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Global Morphology of Ionospheric Scintillations II

JULES AARONS

11 March 1975

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Updating a review of the global morphology of ionospheric scintillations published in 1971, this study adds additional experimental studies on familiar topics to newer types of measurements of ionospheric irregularities, including in situ experiments and artificial heating of the F-layer.

In the geographic studies, equatorial observations have shown varying correlation with magnetic indices as a function of longitudinal region, of season, and of relationship to the midnight local time sector.

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At mid-latitudes there is little correlation with magnetic index.

At subauroral to auroral latitudes, radar skin tracking at 400 MHz at Millstone Hill has allowed a validation of the scintillation boundary. The general forms of the earlier version hold; there is a lowering of the boundary when magnetic index increases. Above the boundary there is increased scintillation at high latitudes during magnetic storms.

At high latitudes F-layer irregularities maximize above the 100-km optical aurora but decrease polewards of the aurora. Scintillations exist across the polar cap.

In situ measurements have shown good correlation with scintillation morphology. The parameters measured include clumping of thermal and suprathermal electrons, isotropic electric fields, and ion density measurements. Continuous measurements with these methods allow for more accurate models of global irregularities.

Artificial heating experiments have shown that irregularities can be produced at F-layer heights with scintillations observed on both radio star and satellite beacon sources.

There are gaps in our knowledge of morphology that call for more observations. The ATS-6 beacons will help in this area with 40-MHz signals sorting out the middle latitude variations and 360-MHz data needed for equatorial and auroral regions. Continuous measurements of quantitative nature at several sites should be made at 1-2 GHz to determine the extent of the equatorial irregularity region and its sunspot cycle variations. More creative experiments are needed to obtain the physics of the production, motion, and maintenance of irregularities at equatorial, mid-latitude, and high latitude regions. In each the physics may be significantly different.

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Global Morphology of Ionospheric Scintillations II

1. INTRODUCTION

The interest in the study of ionospheric irregularities at F-layer heights emanates from two directions. One is from the designer of systems in that portion of the spectrum which is affected by amplitude and phase fluctuations, that is, VHF to 1 GHz at high latitudes and VHF to S band at equatorial latitudes. The other area served by the study of ionospheric scintillations is that of the physics of magnetospheric-ionospheric interactions. For aeronomic studies, the recording of scintillations on beacon signals (and frequently measuring total electron content variations simultaneously) is one of the few ground methods of continuously observing changes in the ionosphere at F-layer heights during magnetic storms.

The irregularity structure during magnetically quiet nights is pictured in an updated version of a figure used earlier by the author and his collaborators in Figure 1. Since the density of hatching is an attempt to describe the depth of fading, it should be noted that equatorial scintillations are of greater intensity than high latitude effects. At high latitudes, present data indicate that the maximum intensity of scintillation occurs in the auroral oval, although irregularity intensity is high over the polar latitudes. The data base for polar scintillation statistics is sparse. Middle latitude scintillation is observed, but it is generally of lesser intensity than high or equatorial latitude fading.

(Received for publication 11 March 1975)

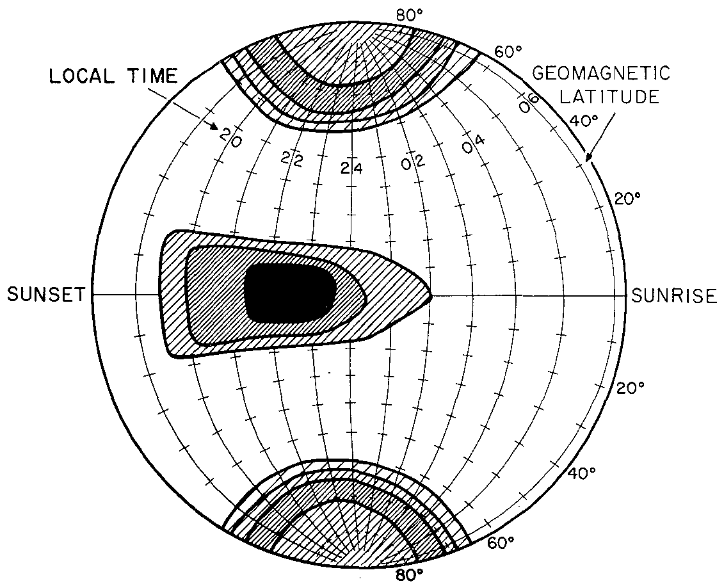

Figure 1. A Nighttime Picture of the Occurrence of Deep Fading. Equatorial scintillations show greater depth of fading than do scintillations observed at subauroral, auroral and polar latitudes. Daytime scintillations occur at high latitudes (<70°) but are low at equatorial latitudes

This review is intended as a follow-up of Global Morphology of Ionospheric Scintillations,[1] which will be referred to as Global Morphology I.

2. AMPLITUDE SCINTILLATION: A COMMON DATA BASE

Since the diffraction process takes the signal level above mean (undistorted) level, as well as below this level, the measurement is frequently described by an index indicating its deviation from mean.

One method of describing these excursions, adopted primarily because of the ease of reducing large numbers of paper charts of both low altitude and synchronous satellite observations is that adopted by AFCRL and the Joint Satellite Studies Group (JSSG)[2] and recently validated by a conversion into more accurate indices.[3]

1. Aarons, J., Whitney, H.E., and Allen, R.S. (1971) Global morphology of ionospheric scintillations, Proc. IEEE **59**:159.
2. Whitney, H.E., Aarons, J., Allen, R.S., and Seeman, D.R. (1973) Estimation of the cumulative amplitude probability distribution function of ionospheric scintillations, Radio Sci. **7**:1095.
3. Whitney, H.E. (1974) Notes on the Relationship of Scintillation Index to Probability Distributions and Their Uses for System Design, AFCRL-TR-74-0004.

Table 1 is a list of peak to peak excursions of signals in decibels, the (SI) scintillation index of AFCRL — JSSG, the S_4 index, and the Nakagami m values where

$$m = \frac{1}{S_4^{\ 2}}$$

Table 1. Conversion of dB Excursion to SI_{JSSG}, S_4 and Nakagami m Values

dB (peak to peak)	SI_{JSSG}	S_4	m
0.9	10	0.07	200.0
1.8	20	0.11	75.0
2.7	30	0.17	37.0
3.7	40	0.20	24.0
4.8	50	0.25	16.0
6.0	60	0.30	11.0
7.5	70	0.36	7.6
9.5	80	0.45	5.2
10.9	85	0.48	4.4
12.8	90	0.56	3.2
15.9	95	0.64	2.4

Treatments of the distributions, the relationship of signals to Gaussian, Nakagami, and log normal distributions are amply explored by Whitney et al,[2] Whitney,[3] Crane,[4] and Rino et al.[5] They will not be covered by this review.

The use of a common index and distribution analysis allows a frequency dependence to be obtained (Whitney et al,[2] Crane,[4] and Rufenach[6]). Thus a common data base is possible if the signals are only weakly scattered.

The consensus is that the distribution of ionospheric scintillations fits closer to Gaussian (and Nakagami) statistics than to log normal distributions. Although the evidence from scintillations produced by interplanetary irregularities

4. Crane, R.K. (1974) Morphology of Ionospheric Scintillation, Technical Note, Lincoln Laboratory, 1974-29, Air Force Contract F19628-73-C-0002.

5. Rino, C.L., Livingston, R.C., and Whitney, H.E. (1974) Some New Results on the Statistics of Radio Wave Scintillations. A. Empirical Evidence for Gaussian Statistics (to be published).

6. Rufenach, C.L. (1974) Wavelength dependence on radio scintillation: ionosphere and interplanetary irregularity, J. Geophys. Res. 79:1562.

in the literature differs from this result, Fremouw and Rino[7,5] have reevaluated these earlier analyses.

3. EQUATORIAL SCINTILLATIONS

3.1 Microwave Observations

Further exploration of the COMSAT data[8] at 4 GHz and 6 GHz indicates that the width of the equatorial irregularity region is plus and minus 20°. This is obtained by noting the latitudes of the stations given in Taur's Figure 16. Some studies indicate that the intensity of the scintillation may not be reduced at the high latitude boundaries of the equatorial region, but the duration of the scintillation may be shortened. Little data is available for determining the extent of the region at this time except for that at 40 MHz, as noted in Global Morphology I.

Reports from COMSAT stations[9] indicate that microwave scintillations at the equator decreased in occurrence during the time period 1972-1973 correlating with the decrease in sunspot number.

Wavelength dependence of the 4 to 6 GHz data is in dispute, but it appears likely at this writing that with weak scattering the wavelength dependence (equivalent to $\sim\lambda^{1.5}$) found by Whitney et al,[2] (using subauroral data with some strongly scattered samples) approximates weakly scattered signals in general.[4]

Some data has been forthcoming at L band. Transmissions from ATS-5 are the source of the recordings with simultaneous 137-MHz observations being made in Peru. Data taken over 48 days showed that on 28 days L-band scintillations of magnitude greater than 1 dB were observed. Peak to peak swings of L-band scintillation as large as 6 dB and VHF fades as large as 27 dB were observed.[10]

Christiansen[11] reported fading greater than 15 dB at 2200 MHz from the ALSEP Mission.

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7. Fremouw, E.J., and Rino, C.L. (1974) in AGARDograph on Electromagnetic Noise Interference and Compatibility, AGARD, Paris, France.
8. Taur, R.R. (1973) Ionospheric scintillation at 4 and 6 GHz, Comsat Tech. Rev. 3:145.
9. Taur, R.R. (1975) Personal communication.
10. Sessions, W.B. (1972) Amplitude Fading of Simultaneous Transionospheric L-band and VHF Signals Received at the Geomagnetic Equator, Goddard Space Flight Center, Greenbelt, Md.
11. Christiansen, R.M. (1971) Preliminary Report of S Band Propagation Disturbance During ALSEP Mission Support, Goddard Space Flight Center, NASA Z861-71-239.

3.2 Dependence on Magnetic Activity

Data from Huancayo, Peru, when analyzed over a long period has shown as a gross statistic little magnetic dependence. New results at 254 MHz are shown in Figure 2.[12] The diurnal occurrence of scintillations in both quiet and disturbed periods for the 575 days analyzed, clearly peaks before midnight and shows similar occurrence statistics. The occurrence of deep fading showed a second increase, that is, after midnight during magnetically disturbed days.

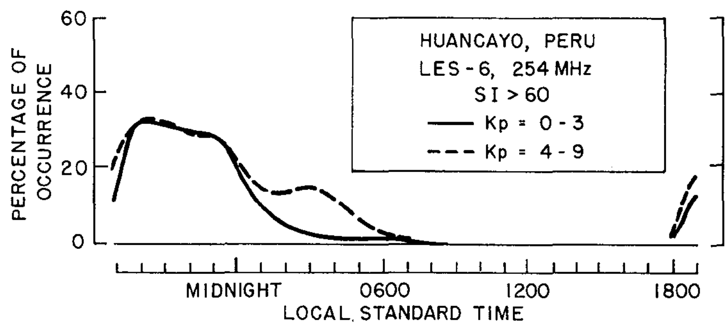

Figure 2. The Occurrence of Fading at Huancayo, Peru. Fading does not vary significantly in the premidnight time period as a function of K index. During magnetic storms an increase in index is seen in the postmidnight period

Koster[13] clearly showed that scintillation is frequently inhibited during large magnetic disturbances at Accra, Ghana. However, for Huancayo, Mullen and Whitney,[14] and Mullen[15] have sorted out the magnetic index dependence of these data. During the months of May, June, and July, an increase of K index produces increased levels of SI. During the months of August, September, and October, there is little dependence of SI on magnetic index before midnight, but after midnight an increasing Kp correlates with an increasing SI. In other seasons both before and after midnight, increasing Kp is correlated with increasing SI. Similar results are not seen in Accra where SI and Kp are inversely correlated even during the same months analyzed by Mullen and Whitney.

12. Bushby, A., and Aarons, J. (1974) Personal communication.
13. Koster, J. R. (1972) Equatorial scintillation, Planet. Space Sci. 20:1999.
14. Mullen, J., and Whitney, H. E. (1974) Equatorial Scintillation Measurements Using the LES-6 and ATS-3 Satellite Beacons, Joint Satellite Studies Group Report 51, C. N. E. T., Lannion, France.
15. Mullen, J. P. (1973) Sensitivity of equatorial scintillation to magnetic activity, J. Atmos. Terr. Phys. 35:1187.

3.3 Seasonal Pattern

The seasonal pattern can be noted by a long series of observations of ATS-3 at Huancayo,[16] as shown in Figure 3. Maxima are noted in the equinoxes, but the November to January amplitudes in some years are only slightly lower than the equinoctial occurrence.

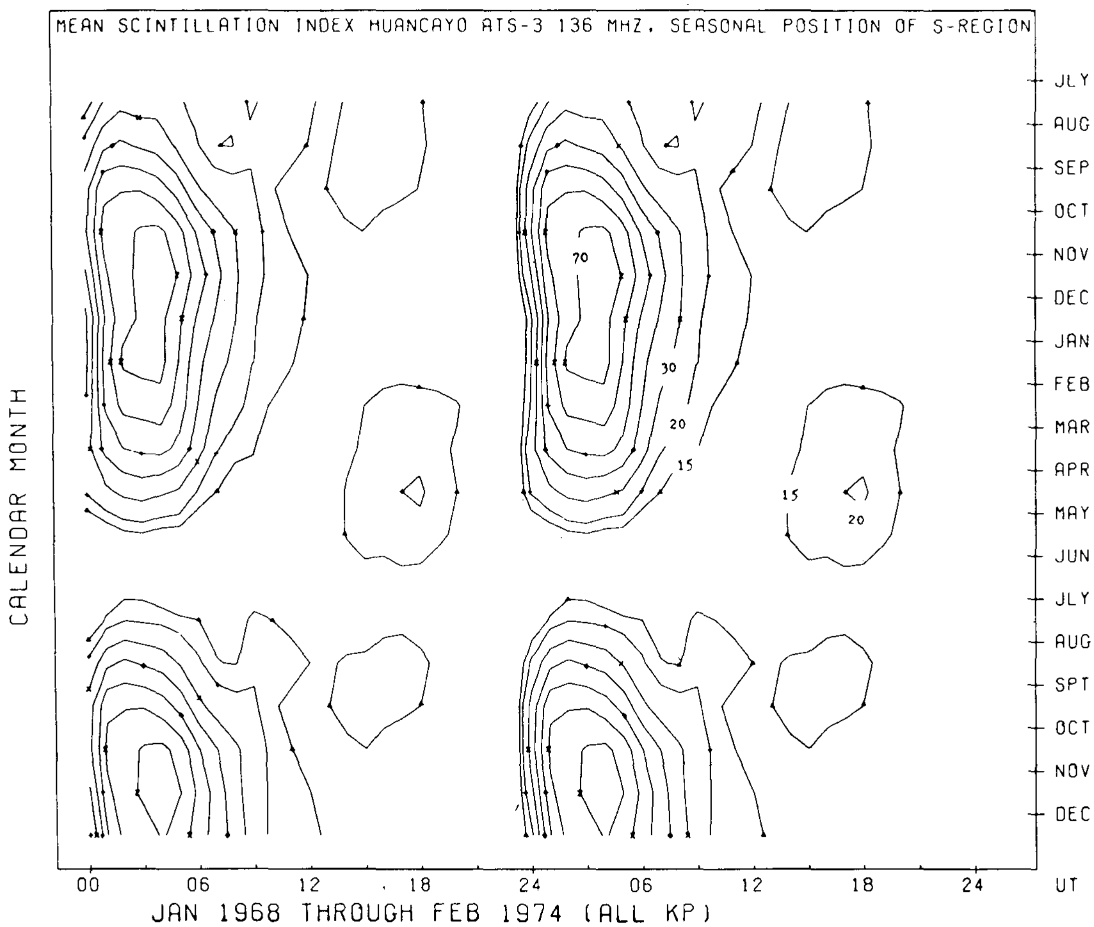

Figure 3. Scintillation Contours at 136 MHz for 6 Years Data from Huancayo, Peru. Some daytime scintillations are observed in the March to May period and in August to October. The local time of the observations is approximately 5 hours less than the UT shown (05 UT is midnight LST). [After G. Hawkins and J. Mullen (1974).]

16. Hawkins, G., and Mullen, J. (1974) Daytime Equatorial Scintillations in VHF Trans-ionospheric Radio Wave Propagation from ATS-3 at Huancayo, Peru, URSI, Boulder, Co.

It should be noted that Taur[8] clearly found maxima in February, March, and April and in September, October, and November. The VHF data may be showing high occurrence during the northern summer solstice months due to the saturation effect of the receiving setup where relatively low signal-to-noise levels for VHF instrumentation lead to periods when signals fade close to noise levels. Scintillation indices are difficult to evaluate accurately with these signal levels. Nichols[17] found the seasonal pattern and distribution of 254-MHz fades shown in Figure 4, with data for Kwajalein pointing up the varying longitudinal patterns as noted in Global Morphology I.

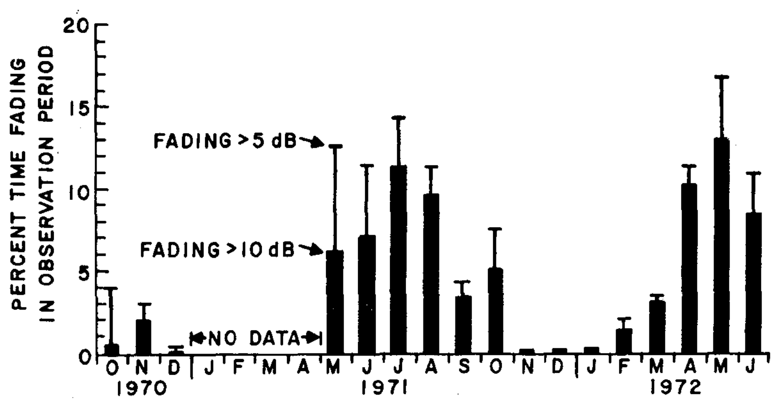

Figure 4. Fading on 254 MHz as Observed at Kwajalein. Maximum scintillation occurs from April to October. [After B.E. Nichols (1974)]

3.4 The Physics

By analyzing observational material on microwave scintillations, Wernik and Liu[18] have found that a thick irregularity slab of the order of 200 km with electron density fluctuation of 20 percent of the background value may account for the S_4 values found as well as the frequency dependence noted on 4- and 6-GHz signals.

In searching for an understanding of the mechanism for the generation of equatorial irregularities, Koster[13] found scintillation associated with a rapid

17. Nichols, B.E. (1974) UHF Fading from a Synchronous Satellite Observed at Kwajelein, October 1970 through June 1970, Tech. Note, Lincoln Laboratory, 1974-19, Air Force Contract F19628-73-C-0002.

18. Wernik, A.W., and Liu, C.H. (1974) Ionospheric irregularities causing scintillation of GHz frequency radio signals, J.Atmos.Terr.Phys. 36:871.

fall of Faraday phase angle around 1900 LT. Koster and Beer[19] have suggested that since the onset of the first stage in the production of the irregularities takes place after the ionosphere has started to descend, the vertical and horizontal components of the ionization's velocity, respectively, match the vertical and horizontal phase velocities of an atmospheric gravity wave. The latter is manifested by a wavelike perturbation in the neutral gas density. More and more collisions between charged and neutral particles take place, and charged particles are swept into the ionization peak. The irregularity will continue to increase until the system is unstable; the irregularity is then fully formed. Thus the irregularities with sizes ranging from 3 m to several kilometers are contained in the larger gravity wave sizes of the order of 1000 to 10,000 km.

4. MIDDLE AND SUBAURORAL LATITUDE VARIATIONS

At latitudes below the auroral oval's position during both magnetically quiet and disturbed periods, various sets of data have yielded behavior indicating little correlation with magnetic conditions. Wand and Evans[20] found no correlation of their 400-MHz radar return scintillations with magnetic index south of their station at 56° invariant latitude. Aarons and Martin[21] found that during the August 4-10 1972 magnetic storms there was a negative correlation of scintillation and magnetic index for Athens, Greece and Camp Parks, California and little correlation for the 45° intersection of Aberystwyth, Wales. Bramley[22] found that except for the December 1971 magnetic storm (when the irregularity region probably encompassed the intersection point of ~45°), there was no correlation between magnetic activity and scintillations.

This type of data essentially corroborates the early radio star observations in the U. K. which found little correlation with magnetic index except in paths to the north (with the exception of some intense magnetic storms).

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19. Koster, J.R., and Beer, T. (1972) Ionospheric Research Using Satellites; an Interpretation of Ionospheric Faraday Rotation Observations at the Equator, Final Scientific Report, University of Ghana, Air Force Contract F61052-70-C-0004.

20. Wand, R.H., and Evans, J.V. (1975) Morphology of ionospheric scintillation in the auroral zone, Preprints of Proceedings of the 1975 Symposium on the Effect of the Ionosphere on Space Systems and Communications, Sec. 2.1, Naval Research Laboratory, Washington, D.C.

21. Aarons, J., and Martin, E., The effects of the August 1972 magnetic storm on ionospheric scintillations, Radio Sci., in press.

22. Bramley, E.N. (1974) Fluctuations in direction and amplitude of 136-MHz signals from a geostationary satellite, J. Atmos. Terr. Phys. **36**:1503.

For the middle latitude region, the scintillation indices are low although there are high values reported at times. The diurnal pattern of weak scintillation shows little increase at night.[23] Some persistence of patches which recur or remain for two to three days running has been shown by Albrecht.[24]

5. HIGH LATITUDE IRREGULARITIES

It is now clear that the high latitude F-layer irregularity structure has similarities with the morphology of the lower altitude aurora -- and differences. The irregularity region descends to its lowest latitude at night and moves close to the invariant latitude occupied by the aurora in the daytime sector. Its differences are that a detectable and significant fading can be observed equatorwards of the optical aurora and that the irregularities are intense in the polar regions. During magnetic storms, in a manner similar to the aurora the irregularity region moves equatorwards of its quiet day position and, in addition, the irregularities gain in intensity.

5.1 Models

As summarized by Pope,[25] the model developed in Fremouw and Rino[26] considered several geographic regions separately. These regions are the equatorial (± 20° geomagnetic), the mid-latitude (20-60°), the high latitude (>60°) and the auroral regions (~65°-70°). Suitable mathematical functional relations were assumed for each. Data pertaining to these regions were selected according to the weak scatter criterion that the phase shift introduced by the irregularities was less than 0.7 radian; these data were used to infer the appropriate coefficients. Pope[25] made modifications to the high latitude term of the model and provided for variations in the position of the scintillation boundary with respect to magnetic activity. Another modification was made to represent the finding that the northern and southern polar regions of the scintillation activity are not symmetrical with the southern hemisphere boundary at higher invariant latitudes than the northern boundary (by about 4° in Pope's modification of the model).

23. Bramley, E.N. (1974) Private communication.

24. Albrecht, H.J., Piening, M., and Rosenback, K. (1974) Long apparent persistence of ionospheric scintillations in polar and equatorial regions of marginal satellite visibility, J.Atmos.Terr.Phys. 36:1527.

25. Pope, J.H. (1974) High latitude ionospheric irregularity model, Radio Sci. 9:675.

26. Fremouw, E.J., and Rino, C.L. (1973) An empirical model for average F-layer scintillation at VHF/UHF, Radio Sci. 8:213.

5.2 Radar Observations

Using 400-MHz radar signals obtained from skin tracking of satellites, Evans[20] made a recent series of measurements at Millstone Hill, Massachusetts. He identified a scintillation boundary, using the S_4 value of 0.04 as the criterion as to whether the entry into the high latitude irregularity region had been reached. His results were similar to those of Aarons and Allen[1] in that the lowest latitude of 57° was reached before midnight for this region.

He found that the probability of observing large scintillations increased during magnetically disturbed periods. The highest scintillation indices ($S_4 \rightarrow 1.0$ and transverse angle scintillations $\sigma_{TR} \geq 20$ m deg) were largely confined to periods when magnetic storms were in progress, including some in the daytime.

Evans found the amplitude during scintillation most closely followed a Nakagami m distribution with a Rayleigh distribution obtained for $m = 1$.

The mean scintillation index as a function of invariant latitude varied with magnetic activity. At latitudes above 53°, a higher Kp is associated with increased scintillation, while below 53° there is a small decrease in scintillation with increasing Kp. The prediction of mean scintillation index from the model proposed by Fremouw and Rino[26] was considerably lower than that observed at Millstone, probably due to problems of extrapolating 40 to 100 MHz data, some with effects of strong scattering, to the 400-MHz frequency.

5.3 The Scintillation Boundary and the Trough

It was clear from earlier work that there were similarities between the electron density trough and the scintillation boundary. Both descended during the night and both moved equatorwards during magnetic storms. However, Aarons and Allen[1] had pointed out several differences between the positions and behavior of the two lines. Kersley et al[27] found the scintillation boundary in general approximately one degree equatorwards of the trough minimum between 1700 and 0130 hours, but after 0200 the positions were reversed until at 0700 the abrupt scintillation boundary was on average some three degrees poleward of the trough minimum. New analyses by Kersley and Van Eyken[28] found that the trough latitude decreases from 1700 to 2000 with a possible very slow decrease to a minimum at 0600 followed by a rapid increase. Few troughs in total electron content were detected in the afternoon sector. The dependence on magnetic activity of

27. Kersley, L., Jenkins, D.B., and Edwards, K.J. (1972) Relative movements of midlatitude trough and scintillation boundary, Nature **239**:11.

28. Kersley, L., and VanEyken, A. (1974) Joint Satellite Studies Group Report 51, C.N.E.T., Lannion, France.

the trough is irregular, whereas they found the scintillation boundary dependence on changing levels of magnetic activity more highly correlated.

Wand and Evans[20] by measuring total electron content using the Transit NNSS satellites found that there was no set spatial relationship between the position of the scintillation boundary and that of the trough when studied on a case by case basis. Statistically there were distinct differences as well.

McClure[29] found that the poleward edge of the trough of ionospheric ions is almost always associated with the onset of soft auroral electron fluxes and large amplitude irregularities in N_i. He also found large amplitude auroral irregularities of ions near the dayside cusp related to fluxes of soft electrons (< 300 eV).

5.4 The Auroral Oval

5.4.1 NIGHT

The outlines of the intensity variations within the irregularity region are clear. At night during periods of magnetic quiet, scintillation index increases several fold from the boundary to the latitudes of the position of the optical auroral oval. Maximum index is recorded when the path traverses the auroral oval. A shallow minimum is then encountered with a second peak located near the corrected geomagnetic pole.[30] Frihagen's[31] data indicated a small trough poleward of the auroral oval. Higher magnetic indices increase intensity levels across the entire irregularity region (Figure 5) as well as lower the boundary between the ordered F layer and the F layer encrusted with small scale irregularities.

One example that can be readily noted is that taken from the August 1972 magnetic storms. Figure 6a is a composite of data from the period August 3 to 10 when K indices were 5 or greater.[21] Quiet day contours of scintillation index are taken at 136 MHz (Figure 6b) while disturbed period indices are taken at 254 MHz (this presentation is used in order to reduce the effects of fading "saturation" shown at times when fading reaches levels indistinguishable from noise). Hawkins[32] has shown that from one to two days after the onset of a period of magnetic quiet (Ap ≤ 2) scintillations disappear in the 50° to 65° invariant latitude range.

29. McClure, J.P. (1973) Final Report for Contract NAS 5-23184, Goddard Space Flight Center.

30. Nielsen, E., and Aarons, J. (1974) Satellite scintillation observations over the northern high latitude regions, J. Atmos. Terr. Phys. 36:159.

31. Frihagen, J. (1971) Occurrence of high latitude ionospheric irregularities giving rise to satellite scintillation, J. Atmos. Terr. Phys. 33:21.

32. Hawkins, G. (1974) Ionospheric Electron Content and Radio Scintillations During Magnetospherically Quiet Periods, AFCRL-TR-74-0160.

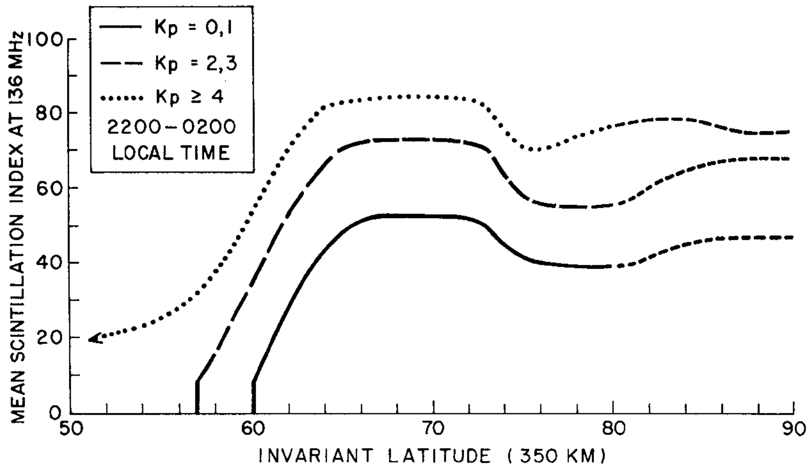

Figure 5. Idealized Mean Scintillation Index as a Function of Latitude and Various Magnetic Sets for the Midnight Local Time Period. Scintillation index increases and the boundary moves equatorwards with higher magnetic activity. Maximum index is noted over the auroral oval

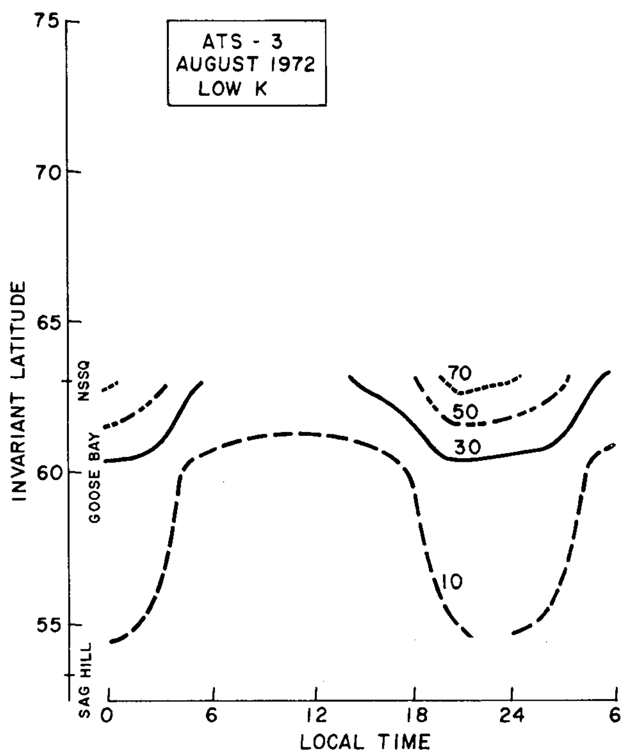

Figure 6a. Contours of Scintillation Index at 136 MHz in August 1972 During Periods of Low Magnetic Activity

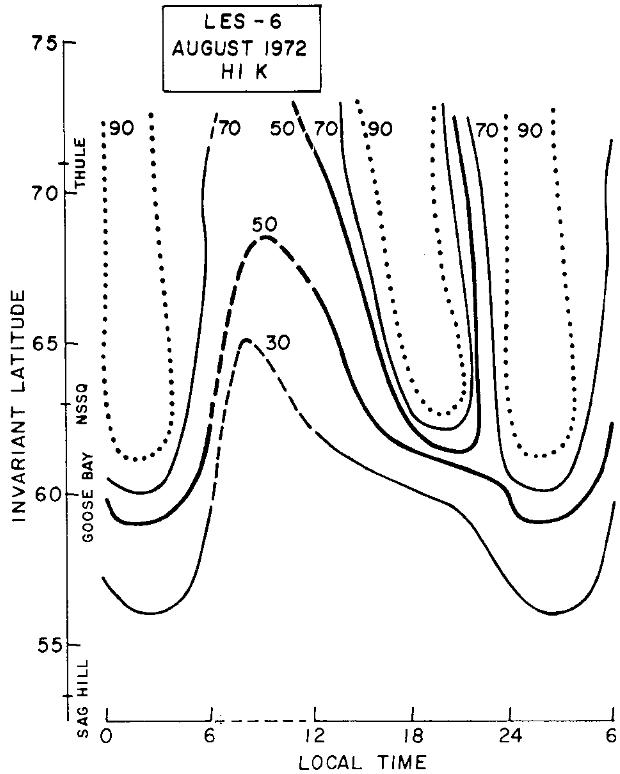

Figure 6b. Contours of Scintillation Index as Taken at Four Stations During the Magnetic Storms of August 1972. Frequency of Observations is 254 MHz

5.4.2 DAY

The daytime boundary is located between 71° and 76° for very low K indices (K = 0, 1) and 68° - 69° for K = 2, 3. Increased magnetic activity brings higher levels of scintillations throughout the region for some magnetic storms. In a study of the magnetic storms of 1972, only a few storms showed high scintillation indices at 136 MHz during the day at latitudes of 53° invariant.

Some new data are being studied which indicate that the cusp region about noon shows an unusually high occurrence of scintillation.

5.4.3 POLAR SCINTILLATIONS

There is clearly from in situ irregularity measurements, from spread F data, and from scintillation studies no polar cap cavity. The spread F measurements indicated a permanent maximum.[33] The in situ measurements of isotropic

33. Penndorf, R. (1962) Geographic distribution of spread F in the Arctic, J. Geophys. Res. 67:2279.

electric fields indicated a decrease in intensity over the dayside polar regions relative to the auroral oval measurements.[34] Nielsen and Aarons[30] using both 40-MHz and 150-MHz observations from Thule found high scintillations over the geomagnetic pole, even allowing for increases in scintillation index due to aspect sensitivity. The diurnal pattern over high latitudes differed from those at other latitudes; however, only brief periods of observation were available from this study.

The field of polar scintillation studies is relatively unexplored. The 40-MHz observations show both multiple scattering effects and saturation of fading. Frequencies of the range of 136 to 400 MHz are needed; the DNA satellite with its unmodulated beacons will, it is hoped, aid in the determination of the polar cap scintillation morphology.

6. IN SITU MEASUREMENTS

Perhaps the largest contribution to new measurements of global morphology of irregularities in the period between 1970 and 1974 comes from the in situ measurements of various ionospheric parameters. These include electric fields, thermal electrons, suprathermal electrons, and ion density measurements.

Correlating in situ measurements with scintillations can only be done with several caveats. In situ measurements give no indication of thickness, an effect of importance on scintillation excursions.[35] In situ measurements are frequently higher in altitude than the 350-km level found to be the predominant height of the (often) thin layer irregularities. In situ measurements unless configured carefully do not show the effects of irregularity elongation, field alignment or zenith angle. More basically, however, in situ measurements may measure the causal element for the production of the irregularities (suprathermal electrons), for example; therefore the ambient atmosphere must be taken into consideration.

One series of significant measurements were obtained with an electrostatic probe on ISIS-1; thermal positive ion observations were made.[36] A spatial resolution of 150 meters was possible. The equatorial boundary of the irregularity

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34. Kelley, M.C., and Mozer, F.S. (1972) A satellite survey of vector electric fields in the ionosphere at frequencies of 10 to 500 hertz. 1. Isotropic, high latitude electrostatic emissions, J. Geophys. Res. 77:4158.

35. Singleton, D.C. (1974) The dependence of high-latitude ionospheric scintillations on zenith angle and azimuth, J. Atmos. Terr. Phys. 36:113.

36. Sagalyn, R.C., Smiddy, M., and Ahmed, M. (1974) High latitude irregularities in the top side ionosphere based on ISIS-1 thermal ion probe data, J. Geophys. Res. 79:4252.

region was defined as the latitude of onset of persistent small scale ionization irregularities extending over at least a few degrees in latitude with amplitudes amounting to 20 percent or more of the mean background levels.

Comparisons with the topside sounder in the same vehicle showed that down to the minimum scale, irregularities map down to the peak of the F region. The boundary of the irregularity zone was found to be 3° to 9° closer to the pole in the southern hemisphere than in the northern hemisphere. The seasonal variation of the mean location was small. At noon in the northern hemisphere the total seasonal variation is 4°; at midnight 6°. The boundary is closest to the pole in June and farthest in December. No poleward boundaries for the irregularity zone were found; the inhomogeneities extend across the pole. Sagalyn et al[36] found that the lower boundary of the irregularity zone was 3° to 7° equatorward of the auroral oval. Comparison of the irregularity boundary of this technique and that of the scintillation boundary was excellent at night and between 21 and 06 local time but differed at 1700 LT (Figure 7). Recent analysis of 40-MHz BEB results from Narssarssuaq[37] indicate that the earlier boundaries found at this time period by data taken at 57° should be revised; the new contours will bring the scintillation boundary closer to Sagalyn's results.

The severe topside irregularity zone was observed using the ionsounder on ISIS 2.[38] It is (probably) the topside observations of the same F-layer irregularity zone[39,40] observed by a flying sounder, where heavy spread F appears.

On the dayside of the earth the equatorward boundaries of this zone and of the ≤ 300 eV electron precipitation coincide. However, the boundary does not coincide with electron precipitation above 300 eV. The zone extends beyond the poleward boundary of the particle precipitation, probably due to magnetospheric convection transporting irregularities poleward of the region of production. It might be noted that the zone is coincident with the irregularities of the largest absolute (rather than relative) amplitude. On the dayside the zone and the cleft are coincident at times. In a significant number of cases the zone can begin equatorward of the cleft. There is no indication that it ever begins poleward of the cleft.

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37. Mikkelsen, S., and Aarons, J. (1975) Private communications.

38. Dyson, P.L., and Winningham, J.D. (1973) Topside Ionospheric Spread F and Particle Precipitation in the Dayside Magnetospheric Clefts, AFCRL F19628-72-C-0230.

39. Pike, C.P. (1971) A latitudinal survey of the daytime polar F layer, J. Geophys. Res. 76:7745.

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NORTHERN HEMISPHERE
INVARIANT LATITUDE VS LOCAL TIME

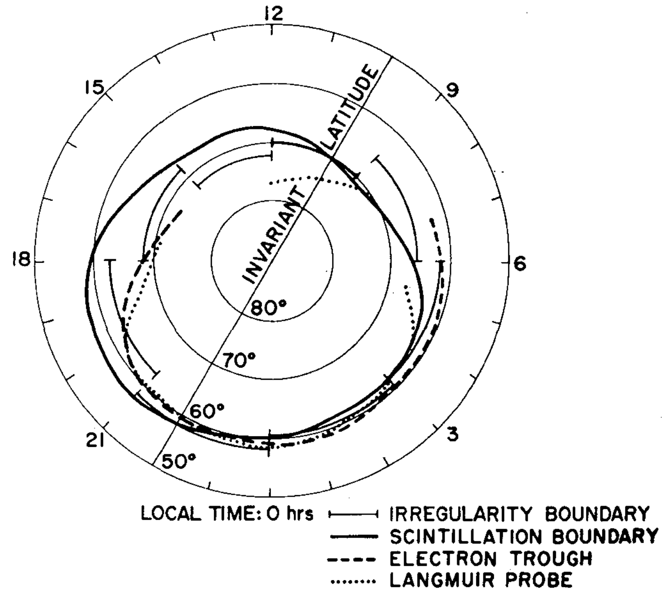

Figure 7. Comparison of Equatorward Boundary from ISIS - 1 Data with Other Boundaries: Scintillation Boundary - Aarons, Kp = 1, Electron Trough - Muldrew, Kp ≅ 2; Langmuir Probe - Dyson, Kp ≤ 3+. [After R. C. Sagalyn et al (1959)]

7. ARTIFICIALLY PRODUCED SCINTILLATION

Two papers have given the details of the study of the production of irregularities by means of the 1-MW HF transmitter of ITSA with its 20° half power beam angle antenna. An area of about 1000 sq km was illuminated; scintillation periods of 1 to 3 sec were noted in the passage of an artificial satellite[41] and longer periods in the passage of a radio star.[42] The rates were similar to those noted in naturally occurring scintillations. The effective height near noon was about 260 km, near the height of the reflection level for the heating frequency.

41. Pope, J. H., and Fritz, R. B. (1974) Observations of artificially produced scintillations using satellite transmissions, J. Geophys. Res. **79**:1065.

42. Rufenach, C. L. (1972) Power law wave number spectrum deduced from ionospheric scintillation observations, J. Atmos. Terr. Phys. **77**:4761.

8. FRESNEL FILTERING

The simplest concept of the rate at which signal fades would be that peaks and nulls are produced by the diffraction pattern of the ionospheric irregularity as it moves across the aperture. In this conception the projection of the ground pattern of the irregularity as the wind takes it across the aperture (in the case of synchronous satellite observations) determines the fading rate. Theoretical considerations[42] indicate that very large irregularities observed at distances shorter than the Fresnel zone distance will not fully develop amplitude fluctuations. Irregularities smaller than the Fresnel zone distance, according to in situ measurements of the intensity of electron and ion irregularities,[36] Dyson et al[43] fall off in electron density with power law behavior. Elkins and Papagiannis[44] Rufenach[45] and Singleton[36] have shown that this behavior is also borne out with spectral measurements. Thus the concept of Fresnel filtering has emerged with each wavelength tied predominantly to an irregularity size determined by the Fresnel zone distance. A simple verification of this would be to determine, from the same source, rates as a function of frequency in the condition of weak scattering ($\Delta\varphi < 1$ radian).

9. FUTURE STUDIES IN MORPHOLOGY

In spite of the large amount of data collected, gaps exist in our knowledge of the morphology of irregularity occurrence and intensity.

At equatorial latitudes the effect of sunspot number is not precise. Measurements indicate scintillation occurrence decreases during years of low sunspot number, but precise comparisons are not available due primarily to the absence of measurements at multiple frequencies with equipment capable of measurements of large signal-to-noise ratios.

The extent of the equatorial irregularity region is not known. Does the region fall off abruptly or does the intensity gradually decrease? What is the width during periods of high and low sunspot number years, during various seasons?

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43. Dyson, P. L., McClure, J. P., and Hanson, W. B. (1974) In situ measurements of amplitude and scale size characteristics of ionospheric irregularities, J. Geophys. Res. **79**:1497.

44. Elkins, T. J., and Papagiannis, M. D. (1969) Measurement and interpretation of power spectrums of ionospheric scintillations at a subauroral location, J. Geophys. Res. **74**:4105.

45. Rufenach, L. L. (1971) A radio scintillation method of estimating the small scale structure in the ionosphere, J. Atmos. Terr. Phys. **33**:1941.

The mid-latitude scintillation picture will be helped by studies of ATS-6 40-MHz transmissions. At middle to subauroral latitudes, there are indications of irregularities appearing a fair portion of the time.

One effect that is not as yet explored for its physical interpretation is that of mid-latitude and subauroral morphology. Clearly the plasmapulse motions and the heating that produces stable auroral red arcs must be a source for the creation of irregularities. Basu[46] has shown correlation of scintillation and stable auroral red arcs during magnetic storms. However, the occurrence of spread F and of scintillations at these latitudes during quiet periods has not as yet been explained.

At subauroral and auroral latitudes, the picture is definitely clearing up with multifrequency studies being made and with the aspect sensitivity more readily calculated. Clearly a detailed correlation with magnetic variations during some intense magnetic storms exists.

The polar irregularity structure is far from clear. The diurnal pattern, the effect of intense magnetic storms, and the quiet day pattern have not been clearly identified with other polar cap phenomena.

The seasonal behavior of subauroral and auroral scintillations has not been clearly shown. Maps of spread F occurrence and some seasonal statistics on scintillation are available, but there has not been a serious attempt at tracing the pattern of behavior as with equatorial seasonal studies. For example, the winter pattern at auroral latitudes during magnetically quiet days has two peaks. Certainly this could be correlated with the complex electric field structure or with seasonal variations of suprathermal electrons.

The advent of ATS-6 with its beacons at 40 MHz and 360 MHz will aid the study of the global morphology of ionospheric scintillations. The 40-MHz signals will be valuable for mid-latitude observations, for frequency dependence studies, and for statistically observing multiple scattering while noting weak scattering (a comparison of 40- and 360-MHz signals at high or equatorial latitudes during some periods). The 360-MHz signals will allow for observations at auroral latitudes during magnetic storms without encountering saturation too often.

Studies of phase scintillations of the small scale irregularities are needed. These fluctuations are easily confused with group path delay variations due to large irregularities (TID's, for example).

The field of ionospheric scintillation studies started in the late 1940's. With both practical and scientific studies noting the significance of the observations it is expected there will be more interest in the studies in the future.

46. Basu, Sunanda (1974) VHF ionospheric scintillations at L = 2.8 and formation of stable auroral red arcs by magnetospheric heat conduction, J. Geophys. Res. 79:3155.

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