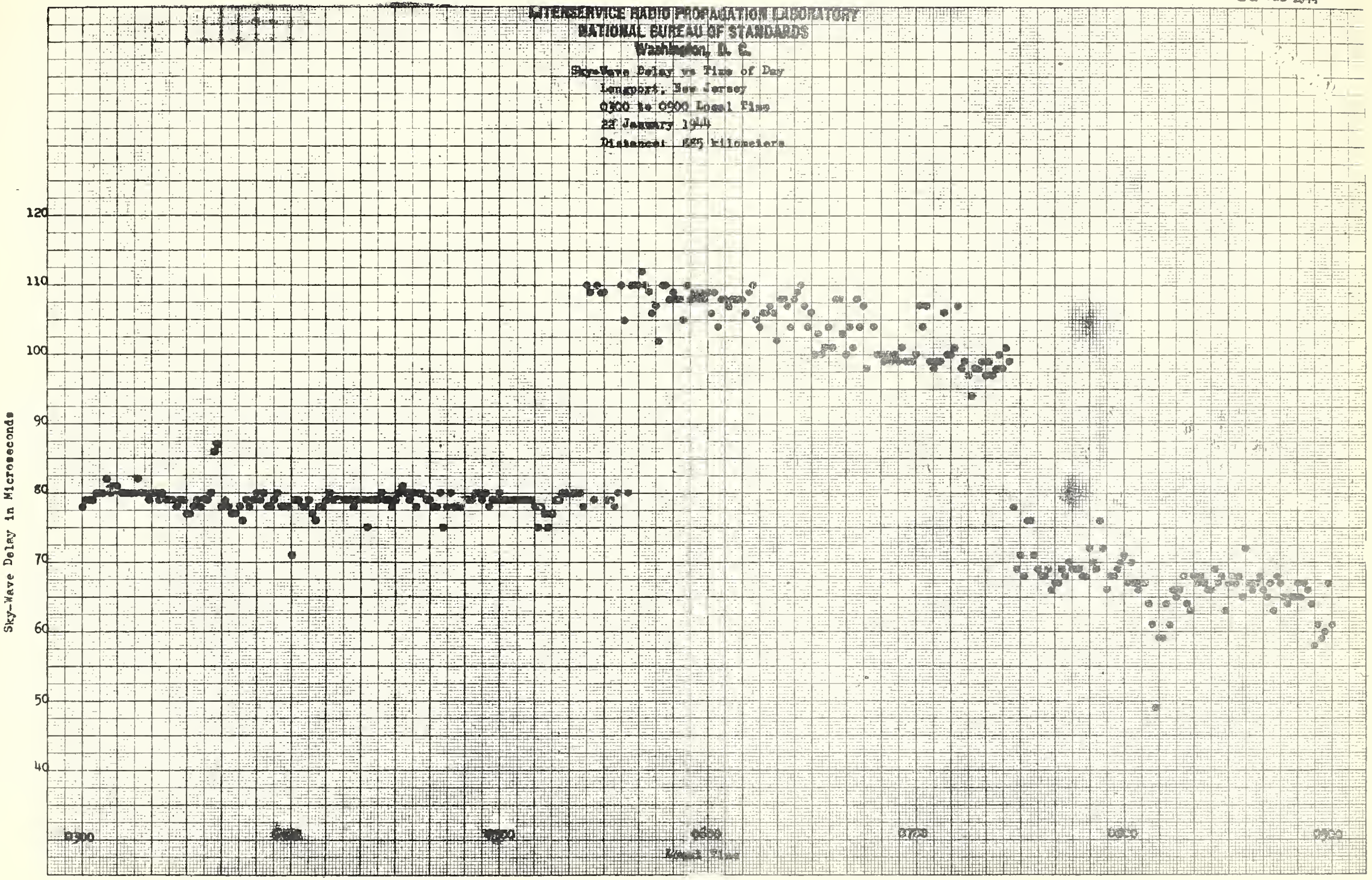

INTERSERVICE RADIO PROPAGATION LABORATORY
NATIONAL BUREAU OF STANDARDS
Washington, D. C.
Sky-Wave Delay vs Time of Day
Longport, New Jersey
0300 to 0900 Local Time
22 January 1944
Sky-Wave Delay in Microseconds
120
110
100
90
80
70
60
50
40
0300
0600
0700
Local Time

Fig.33.

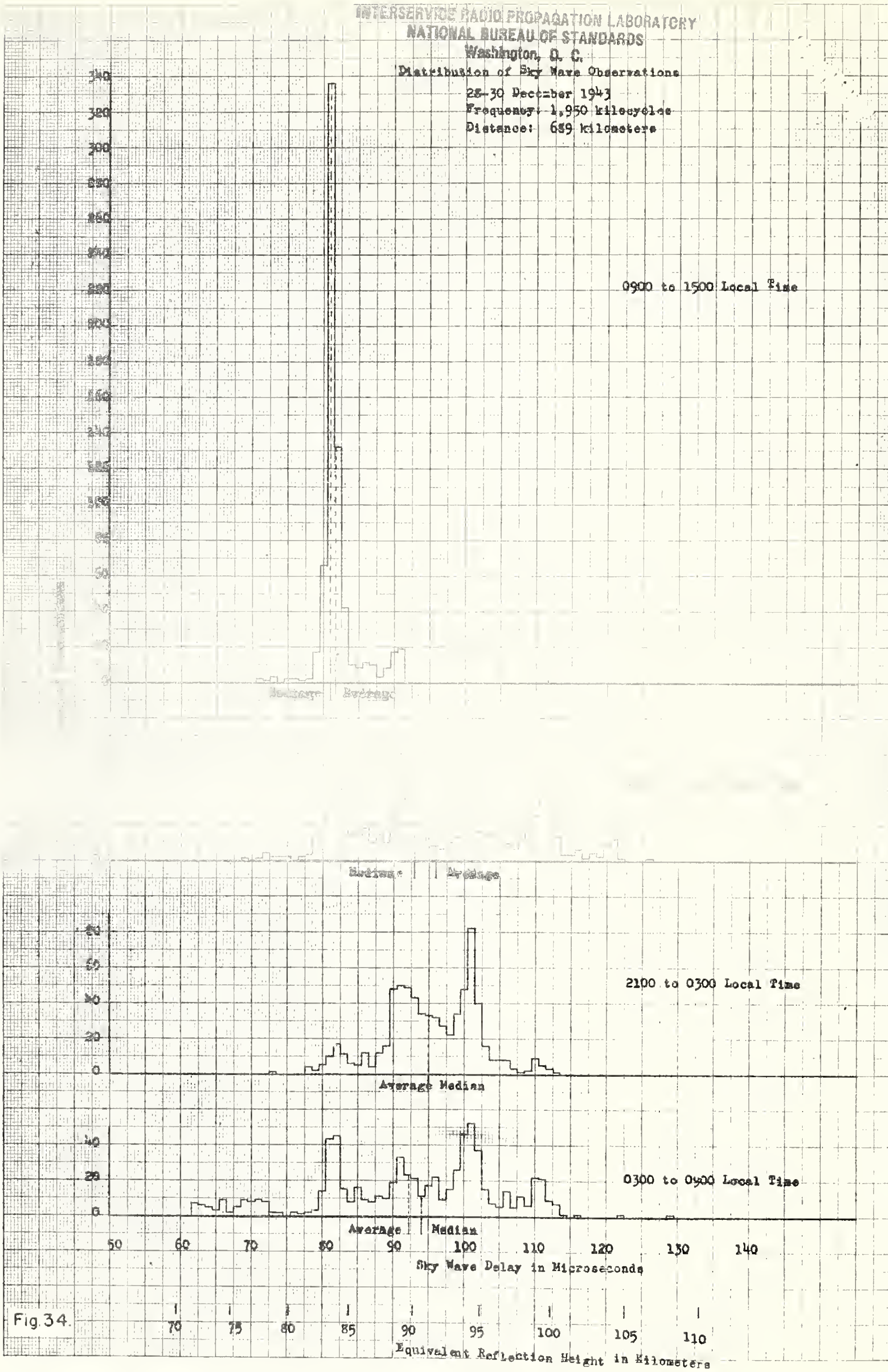

INTERSERVICE RADIO PROPAGATION LABORATORY
NATIONAL BUREAU OF STANDARDS
Washington, D. C.
Distribution of Sky Wave Observations
28-30 December 1943
Frequency: 1,950 kilocycles
Distance: 689 kilometers
0900 to 1500 Local Time
2100 to 0300 Local Time
Average Median
0300 to 0900 Local Time
Average Median
50
60
70
80
90
100
110
120
130
140
Sky Wave Delay in Microseconds
70
75
80
85
90
95
100
105
110
Equivalent Reflection Height in Kilometers

Fig. 34.

INTERSERVICE RADIO PROPAGATION LABORATORY 9 MAR 1944

NATIONAL BUREAU OF STANDARDS
Washington, D. C.

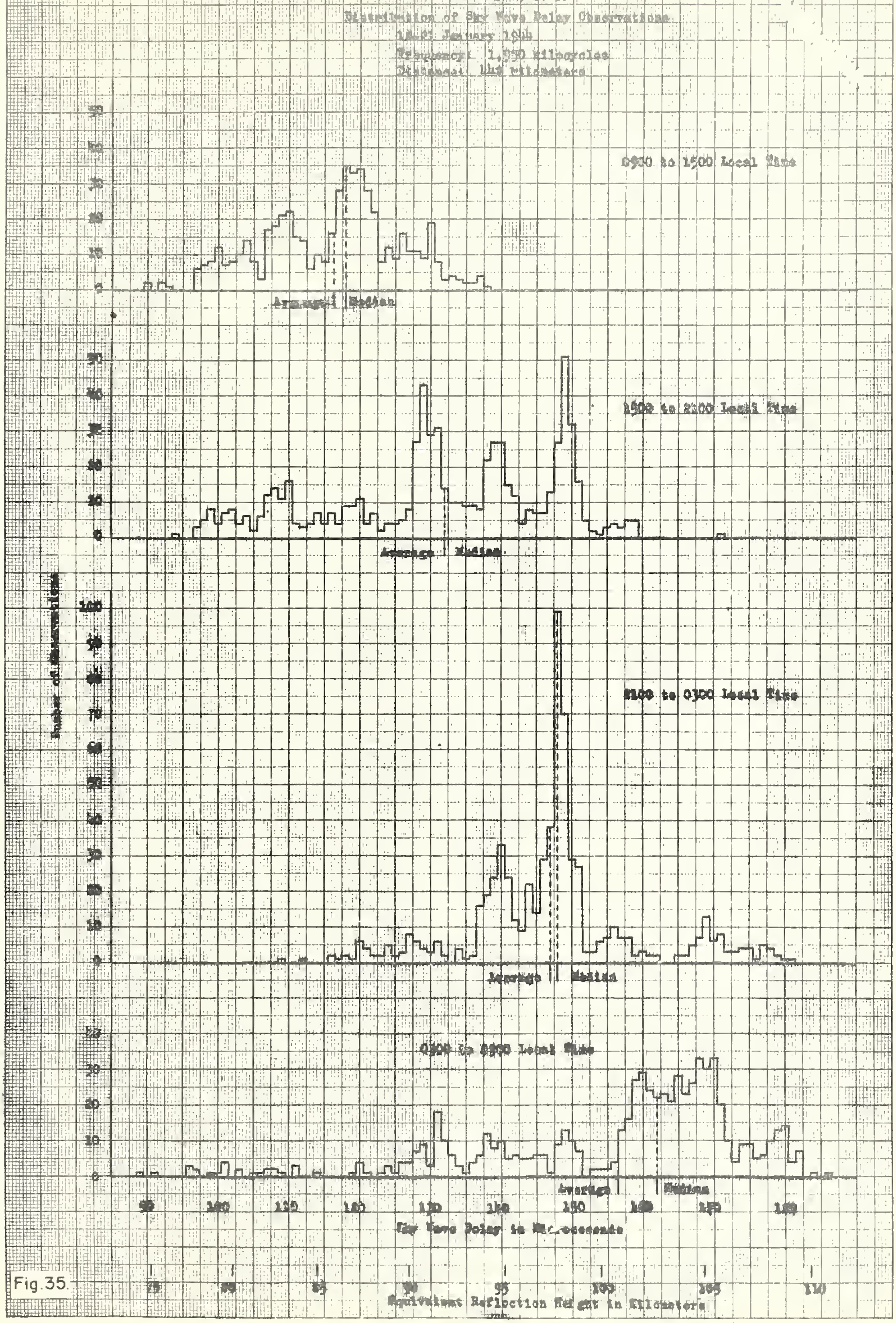


Fig. 35.

8 MAR 1944

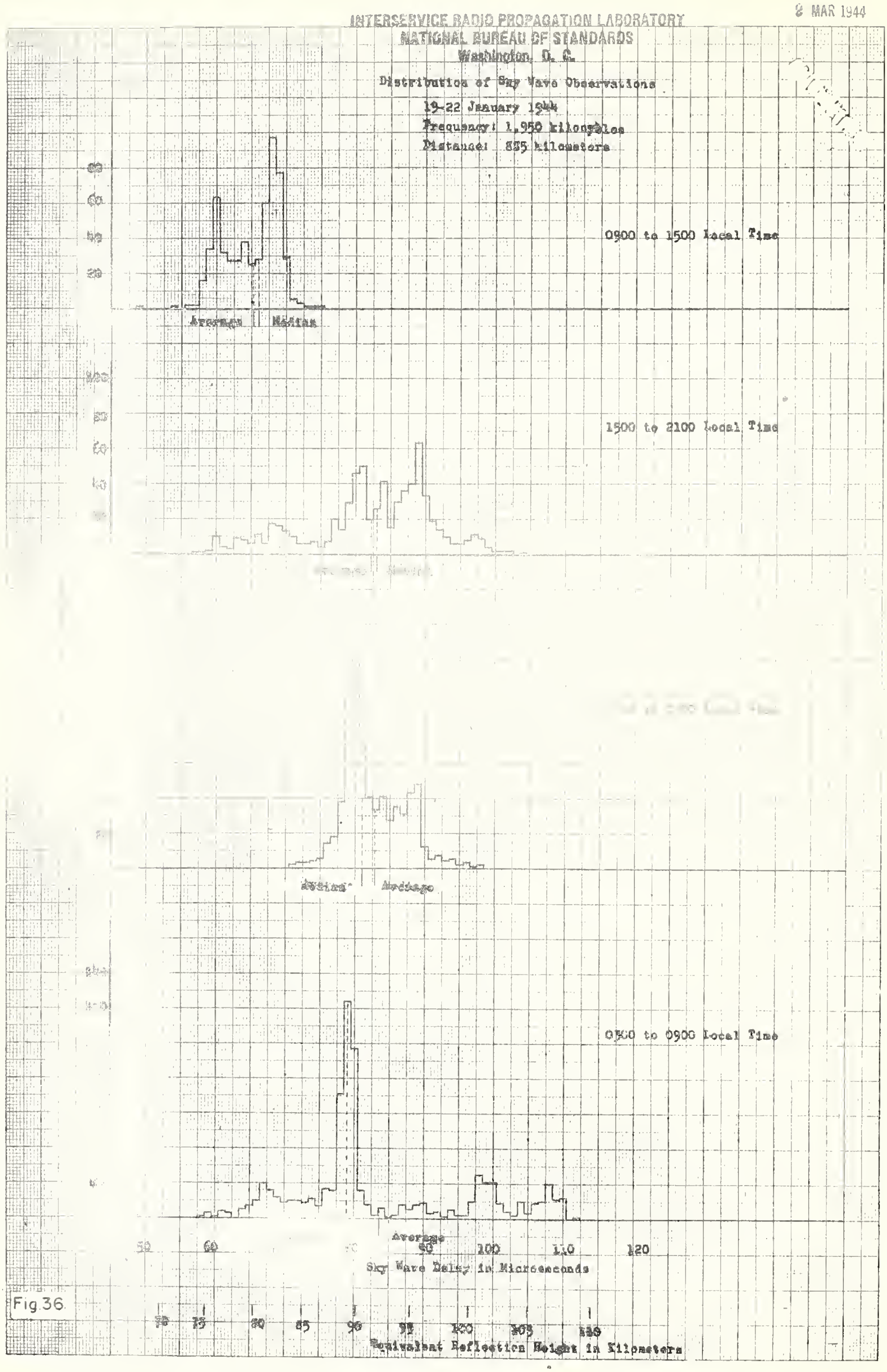


Fig. 36

9 MAR 1944

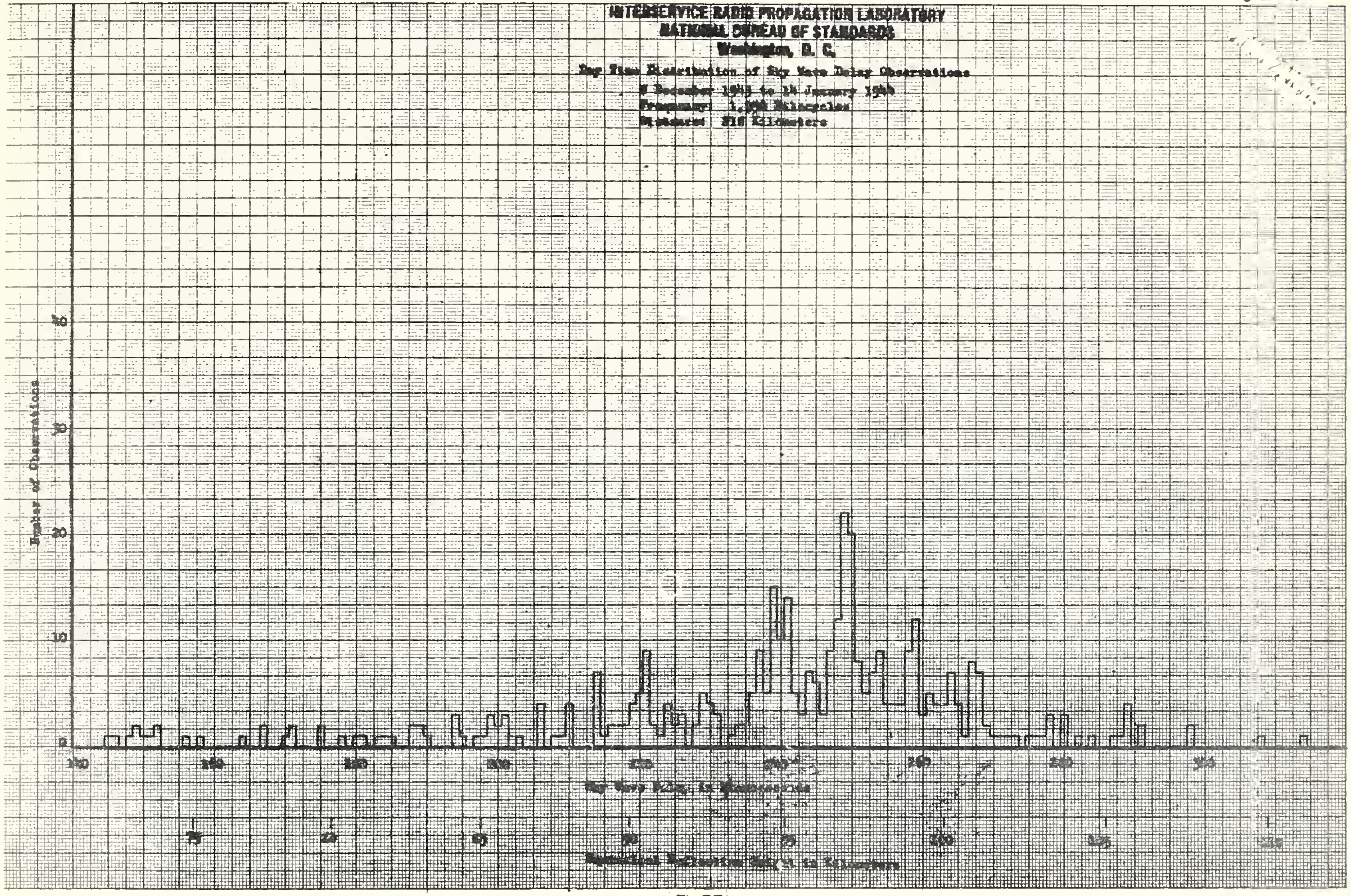


Fig.37.

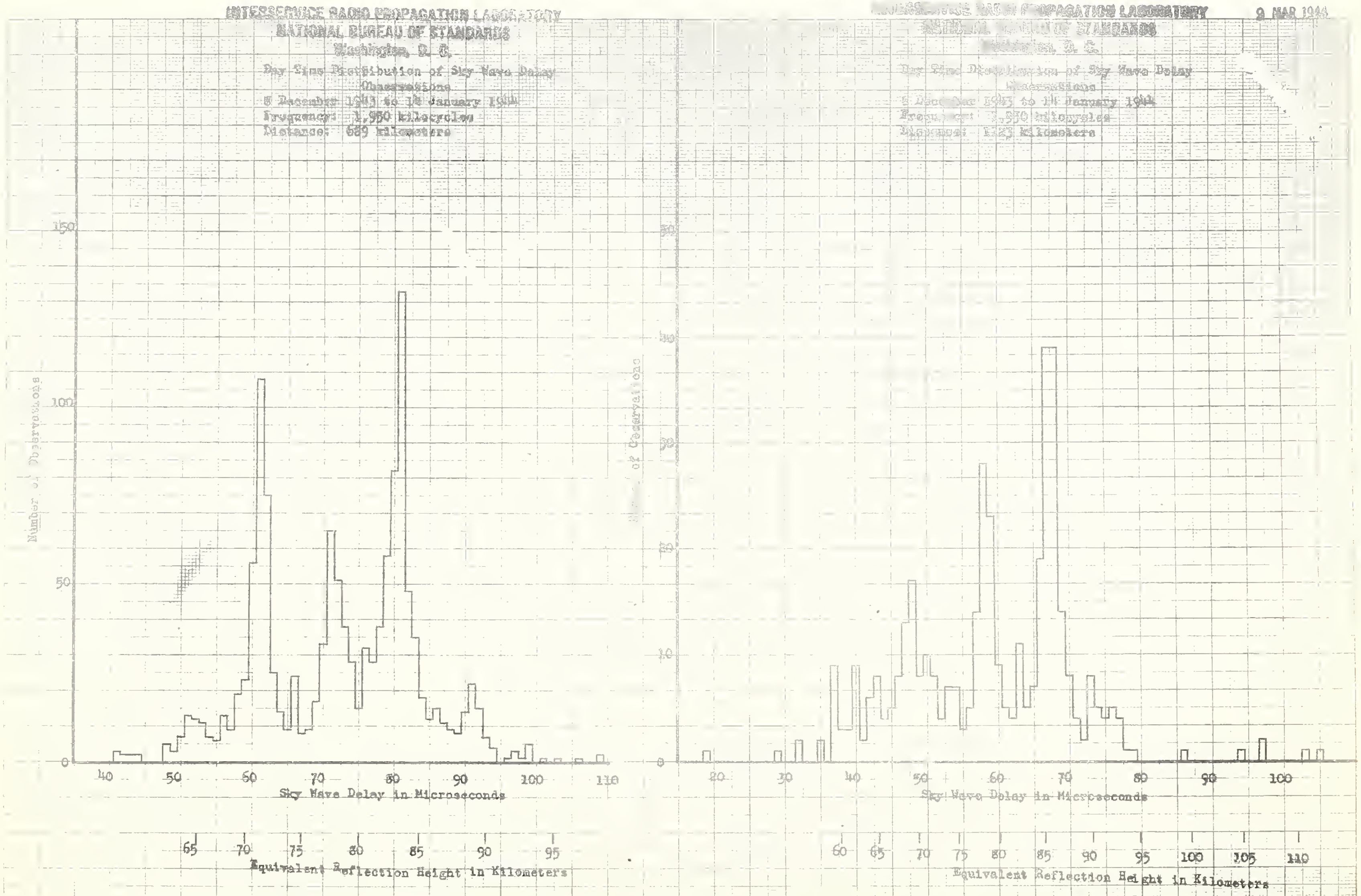

INTERSERVICE RADIO PROPAGATION LABORATORY
NATIONAL BUREAU OF STANDARDS
Washington, D. C.
Day Time Distribution of Sky Wave Delay
Observations
8 December 1943 to 14 January 1944
Frequency: 1,950 kilocycles
Distance: 689 kilometers
Number of Observations
Sky Wave Delay in Microseconds
Equivalent Reflection Height in Kilometers
9 MAR 1944
Sky Wave Delay in Microseconds
Equivalent Reflection Height in Kilometers

Fig 38

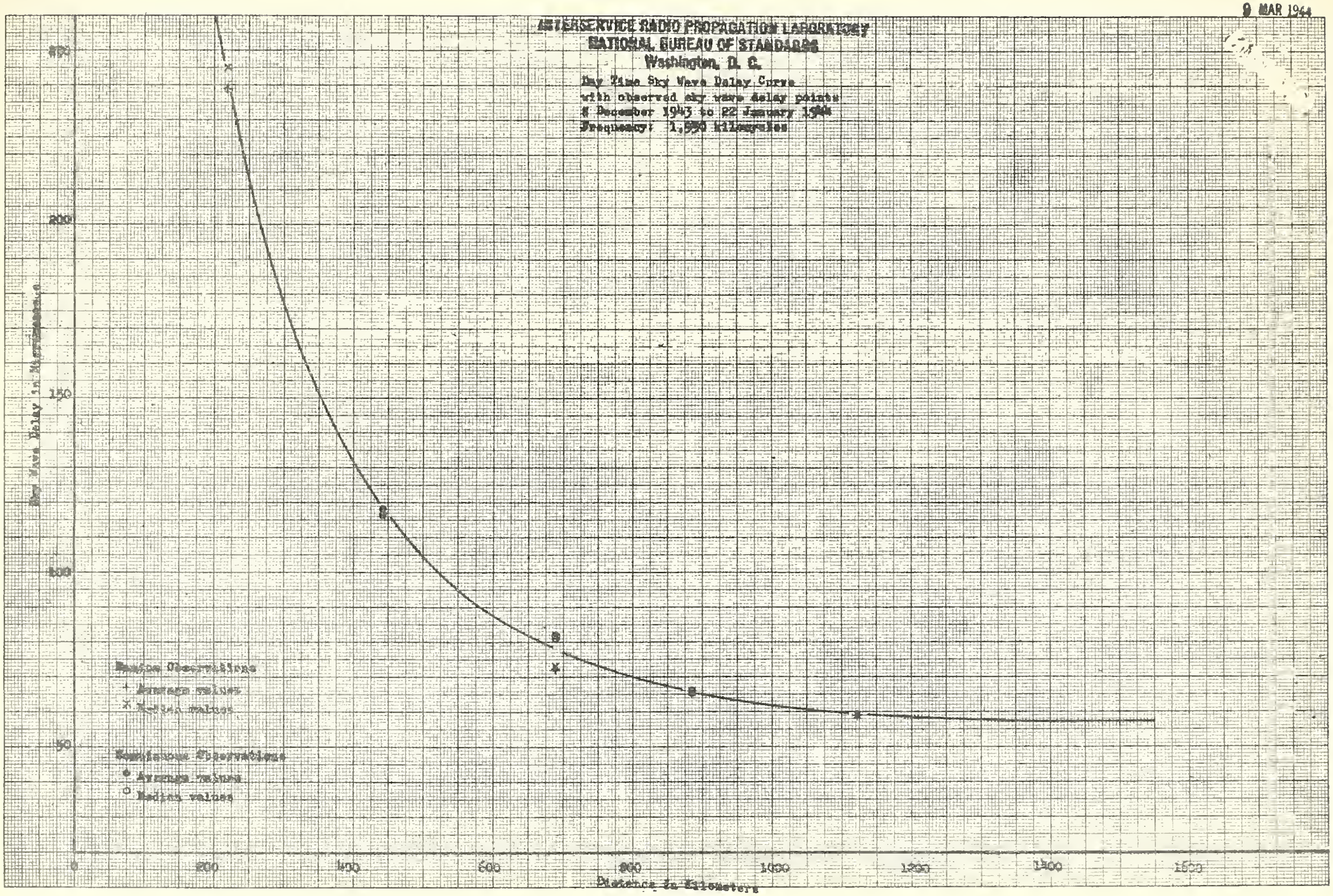

NATIONAL BUREAU OF STANDARDS
Washington, D. C.
Day Time Sky Wave Delay Curve
with observed sky wave delay points
December 1943 to 22 January
Frequency:
Observations
Average values
Median values
Observations
Average values
Median values
Sky Wave Delay
200
150
100
50
0
200
400
600
800
1000
1200
1400
1600
Distance in Kilometers

Fig.39

9 MAR 1944

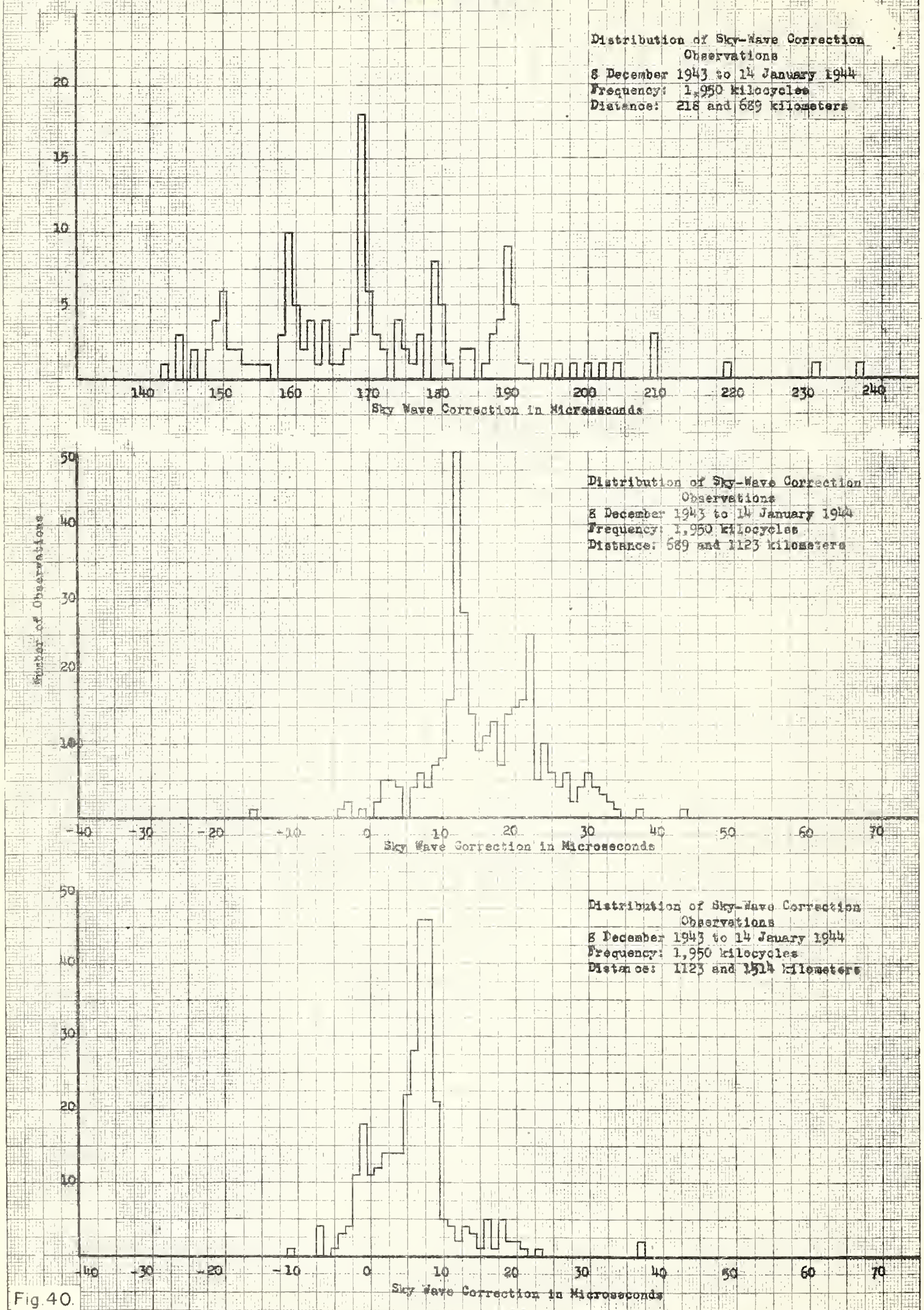


Fig. 40.

9 MAR 1944

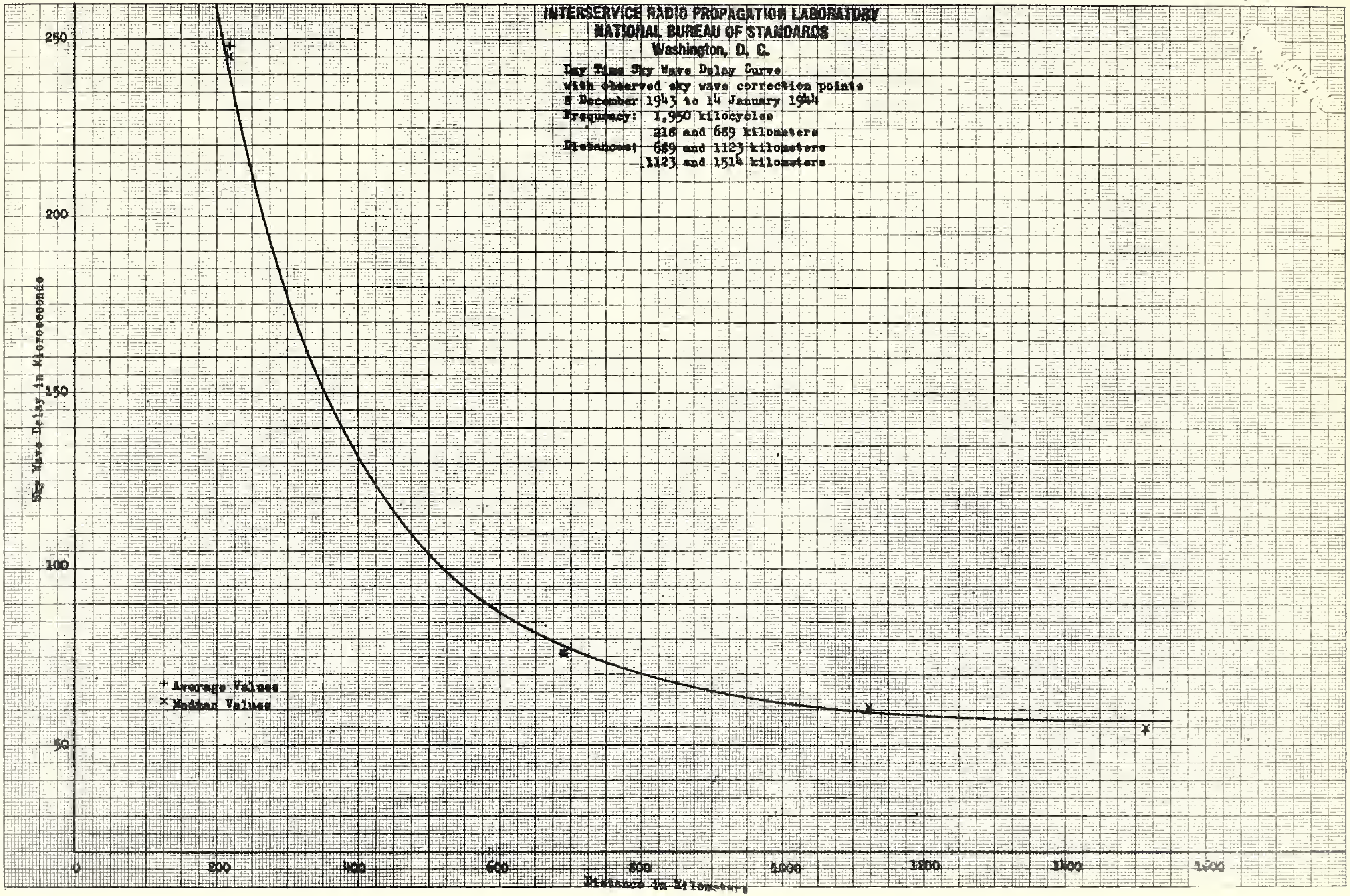


Fig 41.

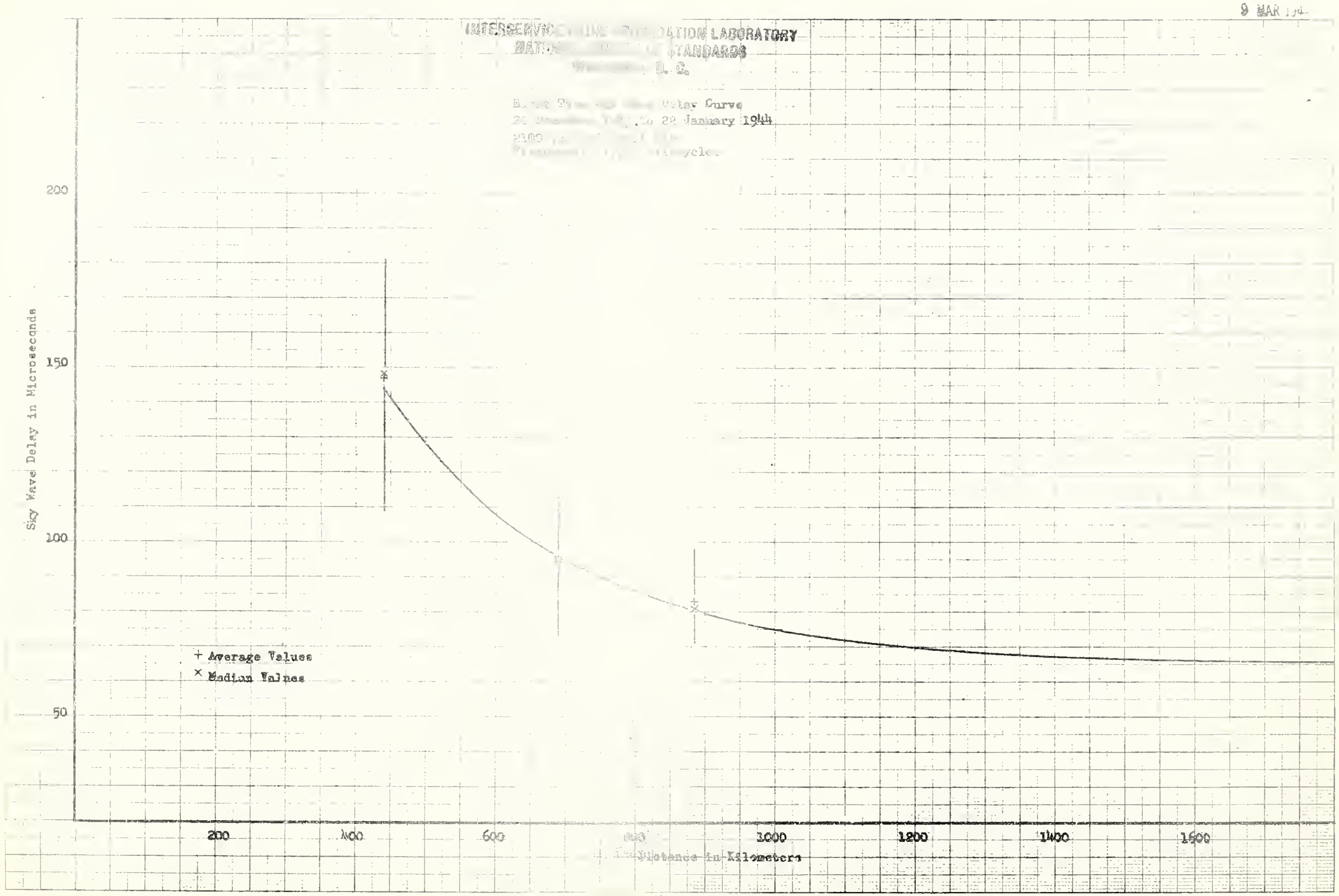

9 MAR 194
INTERSERVICE ... LABORATORY
... STANDARDS
... D. C.
... Curve
... to 22 January 1944
Sky Wave Delay in Microseconds
200
150
100
50
+ Average Values
× Median Values
200
400
600
1000
1200
1400
1600
Distance in Kilometers

Fig.42.

9 MAR 1944

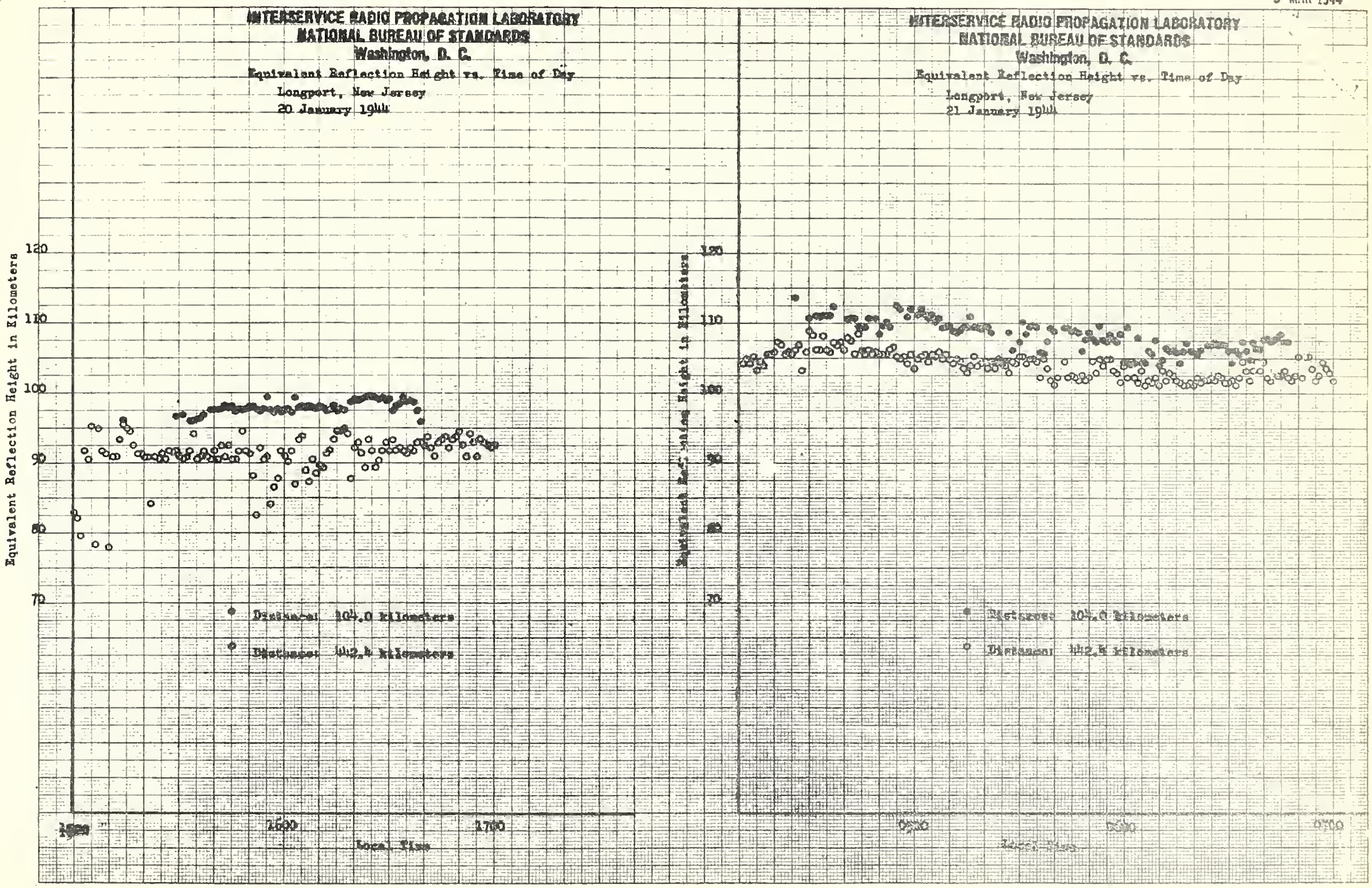


Fig.45.

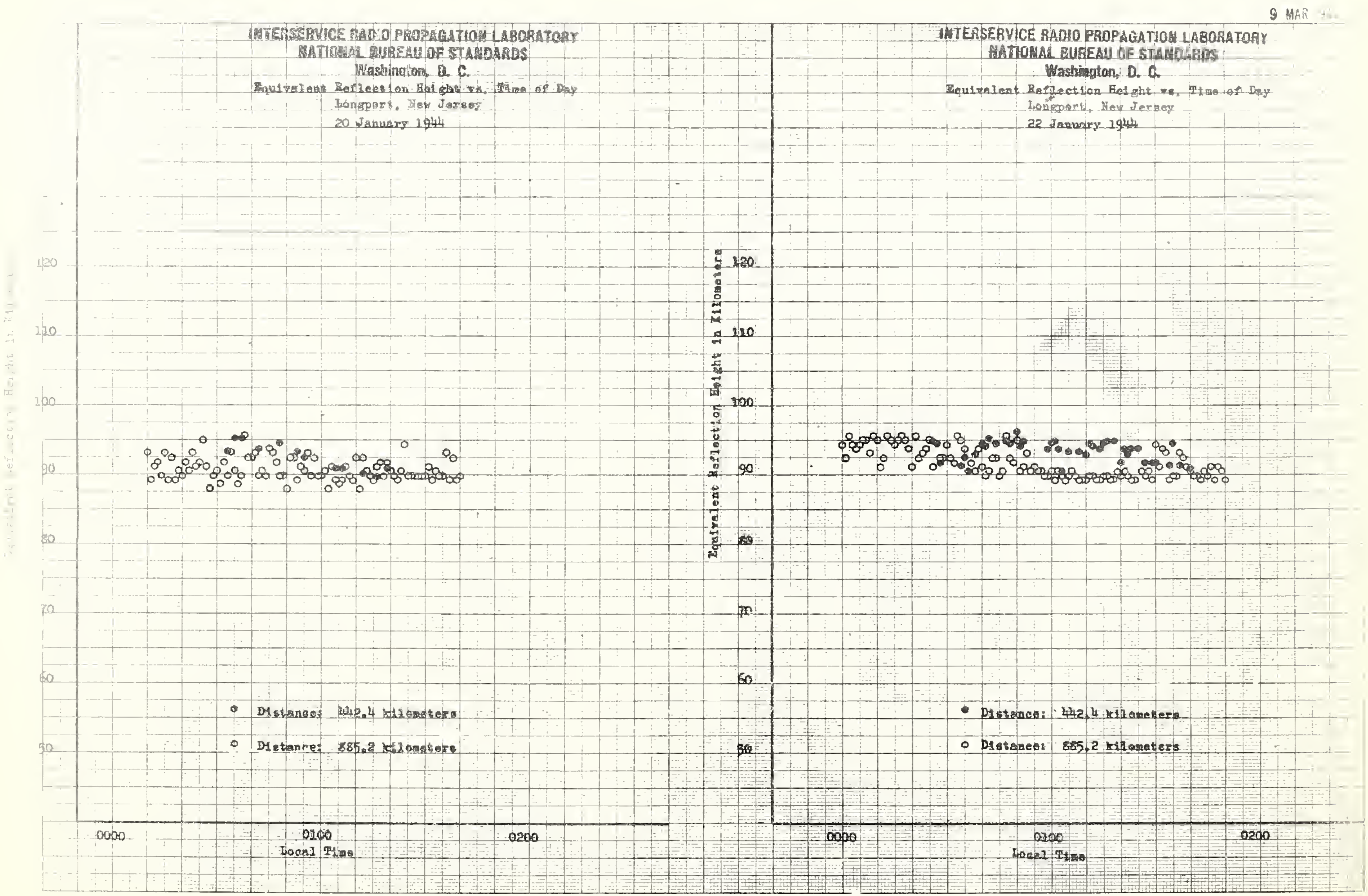

9 MAR
INTERSERVICE RADIO PROPAGATION LABORATORY
NATIONAL BUREAU OF STANDARDS
Washington, D. C.
Equivalent Reflection Height vs. Time of Day
Longport, New Jersey
20 January 1944
Distance: 442.4 kilometers
Distance: 885.2 kilometers
0000
0100
0200
Local Time
INTERSERVICE RADIO PROPAGATION LABORATORY
NATIONAL BUREAU OF STANDARDS
Washington, D. C.
Equivalent Reflection Height vs. Time of Day
Longport, New Jersey
22 January 1944
Equivalent Reflection Height in Kilometers
120
110
100
90
80
70
60
50
Distance: 442.4 kilometers
Distance: 885.2 kilometers
0000
0100
0200
Local Time

Fig. 46.

25 MAR 1944

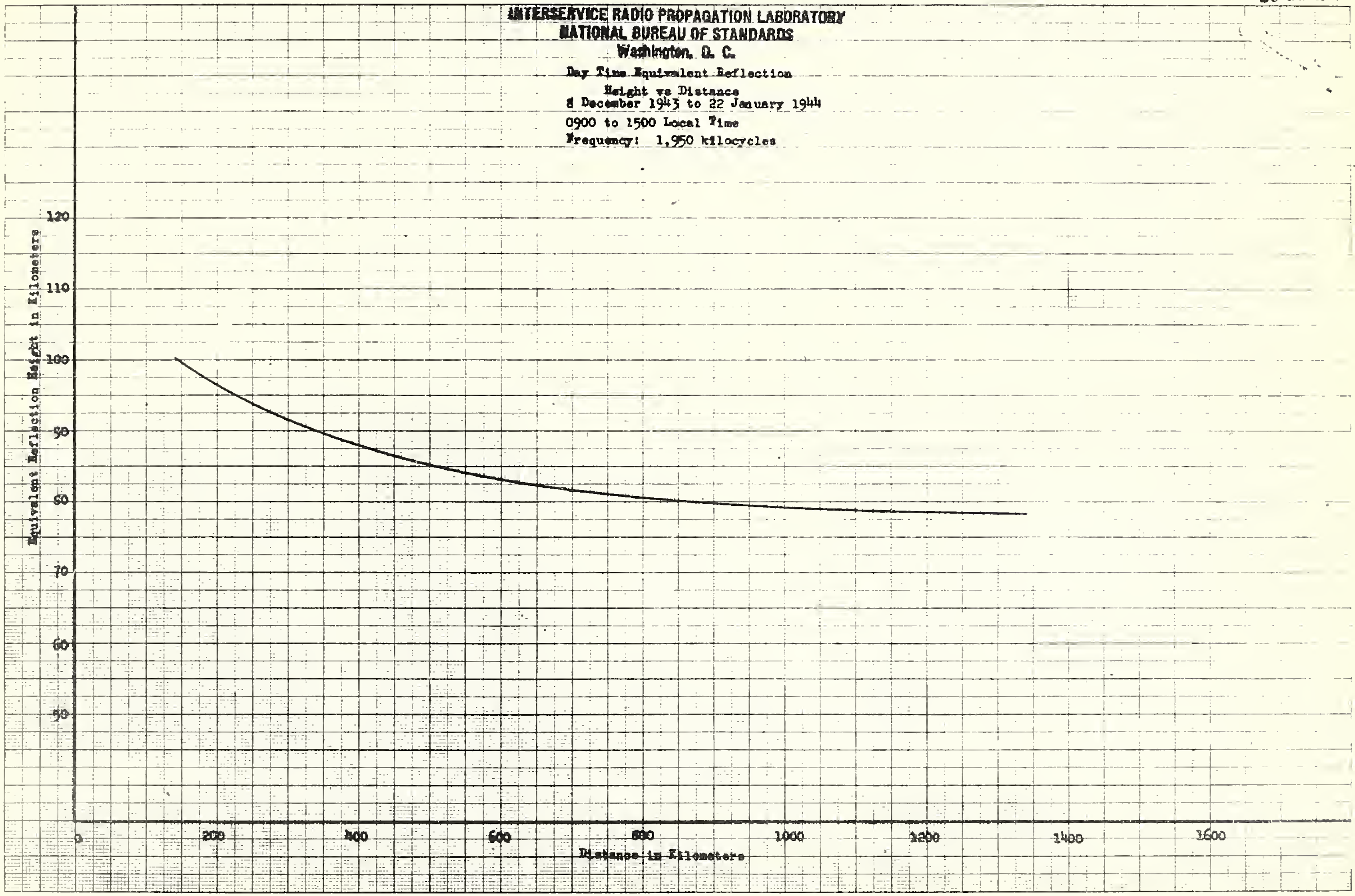


Fig.47

25 MAR 1944

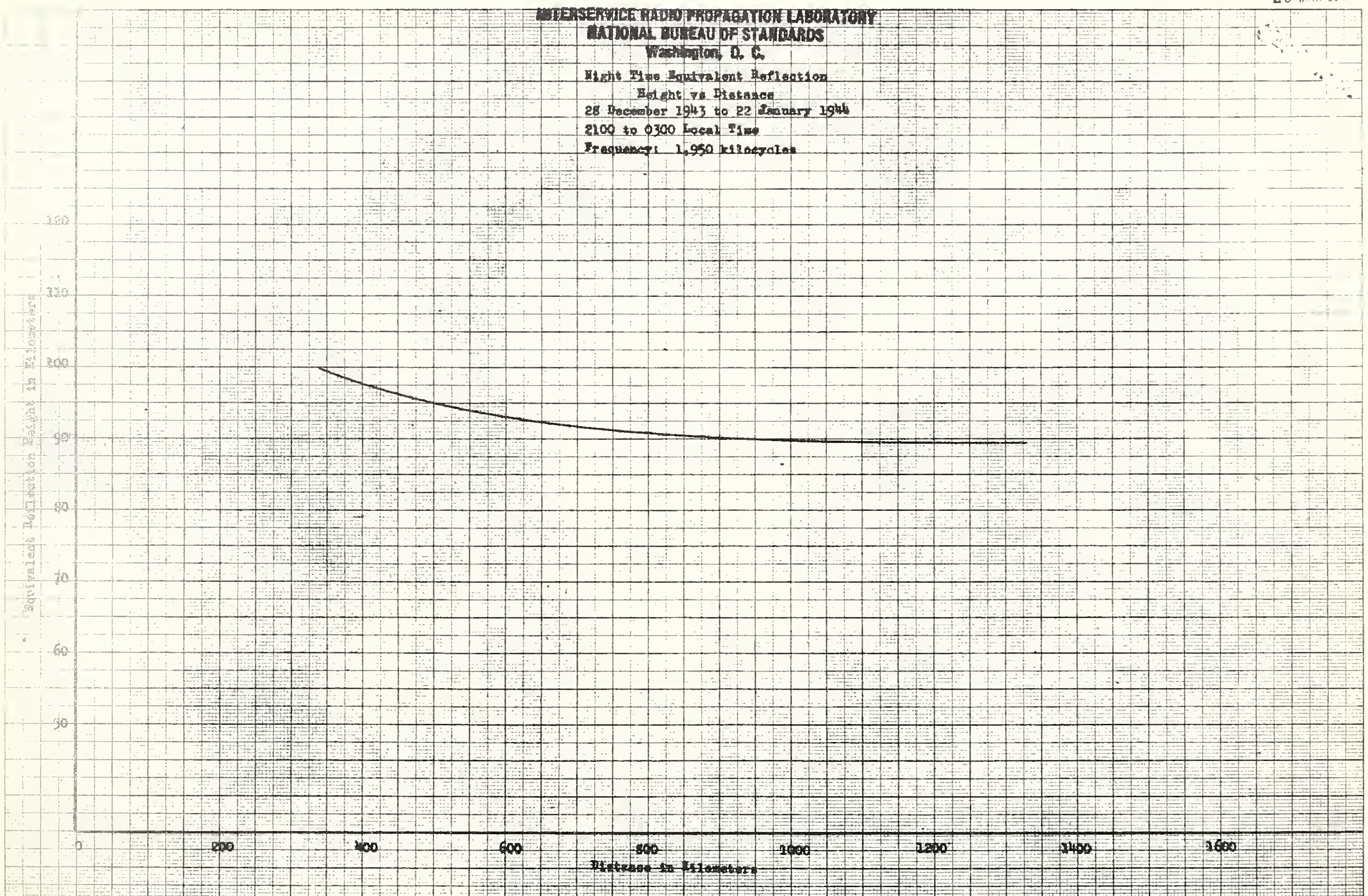


Fig.48.

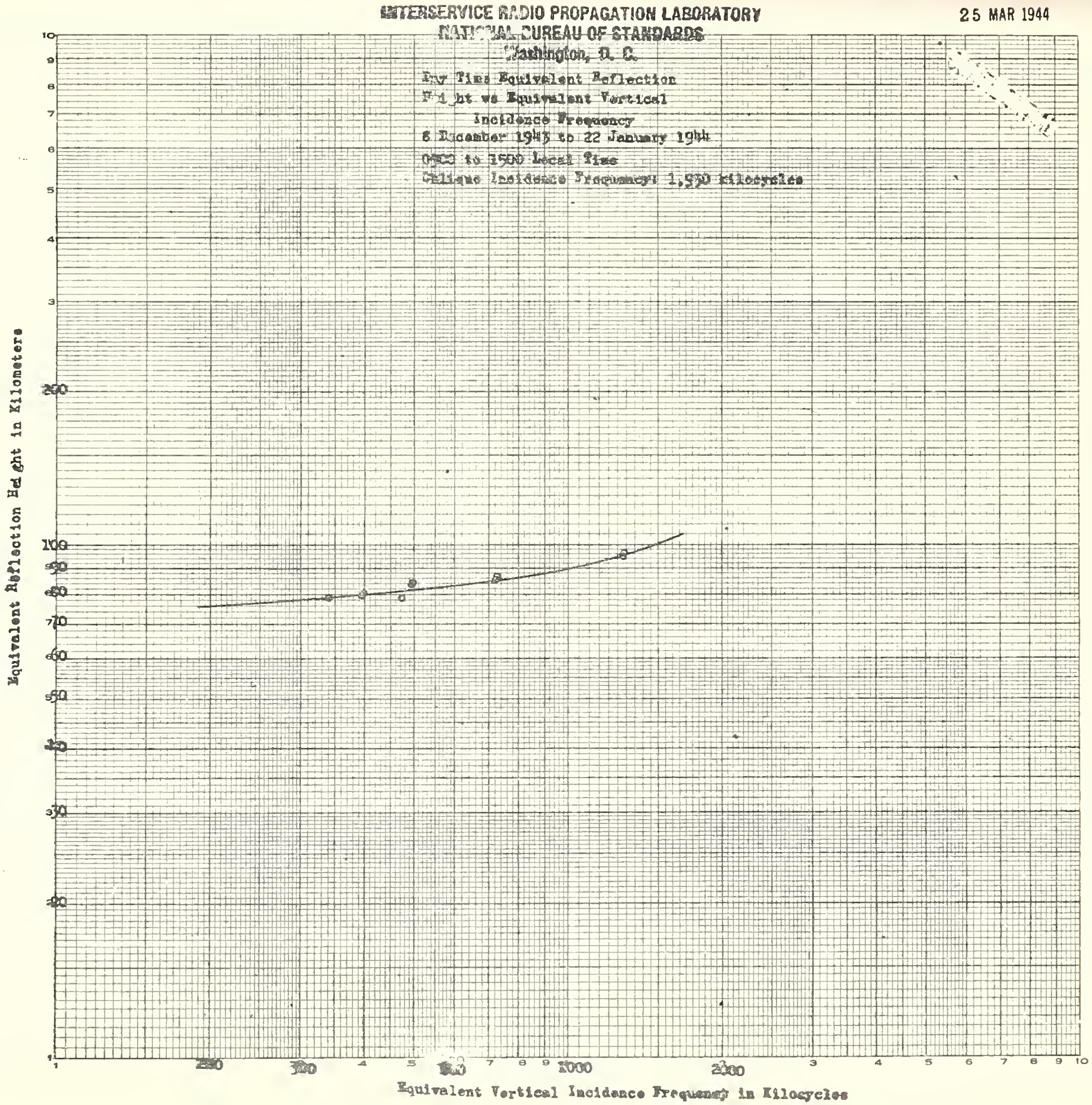

INTERSERVICE RADIO PROPAGATION LABORATORY
NATIONAL BUREAU OF STANDARDS
Washington, D. C.
25 MAR 1944
Day Time Equivalent Reflection
Height vs Equivalent Vertical
Incidence Frequency
6 December 1943 to 22 January 1944
0900 to 1500 Local Time
Oblique Incidence Frequency: 1,930 kilocycles
Equivalent Reflection Height in Kilometers
Equivalent Vertical Incidence Frequency in Kilocycles

Fig.50.

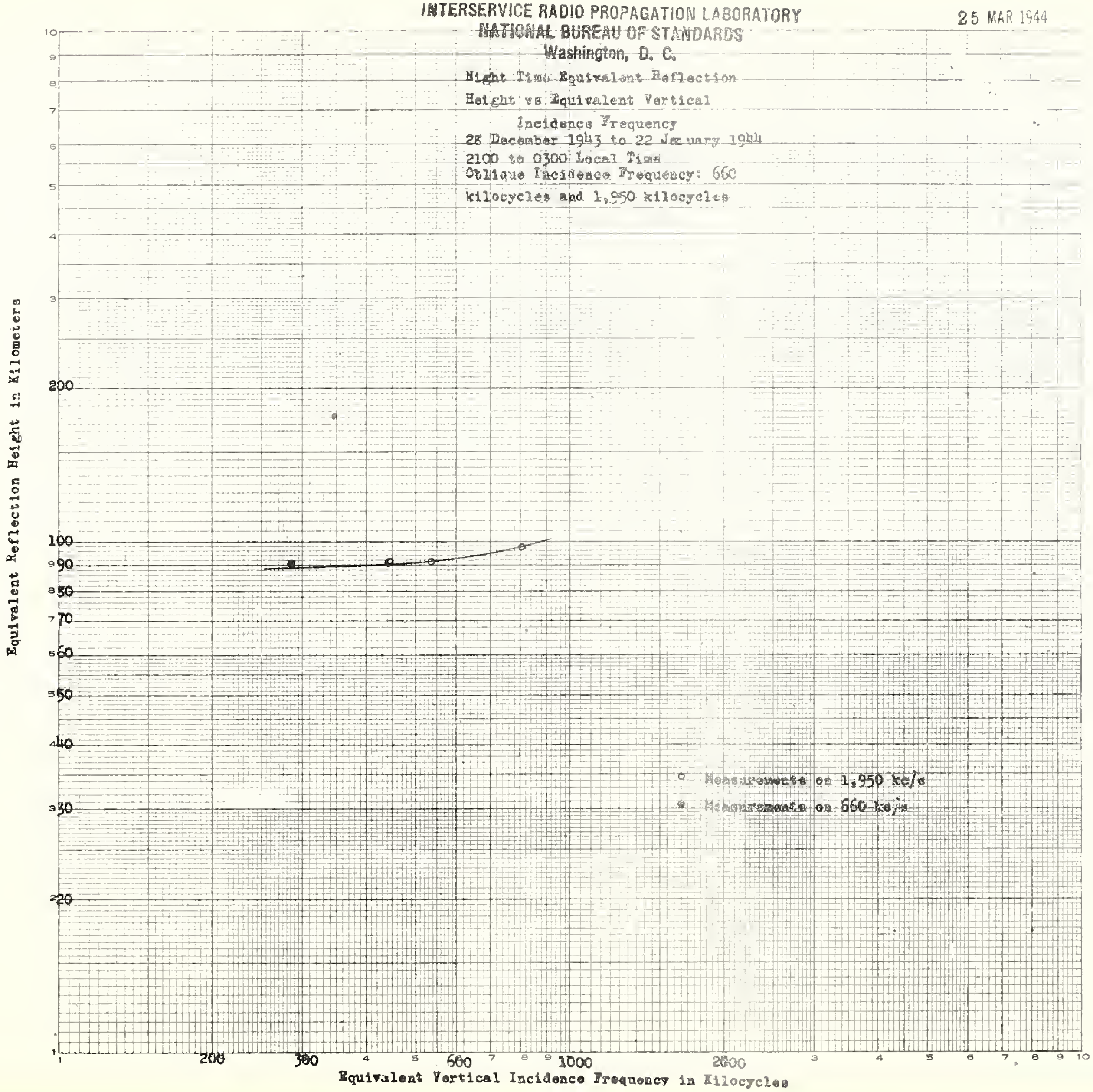

INTERSERVICE RADIO PROPAGATION LABORATORY
NATIONAL BUREAU OF STANDARDS
Washington, D. C.
25 MAR 1944
Night Time Equivalent Reflection
Height vs Equivalent Vertical
Incidence Frequency
28 December 1943 to 22 January 1944
2100 to 0300 Local Time
Oblique Incidence Frequency: 660
kilocycles and 1,950 kilocycles
Measurements on 1,950 kc/s
Measurements on 660 kc/s
200
100
90
80
70
60
50
40
30
20
300
500
1000
2000
Equivalent Reflection Height in Kilometers
Equivalent Vertical Incidence Frequency in Kilocycles

Fig.51.