MEASUREMENT OF IRREGULARITY HEIGHTS BY THE SPACED RECEIVER TECHNIQUE

by

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ABSTRACT

Scintillation of radio signals from an artificial earth satellite has been analyzed using the spaced receiver technique in order to gain a greater understanding of the latitudinal and diurnal variation of the height of the electron irregularities responsible for the observed scintillation on the ground. Other prominent features of the scintillation are also noted. The irregularity heights tend to be greater during the nighttime hours than during the midday hours. Also, the average irregularity height increases towards the north. This increase appears to be due to the existence of small patches of irregularities occurring at higher heights to the north. A large portion of the data falls in the 300-450 km range and thus confirms the observations of others.

A regular type of fading has been observed on many occasions. This regular scintillation is compared to that observed by others and an argument is presented which tends to refute use of the sharp edge diffraction model as an explanation for this phenomenon. Also, irregularity patches at the same sub-ionosphere latitude but at different heights were observed and this phenomenon is discussed.

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I. INTRODUCTION AND HISTORICAL SURVEY

In an attempt to study ionospheric irregularities in electron density and particularly the height of such regions, both radio stars and artificial earth satellites have been used as the source of radio signals. The work involving height determinations has been pursued more vigorously and more thoroughly with artificial earth satellites; therefore this survey will be restricted to such experiments. The basis of the determination of electron density irregularity heights is the observation of the scintillation or high frequency fading after the radio signal has propagated through the ionosphere. With the launching of the first Russian satellite (1957α), it became possible to easily measure these scintillation patterns with fairly unsophisticated equipment. When observed at closely spaced stations, the pattern is seen to move without changing its shape. The velocity of motion obtainable from the time delay measurements at spaced receivers can be used to compute the height of irregularities. Such an experimental technique is usually referred to as the spaced receiver technique.

G. S. Kent (1959) was one of the first investigators to use the received scintillation pattern from an earth satellite to determine the height of these scintillation producing regions. Due to the precession of the satellite used (1957α), its orbital height over the observer went through a large height range within a period of weeks. Kent defined a fluctuation index:

$$S = \frac{\text{standard deviation of the amplitude}}{\text{mean amplitude of the signal}}$$

Using the index, he was able to determine at what satellite heights the scintillation index became large and therefore at what heights such irregularities existed. He found that very little scintillation was observed below 250 km as the scintillation index S did not increase above this height.

Yeh and Swenson (1959) employed a similar method of assigning a scintillation index and a satellite ($1957\alpha 2$, $1958\delta 2$) with a variable perigee. They concluded that the region of irregularities began at about 220 km and extended to about 300 km. Their index was slightly more subjective in that it consisted of the assignment of the values 0, 1, or 2 depending on the observable intensity of the scintillation.

Slee (1958), who used this same index technique, concluded that the region of the ionosphere producing the scintillations must lie below 350 km and possibly be considerably lower. In his paper, Slee showed the high correlation between the observation of scintillation from satellite sources and the scintillation from cosmic sources.

One of the first uses of the spaced receiver technique applied to satellite signals was employed by Frihagen and Troim (1960). As will be shown in more detail, the velocity of the diffraction pattern on the ground can be measured by placing two receivers parallel to the sub-satellite path. The velocity and the height of the irregularity region are related by a fairly simple equation given the assumptions made by Frihagen and Troim. They gave only a few observations for the F and E regions. Values of 365 and 340 km were given for F region observations, while 104 km was given for E region observations.

Kent and Koster (1961) with a modified spaced receiver technique, made a number of observations with 1960π1 (Tiros II). Instead of taking an arithmetic average of the various time delays involved, they computed the cross-correlation and auto-correlation functions. With these functions and the measured time delays, Kent and Koster computed the height at various times for ten nighttime passes at the equator. Their heights ranged from 314 km to 424 km.

Basler and DeWitt (1962) used a combination of the two methods discussed above for height determinations. Using the spaced receiver technique they found the heights ranging from 145 to 1000 km, and concluded that no single height could be associated with the scintillation producing regions. In order to determine the preferred height of irregularity occurrence, if any, they then used the perigee precession of 1958δ2 and the assignation of the index values 0, 1, 2 as done by Yeh and Swenson (1959). They observed that the bulk of ionospheric irregularities occur below 650 km. Basler and DeWitt further concluded that the irregularities occurred with equal probability between 250 and 650 km with occurrence at greater heights being sporadic.

Hook and Owren (1962) with the spaced receiver technique found heights from 90 km up to the height of the satellites (1961αkl, 1962ϵ_1), which averaged 275 km. They concluded that scintillation producing regions were to be found throughout this region, and that they appeared to be aligned with the magnetic field.

Liszka (1963) who continued the spaced receiver technique found heights ranging from 100 km to above F maximum. He concluded from his observations that the low altitude regions are a nighttime phenomenon, while the forenoon observations were closely associated with the higher altitudes obtained.

Lawrence and Martin (1964) who returned to the method of assigning scintillation indexes and the perigee precession, found weak scintillation present down to satellite heights of approximately 200 km. The scintillation activity first steadily increased to a maximum at 550 km, then decreased steadily to satellite heights of 1550 km. From this information they concluded that 275 km was the approximate daytime height of the irregularities. (The transits observed were predominantly daytime passes.)

In one of the most exhaustive studies of irregularity heights, McClure and Swenson (1964) investigated both the diurnal and the latitudinal variation of irregularity heights. Previous investigators had concentrated on studying the diurnal and latitudinal variation of scintillation intensity by using the scintillation index described above. McClure and Swenson, however, concentrated on the height variations in part of their study. They concluded that most nighttime scintillation in temperate latitudes was caused by F region irregularities found principally between 300 and 400 km. They found that daytime scintillation was caused by E region irregularities near 100 km. They further determined that above 130 km the heights often varied considerably during a single satellite pass. Finally, McClure and Swenson observed a slight increase of scintillation height with the north latitude of the sub-ionosphere point. All of the height determinations were based on a spaced receiver technique using Transit IVA.

Frihagen and Liszka (1964) again making use of the spaced receiver technique found a wide range of height values from reducing ten passes of Transit IVA. Figure 5 of their report indicated this wide range of height values. From this figure, they apparently found heights from about 100 km to over 600 km.

In a more sophisticated use of the spaced receiver technique, Turnbull and Forsyth (1965) made use of the relative phase between the signals received at two spaced stations as well as the magnitudes received. Although they confined their study primarily to a theoretical treatment of the effects of isolated irregularities, they gave examples of such irregularities at 210 km and 380 km.

The purpose of this investigation will be to continue the work already done in the determination of irregularity heights, especially that of McClure and Swenson. Both the diurnal and latitudinal variations of irregularity height will be studied and other salient features of the observed scintillation will be discussed.

II. EXPERIMENTAL PROCEDURE

Receiving stations were set up at the Geophysical Observatory (88.222W, 40.07N), the University of Illinois Poultry Farm (88.227W, 40.10N), and at a private home (Watson House (88.214W, , 40.10N). All three stations employed turnstile antennas in order to minimize Faraday rotation so that any scintillation might be more easily observable. The station at the main observatory used a Magnavox model B receiver with a 2.5 khz bandwidth whose A. G. C. was monitored by a Sanborn eight channel voltage recorder. The two remote stations also employed model B receivers whose A. G. C. voltages were in turn used to drive voltage controlled oscillators (V. C. O.'s). This frequency modulated signal was then fed via conventional telephone link to the main observatory where it was demodulated and similarly recorded on the Sanborn recorder.

The spacing chosen was on the order of 3 km. 3 km was used as past experience indicated that the correlation would be high, and this spacing would still allow an observable time difference between the respective patterns. The actual spacings were 3.00 km for the Geophysical Observatory-Poultry Farm leg and 3.33 km for the Geophysical Observatory-Watson House leg. As indicated in Figure 1, the Geophysical Observatory-Poultry Farm leg was constructed to parallel the N-S subsatellite track while the Geophysical Observatory-Watson House leg

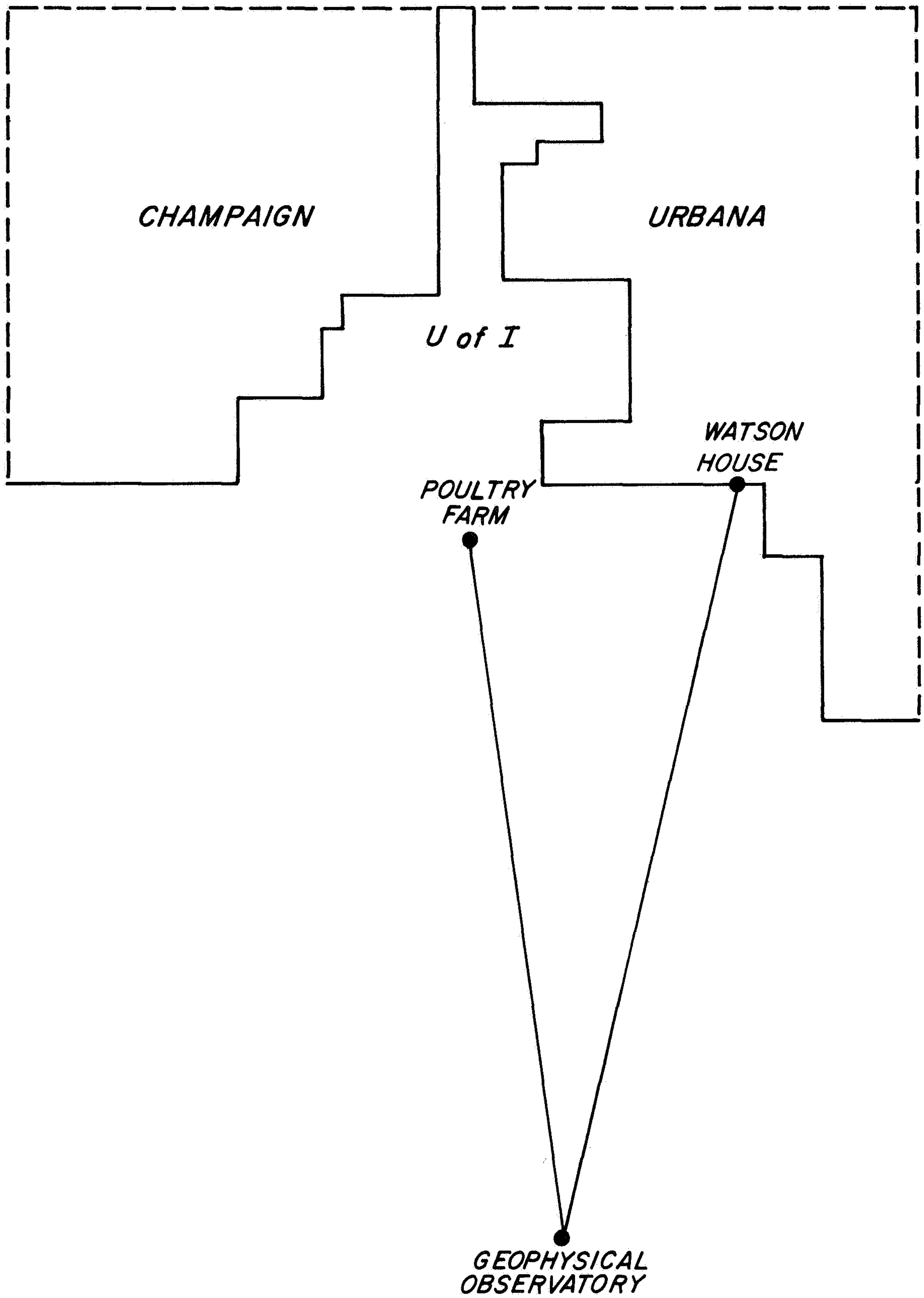

Figure 1. Receiving locations used in this study

was parallel to the S-N sub-satellite track.

The satellite used in this experiment was the beacon explorer BE-B (S-66) with an inclination angle at the equator of 80° and a height above the earth of approximately 980 km. The 40 mhz beacon was used throughout the experiment. As the sub-satellite track is actually parallel only at the latitude of the stations (40.02), the satellite headings are given over the latitude range of interest in Table 1. This point is discussed in more detail in the following chapter.

Table 1.

Satellite Headings in Degrees Measured from Geographic North for BE-B

Satellite latitude	30°	40°	50°	
Satellite heading	167.8°	169.9°	170.9°	N-S passes
	12.0°	11.0°	9.2°	S-N passes

Table 2.

Azimuthal Angles of the Base Station-Spaced Station Line

Location	Azimuth from Base Station
Watson House	12.7°
Poultry Farm	351.9°

The data recording system was incorporated into the existing data recording system at the University of Illinois, which operated automatically and needed only daily programming and routine maintenance.

III. HEIGHT DETERMINATION

Where the 3 km spacing is used as discussed previously, there is a high correlation between the patterns recorded at the two stations. It has been shown that when the correlation is quite high the cross-correlation function highly approximates the auto-correlation function shifted by the time corresponding to the ground velocity of the pattern. The ground velocity of the pattern is determined by simply comparing corresponding features of the two patterns to determine the time shift, and by using the distance between the two receiving stations. Previous investigators have made use of the plane earth formula:

$$h_i = h_s v_g / v_g + v_s \tag{1}$$

where h_i = irregularity height

h_s = satellite height

v_g = pattern velocity on the ground

v_s = satellite velocity

This expression for irregularity height has been used by several investigators including McClure and Swenson (1964).

Equation (1) is applicable when the satellite is relatively close to the station so that plane earth and ionosphere approximation is valid. An extension to the case of spherical earth and ionosphere was desired. The geometry involved is shown in Figure 2. Figure 3 shows an enlarged view

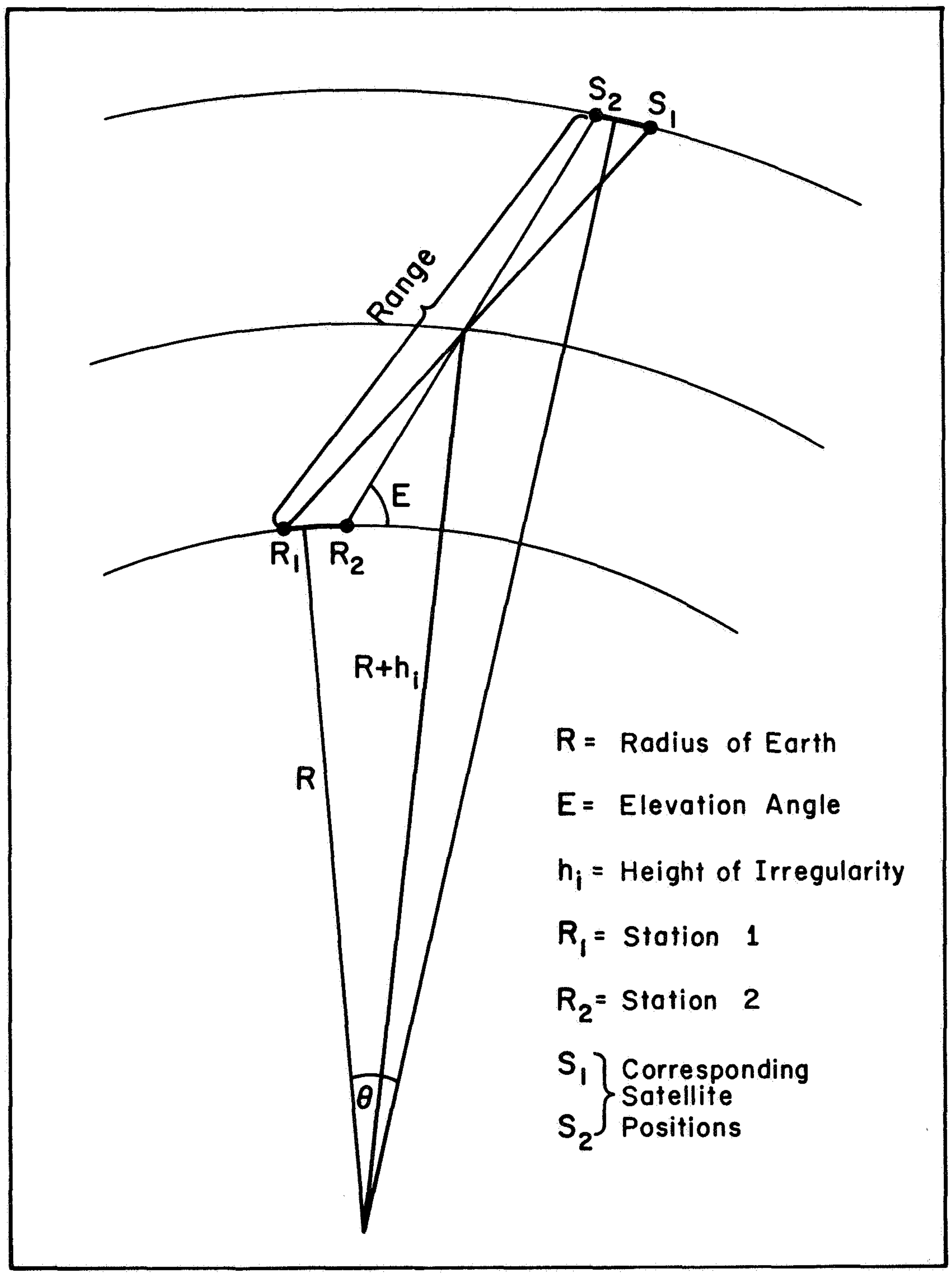

Figure 2. Geometry of the spaced receiver technique for determination of irregularity heights

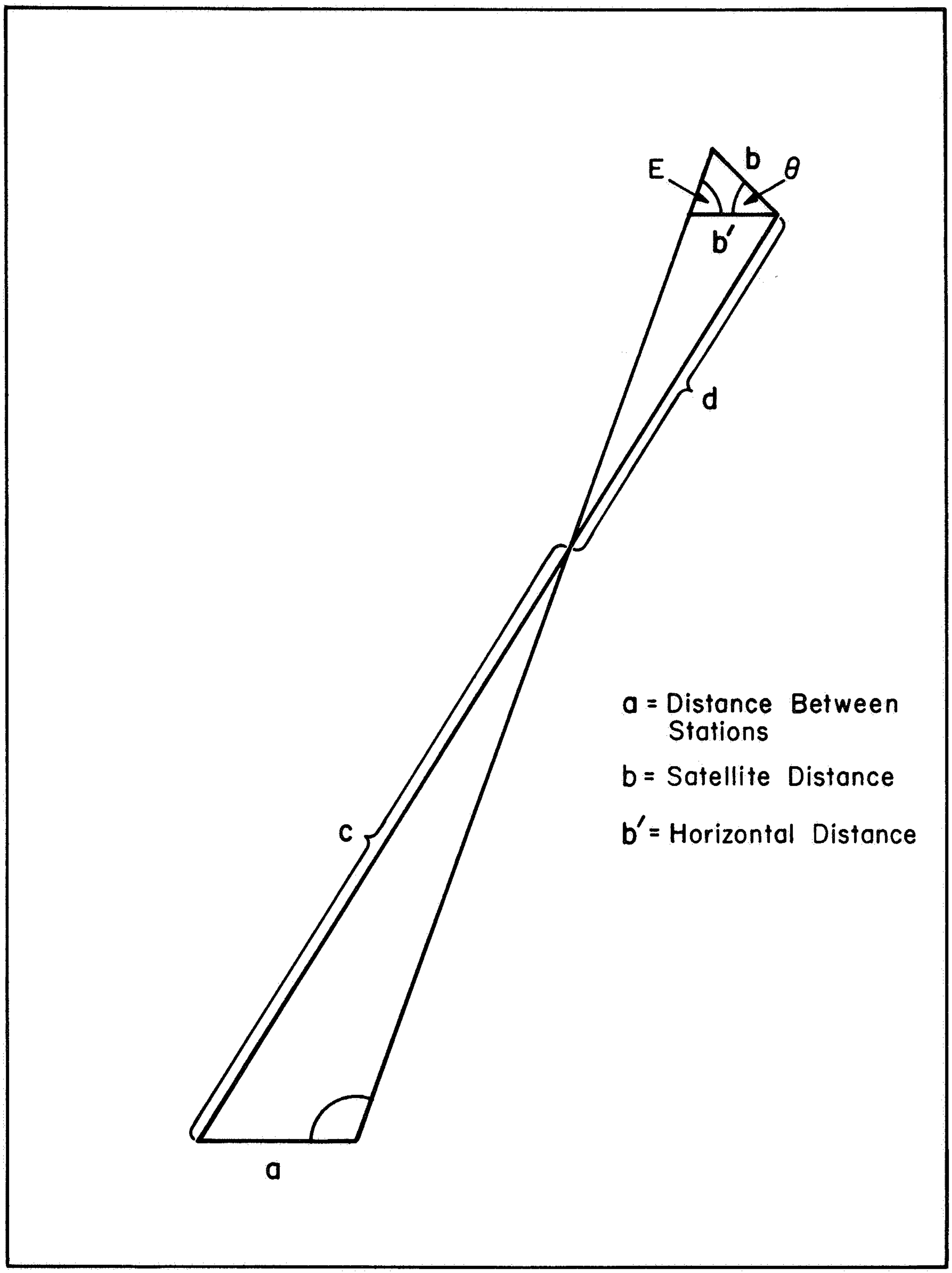

Figure 3. Geometry of the spaced receiver technique for determination of irregularity heights

of the significant features of the geometry. To simplify the analysis, it is assumed that the distance between the two stations along the surface of the sphere can be approximated by the corresponding chord distance and a similar approximation has also applied to the satellite orbit. The station spacing is approximately 3 km and the corresponding satellite travel distance has an upper limit of 25 km which corresponds to a time delay of 3 sec. Since these distances are small compared with Earth radius, the chord approximation is expected to introduce little error. It is further assumed that the satellite is in a circular orbit of 980 km corresponding to a velocity of approximately 7.4 km/sec. This is a valid assumption as the latest NASA bulletin lists a perigee of 888 km and an apogee of 1078 km. By finding the horizontal distance b' in terms of b and by then using similar triangles, an expression for the height h in terms of the time delay can be obtained.

$$h_i = \left(R^2 + \frac{a^2 r^2}{(a+b')^2} + \frac{2Rar}{a+b'} \sin E\right)^{1/2} - R \qquad (2)$$

$$b' = 7.4\tau(\cos\theta + \sin\theta/\tan E)$$

where: R = radius of the Earth

τ = measured time delay

θ = angle between observer and satellite at center of the Earth

r = range

Upon closer inspection, it is noticed that the expression becomes equal to the previous height formula when sin E → 1; in other words, when the plane earth approximation becomes valid.

Due to the anisotropy of the scintillation pattern, an error may arise if the sub-satellite track and the baseline of the two receivers are not parallel. This error can be resolved by placing a third receiver somewhere off the main baseline to find the correlation ellipse. The correction involves satellite and geomagnetic parameters and was discussed fully by Liszka (1963). Tables 1 and 2 indicate the error between the baseline and the sub-satellite track is less than 2.1^{o} for the N-S passes and less than 1.8^{o} for the S-N over the latitude range of interest. These angles are very small. Thus no correction for this effect need be applied. For all purposes, the two receivers and the satellite orbit can be assumed to be in the same plane as shown in Figures 2 and 3.

Eighty-four passes of BE-B extending from February 1968 to July 1968 which displayed scintillation were reduced for height values. The method used was graphical cross-correlation which consists of comparing similar fades of the recordings made at the two stations which parallel the sub-satellite track. Values were derived throughout the entirety of each pass when scintillation occurred except during periods when the scintillation became so violent as to reduce the correlation between stations below the level where graphical cross-correlation could be applied. Further, many of the records reduced in this manner were quite patchy--they alternated between regions of scintillation and regions of either low level scintillation or the total absence of scintillation. Thus the time delays derived for any one pass usually were contained in discrete intervals. After the determination of the time delays, these values were inserted into a computer program which computes the irregularity height by using Equation (2). In order to study the height variation versus latitude, the sub-ionosphere latitudes were needed. These were obtained by making use of an existing computer program which outputs the sub-ionosphere latitude values for different irregularity heights. This program was run for various assumed irregularity heights. The sub-ionosphere latitude for any particular height was determined by using values for the closest height. The method yielded latitudes accurate to $\pm$ 0.5°. The individual passes were then plotted versus north latitude and obvious diurnal and latitudinal features were noted.

The major source of error involved in the height measurements was that of determining the time delay τ. The records could be reduced with an uncertainty of $\pm$ 0.05 sec. A height of 350 km, which has been observed as being quite prevalent by previous investigators, particularly McClure and Swenson (1964), corresponds to a time delay of approximately 0.75 sec. An error of $\pm$ 0.05 sec. at this height corresponds to a height uncertainty of approximately ± 14 km. At this height therefore the error is not appreciable. However, this experimental error tends to have an extremely large effect at higher irregularity altitudes. A height of 800 km, for example, corresponds to a time delay of approximately 0.05 sec. Therefore an error of ± 0.05 sec. makes readings at these heights highly suspect.

Several examples of the graphs of irregularity height versus north sub-ionosphere latitude are shown in Figures 4, 5, and 6. Most of the passes which were reduced for height values were quite patchy. Also, there were a number of periods when the correlation between the spaced stations was reduced below the point where graphical cross-correlation yielded dependable time delay values. This low correlation was usually accompanied by very violent scintillation and further reduced the possibility of graphical cross-correlation. McClure and Swenson (1964) believed that the irregularity region was probably much thicker or more strongly irregular at such times. Therefore little information about the irregularity height variation with north sub-ionosphere latitude could be determined from such passes. Of all the records obtained for the period February 1968 to July 1968, approximately eighty passes yielded good and reliable height measurements. These measured heights were then grouped for statistical studies in the following.

Table 3 shows the average irregularity height computed for

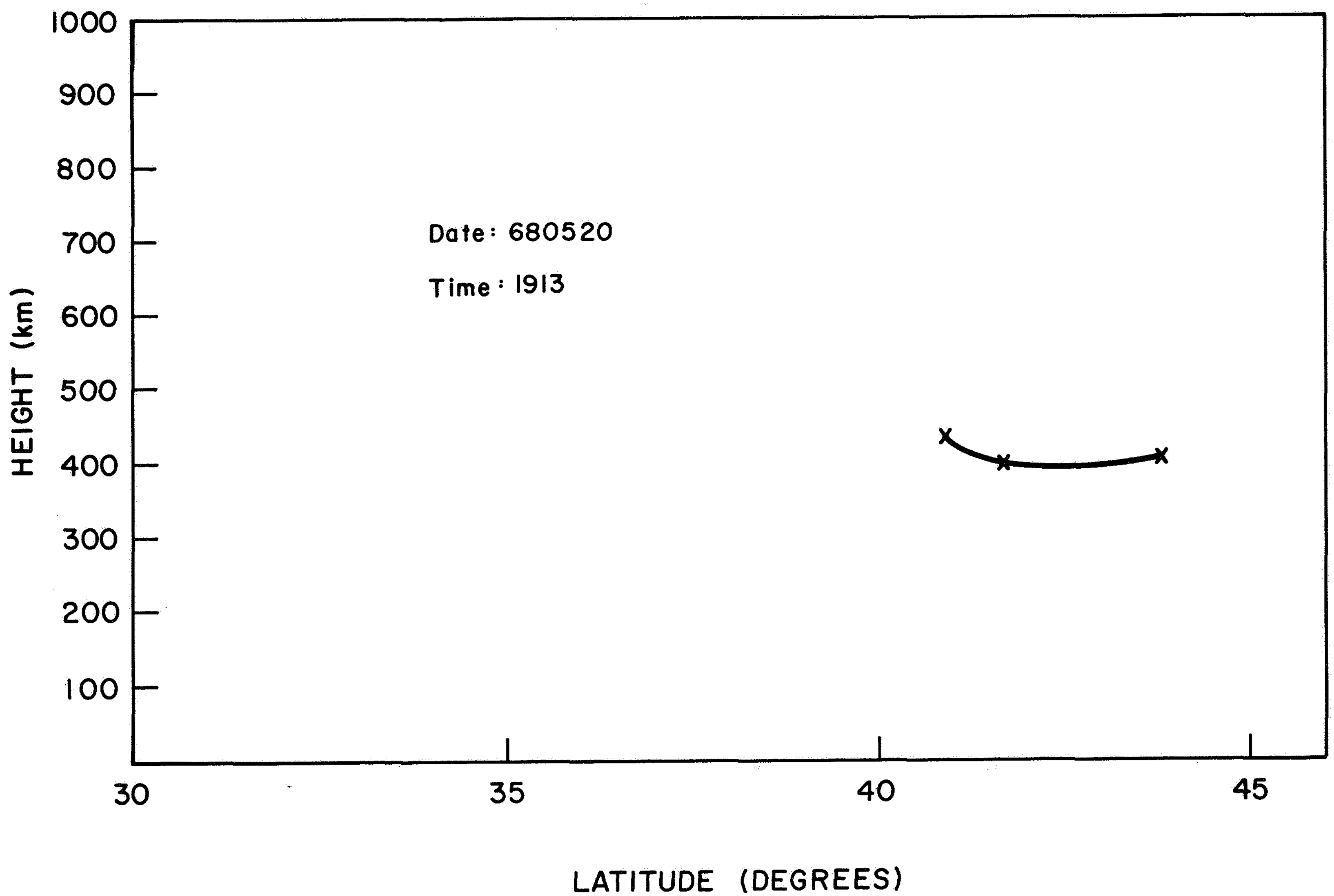

Figure 4. Irregularity height variation with north sub-ionosphere latitude--constant height

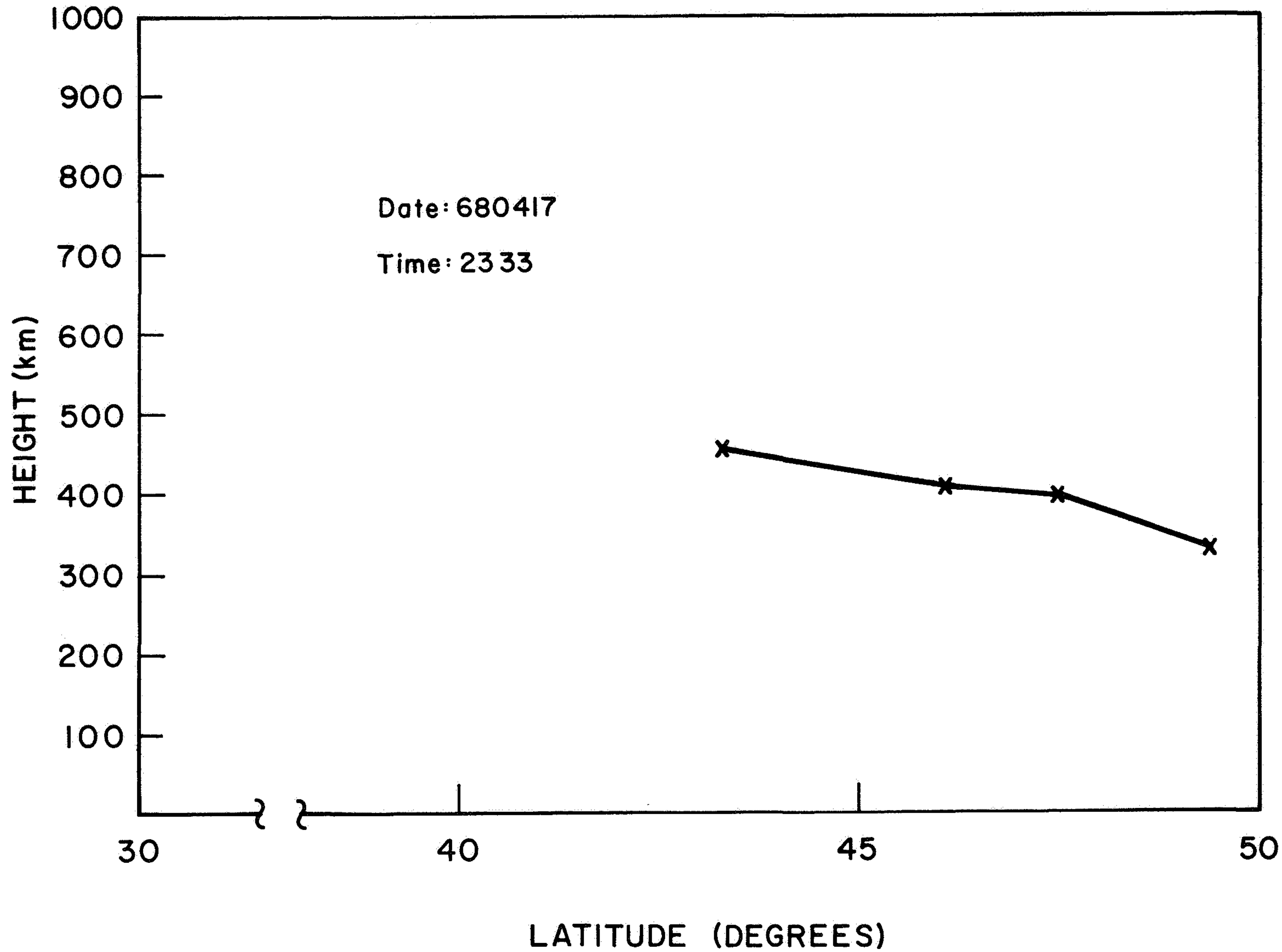

Figure 5. Irregularity height variation with north sub-ionosphere latitude--gradual change

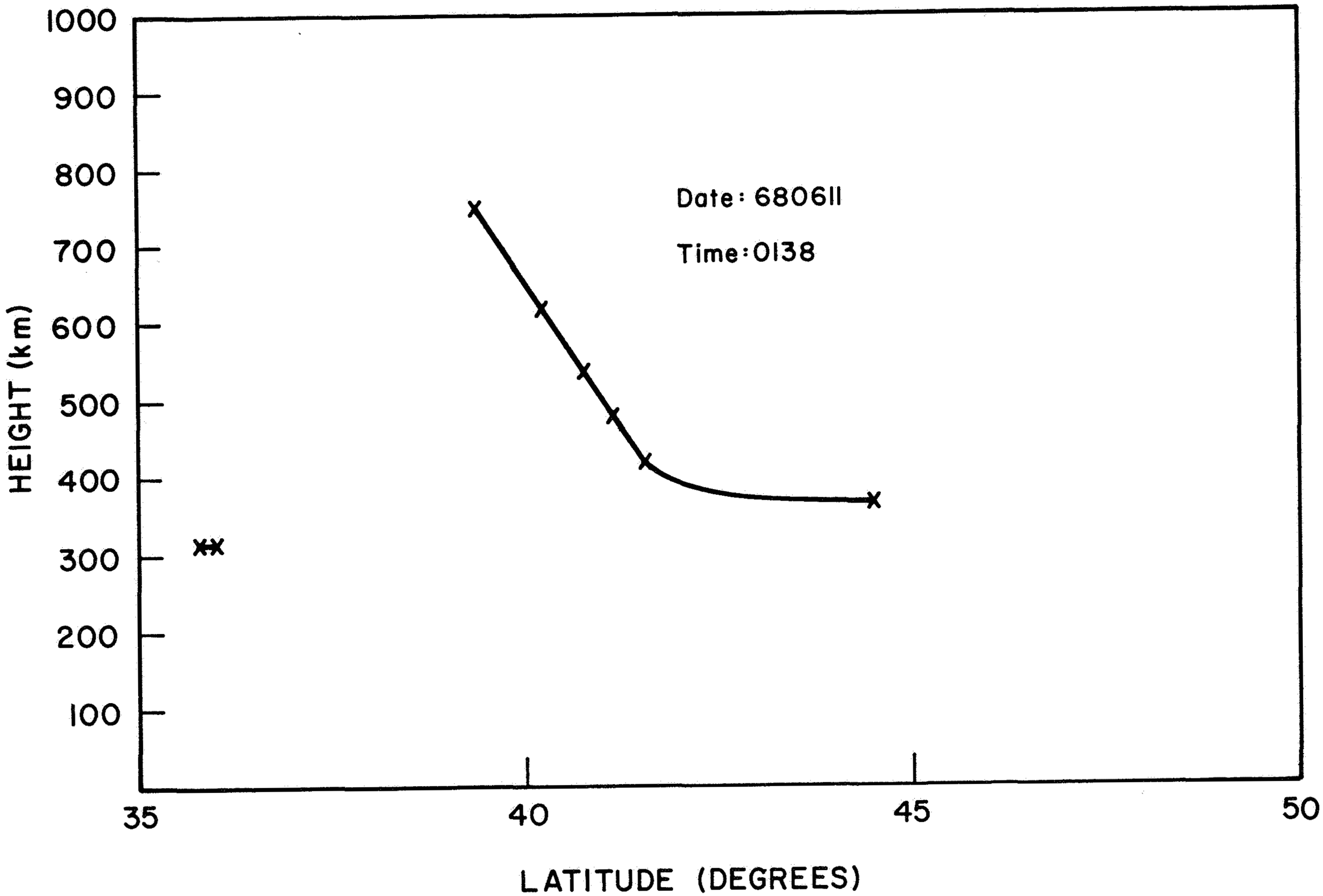

Figure 6. Irregularity height variation with north sub-ionosphere latitude--abrupt change

different latitudes.

Table 3.

Latitude Dependence of Average Irregularity Height

Latitude (degrees)	Average Height (km)	Number of Observations
37	317	15
40	387	30
42	423	35
45	422	27
47	520	20
50	547	12

The table suggests that the scintillation heights increase toward the north. This increase seemed to be relatively free of diurnal contamination as the height values used for each latitude were distributed throughout the day in a similar manner. That is, the proportion of the height values occurring during any one time interval of the day was approximately the same for each latitude listed. The graphs of each pass usually indicated patches of irregularities to be higher in the north. However, during any period of sustained scintillation activity, the irregularity height rarely showed an increase with north latitude. For those periods when the irregularity height did not remain approximately the same, the probability was about the same for the heights to increase or decrease with north sub-ionosphere latitude. This apparent height increase towards the north was then seen to be due primarily to small patches being higher on the average towards the north. During those sustained periods of scintillation when a height gradient was observed, the change in height could be rather slow as indicated in Figure 5, or very abrupt as shown in Figure 6.

To study the diurnal behavior of irregularity height, a histogram was prepared for heights measured at 42° sub-ionospheric north latitude. 42° was chosen as the majority of available data fell in the region 40° - 45°. A question mark is used to indicate those periods with doubtful statistical significance. The results are shown in Figure 7.

The histogram of Figure 7 generally supports the findings of other observers. Although the data are somewhat insufficient in the hours near noon, due to lack of significant scintillation activity, the histogram suggests that there is a change from higher altitudes during the nighttime hours to lower heights during the day. McClure and Swenson (1964) concluded that most nighttime scintillation was in the 300 to 400 km region while most daytime scintillation was near 100 km in height. Liszka (1963), working in the auroral zone, found a large amount of nighttime scintillation in the 100 km region while he observed F maximum scintillation during the forenoon hours. The heights determined in this study are somewhat higher than those found by most of the observers discussed above. However, as

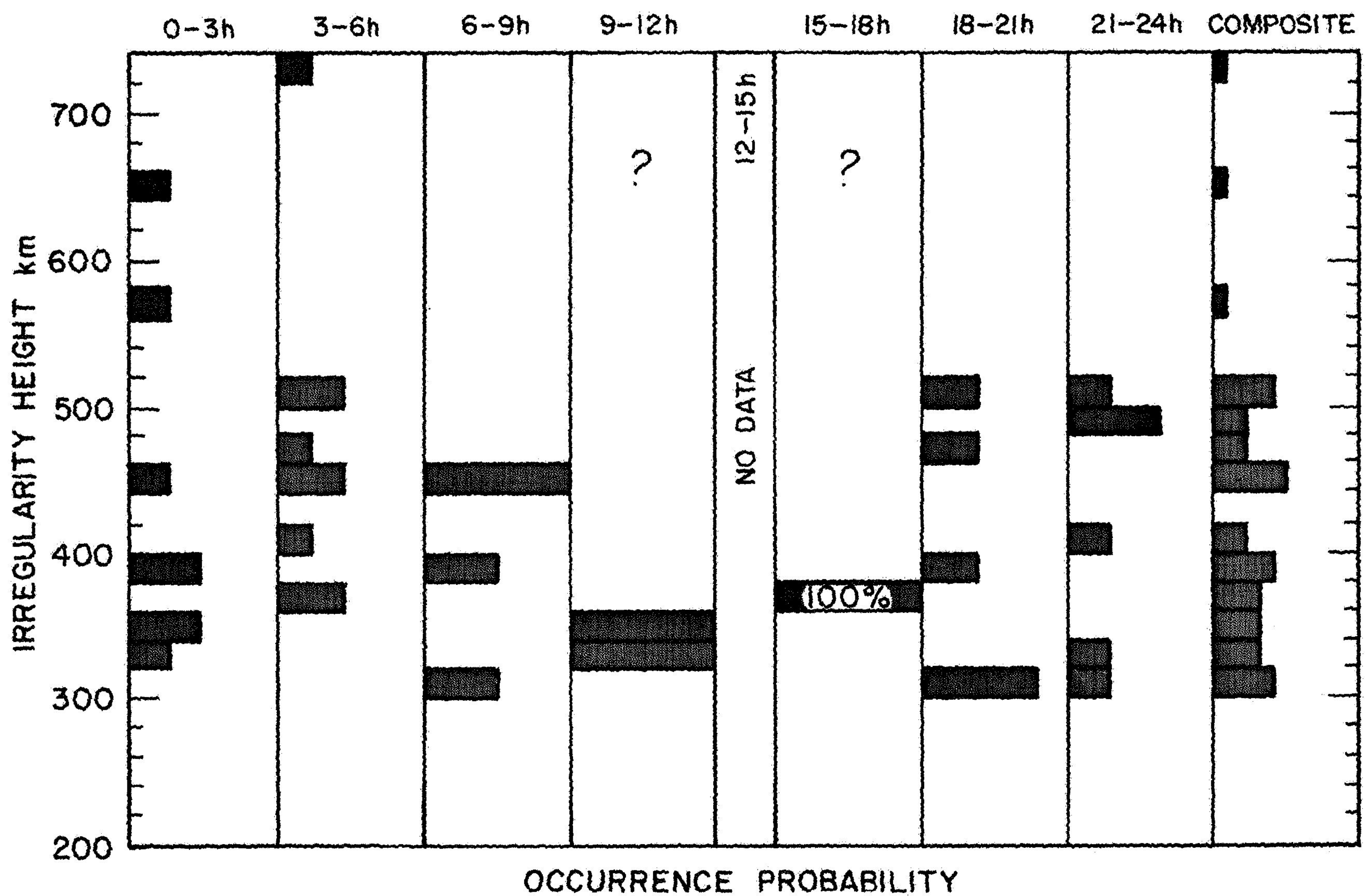

Figure 7. Diurnal variation of irregularity height at 42° north sub-ionosphere latitude

seen in Figure 7 there is a large concentration of heights in the 300-450 km range. Several investigators, notably McClure and Swenson (1964), Basler and DeWitt (1962), and Frihagen and Liszka (1964), did find heights up to approximately 600 km. It should be remembered that the accuracy of the measurement for heights above 500 km is fairly low. This study failed to show significant evidence of 100 km E region irregularities as observed by McClure and Swenson (1964). This may have been due to the relatively small amount of data available in the hours near midday.

IV. SPECIAL EFFECTS

In the process of reducing the collected data for the height of the irregularity regions, several interesting phenomena were observed. The first of these was a type of very regular or sinusoidal type fading. An example of this special fading is shown in Figure 8. This type of fading was present principally towards the beginning or end of an individual pass when the satellite was at low elevation, as seen from the receiving stations. However, there were several examples of weak forms of this regular fading toward the middle of the satellite pass. By using the spaced received technique in the same fashion as for the more prevalent irregular scintillation, the heights of these apparent regions could be determined. The heights determined in this manner were similar to those discussed above for the irregular scintillation. The regular scintillation has been seen by several other investigators. Liszka (1963) observed two types of regular scintillation. The first mentioned was found at high elevation and monitonically increased or decreased in period and amplitude. The second type was found at both high and low satellite elevations and was of fairly constant period. Liszka attributed the first type to a more or less discontinuous "blob" in the ionosphere. Liszka concluded that the second more constant type of regular fading was possibly the result of focusing by a stationary wave pattern although more data were needed. Frihagen and Liszka (1964) also observed this regular fading.

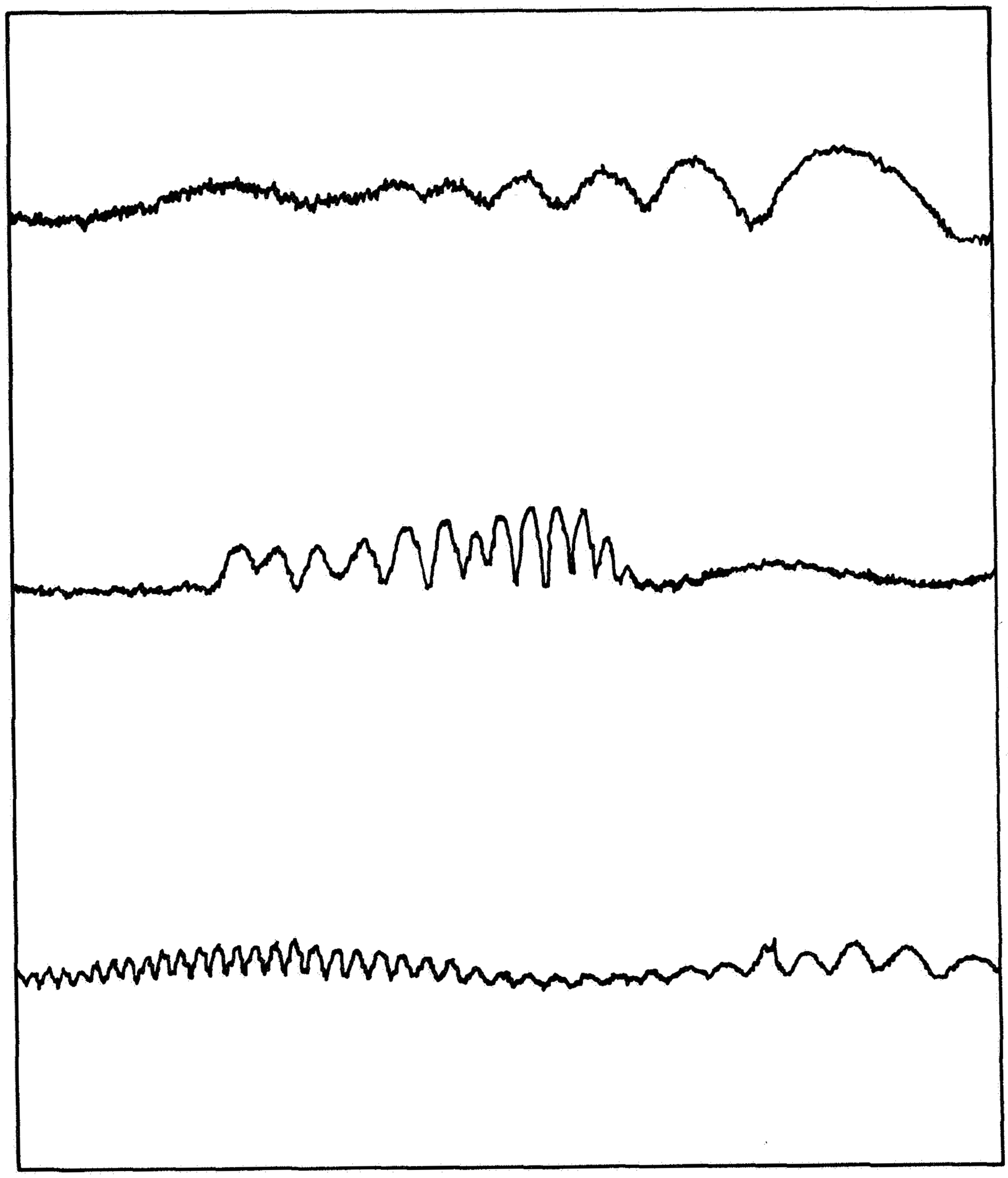

Figure 8. Examples of regular fading observed

They attributed it to signals reaching the antenna by electrically different path lengths, thus producing an amplitude modulated signal at the output of the receiver. They concluded that such a difference in electrical path length was caused by large irregularities in total electron content or multiple reflection from ionospheric layers.

Ireland and Preddey (1967) made a fairly extensive study of this regular scintillation and attributed it to several different mechanisms. They postulated that at lower satellite elevations an E region patch would be opaque to the incoming wave and would thus produce the well known sharp edge diffraction pattern. At greater satellite elevations they thought that the patch might appear somewhat transparent and act as a phase changing lamina. Ireland and Preddey also attributed some of the regular scintillation they observed to the possibility of interference between a direct wave and one which undergoes reflections at the ground and an E region patch. Their theoretical calculations and the results obtained seemed to compare quite favorably with their experimental observations. The type of regular scintillation observed by Ireland and Preddey was quite similar to that seen in this study.

In a very recent investigation, Elkins and Slack (1968), using stationary satellites, also postulated that the regular scintillation they observed was due to a sharp "step" in the ionization profile, or an opaque patch in the F region maximum.

The difficulty in viewing this regulat scintillation caused by a sharp change in electron density and thus producing an edge diffraction pattern on the ground, is the electron density needed. In the following, numerical estimates on electron density needed to make the ionosphere opaque at 40 mhz for different incidence angles are made. The ionosphere is a dielectric medium with electric permittivity given by:

$$\epsilon = \epsilon_o \left(1 - \frac{\omega_p^2}{\omega^2}\right)$$

where:

ω_p	=	plasma frequency = $(Ne^2/\epsilon_o m)^{1/2}$
ϵ_o	=	permittivity of free space
ω	=	probing frequency
N	=	electron density
e	=	electron charge
m	=	electron mass

It is assumed that there is a sharp boundary between the background electron density and the region of extremely high electron density. Table 4 shows the approximate electron densities for total reflection of the incoming wave at an irregularity patch for different angles measured from the normal to the patch. This somewhat simplified picture assumes plane wave propagation.

Table 4.

Electron Densities Required for Opaque Ionosphere at Various Incidence Angles

Angle (degrees)	Electron Density (electrons/m^3)
0	1.92×10^{13}
20	1.70×10^{13}
40	1.14×10^{13}
60	4.62×10^{12}
80	7.7×10^{11}
85	1.92×10^{11}

As the highest electron density at sunspot maximum reported is approximately 1.7×10^{12} electrons per cubic meter, it seems unlikely that this regular fading is due to a sharp edge diffraction effect. It seems more likely that this regular scintillation pattern is due to small differences in the wave path length caused by bending when passing through irregularity patches.

One other phenomenon which was observed during this height determination study is of interest. A number of passes exhibited irregularities of small spatial extent at different heights and at approximately the same sub-ionosphere latitude. Figure 9 shows an example of such a pass. The possibility of such occurrences is explained in Figure 10. If irregularities

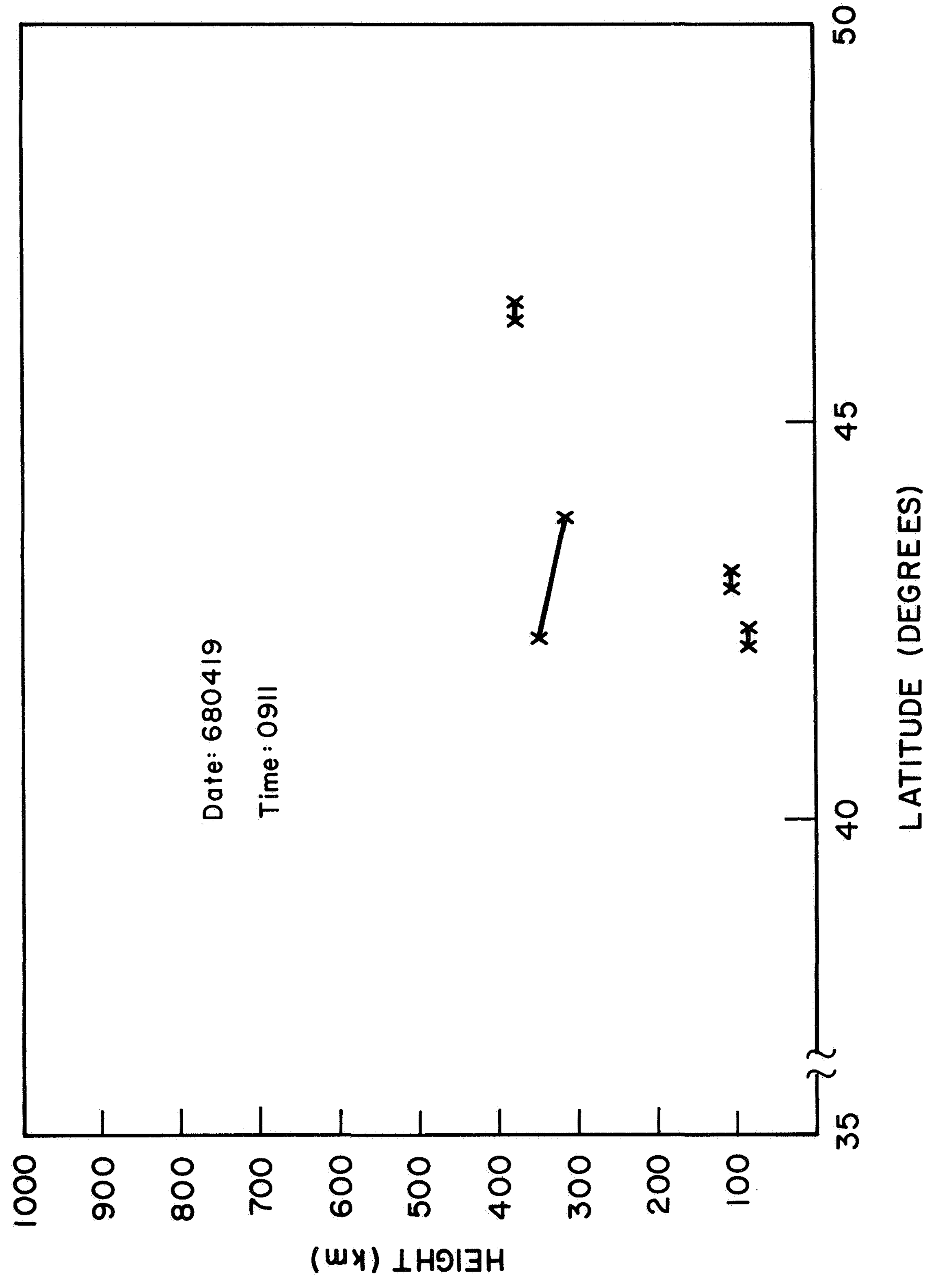

Figure 9. Example of irregularity patches of different height at the same sub-ionosphere latitude

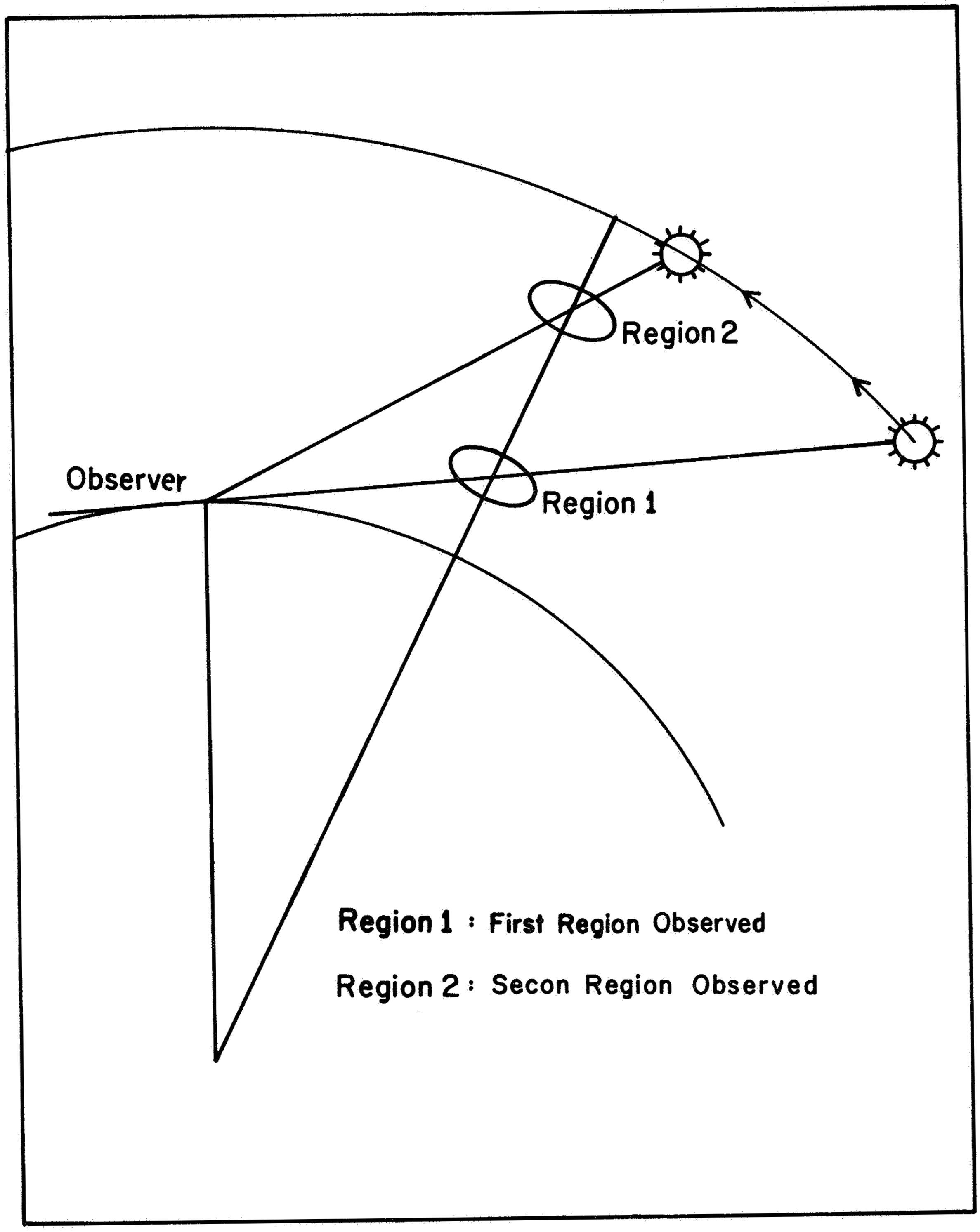

Figure 10. Geometry of the measurement of irregularities at the same sub-ionosphere latitude

are so extended that the radio path has to pass several layers simultaneously, the signals received at spaced stations are expected to have very little correlation. The poor correlation makes height determination nearly impossible.

V. CONCLUSIONS AND SUGGESTIONS FOR FURTHER STUDY

The spaced receiver technique has been reapplied in order to gain a clearer picture of the height of irregularity regions in the ionosphere. This method has proven to be fairly successful in examining the latitudinal and diurnal variation of these heights. The conclusions reached are:

1. There is a change from higher irregularity height near midnight to lower heights near midday.
2. Irregularity heights tend to be higher towards the north on the average. This is due to small patches being higher in the north.
3. A large part of the observed scintillation was quite violent. This has been attributed to very thick regions by other observers. It may also be due to passage through multiple irregularity layers. Further, a significant amount of the scintillation was "patchy; it alternated between periods of scintillation and either very low-level scintillation or the total absence of scintillation.
4. The greater portion of the scintillation observed was above 40^{o} sub-ionosphere latitude.
5. A relatively small amount of data suggests the occurrence of irregularity regions at two different heights at the same sub-

ionosphere latitude.

6. A regular sinusoidal type of fading has been observed and evidence is given which tends to refute the use of diffraction by a sharp edge as the mechanism behind this regular type of fading.

In order to strengthen the statistical accuracy and describe the midday region more properly, this study should be extended to include a larger number of passes. Further, the large degree of uncertainty involved in the determination of the heights of those regions at large elevations should be reduced by possibly increasing the chart recorder speed. This speed-up could be used in conjunction with reducing the receiver spacing in order to make use of those periods when the correlation is considerably reduced. More study should also be given to the regular fading discussed in this paper. The mechanism behind its production should be more thoroughly investigated and described.

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Measurement of Irregularity Heights by the Spaced Receiver Technique

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13. ABSTRACT

Scintillation of radio signals from an artificial earth satellite has been analyzed using the spaced receiver technique in order to gain a greater understanding of the latitudinal and diurnal variation of the height of the electron irregularities responsible for the observed scintillation on the ground. Other prominent features of the scintillation are also noted. The irregularity heights tend to be greater during the nighttime hours than during the midday hours. Also, the average irregularity height increases towards the north. This increase appears to be due to the existence of small patches of irregularities occurring at higher heights to the north. A large portion of the data falls in the 300-450 km range and thus confirms the observations of others.

A regular type of fading has been observed on many occasions. This regular scintillation is compared to that observed by others and an argument is presented which tends to refute use of the sharp edge diffraction model as an explanation for this phenomenon. Also, irregularity patches at the same sub-ionosphere latitude but at different heights were observed and this phenomenon is discussed.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Scintillation of Radio Signals						
Spaced Receiver Technique						
Ionosphere						
Irregularity Heights						

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