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MOVEMENT OF THE F-REGION

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TECHNICAL L



By

Kurt Toman

September 24, 1954

Technical Report No. 207

Cruft Laboratory
Harvard University
Cambridge, Massachusetts

Office of Naval Research

Contract N5ori-76

Task Order No. 28

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Movement of the F-Region

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Abstract

In the course of a fixed-frequency ionospheric study, employing a pulse-triggered transmitter operating on 3.5 Mc/s and three spaced-receivers, the transmission-delay was continuously recorded. Aside from a vertical-incidence transmission two oblique transmissions were thus available with 62 and 109 kilometers as baselines, the latter being correspondingly oriented in an approximate west-east and north west-south east direction.

An analysis of the echoes from the F-region was made for the period between August 1952 and December 1953. Successive irregularities observed simultaneously on three records displayed frequently consistent time displacements. Assuming the mid-points of the transmissions to be characteristic and preferred areas for the reflection of the h.f. -pulses, the time-displacements were interpreted as being due to a mechanical motion of the F-region. Direction and speed of this movement was thus obtained and semiannual and annual periods of these components became apparent.

Movement of the F-Region

by

Kurt Toman

Cruft Laboratory, Harvard University

Cambridge, Massachusetts

Introduction

Several methods have been used to pursue the study of winds in the upper atmosphere: Optical observations of noctilucent clouds and meteor trails, the radio method, the meter-wavelength emission of radio stars, observations of the night air-glow, and the measurement with rockets.

Using the radio method, which is also of primary interest in this investigation, Mitra [1] employed a 4 Mc/s transmitter together with a receiver triangulation system of about 100-meter baselines and recorded simultaneously time-displaced fading-curves of the amplitude of the sky wave. He considered the time displacements to be produced by a movement of the reflecting portion of the ionosphere. However, the atmospheric level of the wind could not be specified. Munro [2] recorded simultaneous transmission-delays by using three triangularly sited 5.8 Mc/s transmitters and three receivers with base lines of the order of 20 km. Time-displaced occurrences of large-scale irregularities, observable as a marked change in the group delay, were interpreted as a translational progression of a disturbance in the F-region due to a horizontal drift or a pressure wave.

In this analysis the continuously recorded F-region transmission-delay was used to investigate the movement of the F-region, during the period between August 1952 and December 1953, utilizing also the presence of large-scale irregularities. The apparatus employed in this experiment

comprised a pulse-triggered transmitter operating on 3.5 Mc/s with a trigger rate of 10 cps and three spaced-receivers. The transmitter and one receiver were located in Concord, Massachusetts, with the latitude of 42.4 degrees North and the longitude of 71.2 degrees West. Additional receivers were installed in Gloucester, Massachusetts, with a base line of 61.2 km, and in Sandwich, Massachusetts, with a base line of 108.8 km as shown in Fig. 1. A 43.5 Mc/s transmitter at Great Blue Hill, Massachusetts, maintained synchronization between the transmitter and the receivers.

Transmission-delay Recording

During intervals which range from one-half hour to sometimes five and six hours, the variations of the F-region group-retardation were similar for all transmissions except for a consistent time-displacement between them. Assuming the midpoints of the transmissions to represent characteristic and preferred areas for a specular reflection, these time lags were interpreted as being due to a mechanical horizontal motion of the observed region. They were determined either by direct inspection or by sampling the records and cross-correlating the time series thus obtained. The sampling was made in reference to the time of arrival of the leading edge of the pulse without correcting for varying amplitudes, neglecting the apparent and small variations of the transmission delay produced by intensity variations of a nonrectangular pulse.

Some examples of simultaneous transmission-delay records for Concord, Gloucester and Sandwich are shown in Fig. 2 for September 18, 1952. The abscissa carries the hour of the day, EST, and the ordinate the transmission delay. The upper trace represents the F-region echo of the ordinary ray, and the more regular trace at the bottom is the ground wave. This type of record is obtained from an intensity-modulated beam of a cathode-ray tube whose horizontal sweep is a measure of the transmission time and is calibrated in 133 μ sec intervals by means of appropriate time-markers. The 133 μ sec delay units were converted into kilometers of virtual path-length as it is indicated along the ordinates of Fig. 2. The photographic paper was advanced perpendicularly to the sweep with a speed of 6 cm/hr.

The Cross-Correlation Method

Of the records seen in Fig. 2 the lower edge of the sky-wave trace was

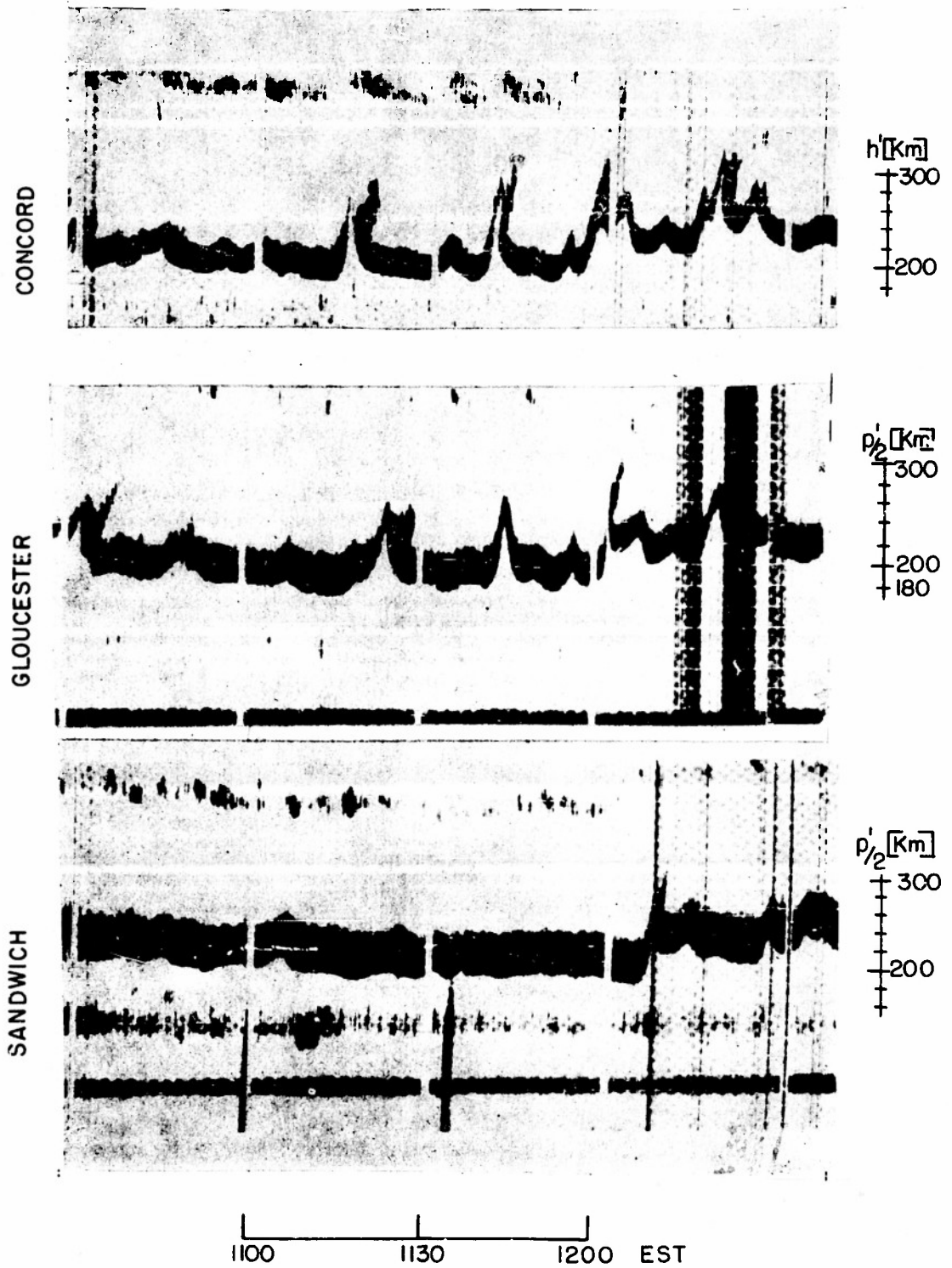


FIG. 2 SAMPLES OF SIMULTANEOUS TRANSMISSION-DELAY RECORDS FOR 3.5 mc/s OF SEPTEMBER 18, 1952 MIDDAY

redrawn in Fig. 3. The abscissa represents the time of day (EST) and the ordinate the virtual path-length. The three traces correspond to Concord, Gloucester and Sandwich records. It is possible to note the variations on one record being repeated on the other records after several minutes have elapsed. In this example for September 18, 1952 the displacements obtained by direct inspection were found to be 4.7 minutes between Concord and Gloucester and 10 minutes between Concord and Sandwich.

Other examples of transmission-delay records obtained at the three receiving-sites for October 8, 1952 midday, were redrawn as shown in Fig. 4. The virtual path-length is indicated along the ordinate and the time of day along the abscissa. As observable in this illustration, the general pattern of the F-traces revealed time-displacements, although a point-to-point comparison of the displaced transmission-delay records yielded some differences. On those days the records had to be sampled and cross-correlated. The sampling was performed from minute to minute and one tenth of a delay unit could be estimated with reasonable accuracy. In view of the following cross-correlation, primary interest was directed towards obtaining distinct maxima of the cross-correlation curve. This determined the choice of reference line with respect to which the sampling was performed. For each record it was chosen to lie one-tenth of a unit below the minimum delay observed during a selected period.

Using the formula

$$r(\tau) = \frac{\sum [x(t) \cdot y(t-\tau)]}{\left\{ \sum [x(t)]^2 \cdot \sum [y(t-\tau)]^2 \right\}^{1/2}} \quad (1)$$

where $x(t)$ is the departure from reference line for one record and $y(t)$ is the departure from reference line of the other record, cross-correlograms were obtained as shown in Fig. 5 for October 8, 1952 midday indicating $r(\tau)$ as a function of the time-displacement τ in minutes for the Concord-Gloucester and Concord-Sandwich analyses. Correspondingly, the maxima were found at 3.3 and 9.9 minutes.

In order to be assured of a consistent time-displacement between records, it was also desirable to cross-correlate after sampling from a reference line lying above the lower edge of the trace. Figure 6 illustrates both methods.

The sampling from reference line 1 was denoted normal and from reference line 2, reversed. Figure 7 displays such normal and reversed cross-correlograms for January 21, 1953, midday, which yielded a displacement of 4.6 minutes for C-G and of 8 minutes for C-S. The fact that both sampling methods rendered identical time-lags confirmed the relative shift between entire echo structures, including the small as well as the large values of the transmission delay during the particular period. This eliminated the possibility of the time displacements to be produced by electrical effects due to the unlike effective frequencies of the three transmissions.

The obtained time-lags were utilized in order to obtain the speed and direction of motion of the F-region. For this purpose two geometries were taken into consideration.

The Straight-front Geometry

It was simple to assume the presence of straight frontal irregularities within the F-region which pass over the receiving sites in a direction perpendicular to their orientation. Figure 8 illustrates the geometry of the stations, including the angles between the base lines and their orientation with respect to the geographic North-South. The three mid-points of the transmissions, which were assumed to be preferred areas for optical reflection, are reached by a progressing front at certain instances of time. Under the condition of horizontal uniform motion during a given period, time was linearly related with distance. Since the reference point was the zenith at Concord, with respect to which the time-lags were desired, the distances between Concord and the mid-points of the oblique trajectories were calculated and their ratio was related to the ratio of the time-displacements. For the particular geometry of the triangulation system the following formula was derived, relating the ratio of the time-lags with the orientation of the progressing front.

$$\Delta t_2 / \Delta t_1 = 0.972 - 1.488 / \text{tg } \gamma \quad (2)$$

where γ is the angle between the front and the Concord-Gloucester base line, and Δt_1 , Δt_2 are the time displacements in minutes.

Since

$$\gamma = 5^\circ + 10'14'',$$

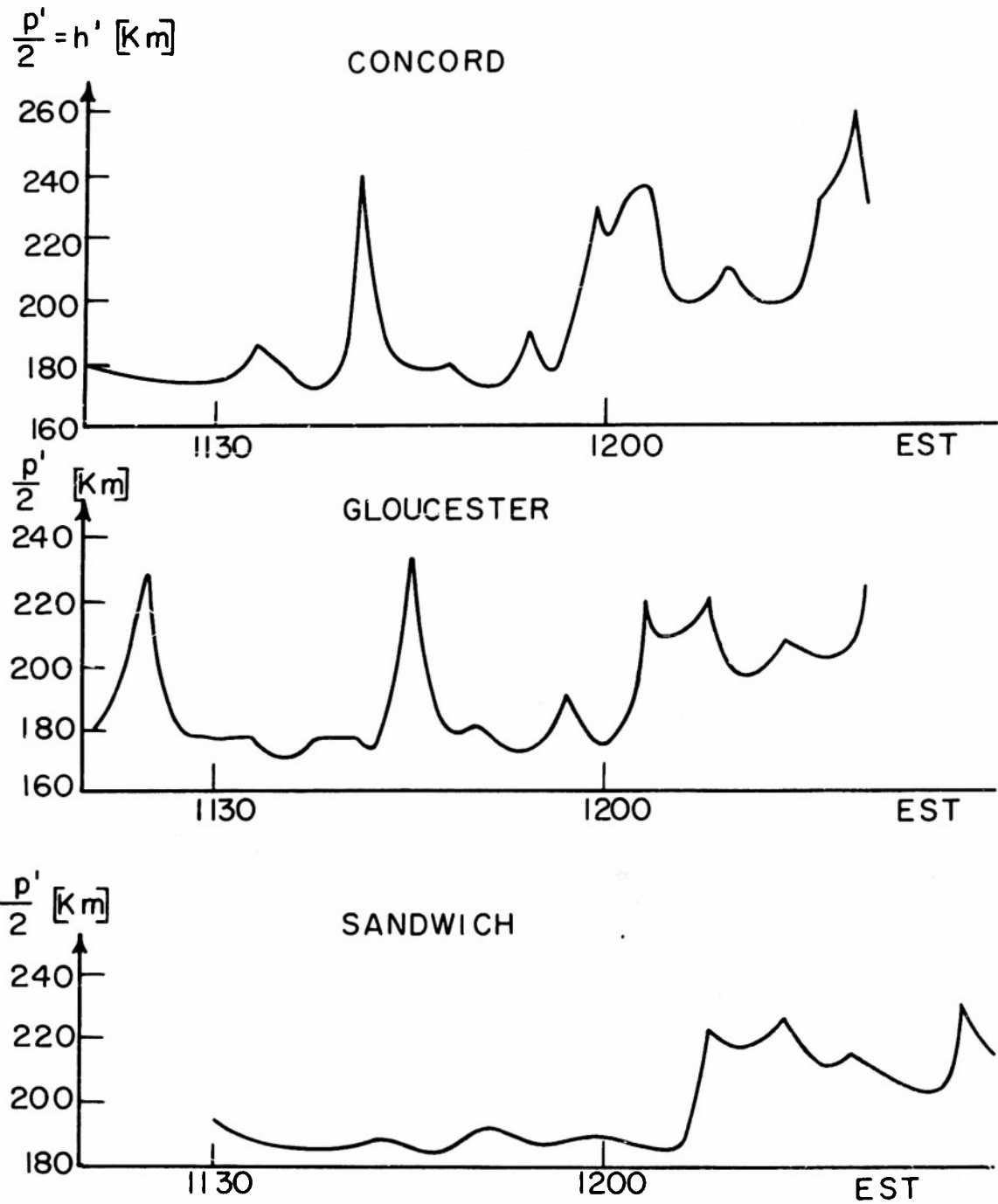


FIG. 3 SAMPLE OF SIMULTANEOUS 3.5 mc/s
 TRANSMISSION-DELAY RECORDS OF
 SEPTEMBER 18, 1952 MID-DAY

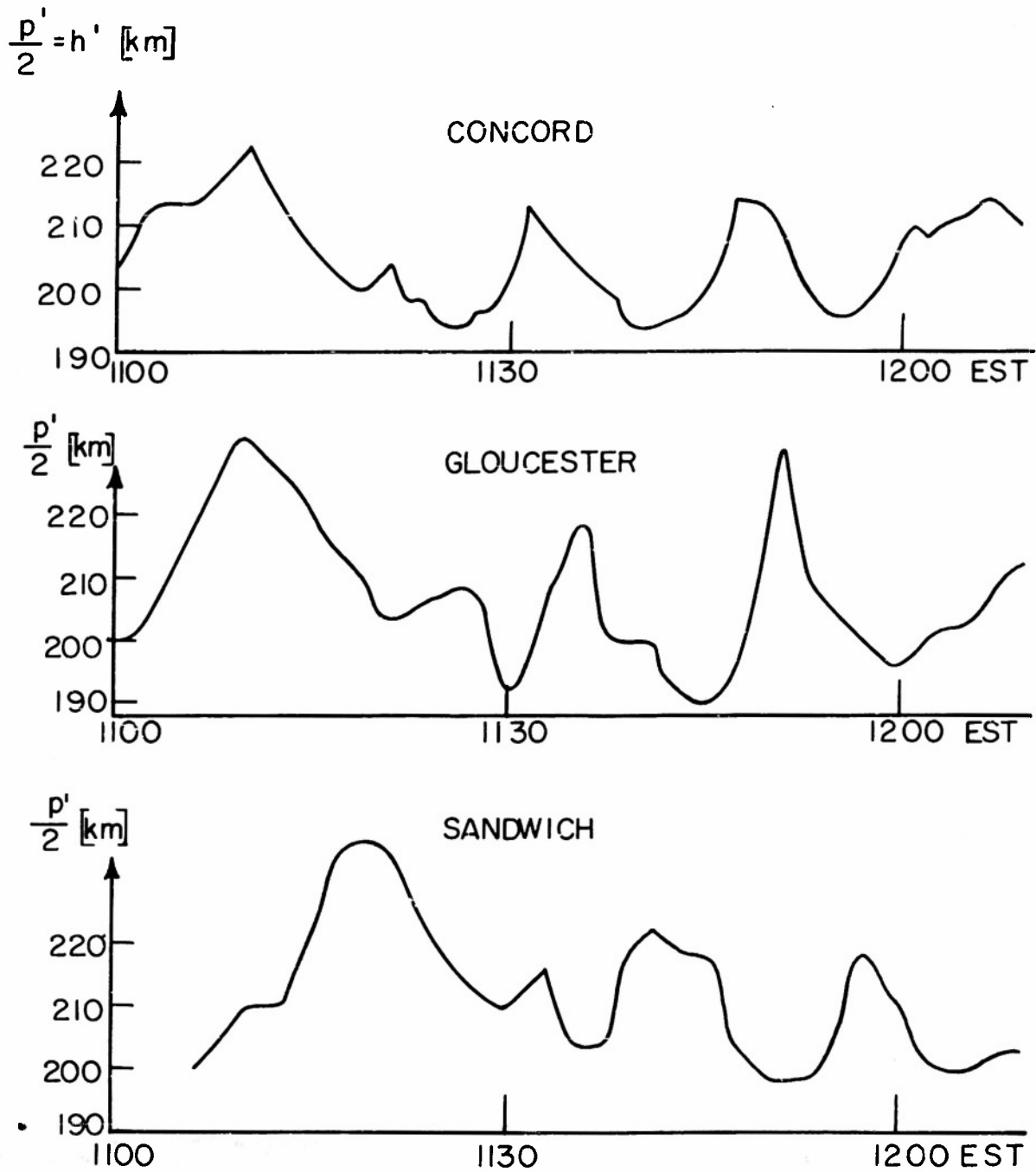
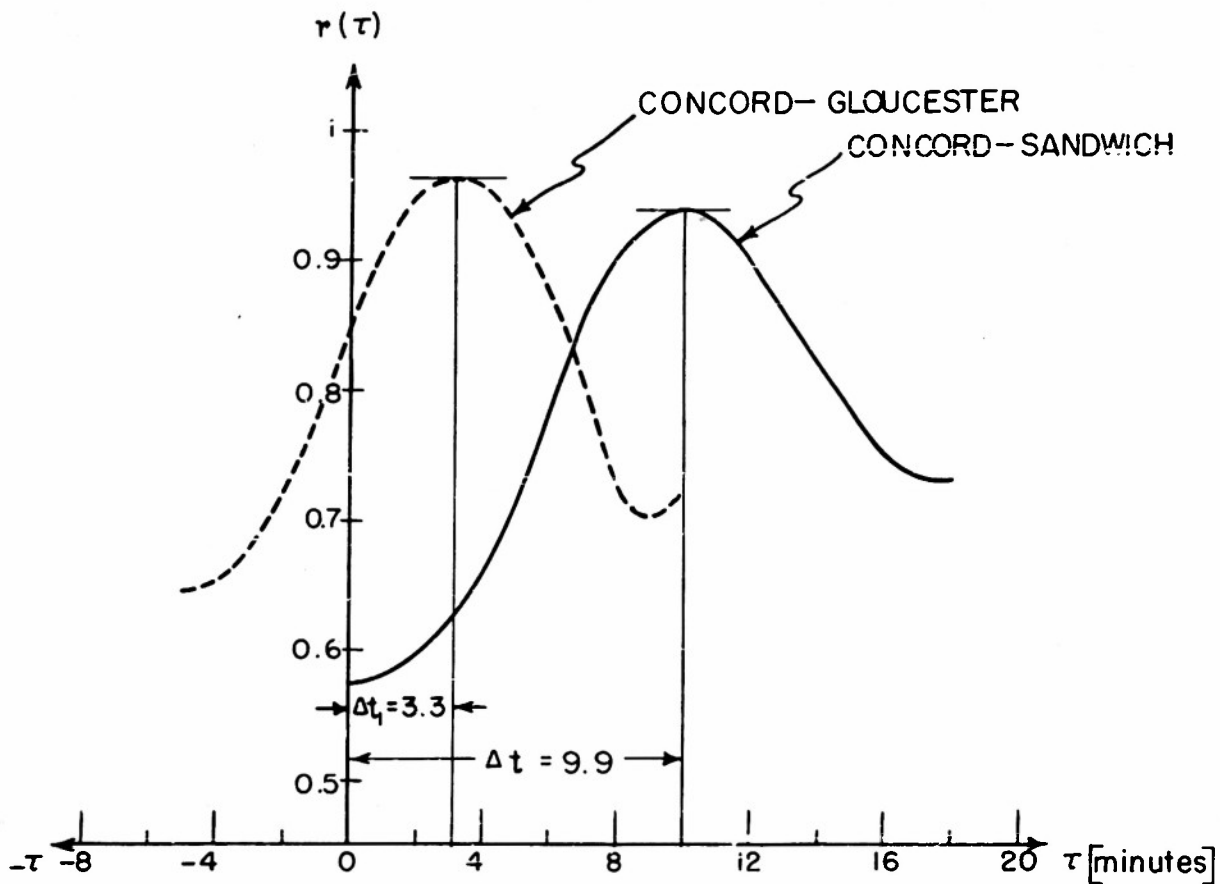


FIG. 4 SAMPLE OF SIMULTANEOUS 3.5mc/s
 TRANSMISSION-DELAY RECORDS OF
 OCTOBER 8, 1952 MID-DAY



DATE: OCTOBER 8, 1952 HOUR: 11 00-12 00 EST

FIG. 5 CROSS-CORRELATION OF CONCORD-GLOUCESTER
AND CONCORD-SANDWICH F-TRANSMISSION-DELAY
RECORDS FOR 3.5 mc/s

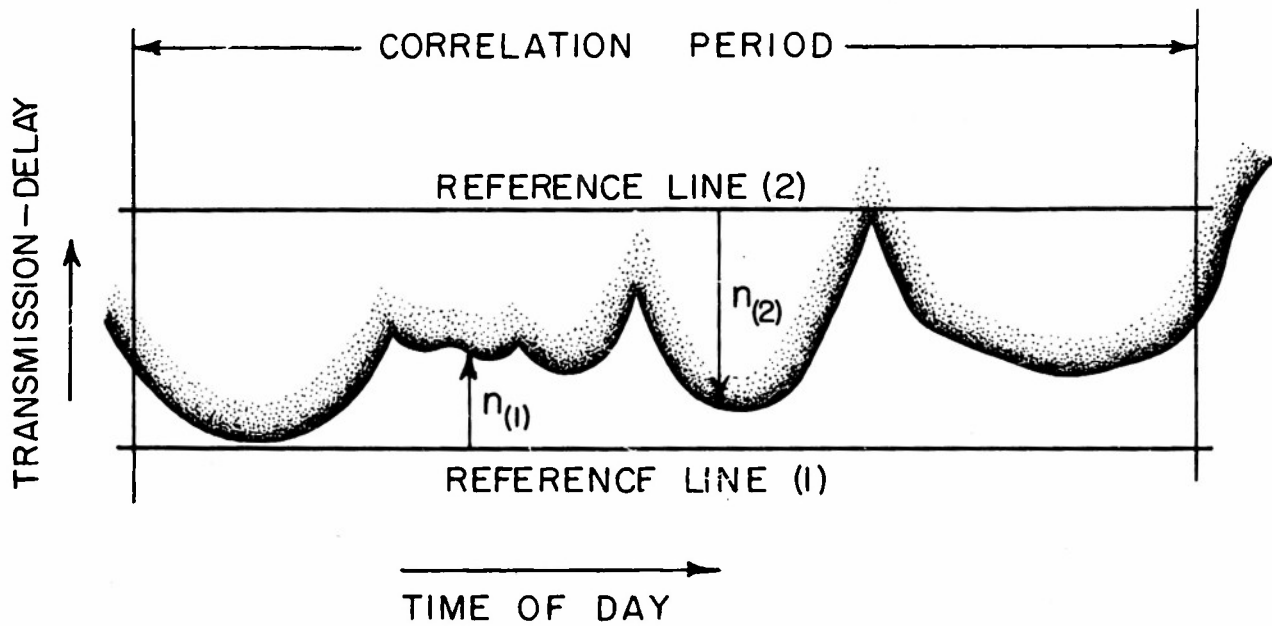
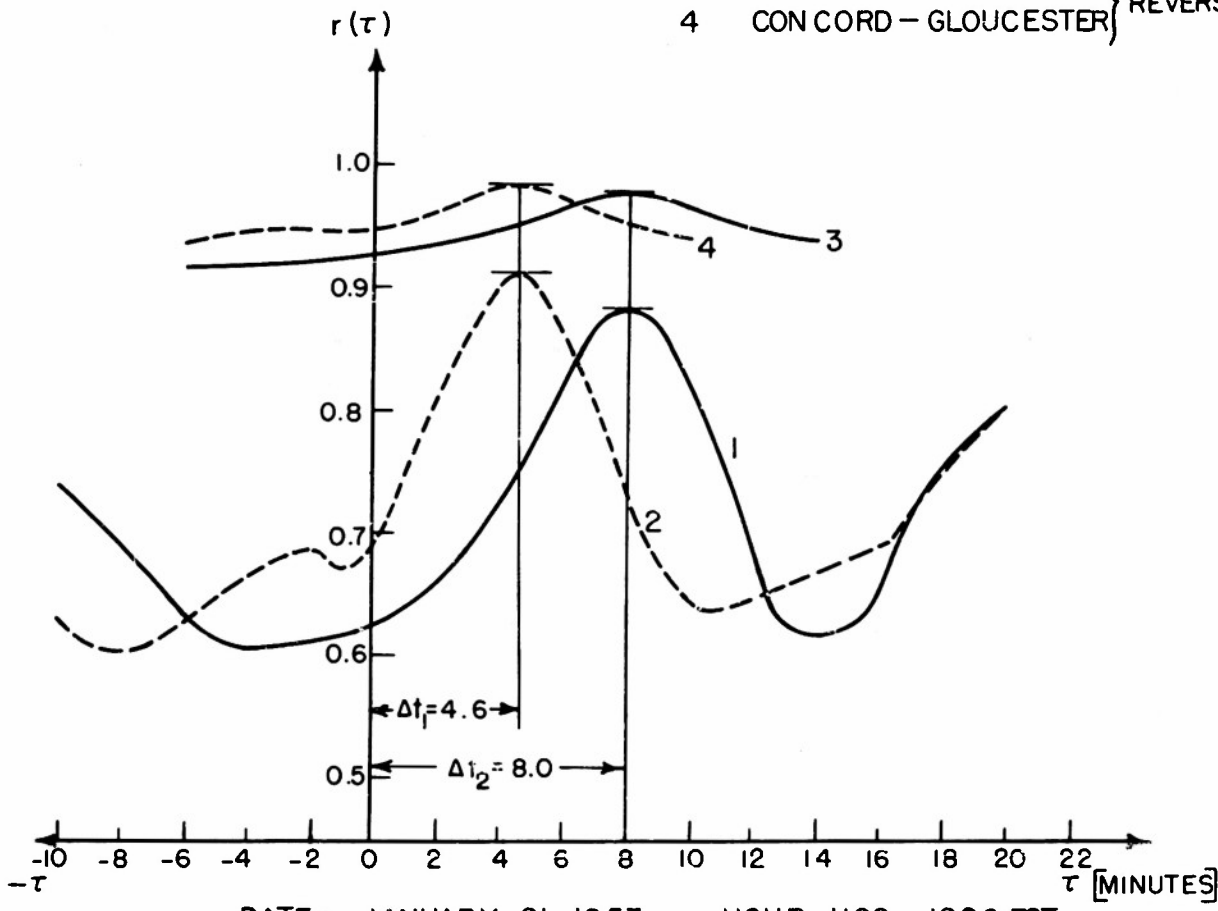


FIG. 6 NORMAL (1) AND REVERSED (2) METHOD OF SAMPLING OF A TRANSMISSION-DELAY RECORD

- 1 CONCORD-SANDWICH } NORMAL
- 2 CONCORD-GLOUCESTER } NORMAL
- 3 CONCORD-SANDWICH } REVERSED
- 4 CONCORD-GLOUCESTER } REVERSED



DATE: JANUARY 21, 1953 HOUR: 1100 - 1200 EST

FIG. 7 CROSS-CORRELATION OF CONCORD-GLOUCESTER AND CONCORD-SANDWICH F-TRANSMISSION-DELAY RECORDS FOR 3.5 mc/s

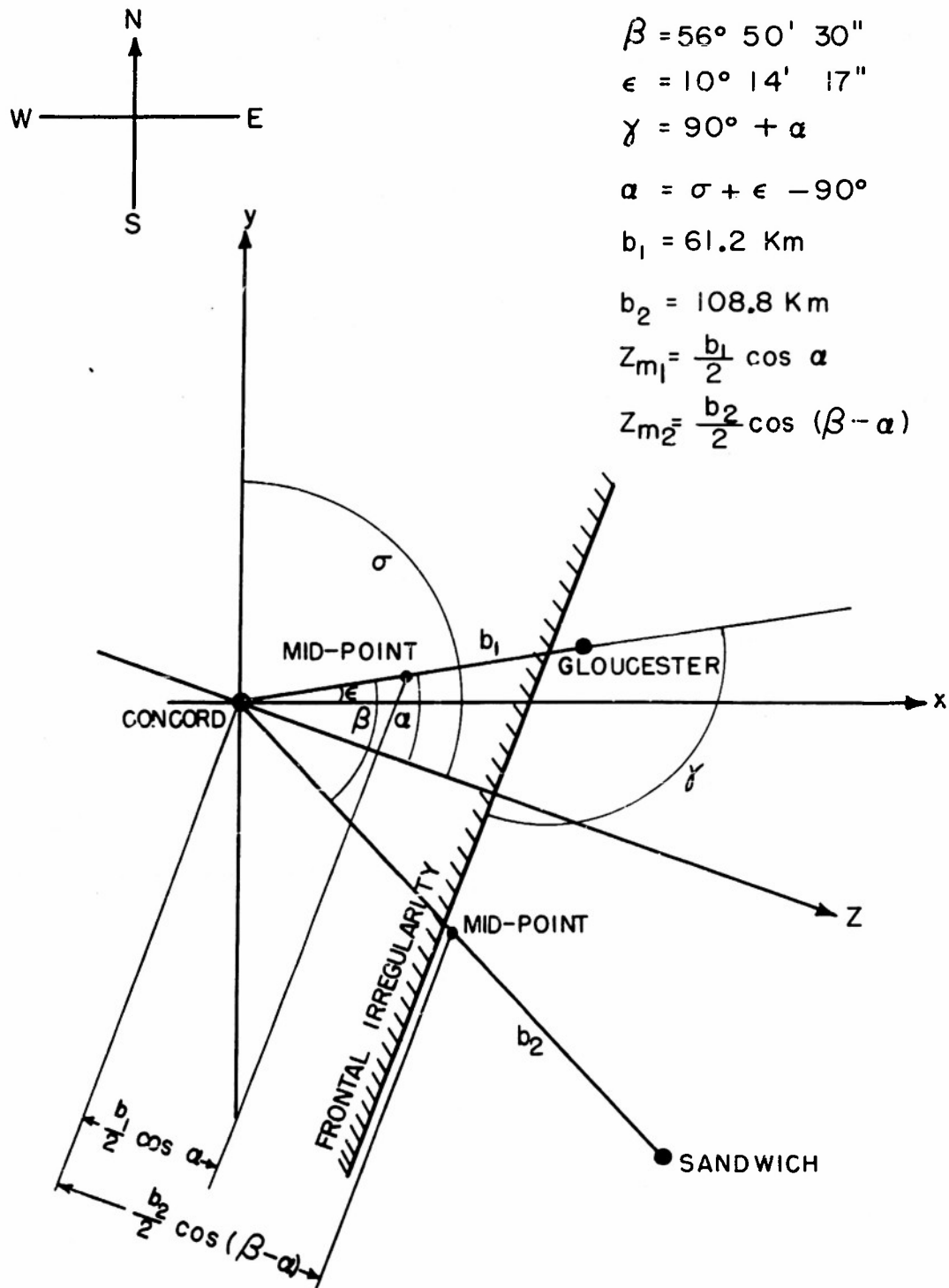


FIG. 8 STRAIGHT-FRONT GEOMETRY

a relation was obtained between the ratio $\Delta t_2/\Delta t_1$ and the direction of movement of the region σ in degrees East-of-North, which was plotted in Fig. 9. Since the time-displacements can assume positive and negative values, the lower portion of Fig. 9 includes specifications regarding the sign of each time-lag relative to Concord. It was considered positive if like irregularities occurred first on the Concord record and subsequently on the other record. It was negative if the opposite was true.

Knowing now the time-displacements Δt_1 and Δt_2 from the cross-correlation analyses, it was possible to obtain the horizontal direction of movement by the use of Fig. 9. From the resulting value σ or γ , the speed of movement was calculated, using the formula

$$v = 30 b_1 \sin \gamma / \Delta t_1 = 30 b_2 \sin (\gamma - \beta) / \Delta t_2 \quad (3)$$

where

- v is the speed of movement in kilometers/hour,
- Δt_1 is the Concord-Gloucester time lag in minutes,
- Δt_2 is the Concord-Sandwich time lag in minutes,
- γ is the angle between the front and the Concord-Gloucester base line
- $b_1 = 61.2$ km, the Concord-Gloucester base line
- $b_2 = 108.8$ km, the Concord-Sandwich base line
- $\beta = 56^\circ 50' 30''$

Here it may be anticipated that the straight-front method was used in this analysis. However, the physical concept of frontal irregularities may not seem very appealing to the mind. Hence for comparison, and also to be accessible to analytic evaluation, the F-region was considered to be composed of individual clouds (electron or ion concentrations) which act like point reflectors. During the period of a consistent time-lag between two records, clouds had to be assumed to move with equal speed in the same direction (laminar flow). It was of interest to study the geometry of moving clouds so as to know what time displacements to expect between transmission-delay records.

The Point-Reflector Geometry

The choice of point reflectors eliminated the consideration of retardation

effects. Accordingly, only geometrical path-lengths were the subject of investigation. Figure 10 displays the three-dimensional geometry of the triangulation system. The path of a moving point-reflector is indicated by z . This path is specified by the angle σ of its deviation from the North, the height above ground h , and the shortest distance s between the projection of z on the ground plane and the location of Concord. Neglecting the curvature of the earth and its surrounding atmosphere, the various path-lengths were evaluated during the course of travel of a patch. An example is shown in Fig. 11 for $\sigma = 120$ degrees East-of-North, an altitude of 200 km and $s = -20$ km. Along the abscissa, two time scales were included in correspondence with two speeds of 300 km/hr (83 m/s) and 600 km/hr (166 m/s). Time was chosen to begin at zero, when the point reflector is closest to Concord. The time-displaced curves correspond to the three transmissions between the transmitter, the point reflector, and each receiver. The indicated scales on the ordinate describe the path-length in kilometers as well as its equivalent 133- μ s delay units. For a speed of 300 km/hr the time displacements of the minima were calculated with $\Delta_1 = 4.6$ minutes between Concord and Gloucester and $\Delta_2 = 10.4$ minutes between Concord and Sandwich. Comparing these values with the time lags of $\Delta_1 = 4.7$ and $\Delta_2 = 10.4$ minutes, obtained by the straight-front analysis for the same specifications, the error was found to be very small.

Assuming several patches to move in succession along the path z , one obtains, during a desirable period, a series of such traces which could synthesize transmission-delay records similar to those observed experimentally. There will be a consistently uniform displacement if the speed of such successive patches is the same and remains unchanged during the appearance of its echoes on the record.

An analysis of the expected error between the straight-front method and the point-reflector method for all directions of movement yielded values of less than 5.4, 2.4, and 1.4 degrees for 100, 150 and 200 km altitude respectively. Consequently, if the actual height of the 3.5 Mc/s contour of the F-region was above 150 km, the error remained below 2.4 degrees. This result was obtained with respect to a series of patches moving in succession along the path z . In practice there are patches which have to be assumed randomly distributed and if long correlation-intervals relative to the fading

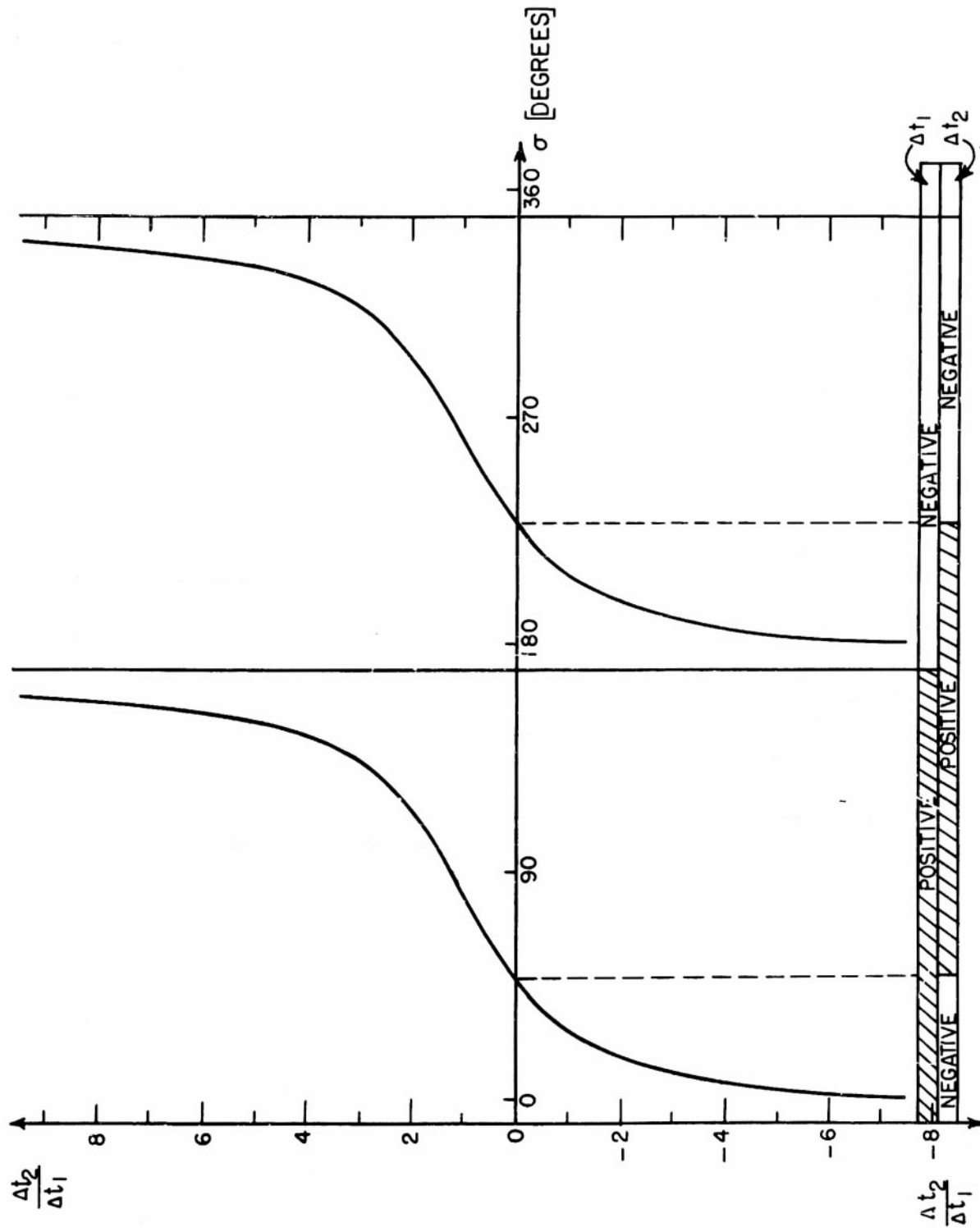
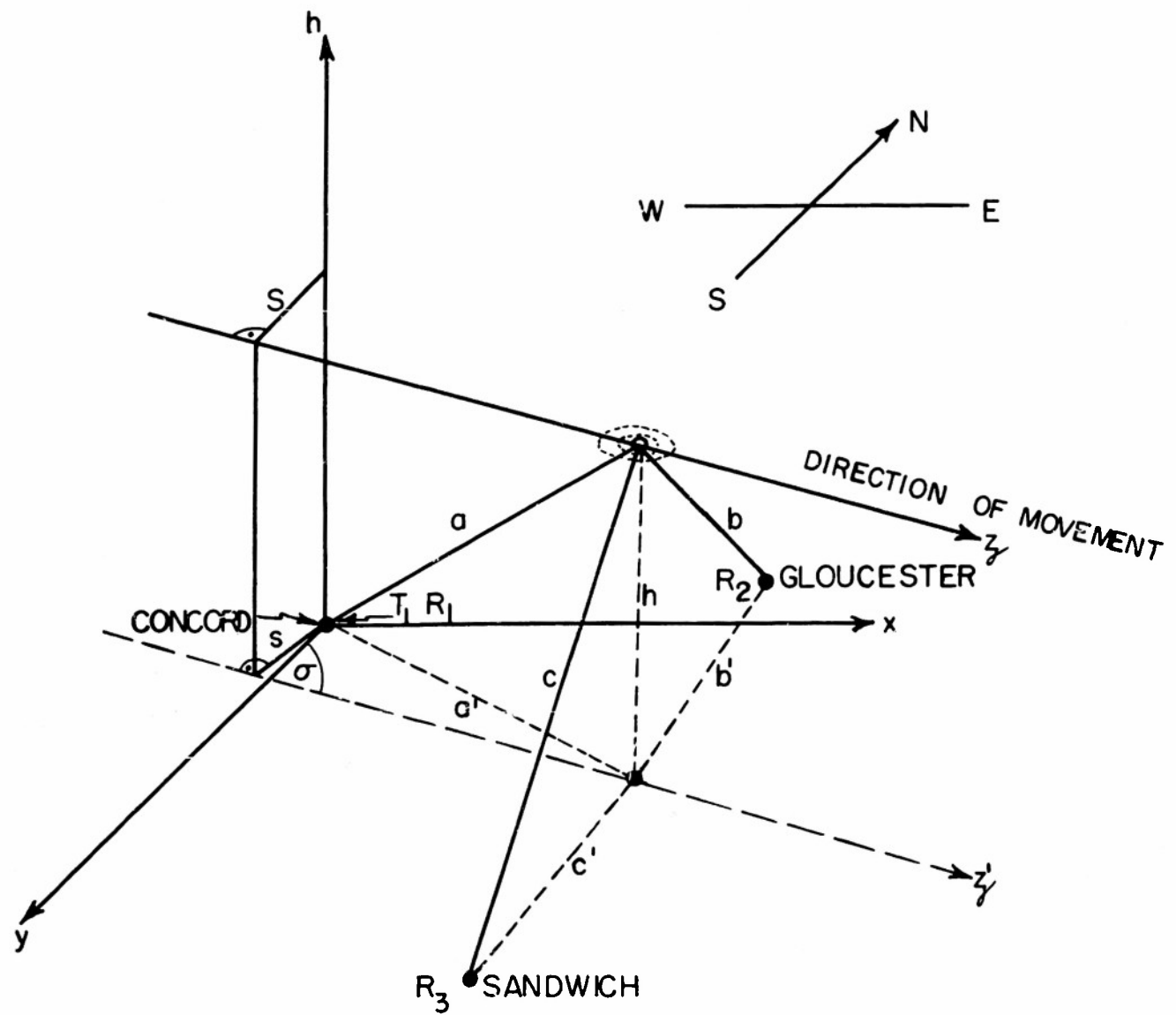


FIG. 9 RATIO OF CROSS-CORRELATION TIME-DISPLACEMENTS $\frac{\Delta t_2}{\Delta t_1}$ AS A FUNCTION OF DIRECTION OF MOVEMENT σ



T -- TRANSMITTER

R -- RECEIVER

FIG. 10 POINT-REFLECTOR GEOMETRY

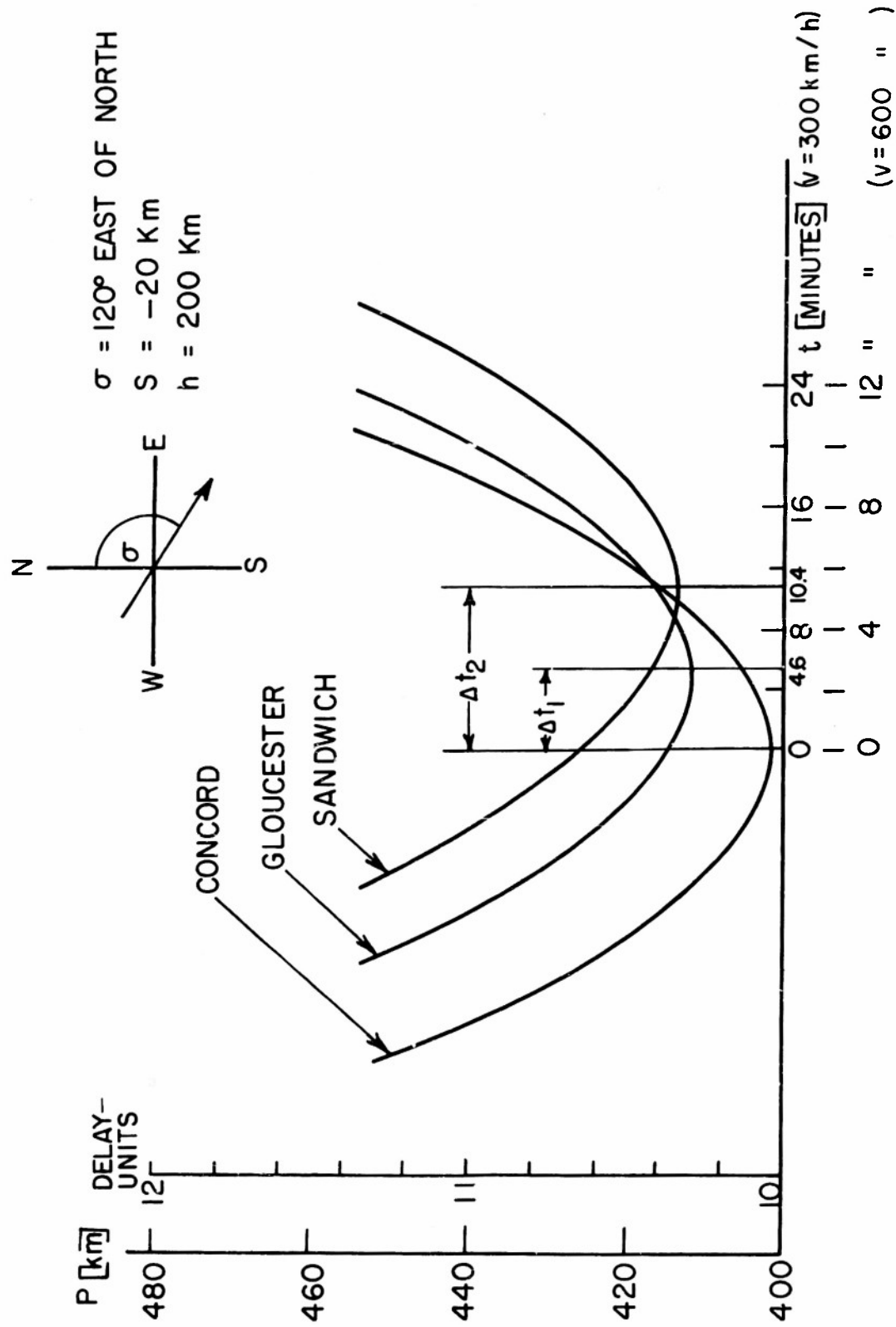


FIG. II IDEAL POINT-REFLECTOR PASSING OVER RECEIVING SITE

period of the transmission-delay are chosen, the above-mentioned errors were compensated in time.

It was also of interest to know what kind of physical conditions, more feasible than point reflectors, can exist in the F-region without invalidating the interpretation of the time displacements which were attributed to its horizontal movement. For the purpose of this study it was found that the patches can have finite dimensions if either the areas of constant ionization-density are concentric spheres, or if the cloud is at least symmetrical with respect to the plane normal to the direction of movement. In the former, the amount of retardation remains essentially constant during the appearance of an echo on the record, and for the latter, although varying, the magnitude of retardation will also not affect the time displacements.

From the preceding discussion it was believed that the use of the straight-front concept is justifiable.

Horizontal Direction of Movement

From the time displacements obtained by cross-correlation, or direct inspection and employing the straight-front method (formula 2), it was possible to calculate the directions of movement of the F-region during the period between August 1952 and December 1953. This period included 510 days. Useful data were available for 177 days. Because of equipment failure, 130 days did not provide three simultaneous records. On the remaining unusable daily records no reliable time-displacements could be obtained, either because of the absence of F-region irregularities (smooth record), or because simultaneous records were not alike. In addition, data had to be eliminated if blanketing effects of underlying regions obscured the F-transmission delay-echoes. The analysis was restricted to intervals around noon since the rate of change of ionization-density for this time of day was zero or very small.

Figure 12 displays a polar histogram of the directions of movement. The radius indicates the number of observations of σ as well as the percentage of readings lying within 10-degree intervals. More than 90 degrees' deviation of σ was comprised by the F-region which moved predominantly towards the Southeast. The angular distribution was better illustrated in Fig. 13, where

the number of observations was plotted as a function of σ . The obtained curve showed a maximum at 135 degrees East-of-North. For the investigated period the monthly averages of the resulting directions were plotted in Fig. 14. A semiannual period was observed with maximum deviation East-of-North close to the equinoxes.

Munro [2] reported for Sydney, Australia, a direction of movement of the F-region between 30 and 60 degrees towards East-of-North. In later experiments, Munro [3] found an annual period of the direction of movement with a predominant West-to-East component. Many other results were summarized by Deb [4] and Maxwell [5]. From these sources it appeared that the prevailing direction of movement of the F-region had a West-to-East component during the day, which compares essentially with the results presented here. Some discrepancies, however, are expected since observations were made on different continents and at various latitudes. A world-wide wind-circulation-system in the upper atmosphere is therefore suggested. The conception of such a system relies on data to which it is hoped that the results obtained here are contributing.

The horizontal speed of movement was derived from the same source as the direction of movement of the F-region. As reported in the following paragraph, it was found to be in good agreement with values obtained by other workers.

Horizontal Speed of Movement

By averaging monthly observations the seasonal variation of the horizontal speed of the F-region was obtained as shown in Fig. 15. In contrast to the semiannual period of $\bar{\sigma}$, the speed \bar{v} was found to have an annual period and its monthly averages varied between 250 and 600 km/hr with higher values in winter than in summer. A histogram of v is displayed in Fig. 16. The most frequently occurring speed was about 350 km/hr. The average speed of the F-region for the period between August 1952 and December 1953 was found to be 362 km/hr, or about 100 m/s. The median values of v were plotted in Fig. 17, of which the ordinate reads the percentage exceeding the value of the abscissa. From this diagram a 50 per cent median speed of 392 km/hr or 110 m/s was obtained.

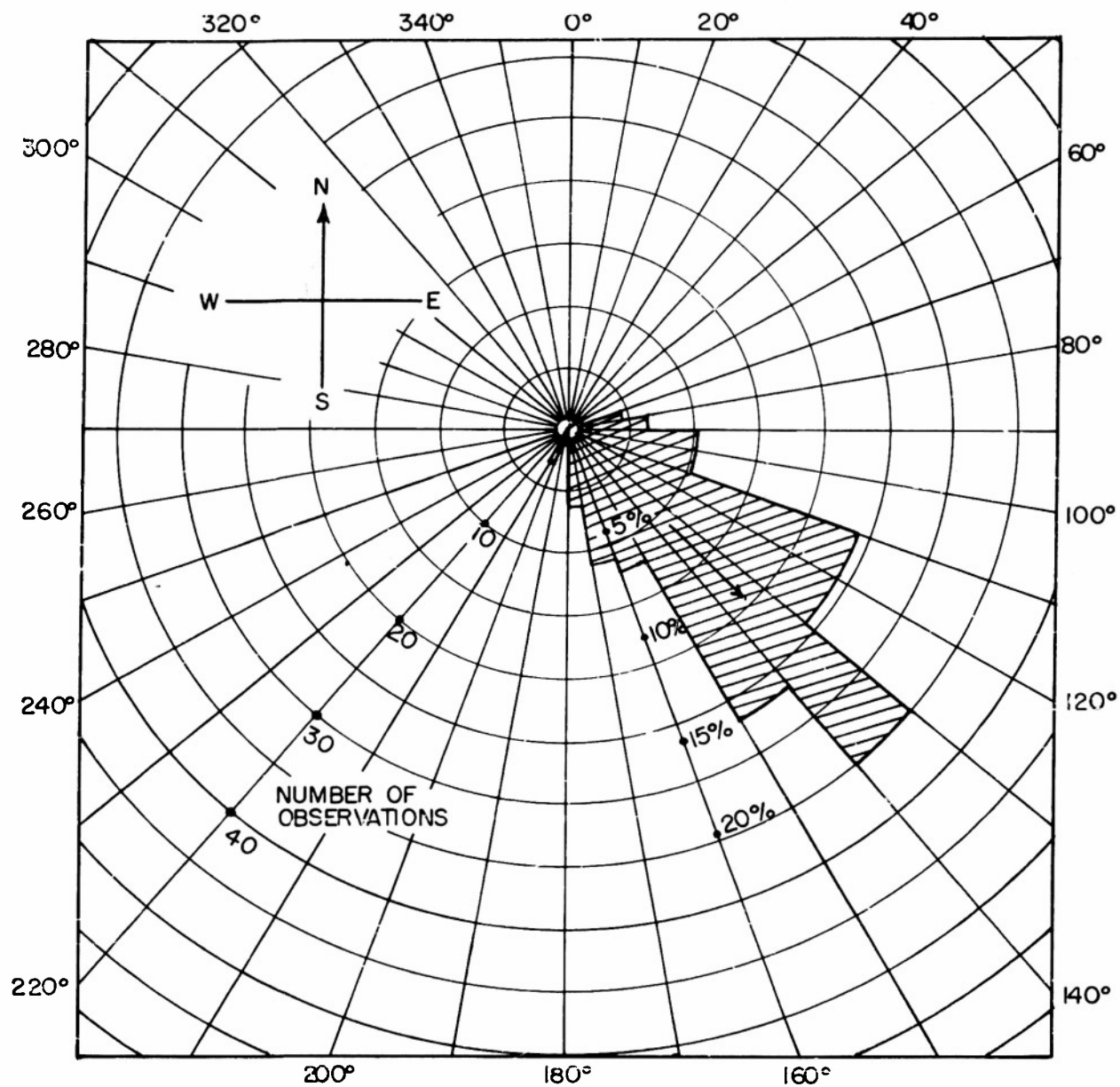


FIG.12 DISTRIBUTION OF THE DIRECTION OF MOVEMENT OF THE F-REGION DURING THE PERIOD OF AUGUST 1952 TO DECEMBER 1953 MID-DAY

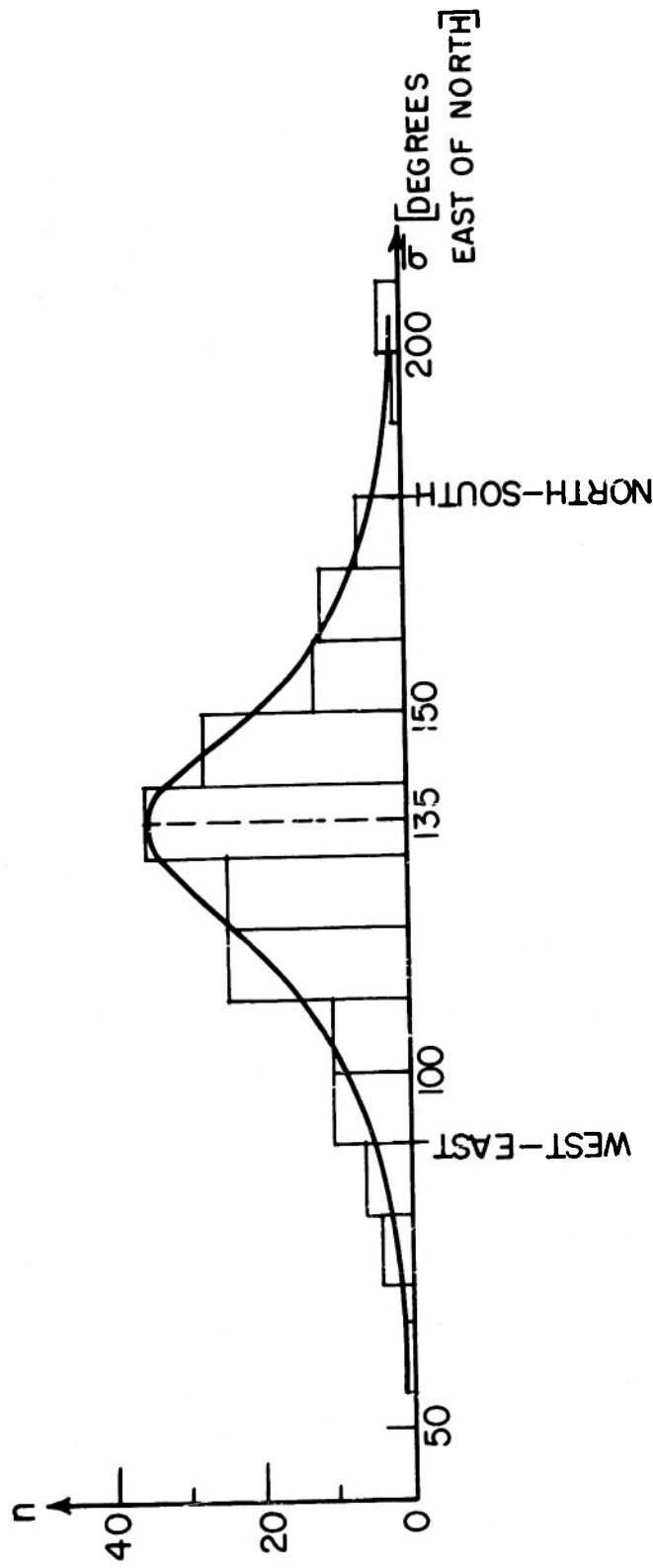


FIG.13 NUMBER OF MEASURED MEAN DIRECTIONS OF MOTION OF THE F-REGION AS A FUNCTION OF THE ANGLE σ FOR THE PERIOD FROM AUGUST 1952 TO DECEMBER 1953 MID-DAY

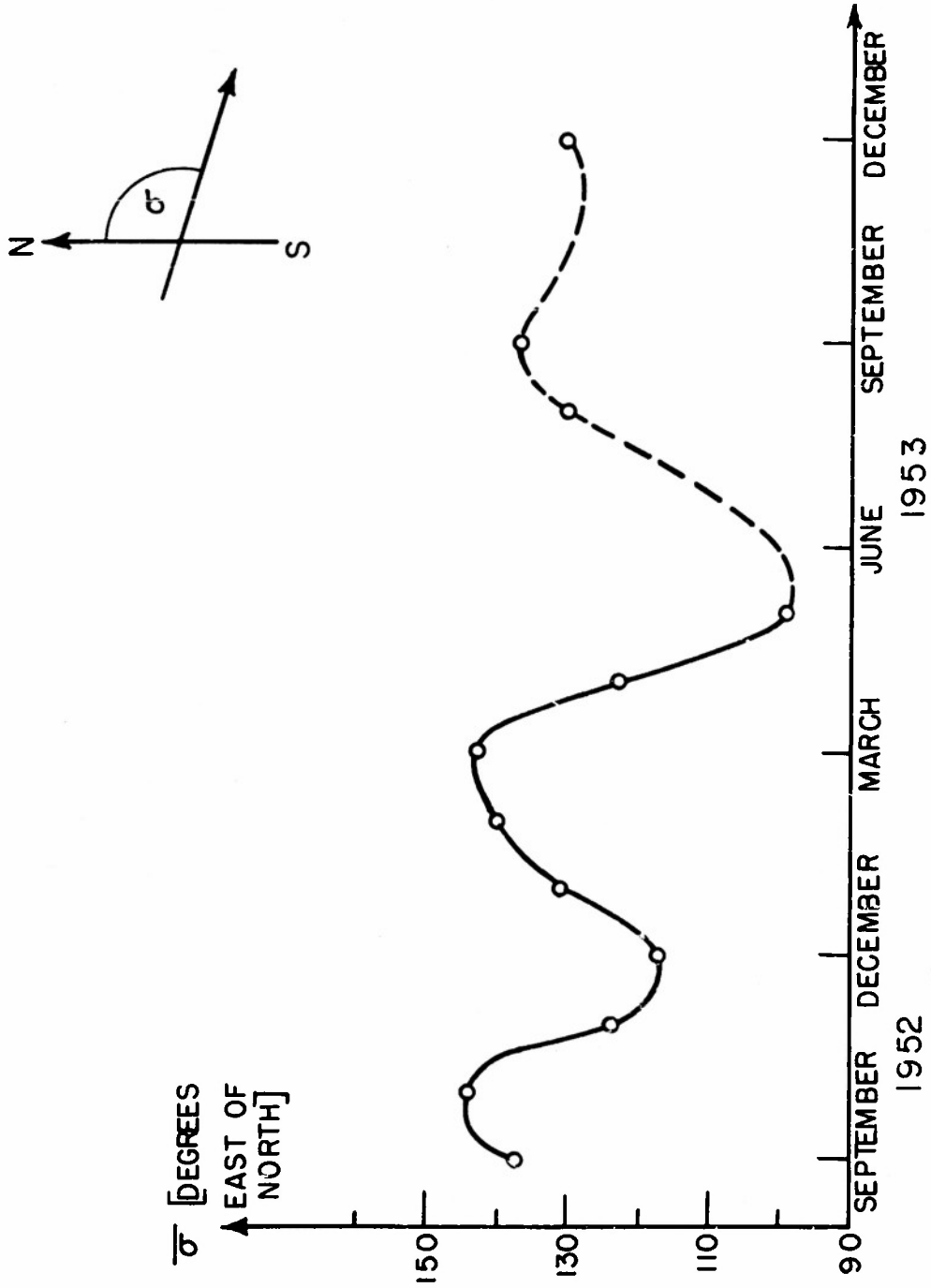


FIG. 14 MEAN DIRECTION OF MOTION OF THE F-REGION AT MID-DAY

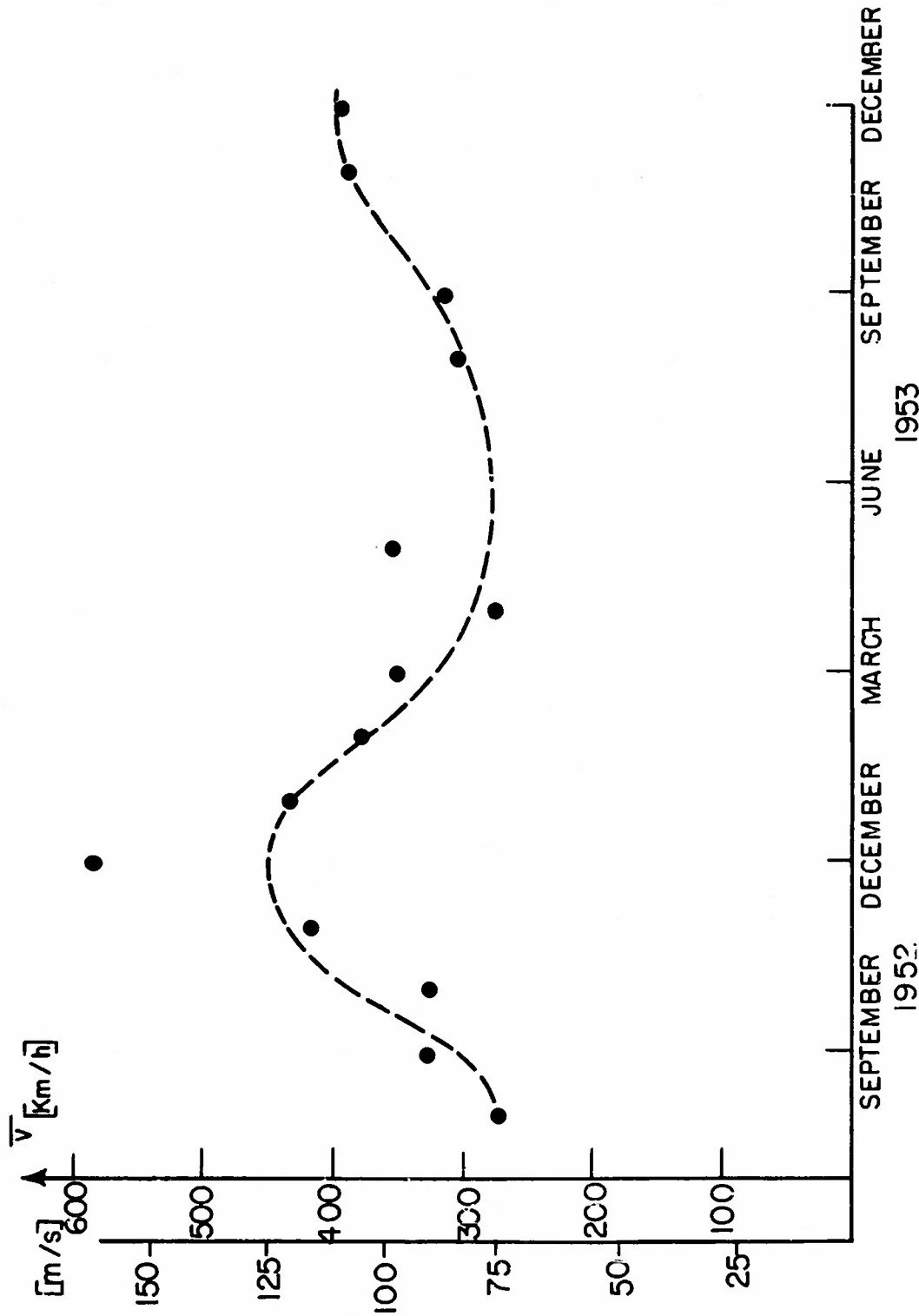


FIG. 15 AVERAGE SPEED OF THE F - REGION AT NOON
DEDUCED FROM 3.5mqs TRANSMISSION-DELAY RECORDS

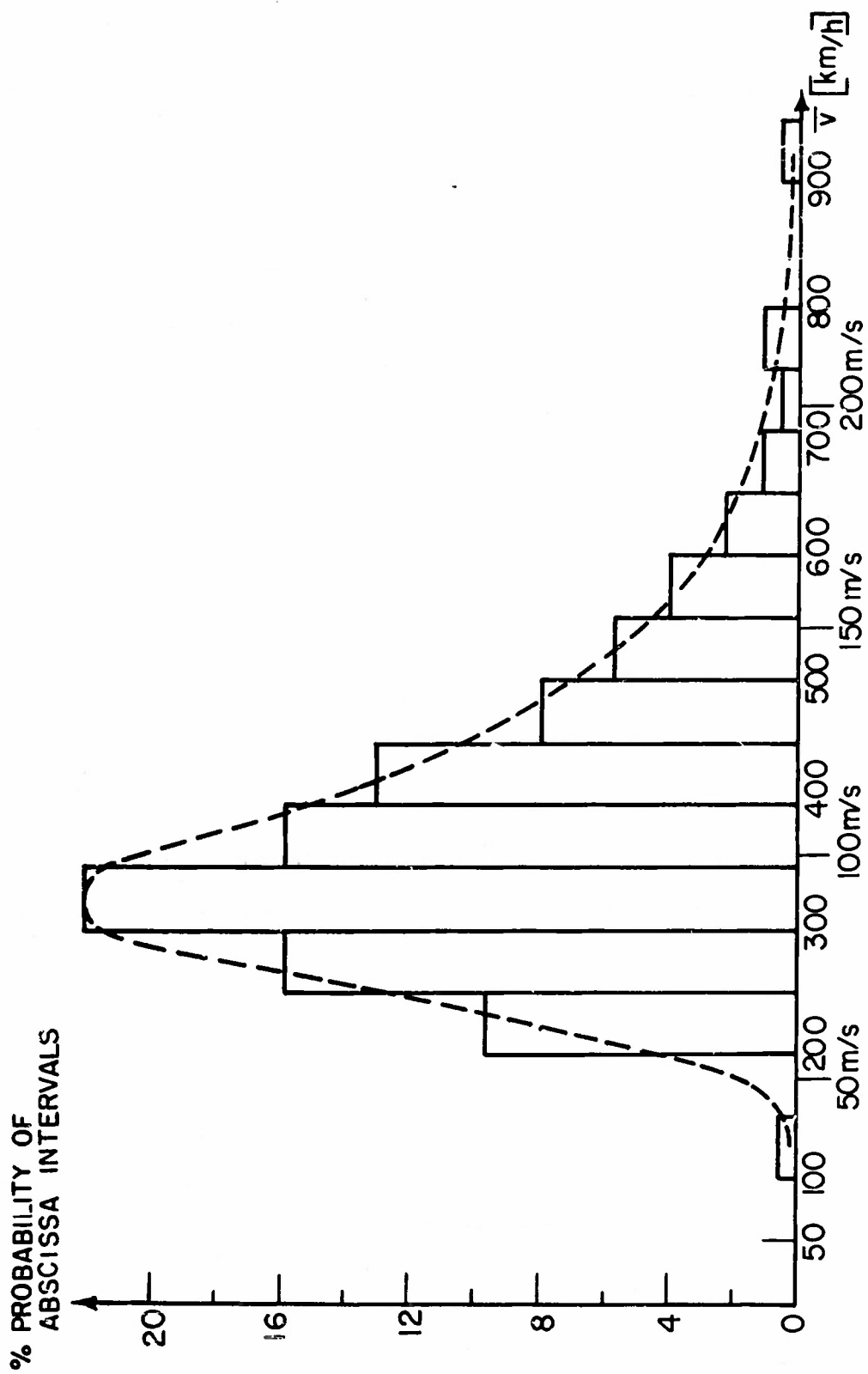


FIG.16 PERCENT PROBABILITY OF AVERAGE SPEED OF THE F-
 REGION DEDUCED FROM 3.5mc/s TRANSMISSION-DELAY
 RECORDS

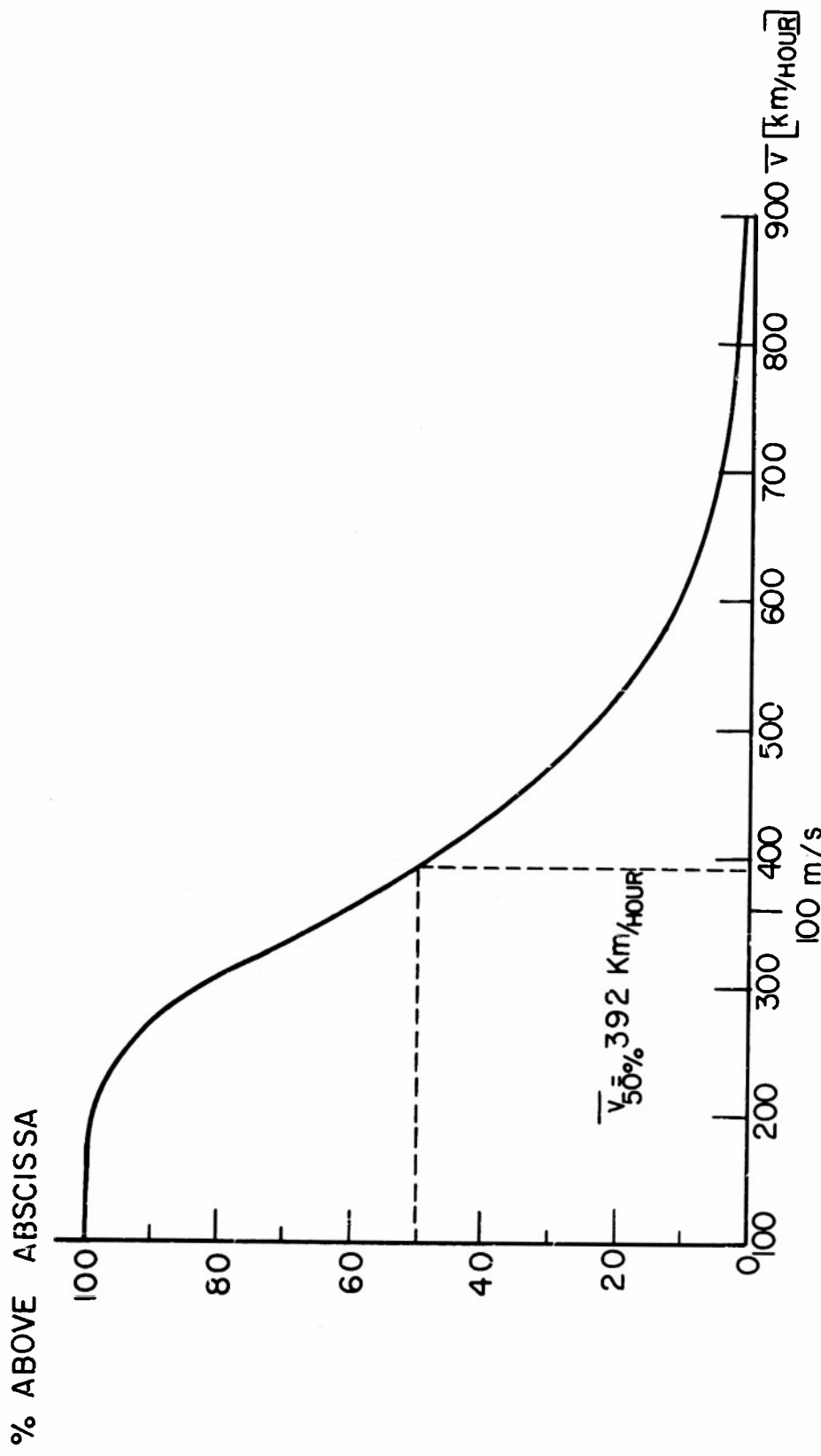


FIG. 17 MEAN SPEED DISTRIBUTION OF THE F-REGION FOR THE PERIOD FROM AUGUST 1952 TO DECEMBER 1953 MID-DAY

For midday, the virtual-height median-values were derived from the Concord record and their monthly averages are shown in Fig. 18, indicating greater delays in winter than in summer of the 3.5 Mc/s signal. Similar to the behavior of the monthly averages of the speed, the mean virtual-height also revealed an annual period. The relation between both was indicated in Fig. 19. The monthly averages of the virtual height plotted as the ordinate were related to the monthly averages of the speed read along the abscissa. Although the data used in this diagram were collected during a long period, increase of speed with increasing height seems consistently indicated.

Operating with a frequency close to the penetration frequency of the region, Munro [2] in Australia reported speeds for the F-region between 288 and 480 km/hr. Beynon [6] in England referred to a speed of 430 km/hr for the F-2 region around sunrise. From later experiments Munro [3] obtained horizontal speeds of the F-region between 300 and 600 km/hr. Maxwell and Dagg [5] in England observed a most-frequently-occurring drift-speed of 360 km/hr for the upper F-region. In America, Salzberg and Greenstone [7], and in Canada, Chapman [8] obtained an average speed of 360 km/hr. From these references it may be concluded that the average horizontal speed of the F-region reported in this study is in good agreement with the results of other investigations.

Discussion

The irregularities of the F-transmission-delay records were assumed to be produced by physical irregularities within the F-region. If these variations were caused by irregularities of the E-region, e. g., the direction of movement obtained here would have to be attributed to the latter. If it were possible to cross-correlate simultaneous E-region records, similar to the F-region analysis, a comparison of the time-displacements would resolve the ambiguity. Unfortunately, whenever the E-region was present, its virtual height was too regular in time to provide appropriate conditions. Daytime data of sporadic Es suitable for movement studies were meager. During the night sporadic-ionization clouds seem to move predominantly towards South-South-West. However, during this time no useful 3.5 Mc/s F-echoes were available for comparison. It was therefore necessary to look for qualitative

indications capable of resolving the E-F calamity. These indications were available by inspecting the E-region activities throughout the year. During the winter months, while extensive correlation data were obtained, the midday monthly averages of the E-region critical-frequency for 1952 were found to lie below 3.0 Mc/s, and for 1953 even below 2.6 Mc/s as reported for Washington, D. C. by the National Bureau of Standards [9]. The monthly rate of occurrence of sporadic E's also displayed a minimum during the winter months. Moreover, the inspection of the records gave only a few indications of strong E-2 activity during the winters of 1952 and 1953.

For the 510-day period the F-1 region showed substratifications on 261 days around noon as observed in Washington, D. C. Consequently, critical frequencies were observed within the F-1 region, which were distributed below the normally-referred-to critical-frequency of F-1, and the 3.5 Mc/s signal was exposed to irregularities which were duly attributed to this region. The number of days per month for which stratification was observed reached a maximum around the equinoxes, similar to the geomagnetic activity. However, the F-region echoes were unusable for cross-correlation studies when the K-index exceeded perhaps 3 or 4. Days of strong geomagnetic activity were therefore by itself excluded from the monthly averages of the directions and speed of movement. Although a notable but small effect of the K-index upon the speed of the F-region has been pointed out by Chapman [8], its seasonal variation seems predominantly influenced by the variations of the virtual height as shown in Fig. 19. On the other hand, the seasonal variation of the direction of movement which displayed a semiannual period as depicted in Fig. 14, may be related to the behavior of the geomagnetic activity.

In winter the F-2 region merges with F-1, the combined region being referred to as the F-region. It may be pointed out that, for the relationship between the monthly mean values of virtual height and speed of movement, a separation of the F-region into F-1 and F-2 becomes irrelevant for this discussion [10].

It is concluded that the transmission-delay variations are mainly produced by physical irregularities within the F-region and that the results of this analysis describe its actual movement. This is also supported by the good

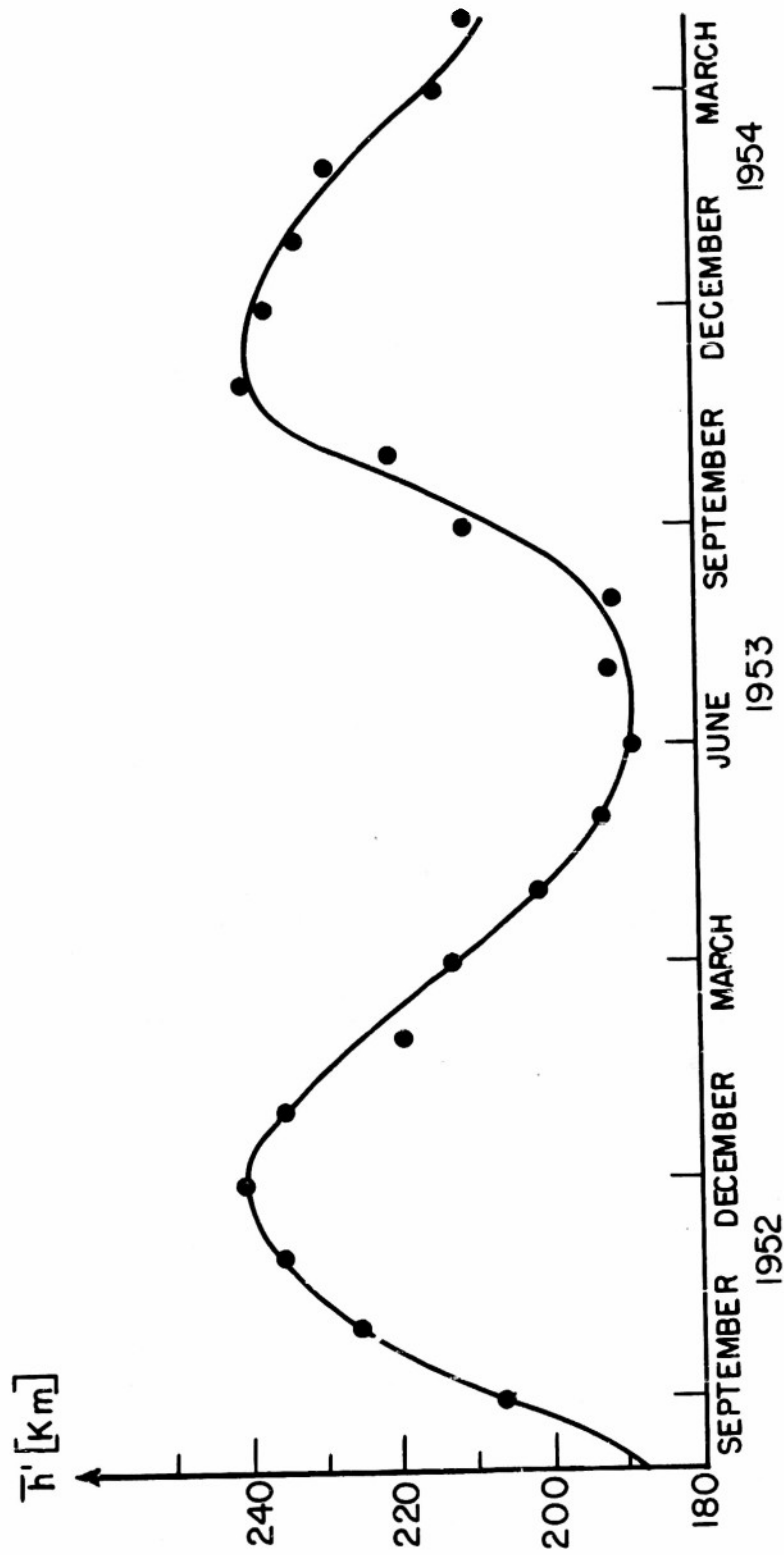


FIG. 18 MEAN VIRTUAL-HEIGHT \bar{h}' OF THE F-REGION AT
 MID-DAY DERIVED FROM 3.5mc/s TRANSMISSION-DELAY
 RECORDS (CONCORD - MASSACHUSETTS)
 LATITUDE : 42.4°N LONGITUDE : 71.2°W

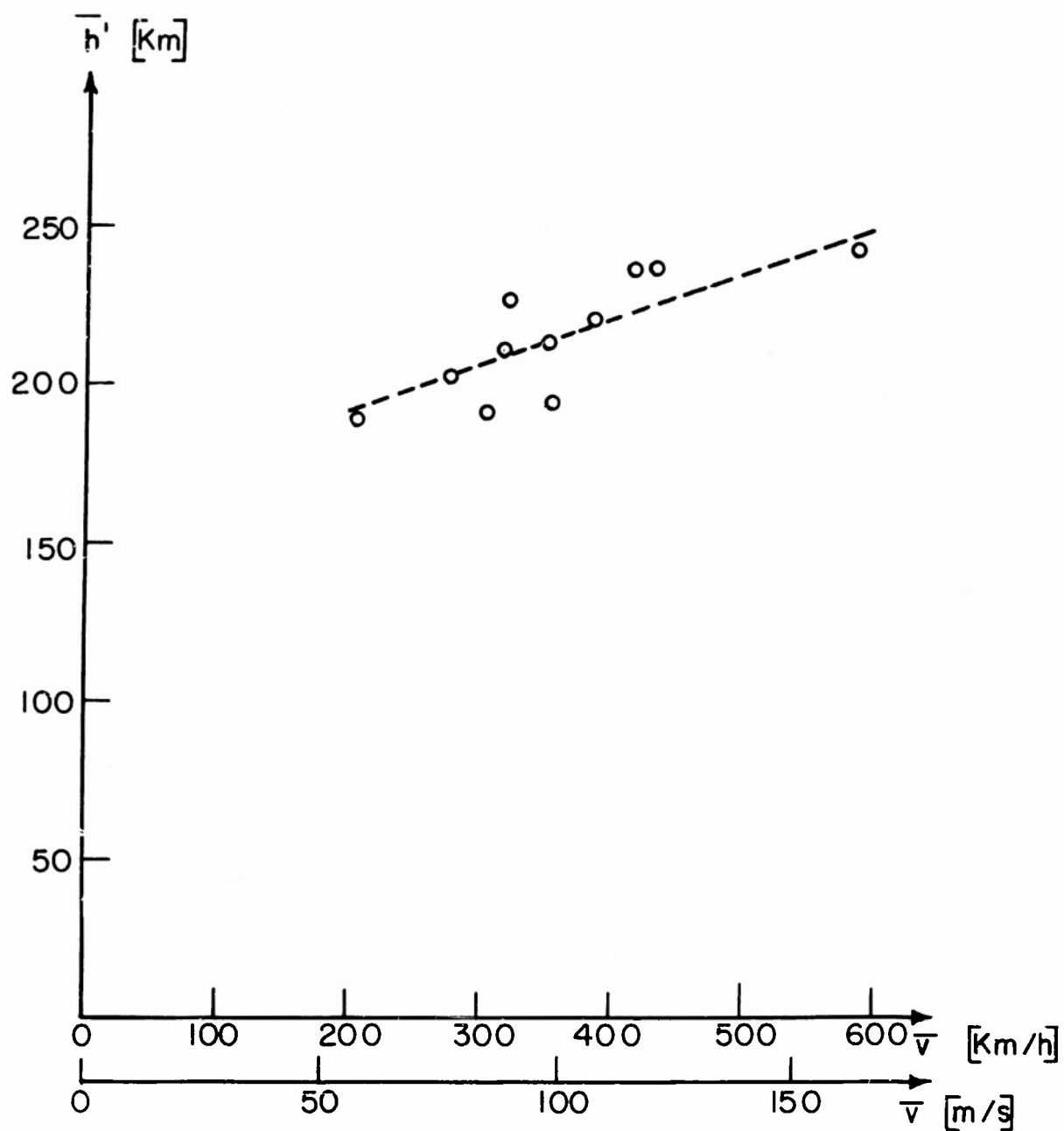


FIG.19 RELATION BETWEEN MEAN VIRTUAL-HEIGHT AND MEAN SPEED OF THE F-REGION FOR THE PERIOD OF AUGUST 1952 TO DECEMBER 1953 MID-DAY DEDUCED FROM 3.5 mc/s TRANSMISSION-DELAY RECORDS

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