SCINTILLATION OBSERVATIONS OF SATELLITE SIGNALS

by
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NsG-24-59

January, 1965

Sponsored by:
National Aeronautics and Space Administration
Washington 25, D. C.

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ABSTRACT

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Satellite scintillation data recorded during the decaying portion of the sunspot cycle shows a decrease in nighttime scintillation north of 40° latitude with a decrease in sunspot activity. Scintillation south of 40° latitude is observed to change little with sunspot activity. Diurnal, seasonal and latitude variations of scintillation are studied and comparisons made between auroral and subauroral scintillation and also radio star and satellite scintillation. Spread F and the latitude of transitions in scintillation are compared. This comparison suggests that the southern boundary of the scintillation-producing region is not a smooth curve lying along a geomagnetic latitude line but is irregular in nature.

A brief discussion is given of some probable causes of scintillation which are then compared with what is observed experimentally.

Author

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I. INTRODUCTION

1. Historical Background

Scintillation was first observed on signals from radio stars in 1946 by Hey, Parsons and Phillips (1946). In 1950, spaced receiver experiments revealed that the scintillations were introduced on the signal as it passed through the earth's atmosphere and were not due to fluctuations in the radio source (Smith, 1950; Little and Lovell, 1950). When the first satellites were launched it was noted that their signals contained the same type of scintillation as did the signals from radio stars, therefore making it possible to use satellite signals to study the ionospheric irregularities.

These scintillation-causing irregularities are thought to have an elliptical shape with dimensions of 1 km wide by 5 km to 10 km long and are observed to be oriented with their major axis parallel to the earth's magnetic field lines. Their height seems to vary with the observers' latitude, with a major peak ranging from 300 km to 400 km and a minor peak at 100 km at temperate latitudes (McClure, 1964) and from 145 km to about 600 km in the auroral zone (Basler and DeWitt, 1962).

The amount of scintillation present is a function of the frequency of the received signal having a $1/f^2$ dependence for weak scattering in the near field and a 1/f dependence for strong scattering at longer wavelengths (Aarons, 1964).

There are varying opinions on the relationship between magnetic activity and scintillation. Liszka (1962a), observing in the auroral zone, notes a good correlation between satellite signal scintillation and magnetic activity on 54 Mc/s. In the subauroral zone a very small positive correlation was observed between the position of the southern boundary of the scintillation-producing region and magnetic activity (Yeh and Swenson, 1964; Aarons, *et al.*, 1963). This correlation indicates that as the magnetic activity increases this boundary may move southward. No correlation between radio star scintillation and magnetic activity is observed by Singleton (1964) at Boulder, Colorado.

Another area of interest is the observed relationship between scintillation and red auroral arcs. Tubes of 6300 Å emission have been observed by several writers to be oriented along magnetic isoclines with their maximum intensity occurring at about 400 km. The tubes are elliptical in shape and extend 400 km north and south of their center. Roach (1963) observed strong satellite scintillation when the satellite signal was propagated through a system of multiple 6300 Å red auroral arcs during a time of major magnetic activity on November 12 and 13, 1960. Yeh and Swenson (1964) have examined the correlation of satellite signal scintillation with 6300 Å arcs at Urbana, Illinois and have found that transition latitudes of scintillation agree well with the location of the red arcs as described by other authors. Three observations indicate that if the ionosphere is sufficiently disturbed, 6300 Å red auroral arcs and strong satellite scintillation may be simultaneously observed. These data seem to indicate that when the scintillation-producing mechanism becomes strong, red auroral arcs may be observed at the same time that strong scintillation occurs.

2. Statement of the Problem

This thesis will be concerned with the study and interpretation of scintillation statistics of satellite radio signals recorded at Urbana, Illinois.

II. PRELIMINARY DATA

1. Satellite Data

Some information concerning the satellites used in this study is given in Table 1. Explorer VII data were used from fall 1960 to summer 1961, and Transit 4A data were used from summer 1961 to winter 1962-1963. All these data were recorded at the University of Illinois, 40.069° north latitude and 88.225° west longitude.

Table 1. Pertinent Satellite Information

Satellite Name	Launch Date	Transmitting Frequency Mc/s	Apogee km	Perigee km	Inclination degrees
1959 Iota (Explorer VII)	October 13, 1959	20	1076	551	50.31
1961 Omicron (Transit 4A)	June 29, 1961	54	1002	877	66.81

2. Statistics of Data

The same definitions of season as used by Yeh and Swenson (1964) are used and appear as follows:

Spring, February 15 - May 15

Summer, May 15 - August 15

Fall, August 15 - November 15

Winter, November 15 - February 15

The number of passes recorded for each satellite is shown in Table 2.

Table 2. Number of Passes Recorded

20 Mc/s (1959 Iota)

Winter '59	Fall '60	Winter '60	Spring '61	Summer '61
53	113	39	13	4

54 Mc/s (1961 Omicron)

Summer '61	Fall '61	Winter '61	Spring '62	Summer '62	Fall '62	Winter '62
5	23	72	138	135	145	116

Due to the spin fading on 1959 Iota's signal, a purely quantitative scintillation index could not be determined and the method employed by Yeh and Swenson (1959) was used. This method uses indices of 0, 1 and 2 which were converted to percentages with an index of 2 being 100% scintillation. An example of this spin fading on 1959 Iota's 20 Mc/s signal is shown in Figure 1.

The 54 Mc/s signal from 1961 Omicron did not have spin fading superimposed on it so that a quantitative method of measuring the scintillation could be used. A sample pass having a transition in scintillation on 54 Mc/s is shown in Figure 2. The definition of scintillation index used on 54 Mc/s appears in the equation below where A_0 is the average value of the signal amplitude and ΔA is the fluctuation in the signal amplitude.

$$S = \left\langle \left(\frac{\Delta A}{A_0} \right)^2 \right\rangle^{1/2}$$

Here S is the square root of the ratio of the "noise power" to the average power.

An IBM 7094-1401 digital computer system was used to determine the satellite's position and the point at which the ray from the satellite to the observer passes through the ionosphere. An average height of 350 km was used for the ionosphere. The scintillation index read from the satellite pass record was then tabulated with the time of occurrence and the latitude of the subionospheric point. In this analysis of the data, the latitude of the subionospheric point was restricted to $\pm 10^{\circ}$ of the observation station in hopes of eliminating any elevation angle influence upon the scintillation observed. The plots made of scintillation index versus latitude, described later, show no elevation angle effect similar to that observed by Aarons (1964). This result does not mean that no elevation angle effect is present but that the latitude restriction of $\pm 10^{\circ}$ was probably successful in eliminating the influence of the elevation angle upon the scintillation index.

The average nighttime scintillation index was found by averaging the scintillation index over two-degree intervals of latitude for passes occurring between 6 p.m. and 6 a.m. This average was obtained for all seasons from fall 1960 to winter 1962 except for the season summer 1961 for which not enough data were available. A plot of these data as a function of latitude and season appears in Figure 3.

Since an hourly picture of the variation of scintillation was needed, Figures 4 through 7 were constructed. Again, two-degree increments of latitude were used. It was decided to find the average scintillation index over three-hour periods beginning at midnight which divided the day into eight three-hour intervals. These data were then plotted as a function of latitude and local time, showing contours of constant scintillation index.

Figures 8, 9, and 10 were plotted from spread F data and scintillation transition data and are discussed more fully in Chapter III.

In order to examine the relative frequency of occurrence of different types of scintillation, Table 3 was constructed.

Table 3. Scintillation Statistics

a) 1959 Iota (20 mc)

No scintillation in entire pass	41 %
S = 2 for entire pass	1
At least part of pass has S = 0	89
At least part of pass has S = 2	1
At least part of pass has scintillation	60
S = 1 or greater for entire pass	6
Transition observed from S = 0 to S = 1	12

b) 1961 Omicron (54 mc)

No scintillation for entire pass	54 %
$0 < S \leq .2$ for entire pass	0
$S > .2$ for entire pass	0
At least part of pass has S = 0	98
At least part of pass has $0 < S \leq .2$	34
At least part of pass has $S > .2$	34
Transitions from 0 to .2 or vice-versa	6

Comparing the 20 Mc/s data appearing here for the decaying portion of the sunspot cycle with a similar table of data for sunspot maximum (Yeh and Swenson, 1964), several points are worth mentioning. First, the percentage of passes having scintillation is relatively the same at sunspot maximum as it is in this table for 1961. Also, as sunspot activity decreases, these two tables show little change in the percentage of passes having no scintillation. This seems to indicate that there is little change in the frequency of occurrence of scintillation during the sunspot cycle. Examining these two tables again, a large change is observed in the percentage of passes exhibiting high indices of scintillation, S = 2, which suggests a significant decrease in the frequency of occurrence of large scintillations over the declining part of the sunspot cycle.

In summary, it may be inferred that a long-term decrease in sunspot activity appears to have little effect upon the presence or absence of scintillation while this decrease in sunspot activity may be responsible for the large decrease in the frequency of occurrence of large scintillations.

Returning to Table 3 and comparing parts (a) and (b), taking into account the difference in frequency of the satellite signals recorded, again little change is apparent in the percentage of records exhibiting no scintillation over the entire pass.

These observations and their implications will be more fully discussed in Chapter III.

III. EXPERIMENTAL RESULTS AND OBSERVATIONS

1. Diurnal Variations

One of the most easily observed characteristics of scintillation is its diurnal variation. Figures 4 through 6 show that there is a maximum in scintillation occurring at night and that the exact time at which this maximum occurs is dependent upon the observer's latitude. Figure 7, on the other hand, exhibits similar scintillation versus latitude characteristics for the periods 18-21, 21-24, and 12-15 hours, making it difficult to determine the time at which the maximum scintillation occurs.

This nighttime maximum always occurs near local midnight and to the north of the station. However, if the observation latitude of 40^{o} is chosen, the nighttime maximum occurs at this latitude at about 03-04 hours during winter 1959 and fall 1960 and near local midnight during spring 1962 and summer 1962. This observation is in fair agreement with other observers; (Liszka, 1963; Aarons, 1964; Booker, 1958; Dagg, 1957).

A daytime secondary maximum is sometimes present at 40^{o} north latitude, but the hour during the day at which this secondary maximum occurs is not the same for all seasons.

2. Seasonal Variations

The seasonal variations of nighttime scintillation can best be studied by using Figure 3. This figure is a continuation of a similar one, Figure 16, by Yeh and Swenson (1964) and permits the study of seasonal variations over the entire declining portion of the sunspot cycle.

From Figure 3 the season of maximum scintillation index is seen to change as the year advances and in fact seems to occur earlier each year so that in

1962 it occurs between spring and summer whereas it occurred in fall during 1959. The season of minimum scintillation precedes the season of maximum scintillation by about one season.

Aarons (1964) notes a maximum of scintillation during spring and summer and a minimum during the winter for 1961 on 54 Mc/s, while little or no seasonal variation was observed for 1949-1950 at Cambridge (Booker, 1958). Australian data show a maximum at the solstices and a minimum at the equinoxes (Booker, 1958).

There is therefore little agreement upon the variation of scintillation with season.

3. Sunspot Cycle Variations

Since Figure 3 contains nighttime scintillation data for the entire declining portion of the sunspot cycle, it is a simple matter to study the variation of scintillation with sunspot activity. This figure shows that the nighttime average scintillation falls off in magnitude as sunspot minimum is approached and that the variation of scintillation with latitude is seen to become less predictable.

The data for winter 1959-1960; fall 1960, spring 1962 and summer 1962 have been plotted in a similar form to that of Figure 3 except that local time now appears on the horizontal axis. This data appears in Figures 4-7 and represents the variation of scintillation index with local time and latitude for a particular season. From these figures the contours of constant scintillation index are seen to become more vertical as sunspot minimum is approached which indicates that the variation of scintillation with latitude becomes less pronounced.

The influence of sunspot activity upon the latitude of the scintillation-producing region is discussed more fully in the following section.

Other observers also note a decrease in average scintillation as sunspot minimum is approached (Yeh and Swenson, 1964; Aarons, 1964).

4. Latitude Variations

The latitude variations of scintillation as observed at Urbana, Illinois are quite pronounced and seem to be related to sunspot activity. From Figure 3 a strong latitude variation of scintillation index is evident. For latitudes above 38^{o}N the contours during sunspot maximum have a general parabolic shape while the contours below this latitude have no definite shape. During sunspot minimum, the above picture appears to be shifted northward and decreased in magnitude. From Figure 3 the scintillation index for latitudes south of 38^{o}N does not exhibit much change with changes in the sunspot number which suggests that this type of scintillation may be independent of sunspot activity.

Referring to Chapter II, the conclusions to the data appearing in Table 3 indicated that strong scintillation was dependent upon sunspot activity while weaker scintillation was not. The data appearing in Figure 3 supports this same conclusion and provides an additional piece of information, that during sunspot minimum stronger scintillations are still observed at Urbana but appear much farther north of this station than they did during sunspot maximum. Therefore, the variations of scintillation with sunspot activity and latitude may be somehow related.

These observations indicate that there may be two different causes for scintillation, one whose influence is strong during sunspot maximum and weaker during sunspot minimum and a second cause which is independent of sunspot activity and whose influence is observed at latitudes below some mid-northern latitude. These regions of strong and weak scintillation seem to be separated by a boundary which may be fairly sharp (Aarons, et al., 1964; Aarons, 1964; Munro, 1963). The characteristics of this boundary will be more fully discussed in section 5.

5. Spread F and Transitions in Scintillation

Over a period of 7 months during 1962 about 20 transitions from strong scintillation to no scintillation were observed on 54 Mc/s. These transitions are of the same type as described by Yeh and Swenson (1964) and occur in a very short time, usually less than 20 seconds. All 20 of these transitions occur within $\pm 5^{\circ}$ of the station at 40°N latitude and all except one showed scintillation to the north and no scintillation to the south. The location of these transitions and their sharpness are good evidence in support of the existence of the before-mentioned boundary region between strong and weak scintillation-producing regions.

In order to study the relation between scintillation and spread F, Figure 8 was constructed to show whether scintillations occurred at the same time that spread F was observed. Only enough ionograms were available to obtain 9 points. Assuming that scintillation and spread F are positively correlated and that the edge of the above-described boundary is smooth and parallel to a geomagnetic latitude line, this plot should then show no transitions with spread F north of 40°. However, Figure 8 shows as many transition points with spread F above the 40°N latitude line as transition points without spread F below this line.

Before any conclusions are drawn from Figure 8, other observers' results on the correlation between scintillation and spread F should be investigated.

Aarons (1964), Booker (1958) and Singleton (1964) all give evidence of a positive correlation between scintillation and spread-F, and Liszka (1962a) observes the same for 54 Mc/s in the auroral zone. If scintillation and spread F are correlated positively then some other explanation must be found for the data in Figure 8. A possible explanation is that the boundary is sharp but that its edge may be irregular and is not parallel to either the geographic latitude or geomagnetic latitude or the L-shell values. This type of boundary may appear as shown in Figures 9 and 10.

The small triangle in Figure 8 is the only point out of 20 that had strong scintillation to the south and no scintillation to the north. At the time of this transition, no spread F was observed at the ionosonde. The existence of scintillation south of this point is in disagreement with the average statistical behavior of stronger scintillation to the north.

6. Auroral and Subauroral Scintillation

Since there are some differences between scintillation occurring in the auroral and subauroral zones, a brief comparison will be made. The terms "auroral" and "subauroral" are used as defined by Bates (1960).

Diurnal variations of scintillation in the auroral zone are very small with a maximum occurring at local magnetic midnight and the seasonal variations are observed to be even less (Liszka, 1963a). In subauroral latitudes, strong diurnal variation is present and so is strong latitude variation which Frihagen and Trøim (1961) find little evidence of in the auroral zone. The height of the irregularities in the auroral zone is reported to range from 145 to 1000 km (Basler and DeWitt, 1962) while heights of the F region irregularities range from 320 to 430 km at a station of temperate latitude (McClure, 1964).

IV. THEORIES OF IRREGULARITY FORMATION

1. Corpuscular Bombardment Theory

The Corpuscular Bombardment Theory proposes that ionospheric irregularities are produced by precipitation of high-energy particles from the outer radiation belt which is the same process that causes the aurora at 100 km. Aarons, et al. (1963) show that curves of scintillation index versus latitude appear to move slightly equatorward when magnetic activity increases, and he feels that there may exist a curtain of irregularities having a boundary whose latitude is a function of magnetic activity, local time and other localized factors. This indicates that a station near the boundary would observe an increase in scintillation with an increase in magnetic activity whereas an auroral station might not observe any significant change in scintillation.

Scintillation and magnetic activity correlation at Urbana, Illinois has indicated that the influence of magnetic activity upon scintillation here is very small. However, the boundary described does exist at Urbana although no significant motion of this boundary has been observed. If this precipitation process causes scintillation and auroral activity, then there should be some correlation between these two phenomenon. The observed strong connection between red auroral arcs and scintillation is then in support of this theory.

2. Instabilities and Vertical Drift

D. F. Martyn (1959), in describing the normal F region, credits the formation of ionospheric irregularities to the unstable upward drift of a patch of ionozation on the undersurface of the F region moving under the influence of electrodynamic forces. The ionization is initiated near the E region by meteors or turbulence and is shown by simple equations to move upward along the geomagnetic field lines into the more dense F region.

If these irregularities cause both scintillation and spread F, then both phenomenon should occur at night since the ionization gradient of the undersurface of the F region is much steeper at night than during the day. The phenomenon should also occur at subauroral and auroral latitudes during times of magnetic activity since the F region has an upward velocity at this time which causes "amplification" of the small irregularities. Martyn also predicts scintillation and spread F in the equatorial zone in early evening at magnetically quiet times since the F region can be shown to have an upward velocity at these times also.

Martyn's experimental observations conform to his theoretical predictions. He observes that spread F and scintillation have a maximum at night and have the same diurnal variations at subauroral, auroral and equatorial latitudes.

Martyn's theory amply explains diurnal variations, but no explanation is given for the observed strong influence of solar activity on scintillation as is observed at Urbana. The strongest objection to this theory is that the majority of the irregularities are observed to occur above the F region peak. This theory predicts that the majority of the irregularities should occur on the undersurface of the F region.

3. Turbulence in the Dynamo Region

Dagg (1957) attributes the cause of the ionospheric irregularities to the conduction of dynamo region turbulence along magnetic field lines to the F region. The wind velocity in the dynamo region will determine the magnitude of the E field produced there which has as its equipotentials the magnetic field lines. There will be a transfer of turbulence from the dynamo region along these equipotentials to the F region where the two are closely coupled. This causes a turbulent component of velocity in the F region. The transferred turbulence produces eddies or patches of ionization which in turn cause scintillation.

Dagg shows that turbulent flow varies inversely with temperature gradient, thus explaining why scintillation is more often observed at night. The seasonal variations of scintillation may then be caused by a lower temperature gradient of the F region in winter than in summer. However, the ionization density in the dynamo and F regions are greater in summer than in winter and should offset the lower winter temperature gradient, thus causing a maximum of scintillation in summer. Magnetic activity is a secondary cause of scintillation, according to Dagg, which then accounts for the weak correlation between scintillation and magnetic activity.

Dagg's theory does not provide for the existence of the boundary observed between the region of strong scintillation and the region of weak scintillation. Also, no provision is made for the observed strong influence of solar activity on scintillation. The predicted diurnal variation of scintillation and weak correlation between scintillation and magnetic activity are observed at this station, however.

4. Magnetospheric Convection Theory

Axford and Hines (1961) have submitted the proposal that the cause of ionospheric irregularities may be due to the turbulence produced in the earth's magnetosphere by the impinging solar wind. There are two magnetospheric flow patterns occurring. One is due to the flow of the solar wind around the magnetosphere, and the second is the flow introduced by the earth's rotation and the consequent rotation of its atmosphere. These two flow patterns are combined and a resultant flow pattern found which when extrapolated down magnetic field lines to the earth's ionosphere produces a group of zones, one of which is turbulent and another which compresses this turbulence and conducts it to lower latitudes. This turbulent zone occurs on the morning side of the earth, and convection brings the turbulence to the night side of the earth and to lower latitudes.

The zone of convected turbulence is felt to be a cause of radio star and satellite scintillation as well as spread F. The theory predicts a nighttime maximum for scintillation and a positive correlation between scintillation and magnetic activity. Axford and Hines assume coincidence of the geographic and geomagnetic poles and predict that the above phenomenon should extend down to 60^{o} latitude. If the poles are considered in their correct position and a new flow pattern deduced, the new pattern may resemble the first one and would extend more southward at the geographic longitude line of the geomagnetic pole. It may then be possible for this flow pattern to influence ionospheric conditions at Urbana.

The theory provides an explanation for the observed boundary between the region of strong scintillation and the region of weaker scintillation. It is difficult to say whether this boundary exhibits any north-south motion and what the predicted seasonal variation of scintillation would be. Since the cause of these irregularities is directly traceable to the solar wind, a good explanation for the observed variation of scintillation with sunspot activity is available.

V. CONCLUSIONS

In this discussion several observations have been made that are worth restating.

There is apparently little agreement among authors as to what season a maximum in scintillation is observed. The variation of scintillation with latitude and with sunspot activity shows that the scintillation north of 40° is much less during sunspot minimum than it was during sunspot maximum, while the scintillation south of this latitude remained fairly constant. Consequently, there may be two causes for scintillation. Scintillation at northern latitudes might depend upon extra-terrestrial forces such as high energy particle precipitation as believed by Aarons, et al. (1963) or flow patterns produced by the solar wind as believed by Axford and Hines (1961). Low latitude scintillation may be caused by terrestrial forces which are not influenced greatly by sunspot activity such as turbulence as described by Dagg (1957). There also may be a boundary between these two regions as is suggested by transitions in scintillation.

In conclusion to the above suggested origins of ionospheric irregularities, it would be difficult to select one that would be accurate in predicting all the characteristics of scintillation and the observed positive or negative correlations of scintillation with other phenomenon. In fact, at the present there is considerable disagreement among authors over many of the characteristics mentioned and much further investigation of these characteristics at many locations is necessary before the main cause of scintillation can be determined.

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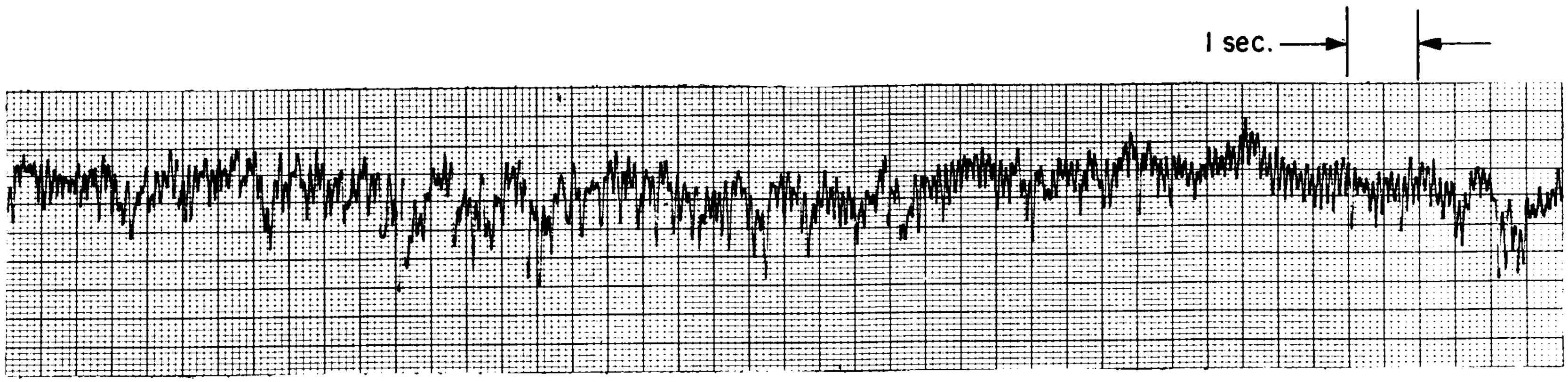

Figure 1. Sample record showing spin fading and scintillation on 20 Mc/s (1959 Iota, December 15, 1959 at 2011 CST).

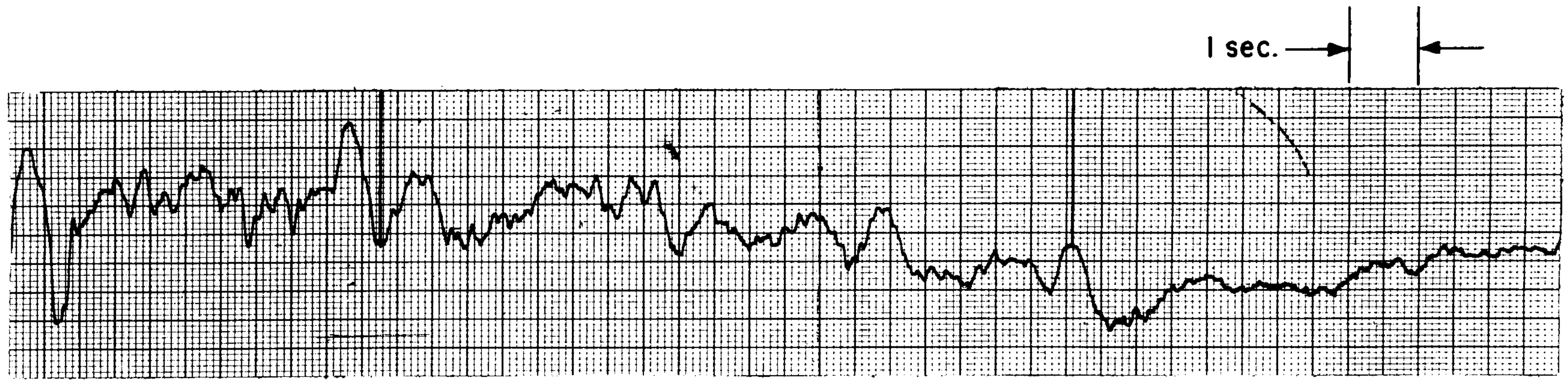

Figure 2. Sample record showing a transition in scintillation on 54 Mc/s (1961 Omicron, March 28, 1962 at 2343 CST).

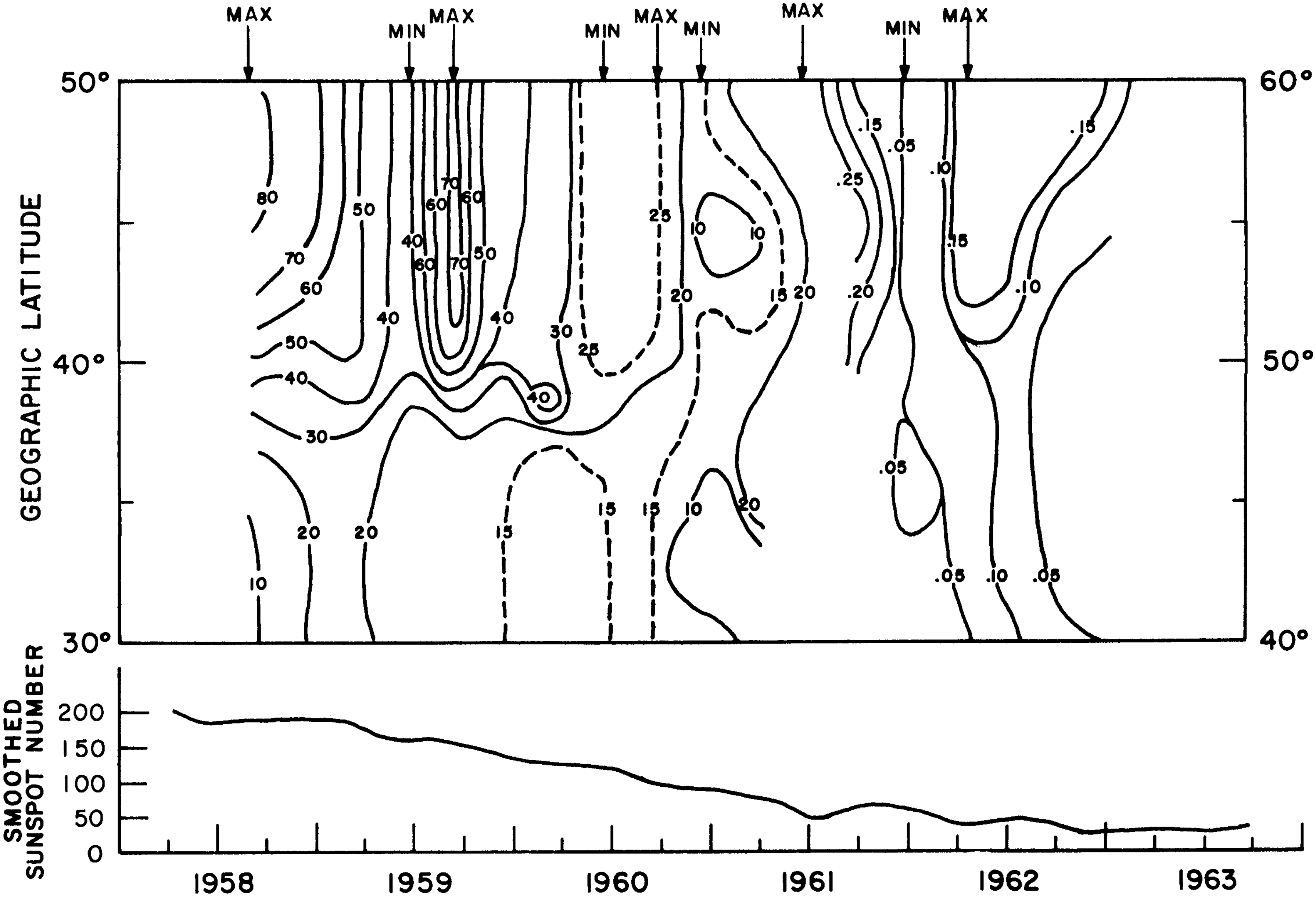

Figure 3. Contours of equal average scintillation on 20 Mc/s (percent) and on 54 Mc/s (scintillation index) near 88° W.

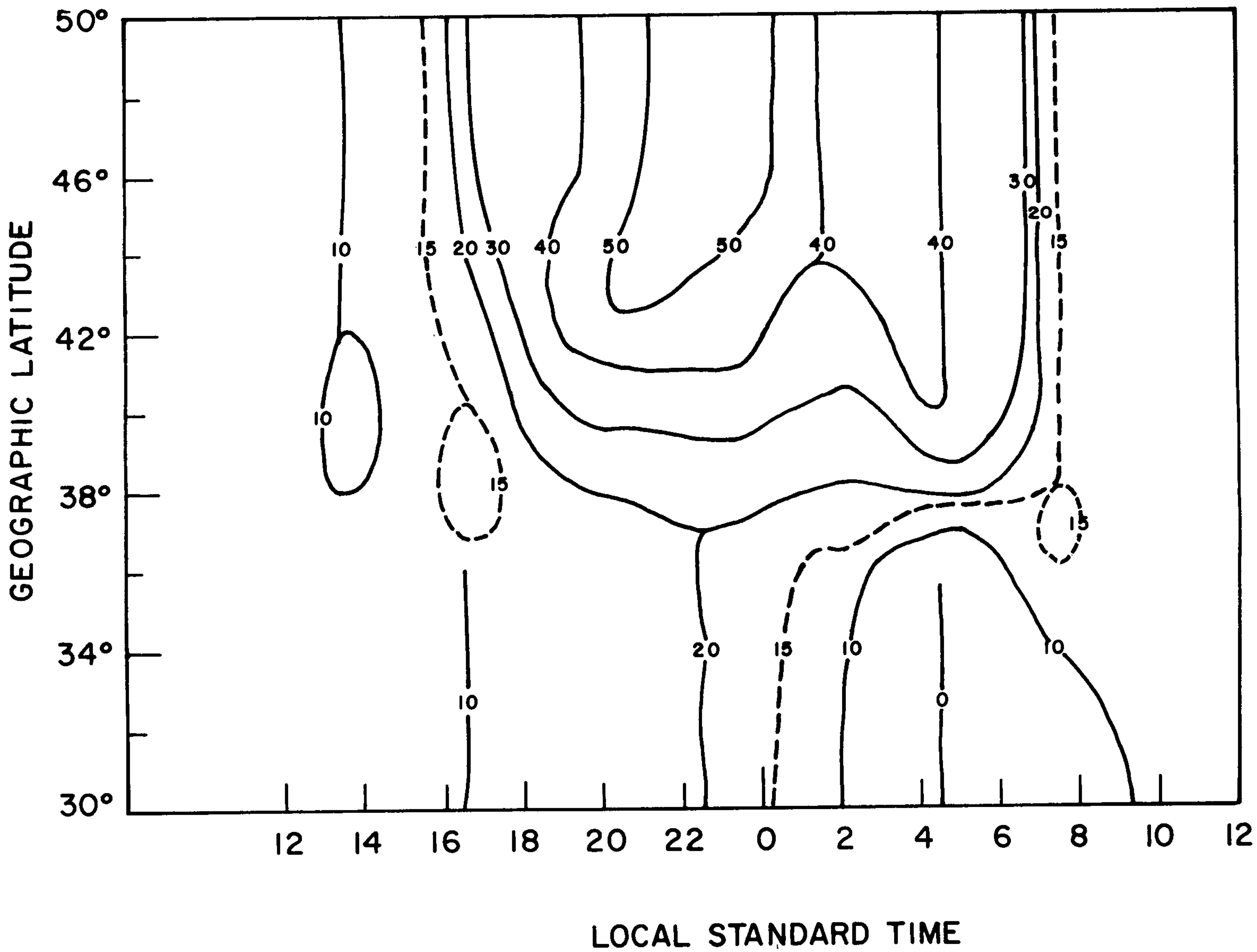

Figure 4. Contours of equal average scintillation on 20 Mc/s (percent) for Winter 1959.

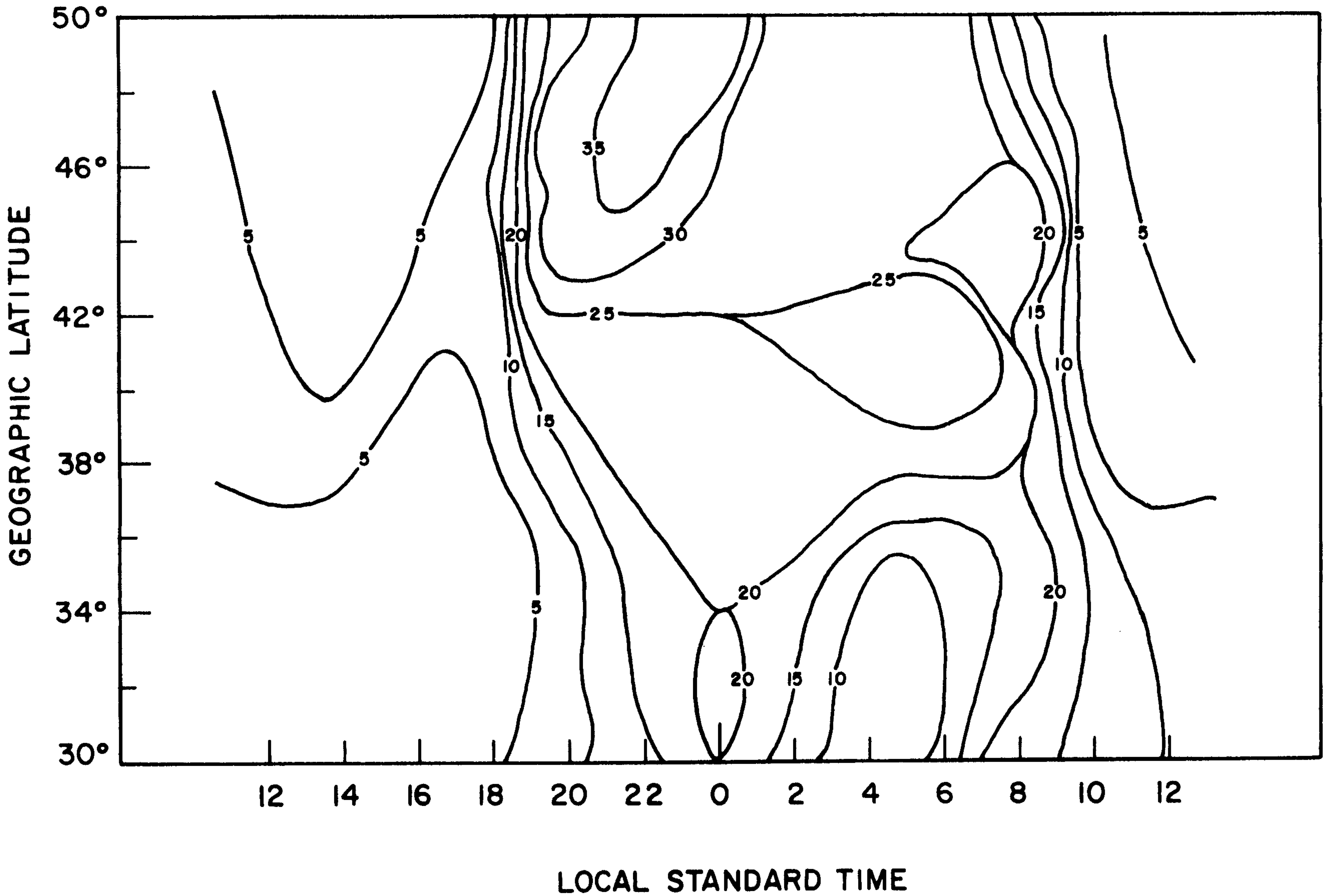

Figure 5. Contours of equal average scintillati on 20 Mc/s (percent) for Fall 1960.

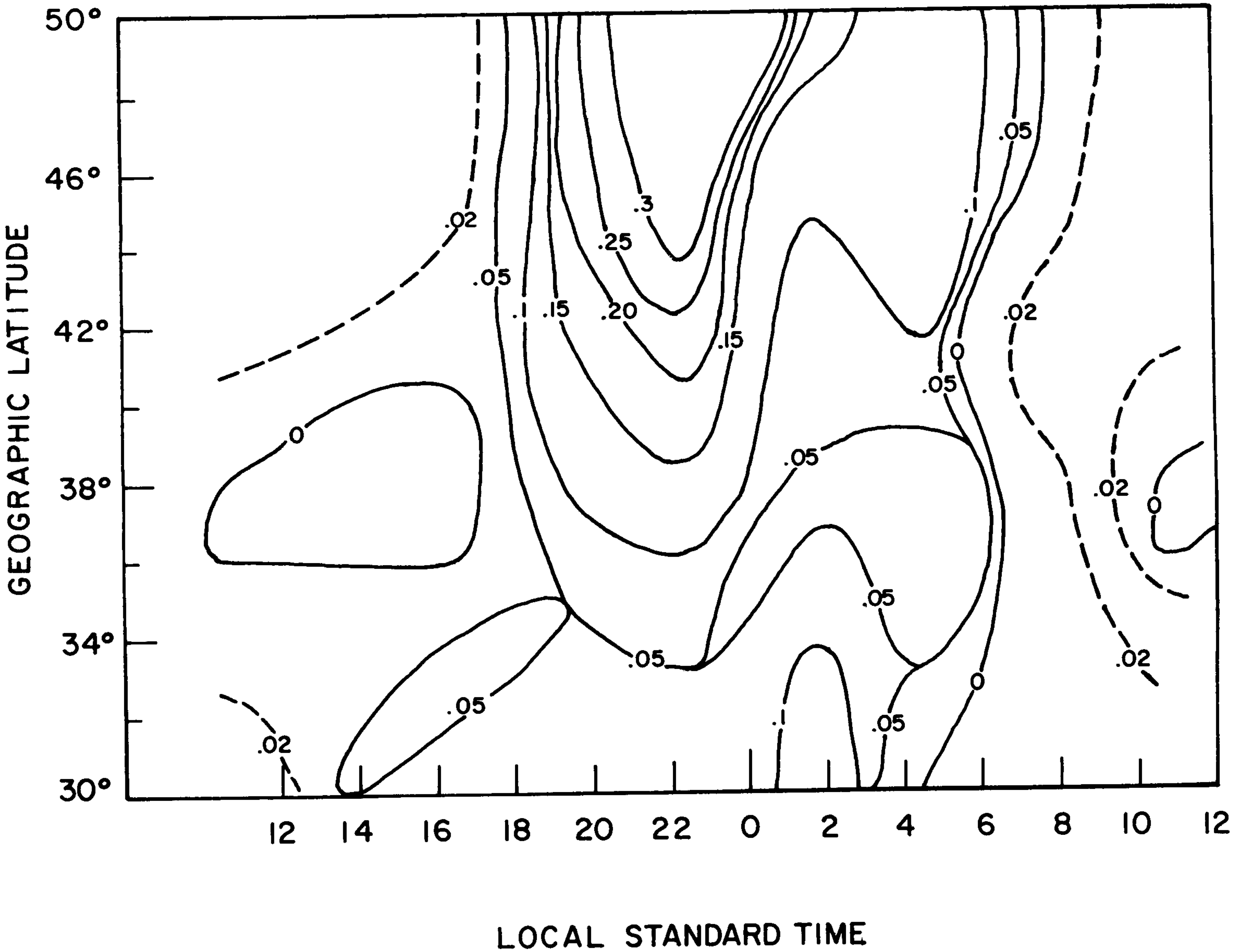

Figure 6. Contours of equal average scintillation index on 54 Mc/s for Spring 1962.

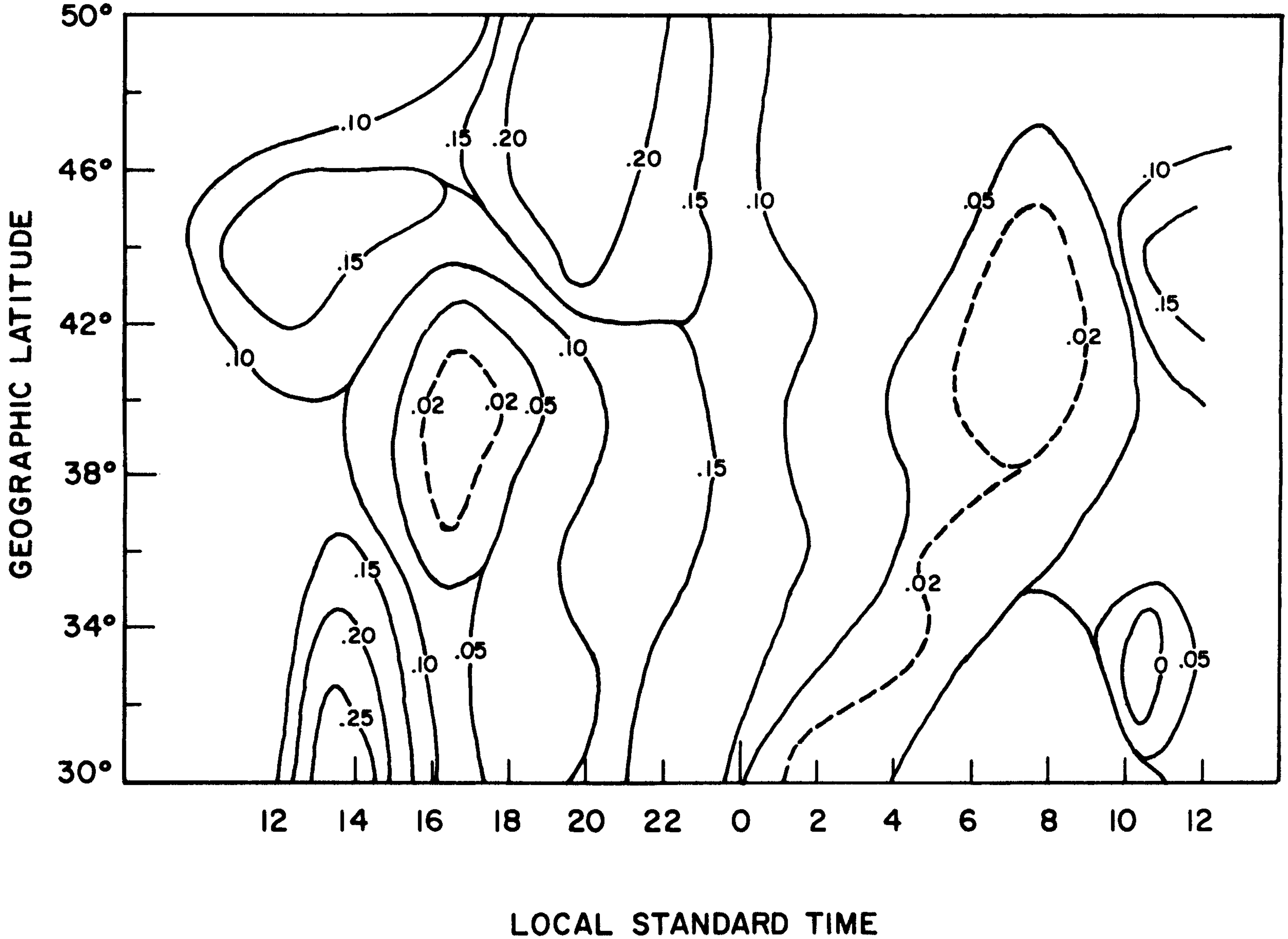

Figure 7. Contours of equal average scintillation index on 54 Mc/s for Summer 1962.

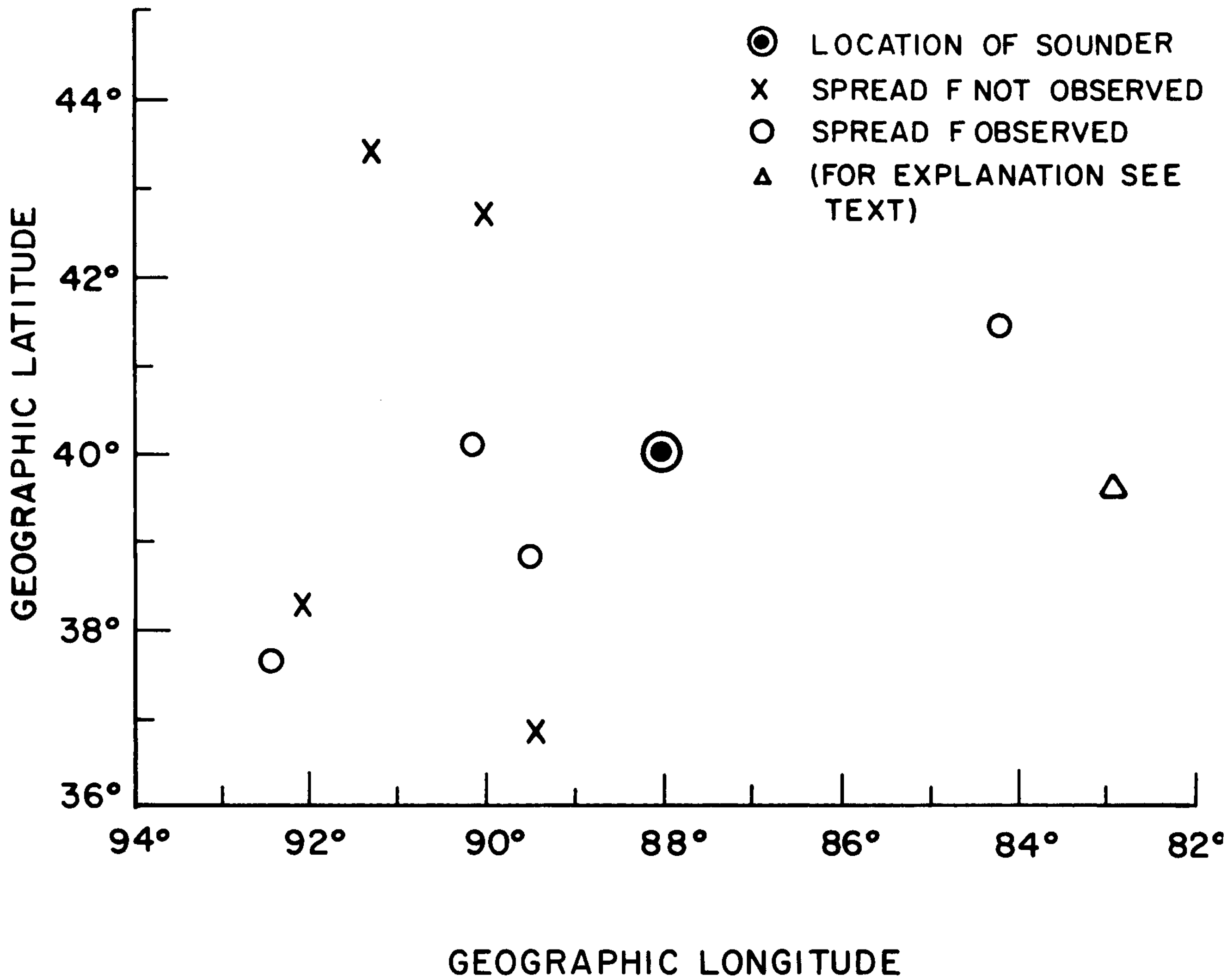

Figure 8. Transition points in scintillation on 54 Mc/s and simultaneous spread F data.

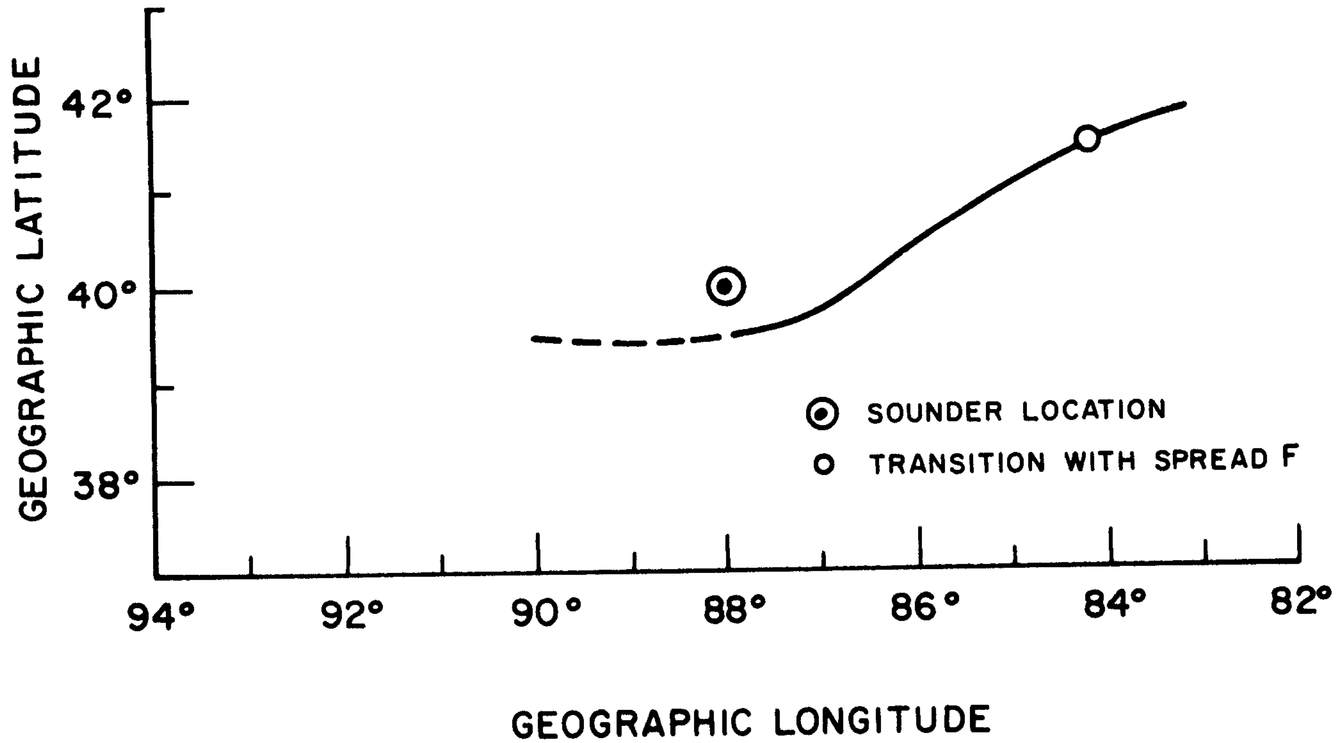

Figure 9. Possible scintillation boundary shape for a transition with spread F.

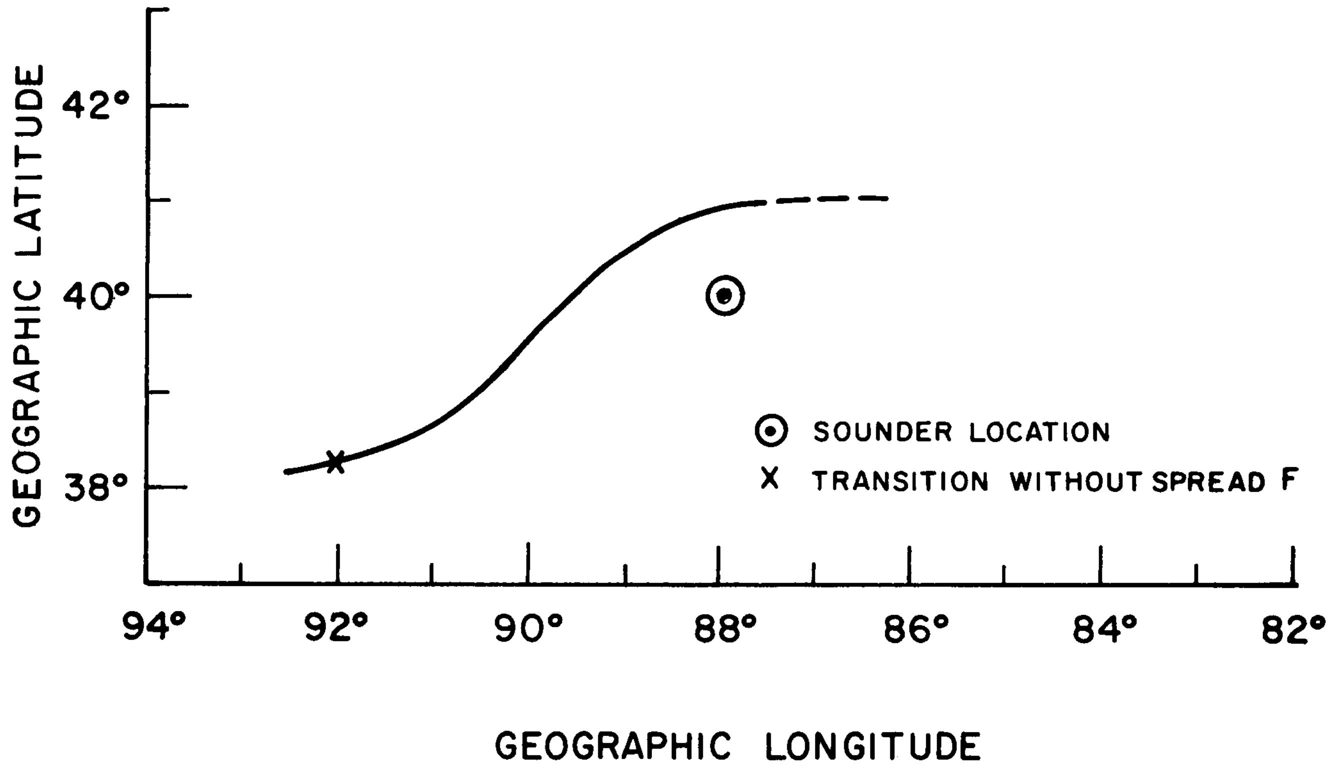

Figure 10. Possible scintillation boundary shape for a transition without spread F.