

THE HILAT SATELLITE PROGRAM: INTRODUCTION AND OBJECTIVES

Irregular plasma-density structures in the earth's ionosphere can distort electromagnetic waves propagating through them, producing troublesome scintillations of the phase, angle of arrival, and intensity of radio signals. HILAT, a multiexperiment satellite, currently is providing information on those structures at subauroral, auroral, and polar latitudes and on the scintillations that they produce.

BACKGROUND

On June 27, 1983, a multiexperiment satellite (P83-1) was launched to investigate the dynamics of irregularities in plasma density in the high-latitude ionosphere. Called HILAT, its five experiments are intended to probe the development, evolution, and decay of such irregularities on scales that produce radio wave scintillation (hundreds of kilometers down to tens of meters). Scintillating signals from sources such as radio stars and satellites are the radio-frequency analogs of the familiar twinkling of optical sources such as visible stars.

Scintillation consists of random fluctuations in the intensity, the angle of arrival, and, for coherent sources, the phase of a radio signal. It is of interest for two reasons. First, the signal fluctuations contain information about the plasma structures (located mainly between 250 and 500 km altitude) that produce them. Second, the phenomenon is of direct practical interest because it can degrade the performance of radar and communication systems that send signals through the structured ionosphere. The problem would be exacerbated by the substantially enhanced plasma density created in the ionosphere by high-altitude nuclear detonations. It occurs also under conditions of natural disturbance, however, particularly near the geomagnetic equator and at high latitudes.

In the HILAT program, we define high latitudes (in geomagnetic coordinates) as extending from the plasmopause to the pole (see Fig. 1). The plasmopause is a region of substantial plasma density gradient between the relatively smooth mid-latitude ionosphere (which is produced almost entirely by solar ultraviolet radiation during the daytime) and much more varied and structured regions at higher latitudes. Just poleward of the plasmopause, especially on the night-side of the earth, is a region of low electron and ion (i.e., plasma) density called the main ion trough. Poleward of the main ion trough lie several ionospheric regions controlled largely by the interaction of the solar wind with the earth's magnetosphere and produced, in large part, by incoming energetic electrons. The precipitating electrons deposit their energy during ioniz-

ing collisions with neutral molecules at different altitudes, with the altitude depending on the amount of kinetic energy they carry.

Immediately adjacent to the main ion trough on the nightside is a region of diffuse auroral glow; most of the photons there are produced by electrons that deposit their energy between about 100 and 125 km altitude (the ionospheric E layer). At the poleward edge of the diffuse aurora lies the familiar visual aurora, its structured and variable shapes being produced largely at similar altitudes by precipitating electrons whose flux density and energy spectra are much more varied latitudinally. Poleward of the auroral oval is a region of rather incessant influx of lower energy electrons called the polar rain. Often imbedded in the polar rain are localized regions of elevated precipitating-electron flux density. Continuing through the polar cap and over the pole, one again encounters the auroral oval, in an incompletely explored region called the day-side cusp.

While the visually identifiable regions of the high-latitude ionosphere refer mostly to the E layer, most of the plasma through which transionospheric radio waves must travel is contained in the higher F region. It appears that this plasma and the influx of the relatively low-energy precipitating electrons largely responsible for it also are latitudinally structured on a macroscale. Thus, regions of relatively high and relatively low plasma density are interspersed with regions of considerable north- and south-directed gradients, as well as some eastward and westward gradients (especially at the highest latitudes).

It is known from several research efforts that regions of plasma-density gradient across which plasma attempts to flow in competition with a restraining force are structurally unstable. Near the magnetic equator, the vertical gradient on the bottom side of the post-sunset F layer, constrained as it is by the essentially horizontal geomagnetic field, is unstable to collisional forces imposed on it by the gravitationally assisted wind in the intervening neutral gas. The development of structured regions is much the same as that resulting from Rayleigh-Taylor instability at the interface between one neutral fluid (e.g., fresh water) and a

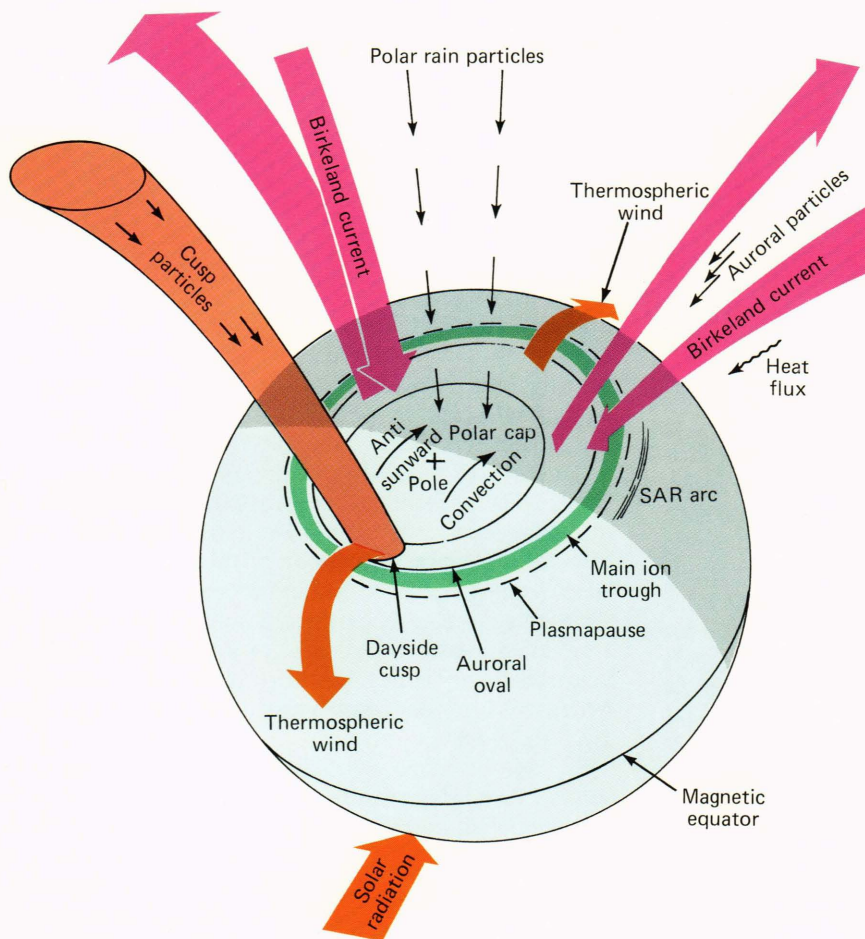


Figure 1 — The ionosphere and some of its pertinent high-latitude couplings with the more distant magnetosphere.

denser one (e.g., salt water) overlying it and constrained by friction.¹

Experiments have been carried out at middle latitudes² and elsewhere in which neutral barium vapor was released in the F layer and allowed to ionize under the influence of solar ultraviolet radiation. The barium ion clouds, also constrained by the magnetic field, were observed to “steepen” as the horizontal neutral wind in the thermosphere blew through them. From the steepened gradient on the downwind side, plasma structures developed on scales smaller than the cloud radius, a condition called gradient-drift instability. When the structured cloud intercepted the radio path to a satellite, strong intensity and phase scintillations were recorded.

The F layer between the plasmopause and the poles is replete with macroscale gradients resulting from spatially irregular plasma production by energetic-electron bombardment and probably other causes. It also contains several sources of free energy that can set in motion the neutral, ion, and electron gases. The latter two are constrained by electrostatic forces to act largely in concert, but they do sustain certain electric currents. Moreover, the electron-ion plasma is strongly guided in its motion and structural evolution by the largely vertical geomagnetic field, **B**.

In the high-latitude F layer, an electric field, **E**, produced by dynamo interaction of the solar wind with the highest reaches of the earth’s magnetosphere (at altitudes of many earth radii) is a major cause of plasma motion, namely convection in the $\mathbf{E} \times \mathbf{B}$ direction. Because the neutral gas is not subject to electric and magnetic forces, plasma undergoing an $\mathbf{E} \times \mathbf{B}$ drift again experiences a neutral wind in its own rest frame. The trailing edge of any isolated patch of such convectively drifting plasma would be expected to steepen and develop structure under the $\mathbf{E} \times \mathbf{B}$ instability, and there is evidence that it does so. Currents flowing along the **B** field into or out of such plasma may further destabilize its density gradients.

In all the foregoing instabilities—plasma Rayleigh-Taylor, gradient-drift, $\mathbf{E} \times \mathbf{B}$, and the current-convective augmented form of the latter—internal currents deposit surface charges on plasma-density boundaries that produce local perturbations of the $\mathbf{E} \times \mathbf{B}$ drift velocity. If certain directional requirements are satisfied, the differential drifts can cause steepening of gradients and growth of incipient structures. The latter take the form of excursions of more dense plasma from the patch into the background ionosphere and incursions of less dense background plasma into the patch or cloud. These instabilities form a class or fam-

ily that produces a convective interchange of different-density plasmas on decreasing scale sizes, resulting in a spectrum of plasma structures.

A less familiar member of the family is one driven by a sort of “wind” in the electron gas that can arise from an initial gradient in electron temperature. This temperature-gradient-drift (TGD) instability may account for scintillations observed near the plasmopause under highly disturbed geomagnetic conditions.³ Thermal flux is thought to flow along magnetic field lines into the F layer from above, producing stable auroral red arcs at high midlatitudes (just equatorward of the plasmopause). This may be the energy source for temperature-gradient-drift-produced irregularities at the plasmopause (see Fig. 1).

Whatever the source of plasma-density irregularities, they represent perturbations in refractive index to a passing radio wave, appearing as irregular and highly imperfect (distorting) lenses. An initially plane wave propagating through a field of such irregularities emerges as a corrugated wavefront. In subsequent propagation, the radio rays converge and diverge toward foci and defoci. At a distant observing plane such as the earth, a diffraction pattern develops from the originally imposed phase corrugations having scales comparable to or smaller than the radio wave Fresnel-zone size. When the plasma structures drift across the radio line of sight between a transmitter and receiver or when the latter scans across the structures, random fluctuations in the phase and intensity of the received signal can seriously distort any information originally carried by the signal’s modulation.

OBJECTIVES

The reliable statistical characterization of the complex signal (amplitude and phase) scintillations would permit the design of mitigation schemes. In addition to the strength and radio-frequency dependence of the fluctuations (the latter being well known), their spatial and temporal spectra are of particular interest. From an operational point of view, areas of concern include the observing-geometry dependence of scintillation, which is dictated largely by the three-dimensional shape of the irregularities. Beyond this, it would be useful to be able to predict when, where, and under what solar-geophysical conditions disruptive levels of scintillation will occur. This is possible now only in a very crude statistical sense.

The first objective of HILAT is to provide definitive, quantitative information on high-latitude scintillation strength, particularly on the spatial and temporal spectra of the intensity and phase fluctuations comprising it. The second objective is to extend into new locations and local times of day and night the diagnosis of three-dimensional irregularity shape that was begun with HILAT’s single-experiment predecessor, the Wideband Beacon Satellite.^{4,6} The third objective is to provide additional diagnostic information on background ionospheric processes that cannot be provided by a beacon experiment alone and that

is needed for the definitive identification of irregularity development and dynamics.

DESCRIPTION

The Wideband Beacon Satellite’s sole experiment was a 10-frequency coherent radio beacon for measuring the total electron content of the ionosphere (i.e., the integral of electron number density along the line of sight) and for observing complex-signal scintillation. Because a plasma is a dispersive medium for radio waves (its effects decreasing with increasing radio frequency), the Wideband Beacon Satellite transmitted a continuous-wave signal at S band (2891 megahertz) for use as a relatively undisturbed phase reference against which phase perturbations were measured on nine lower, mutually coherent frequencies.

The forte of a beacon experiment for diagnostic purposes is that it is directly sensitive to scintillation-producing irregularities and that it can provide three-dimensional shape information⁷ through the geometrical dependence of scintillation⁵ and, more directly, through spaced-receiver measurements.⁶ It cannot definitively reveal, however, the processes leading to development of scintillation-producing irregularities, because it provides results only after the irregularities have developed.

In addition to electric-field-driven convection, other ionospheric-magnetospheric processes may contribute to the development of scintillation-producing irregularities. For instance, it is possible that precipitation patterns of ion-producing electrons are structured on scales smaller than macroscale, even down to the scale of the scintillation-producing irregularities themselves. Moreover, the electric fields that are carried down the highly conductive magnetic field lines from the magnetosphere also may be structured on the relevant scales. In addition to a scaled-down version of the Wideband Beacon Satellite experiment, HILAT carries experiment payloads designed to probe both finely scaled precipitation and electric fields (the latter being expected in structured-plasma regions, in any case), as well as magnetic-field-aligned currents (commonly referred to as Birkeland currents). It also carries an optical remote-sensing photometer experiment intended to provide macroscale information on auroral activity as a general indicator of the disturbance state of the ionosphere.

Table 1 lists the HILAT experiments, their intended purposes and basic characteristics, and the principal experimenters associated with each. Each experiment is described in detail in ensuing articles. The satellite is controlled by the Naval Astronautics Group, Pt. Mugu, Calif., which issues commands under a letter of agreement with the Space Division of the USAF Systems Command. In-orbit operations are planned by the Science Team and carried out by the Naval Astronautics Group upon request from the Project Scientist.

Data are collected by means of real-time transmissions to the following four high-latitude stations shown by encircled dots on Fig. 2: Tromso, Norway (auroral zone); Sondre Stromfjord, Greenland (polar cusp);

Table 1 — HILAT experiments.

<i>Instrument</i>	<i>Observations</i>	<i>Operating Characteristics</i>	<i>Experimenters</i>
Coherent beacon	Scintillation Total electron content	Phase-coherent radio-wave signals at 138, 390, 413, 436, and 1239 MHz; circular polarization.	Carlson (Air Force Geophysics Laboratory) Forsyth (University of Western Ontario) ³ Fremouw (Physical Dynamics, Inc.) ⁴ Rino (SRI International)
Plasma monitor	Ion and electron concentration Dominant ion species Ion and electron temperature Electric field	¹ Langmuir probe: electron concentration and temperature; spectral density of concentration irregularities at 3, 10, 35, 500, and 750 m wavelengths. Retarding potential analyzer: ion concentration and in-track ion velocity, 3.5 km resolution; temperature and mass of dominant ion. Ion drift meter: cross-track drift velocity field with 880 m resolution.	⁴ Rich (Air Force Geophysics Laboratory) Heelis, Hanson (University of Texas, Dallas)
Vector magnetometer	Magnetic field Electric current along magnetic field lines	Three-axis fluxgate: 13 nT quantizations, 400 m resolution.	⁴ Potemra (APL)
Electron spectrometer	Electron flux and energy spectra	Energy range: 20 eV to 20 keV; three look directions: up, down, and 45° from zenith. Three modes, spatial resolution 300, 600, and 1800 m.	⁴ Hardy (Air Force Geophysics Laboratory)
Auroral Ionospheric Mapper	Night and day auroral and F-layer emissions	² 1150 to 2000 Å imaging spectrophotometer. Wavelength resolution: 30 Å; spatial resolution in E (F) layer is 5 × 20 km (3 × 13 mi) at nadir. 3914 and 6300 Å nadir-viewing photometers.	⁴ Huffman (Air Force Geophysics Laboratory) Meng (APL)

¹Not fully operable.²Imager failed on 23 July 1983.³HILAT Project Scientist.⁴Experiment principal investigator.L. A. Wittwer (Defense Nuclear Agency),
Program Manager

Churchill, Manitoba (auroral zone); and Seattle (plasma-pause). A second Canadian station (the noncircled dot) is planned for Inuvik, Northwest Territories (auroral cusp); operations are likely to begin in the boreal spring of 1984. The Seattle and Inuvik stations are intended to be transportable to other locations for limited-duration observing campaigns. Ephemeris information for program tracking of the satellite at the receiving stations is provided by the North American Air Defense Command.

The data collected at the stations shown in Fig. 2 (plus early mission data from the APL ground station in Laurel, Md., and the European Space Research

northern range station in Kiruna, Sweden) are distributed to the participating organizations by means of the network indicated in Fig. 3. Raw data are reduced to summary form at the three fixed stations and at the home locations of the organizations that operate the two transportable stations. Summary tapes (black lines) are sent to the Air Force Geophysics Laboratory for reproduction and routine distribution, while raw tapes (colored lines) are archived there and copied for experimenters on request.

The experiment payloads normally are operated over the northern quadrisphere of the earth, although they can be turned on for any quarter of the orbit. The sat-

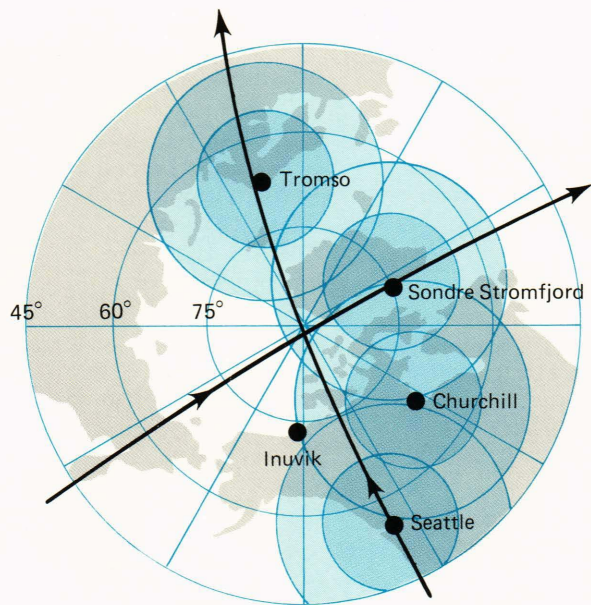


Figure 2 — HILAT ground stations (dots) on a geomagnetic latitude-longitude grid. The dark circles indicate beacon coverage at ionospheric height (350 km). The light circles indicate the horizon at satellite height (about 800 km). Two typical satellite trajectories also are shown.

ellite is in an approximately 800 km circular orbit at 82° inclination, and the orbital plane precesses through 24 hours of solar time approximately twice per year. Data collection is planned for three years.

Following launch, all experiments operated as designed, with the exception of the electron sensor (Langmuir probe) of the plasma monitor. Apparently, a faulty connection developed in it during boost or orbital insertion, resulting in an uncertain bias that undermines reliable interpretation of its data.

More distressing, the high-voltage power supply to the imaging ultraviolet spectrophotometer (the Auroral

Ionospheric Mapper) in the optics package failed after producing several tantalizing ultraviolet images of the aurora. The Auroral Ionospheric Mapper produced data simultaneously with the energetic-electron spectrometer, magnetometer, and plasma probe on approximately 40 passes during the engineering-initialization phase of the HILAT mission. Unfortunately, the failure occurred prior to activation of the fully equipped HILAT receiving stations for the operational phase of the mission. Consequently, beacon data are not available from the passes that produced auroral images.

Figure 6 in the article by Huffman and Meng in this issue shows one of the spectacular ultraviolet images produced by the Auroral Ionospheric Mapper during the HILAT initialization phase, recorded at Kiruna on July 23, 1983. Partial data from the other on-board sensors are shown in Fig. 4 of this article. At about 1919 universal time (UT) (about 1930 magnetic local time (MLT)), HILAT reached the auroral oval on the eveningside of the earth near 69° N magnetic eccentric dipole latitude. After traversing the eveningside oval, it passed over the polar cap and emerged from the morningside oval near 0255 MLT and 70° N eccentric dipole latitude at about 1928 UT.

The two traverses of the auroral oval are demarked clearly by elevated fluxes of precipitating electrons, multiple electric current sheets inferred from the magnetometer (especially on the evening side), and directly from the ultraviolet emission recorded in the auroral mapper's nadir pixel. The plasma probe disclosed rapid shear flows in the auroral-oval plasma; the horizontal ion velocity was closely correlated with the magnetic-field perturbations on the eveningside. The electron spectrometer also clearly revealed diffuse auroral precipitation equatorward of the discrete arc oval and the polar rain of soft particles.

Figure 5 shows data from an operational pass over the HILAT station at Sondre Stromfjord, on Septem-

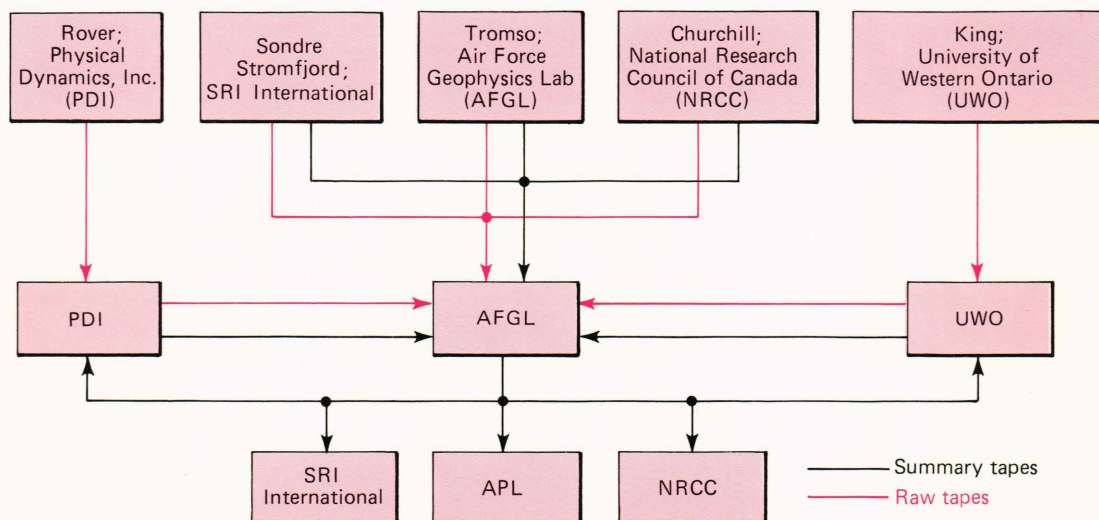


Figure 3 — The data distribution network.

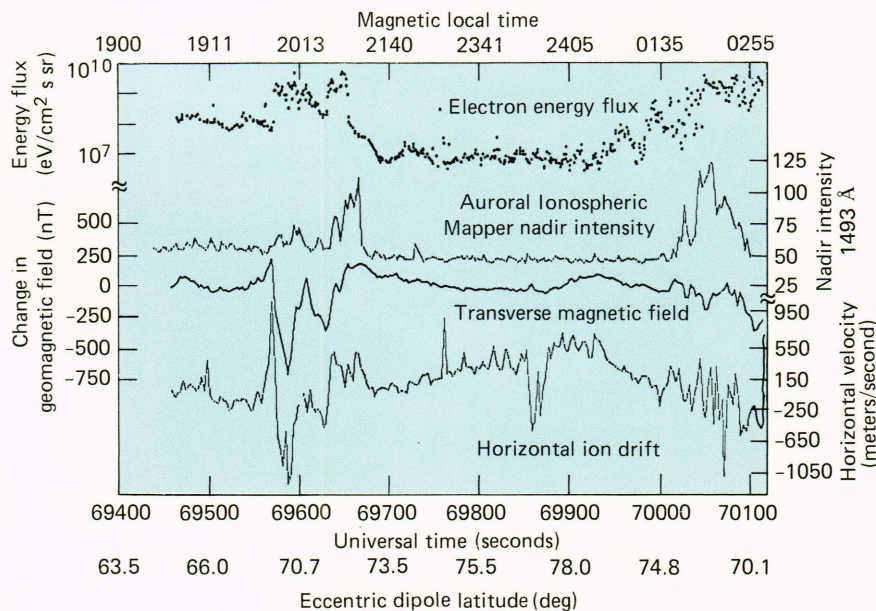


Figure 4 — Data from on-board sensors taken during passage over the auroral oval and northern polar cap on July 23, 1983, between 1916:40 and 1928:20 UT.

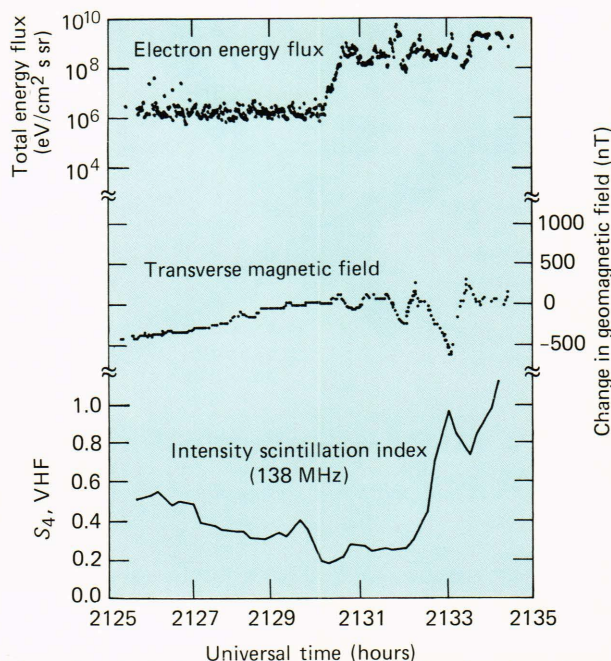


Figure 5 — Data from a HILAT pass over Sondre Stromfjord, on September 19, 1983, as the satellite traveled equatorward essentially along the 2130 MLT meridian.

ber 19, 1983. The total energy flux carried by precipitating electrons clearly shows passage of the satellite from the polar cap into the nightside auroral oval near 75° N eccentric dipole latitude, at about 2130 UT, as it moved equatorward essentially along the 2130 MLT meridian. The magnetometer again revealed considerable current flowing in the region. Moreover, the beacon receiver now showed that at least the equatorward portion of the oval was the seat of decidedly elevated levels of both phase and intensity scintillation, indicated in Fig. 5 by nearly saturated intensity scintilla-

tion (normalized standard deviation, S_4 , near unity) at VHF (138 megahertz).

Careful attention must be given to the relative locations of the in-situ sensors and the transionospheric radio propagation path before forming conclusions about the development of scintillation-producing irregularities. Equally important will be consideration of the dynamics of the situation, as revealed, for instance, by yet-to-be-processed ion-drift data from the plasma probe. Early data from HILAT, illustrated here and in subsequent articles, show considerable promise toward that end.

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