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Study of Potential Ionospheric Effects on Space-Based Radars

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The Air Force and the Navy have considered development of space-based radars for purposes of defense surveillance. System configurations considered include sufficiently low frequencies and grazing angles and sufficiently large apertures (synthetic or otherwise) to require consideration of the effects of the ionosphere on the radar propagation path. Toward this end, the Air Force Geophysics Laboratory hosted a Workshop in which engineering organizations responsible for system design were brought together with research organizations active in identifying and characterizing ionospheric effects to assess the need for and state of relevant knowledge. This report summarizes an assessment of the suitability and limitations of information presented at the Workshop and available from related studies.

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STUDY OF POTENTIAL IONOSPHERIC EFFECTS ON SPACE-BASED RADARS

I. INTRODUCTION

Task Requirement Notice (TRN) 15 under the subject contract outlined three tasks to be performed. The first (a) was to "study application and limitations of existing data sets, models, and theory to the derivation of parameters for and the assessment of impacts on space radar designs." Within this task were three subtasks: (1) examine application and limitations of existing scintillation models, (2) study potential application of existing data sets to generation and improvement of such models, and (3) study the issue of translating existing models or data to low grazing angles.

The second major task (b) was to "participate in AFGL research Workshop to identify ionospheric impacts on space-based radars applied to cruise missile surveillance." It had the following two subtasks (1) summarize initial results of task (a) at the Workshop, and (2) apply specialized expertise to identify and clarify ionospheric impacts and shortfalls at the Workshop. The final task (c) was to "review and evaluate presentations and reports from Workshop to identify specific shortfalls in models or analysis of existing data or needs for specific new data sets," and to "assess approaches to mitigate shortfalls."

Deliverables under the TRN are an Interim Technical Report on work carried out under Task (a) prior to the Workshop and orally summarized there, and a Final Technical Report on all tasks, including results from and evaluation of the Workshop. The Interim Technical Report, NWRA-CR-87-R014, was submitted on 30 September 1987. This document is the Final Technical Report.

II. APPLICATION AND LIMITATIONS OF MODELS, THEORY, AND DATA

A. Overview

Three effects of concern were identified at the Workshop. The first actually is a family of effects: group delay, dispersion, and Faraday rotation. We group them as one because they all depend upon the integral of electron density along the ray path through the ionosphere, that integral being called Total Electron Content, or TEC. This family of effects is controlled by TEC on the very largest horizontal scales (global and meso-scales). On these scales, TEC has been described by Klobuchar (1987). At the Workshop, the Klobuchar model was applied by Brown (1988) to assessment of Faraday rotation on Space-Based Radar (SBR) performance. **Faraday rotation must be considered at L Band, and linear polarization should be avoided at lower frequencies.**

The second effect of concern is clutter that can result from backscattering by plasma-density irregularities on the finest scales (comparable to the SBR wavelength, typically meters or smaller). At the Workshop, Tsunoda pointed out that E-region clutter (e.g., radar aurora) is likely to enter through SBR sidelobes and occasionally through the main lobe. Such backscatter occurs frequently at high latitudes and occasionally (under conditions of geomagnetic disturbance) at middle latitudes. At equatorial latitudes, clutter is quite likely to enter through either the main lobe or sidelobes due to backscatter in the E-layer.

Less well-known from ground observations, but a potential threat to SBR performance, is clutter due to backscatter from fine-scale irregularities in the F layer. Unlike their E-layer counterparts, which are confined between about 105 and 120 km altitude, F-layer irregularities probably are very extended in altitude. If so, they would represent a more extensive threat that the better-known E-layer structures. **The strength, spatial spectrum (which dictates the backscatter frequency dependence), and degree of magnetic-field alignment of such F-layer structures and the doppler spectrum of the backscatter they produce should be ascertained.**

The third effect again really is a family of effects, which goes collectively under the name "scintillation." The term refers to spatial and temporal fluctuations in any signal parameter -- intensity, phase, angle-of-arrival, and polarization -- caused by narrow-angle forward scatter in intermediate-scale (tens of meters to tens of km) structures. **Scintillation is the most likely threat to SBR performance, especially at low frequencies and/or low grazing angles on the ionosphere (or on elongation axes of the scattering structures).** We devote the remainder of this report to assessment of scintillation models, theory, and data.

B. Status of Scintillation Research Relevant to SBR's

There are two practical applications of scintillation models. The first is to design systems that are automatically of adaptively robust to its effects. The second is to schedule operations of less robust systems for times and/or observing geometries immune from those effects, or at least to recognize the effects so as to work around them. The former application requires primarily a knowledge of the signal statistics of scintillation, which are well-known (Fremouw *et al*, 1980). More particularly, it is aided by estimates of channel parameters that are less well known and highly variable. Wittwer (1980, 1982) has provided a description of the most relevant parameters, which should be of considerable use to systems designers.

The second application has been addressed in three ways. The first is exemplified by the work of Aarons *et al* (1976). In this approach, long series of observations of a particular signal parameter are summarized by empirical equations relating the observations to some variable of interest, such as time of day, for a particular observing geometry at a particular location.

A more fundamental approach (Basu *et al*, 1981) involves direct measurement of the spatial spectrum of forward-scattering irregularities *in situ* by means of satellite plasma probes and then application of propagation theory to calculate various channel parameters. This approach has the great advantage of permitting use of truly global data bases. It suffers, however, from lack of information on some important irregularity parameters. Missing are parameters that describe the three-dimensional anisotropy of the irregularities, which dictates the look-angle dependence of scattering. Also missing is the thickness of the irregular layer, on which the aggregate scattering strength depends.

The third approach is something of a hybrid between the first two. As does the first method, it employs scintillation measurements instead of *in-situ* measurements, thereby providing height-integrated measures of irregularity strength and the opportunity for description of geometry dependence. It shares with the second approach direct use of propagation theory for the purpose of separating geometrical from geophysical behaviors. Thus, it should permit reliable calculation of, say, the elevation angle and (geomagnetic) azimuth dependence of scintillation indices from a given station as well as the (geomagnetic) latitude dependence of scintillation experienced at different stations.

An early model developed by means of the third approach, by Fremouw and Rino (1978), was committed to the computer program IONSCNT. That program provided outputs of several channel parameters. Based on the two-component signal-statistical model of Fremouw *et al* (1976), calculation of some of those outputs was quite time-consuming.

Accordingly, IONSCNT's successor, WBMOD (Fremouw and Lansinger, 1981; Secan and Fremouw, 1983; Fremouw and Robins, 1985; Robins, Secan, and Fremouw, 1986) has been developed without provision for output of some channel parameters. In particular, **the complex signal's space-and-frequency and time-and-frequency mutual coherence functions are not calculated.** These two functions are closely related, by means of an effective scan velocity, and the Fourier transform of the latter is well-known by and useful to radar designers as the signal ambiguity function. **Measures of its width in the time (and/or space) and frequency (and/or angle) domains should** (and probably shortly will) **be added to WBMOD.**

WBMOD is based on published scintillation results such as those summarized by Aarons (1982) and, more particularly, on equatorial, mid-latitude, and auroral-zone data from the DNA Wideband (hence, the program name) Satellite (Fremouw *et al*, 1978). It describes the known dependences of the relevant irregularity parameters on geomagnetic latitude, time of day, season, epoch of the solar cycle, and the state of solar-geophysical disturbance.

Figure 1 is an example of an output from and a check on WBMOD. The check is provided by observations from Basu *et al* (1982). The two dashed curves are median diurnal variations observed in spring (upper) and fall (lower). The model, based on observations at different frequencies at different

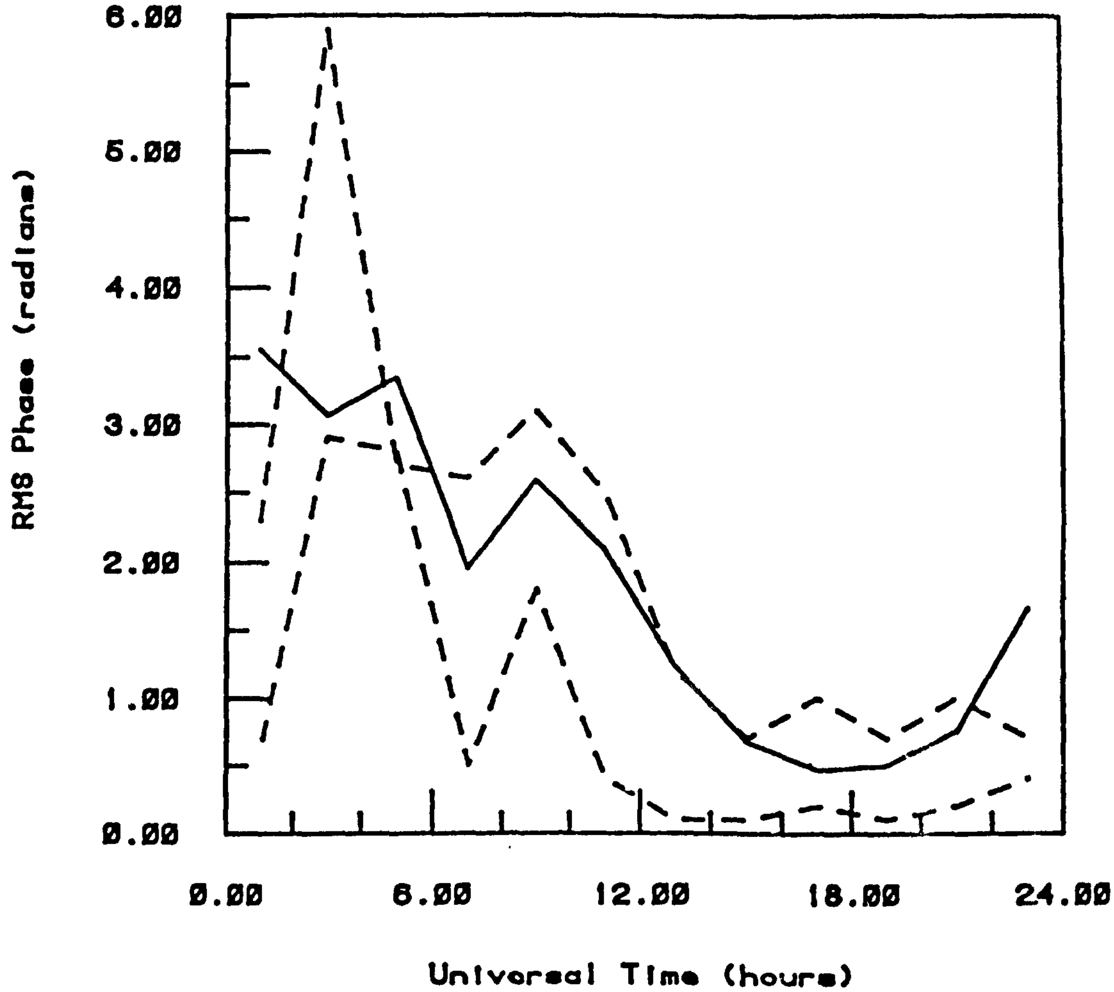

Fig. 1. Independent check on WBMOD output (solid curve) of 244 MHz rms phase to be expected at Goose Bay, Labrador. Comparison curves (dashed) are median values reported for spring (upper) and fall (lower) by Basu et al (1982).

locations and for different observing geometries, reproduces the general level and diurnal variation in measured rms phase fluctuation quite well. What it does not reproduce is the seasonal variation, which is quite clear in the Atlantic (Labrador) sector and essentially nonexistent in the Pacific (Alaska) sector.

Figure 1 is representative of the status of modeling of known scintillation behaviors. That is, the general level and variations are sufficiently well documented to have been committed to a reasonably reliable (and widely used) computer code, but the model is known to be incomplete. In the example here, **a combined seasonal/longitudinal dependence of scintillation is known to exist at high latitudes, and a geophysical basis for it has been postulated** (Basu, 1975), **but it has not been fully documented or modeled.** This and other high-latitude deficiencies soon will be remedied in WBMOD by means of data from the DNA HiLat (HiLat Science Team, 1985) and Polar BEAR (Fremouw, 1986) Satellites collected in Norway (Tromso), Greenland (Sondre Stromfjord), and Canada (Churchill), as well as brief series of measurements in Alaska (Poker Flat and Barrow).

Another known deficiency is in the seasonal/longitudinal variation at equatorial latitudes. WBMOD does include a description thereof, based on a published hypothesis (Tsunoda, 1985) and general agreement of worldwide data therewith. Wideband data from the Marshall Islands (Kwajalein) and Peru (Ancon), however, are biased somewhat away from precise agreement, toward the local summer hemisphere, suggesting an additional controlling factor possibly related to thermospheric winds.

There remain other uncertainties in scintillation behaviors and their underlying geophysical causes. **First and foremost is the need for an accurate assessment of the solar-cycle dependence of scintillation at equatorial, auroral, and, especially, polar-cap latitudes.** *This deficiency is being* addressed at high latitudes by means of on-going observations of HiLat and P.BEAR, as well as of the Navy Navigation (Transit) Satellites (Kersely, 1987) and those (Rino *et al*, 1981) in the Global Positioning System (GPS). Success depends upon continued health of the signal sources and continued commitment by funding sources. **It does not appear that the deficiency is being addressed at equatorial latitudes.**

On a more detailed level, questions remain about the three-dimensional spectrum of high-latitude irregularities, both about the spectral shape itself and about its anisotropy. The shape, which dictates both the spatial and temporal spectrum of signal fluctuations encountered, appears often to be more complicated that the single-regime power law contained in WBMOD. The anisotropy determines the look-angle dependence of scintillation, apart from a general increase in severity as elevation angle decreases.

A representative example of a VHF phase spectrum from Wideband appears in Figure 2. Routine Wideband spectral processing did not include time-domain windowing. When a subset of 214 passes over Poker Flat was more carefully analyzed (Fremouw *et al*, 1985) with windowing to suppress spectral leakage, 23% of them showed a downward spectral break at a fluctuation frequency of several Hz. Presumably, this break is the phase signature of a similar break seen *in situ* at spatial wavelengths of several hundred meters to a km (Basu *et al*. 1984). To accommodate it, **the propagation theory employed in WBMOD needs to be modified to permit a more general spectral form. One outcome of the Workshop is that such an effort is underway.**

The low-frequency, upward break in the spectrum shown in Figure 2 was observed in 77% of the more carefully analyzed data from Poker Flat, but it was not generally accepted as a meaningful feature because it included only the first few bins in the spectrum of Wideband detrended data. Subsequently,

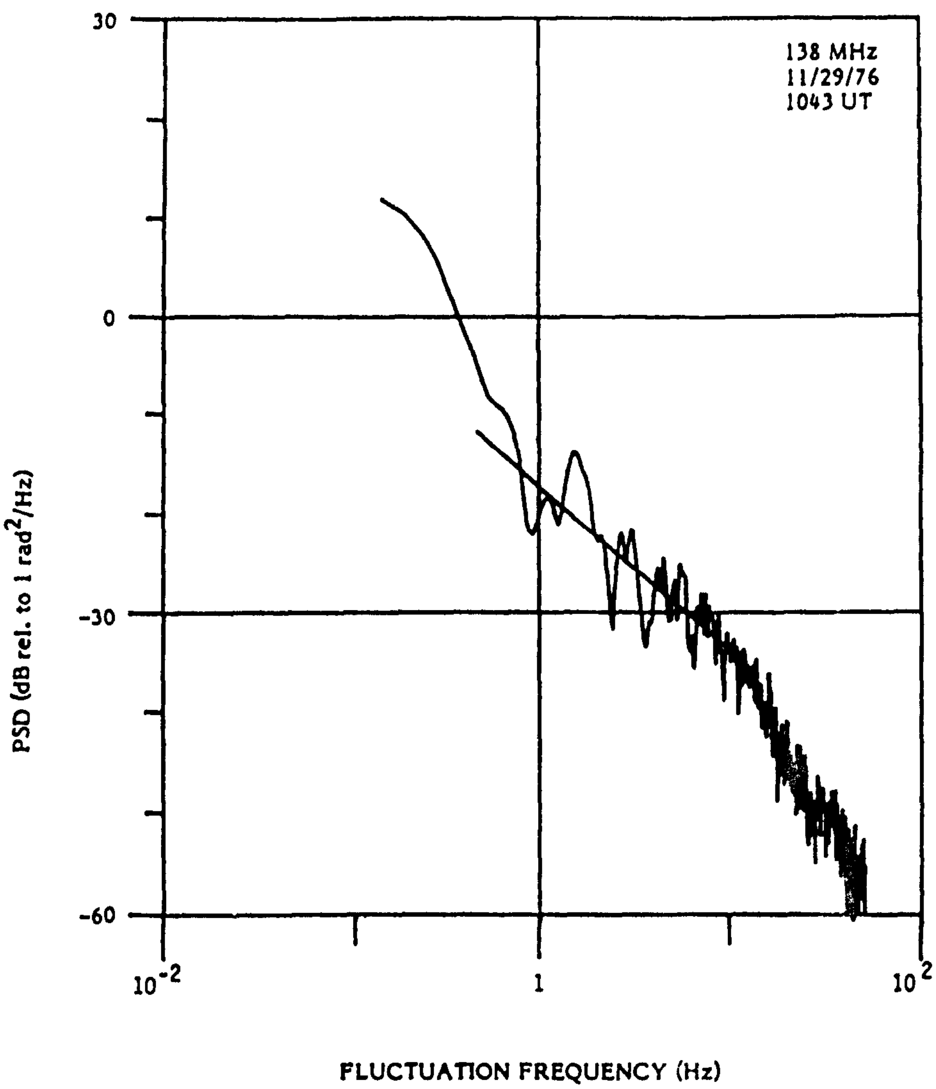

Fig. 2. Example of a fully developed, three-regime power-law phase spectrum, observed at VHF (138 MHz) by means of Wideband from Poker Flat just after local midnight on 29 November 1976.

Livingston (1987) reprocessed some of the raw Wideband data from Poker with a longer detrend cutoff (30 sec instead of 10 sec), finding 62% of the resulting spectra to show the upbreak. Moreover, routine processing of HiLat data employs a 30-sec detrender, and it also reveals the upbreak. An example is shown in Figure 3. Simultaneous incoherent-scatter data have prompted Livingston to suggest that the enriched low-frequency portion of the spectrum arises from a contribution by large-scale arc structures in the E layer.

Livingston's suggestion provides an interpretation for another behavior observed in Wideband. It is illustrated in Figure 4, which shows the magnetic-latitude dependence of the phase spectral index, p, routinely observed (best log-linear fit to a presumed single-regime power-law spectrum) from Poker Flat at night, excluding the quietest magnetic conditions. Increased steepness (larger p) occurred at auroral latitudes, a behavior consistent with a contribution by E-layer arcs. Figure 4 does not complete the story, however, which becomes more complicated when the same data are displayed in two dimensions.

Figure 5 contains a contour plot of p values from essentially the same data population on a grid of angles between the line of sight and (y) the magnetic L-shell at 350 km and (x) the local magnetic meridian at the same altitude, which is similar to a magnetic latitude-longitude grid. The plot shows that, while the phase spectral index generally peaks near the L-shell through Poker Flat, it does not do so in a corridor including the magnetic zenith (0,0 at the center of the plot). We believe that the foregoing behavior results from a combination of (a) the enrichment of large-scale structures by E-layer (and possibly F-layer) arcs and (b) breakdown of an assumption nearly always made in scintillation analysis and modeling.

We believe that large-scale structures increase the plasma-density spectral index in the vicinity of auroral-zone L-shells. We suspect further, however, that **the phase spectral index responds in a manner not described by the statistical scattering theory employed**, when the line of sight approaches alignment with the geomagnetic field. Consistent with the latter suspicion is a recent finding that the phase spectral index decreases near the magnetic zenith in HiLat data from Churchill, as shown in Figure 6. To treat this situation properly, **the propagation theory needs to be generalized.** Specifically, the theory must not rely, as it currently does, on an assumption that the layer always is many irregularities thick along the line of sight. At least a portion of this task has been taken on by Franke (1987), but the result has not appeared in print.

Related to this point is the elevation-angle dependence of scintillation. The thick-layer assumption leads to proportionality between a commonly employed index of phase-scintillation strength and the secant of the incidence angle between the line of sight and the (horizontal) scattering layer. Extension of large-scale irregularities vertically through the entire layer would lead to a proportionality with the square of that secant. **This difference could amount to almost an order-of-magnitude difference between the ratio of phase variance near the zenith and that at low elevation angles.** It deserves near-term research attention.

Regarding the shape of irregularities, which dictates the geometrical behavior of scintillation when the line of sight approaches grazing incidence with elongation axes of anisotropic irregularities, one uncertainty remains. All scintillation-producing irregularities are elongated along the geomagnetic field. In addition, localized but extended and persistent scintillation enhancements reported by Fremouw *et al*

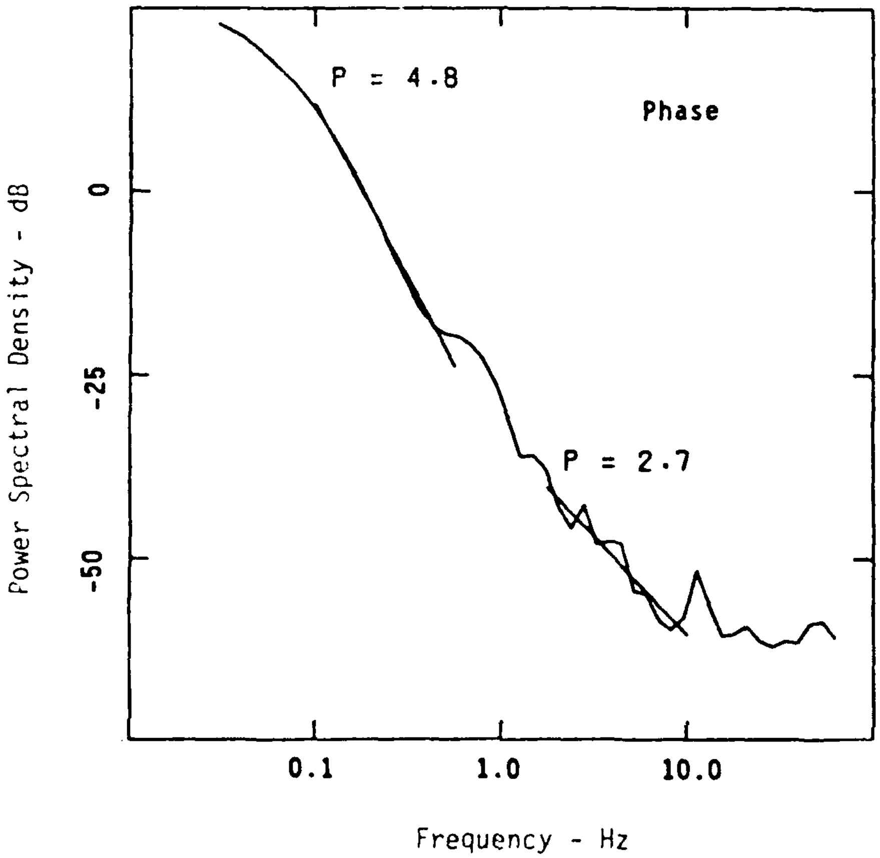

Fig. 3 Phase spectrum from HiLat pass over Sondre Stromfjord at 0235 GMT on 30 January 1987.

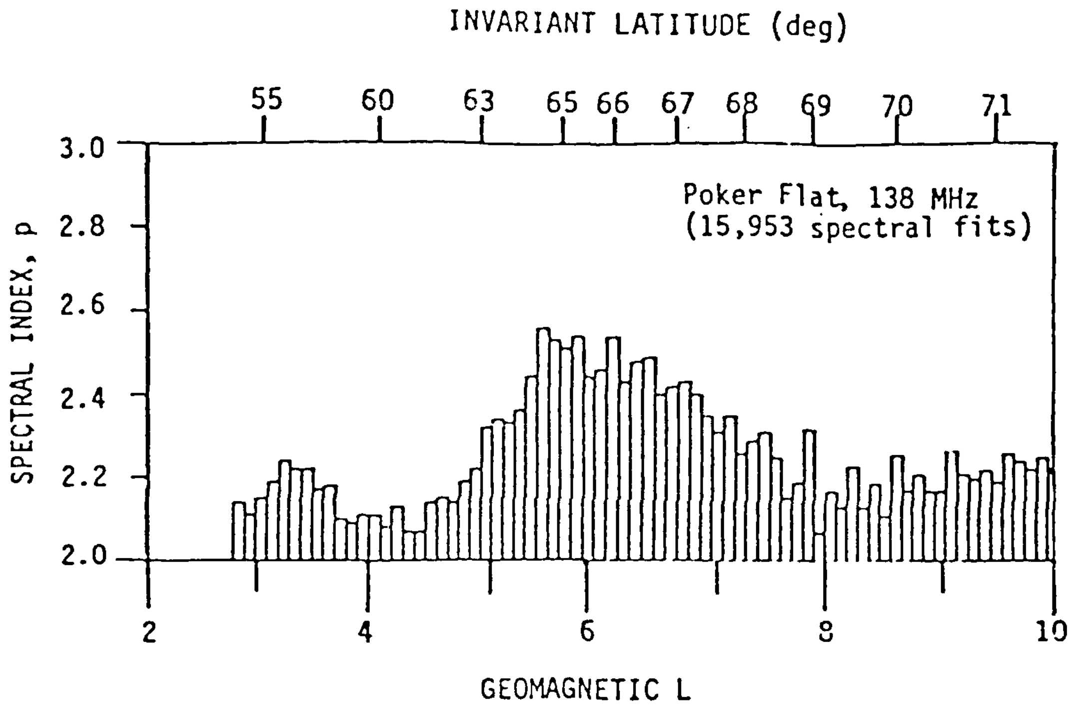

Fig. 4. Average values of phase spectral index observed at night during Wideband (except for local K < 1) from Poker Flat as a function of geomagnetic L value and latitude at the ionospheric penetration point of the VHF line of sight with the F layer (at 350 km).

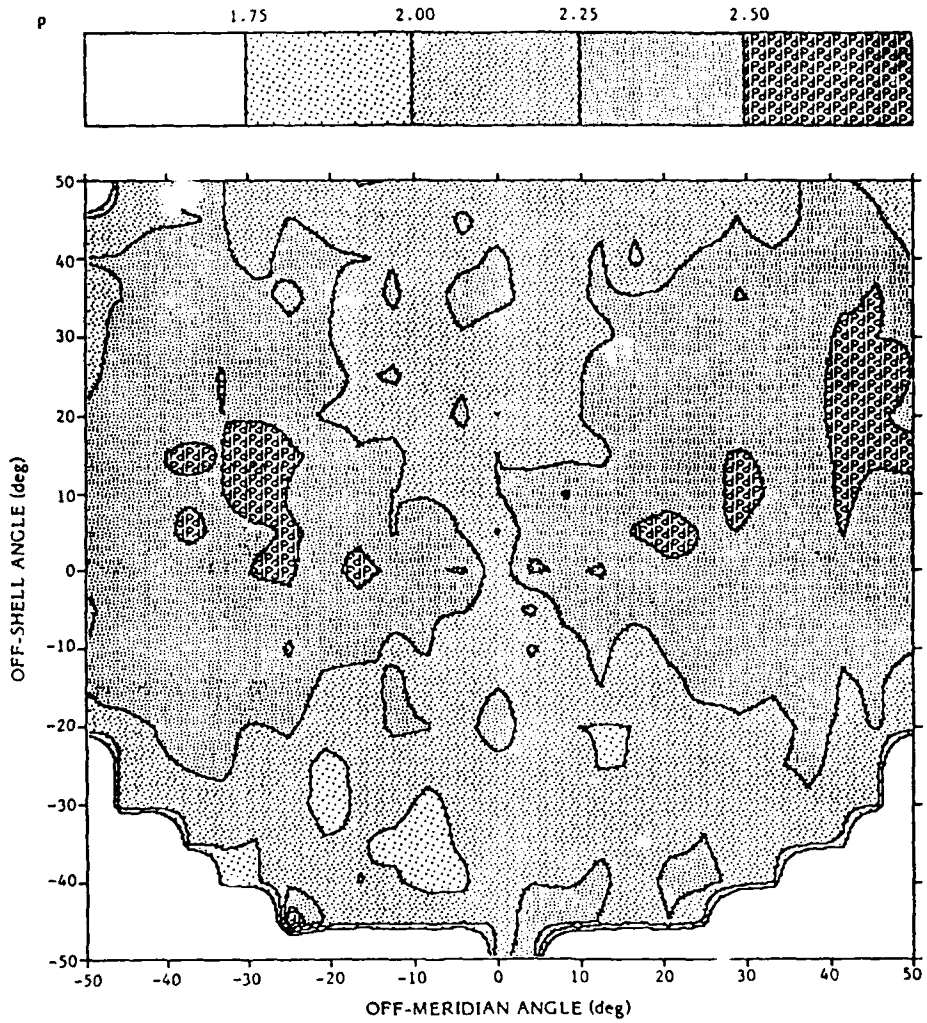

Fig. 5. Contour plot of VHF phase spectral indices measured by means of Wideband at night at Poker Flat, on a grid of angle between the radio line of sight and (y) the local L-shell in the F layer (350 km) and (x) the magnetic meridian at the same altitude.

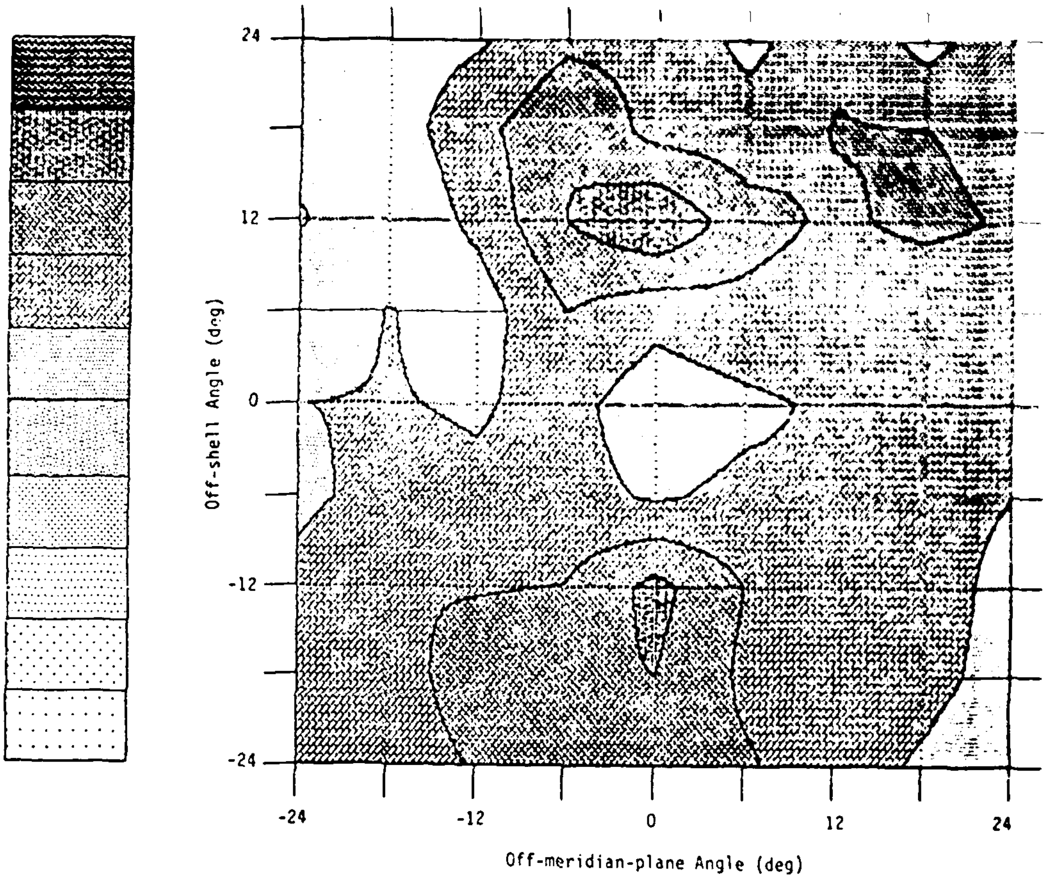

Fig. 6. Same as Fig. 5, except for HiLat data from Churchill collected over a period of about 33 months ending in mid-1987.

sheetlike elongation along geomagnetic L-shells. To date, no such feature has been detected in scintillation data from HiLat.

The feature's absence from HiLat data collected at Sondre Stromfjord is consistent with the observation by Livingston *et al* (1982) of decreasing anisotropy (in particular, across the field) poleward of the (nightside) auroral oval at Poker Flat. The feature also is absent from the HiLat data bases collected at Tromso and Churchill, however, which are at magnetic latitudes similar to that of Poker. Thus, at this juncture, **specification of an operationally relevant aspect of the anisotropy of high-latitude irregularities is incomplete.**

III. CONCLUSION

By way of conclusion and recommendation, we have highlighted in Section II points that we perceive to be particularly relevant to SBR design and operation and as deserving of research attention between now and the increased solar activity expected in the early 1990's. In addition, for assessment of likely worst-case scintillation, we recommend nighttime observations from a mid-Atlantic location such as Ascension Island.

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