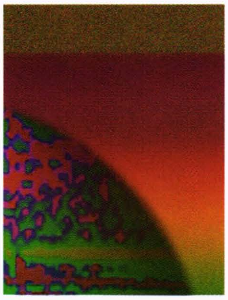


Magnetic Field Experiment on the Swedish Freja Satellite

Lawrence J. Zanetti and Thomas A. Potemra

Freja is a joint Swedish and German scientific satellite launched on 6 October 1992 to acquire high-resolution measurements of plasmas, fields, and ultraviolet emissions associated with auroral phenomena. The Magnetic Field Experiment was developed by APL and incorporates a ring-core fluxgate sensor and an APL-designed Forth reduced instruction set computer microprocessor. This programmable microprocessor has significant advantages including (1) the flexibility to adapt to different mission requirements with only software changes, (2) the ability to substantially reduce the need for ground-based data processing with powerful onboard real-time processing, and (3) the capacity to increase the sensitivity and resolution of the basic measurements using onboard processing to compress the data stream to fit the available telemetry bandwidth. The Freja mission enables real-time data display on a laptop-sized computer linked to the ground receiving station in Kiruna, Sweden. This PC–telephone link also provides the real-time means to send commands to Freja to change instrument modes and even to reprogram the entire processor. The details of this unique instrument and satellite mission and some uses of its real-time data capabilities are described in this article.

INTRODUCTION

The Freja real-time system (Fig. 1) provides the electric power industry information on geomagnetic conditions and auroral zone locations. Geomagnetic storms originate from the interaction of the Earth's magnetic and plasma environment with the fluctuating, magnetized plasma of the solar wind, which is ultimately due to solar activity (e.g., flares, coronal mass ejections). This energy transfer near the Earth is concentrated in the northern and southern auroral zones. It produces the well-known aurora borealis and aurora australis as well as large-scale electric currents containing millions of amperes in the ionosphere.

Temporal and spatial fluctuations of these currents have long been known to induce current and voltage in the Earth's surface and on large, man-made conductive structures. These "Earth currents" have been recognized and measured.[1,2] Strong, persistent periods of solar wind interaction with the geomagnetic environment can extend this auroral activity region to midlatitudes. The distortion of the Earth's intrinsic magnetic field into a comet-shaped configuration, called the magnetosphere, is due to its interaction with the streaming solar wind.

The form of the magnetosphere is defined by a complex current system identified by a variety of names; magnetopause, ring, and tail currents are the major outer components. Energy and driving fields are connected to the inner region (the near-Earth

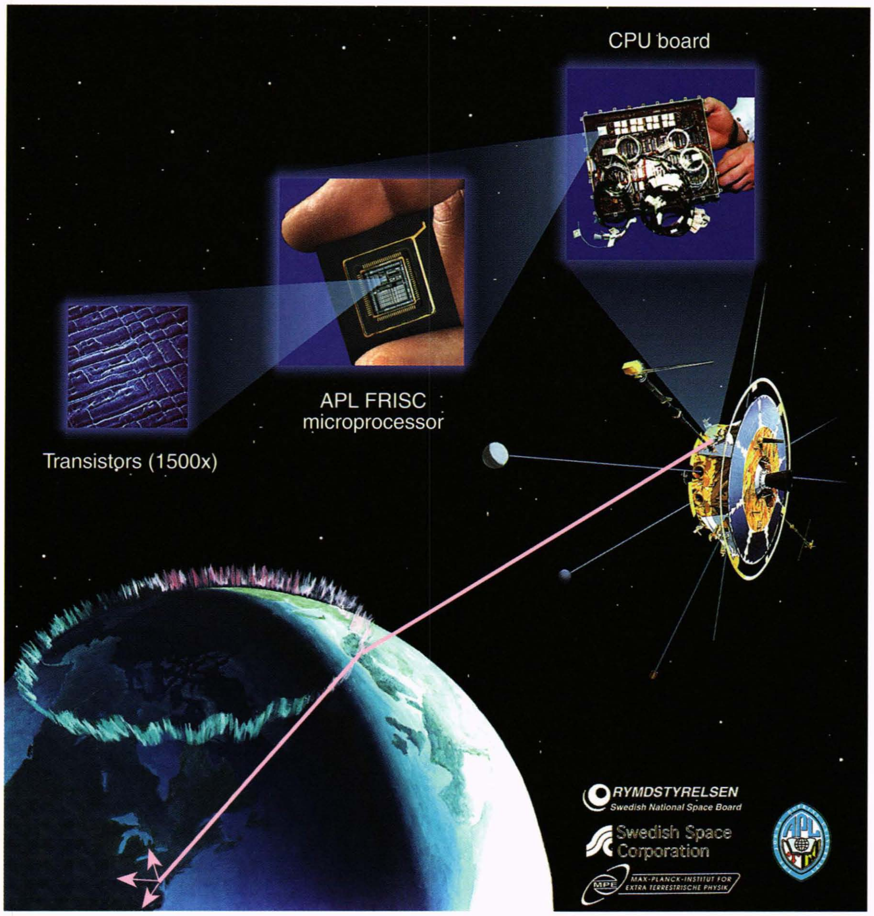


Figure 1. Artist's conception of the joint Swedish–German Freja satellite above the northern auroral zone showing the central processing unit (CPU) with the Forth reduced instruction set computer (FRISC) and 3 of the 40,000 transistors of the FRISC.

ionosphere) by field-aligned or Birkeland (after the Norwegian proposer of such in 1908) currents. A statistical, empirical model of field-aligned currents has been developed from polar-orbiting, low-altitude APL navigation satellite magnetometer data[3–5] and is depicted in Fig. 2a.

Previous studies of these field-aligned current systems from NASA's Magsat[7,8] and UARS[9] (Upper Atmosphere Research Satellite) missions have shown them to be colocated with the horizontal ionospheric Hall currents known as electroject currents, which flow azimuthally within the auroral zone. It is this horizontal electrojet system—at about 100 to 120 km in the ionosphere, with its temporal fluctuations and quick movements during the geomagnetic storm process as well as its diurnal variation in geographic location—that inductively couples to ground-based conductive paths (e.g., the North American power distribution grid).

The statistical correlation between geomagnetic activity and ground system effects is well established,[2,10,11] and general event correlations have been made, for example, for 13 March 1989[6] and 4 August 1972.[12] The intensity of this ionospheric system can reach millions of amperes and can dissipate up to 0.1 terawatt (10^{11} W) of power in the auroral ionosphere; the estimated power-generating capacity in the United States is 0.8 terawatt.[13] The system contains enormous inertia due to the great size of the Earth's magnetosphere and is continuously changing in response to variations in the solar wind pressure and interplanetary magnetic field (IMF).

The auroral zone is typically found in the 65 to 75° magnetic latitude range but can extend significantly beyond those limits during geomagnetically active times. This induction of currents interferes with power system operation and equipment, as dramatically illustrated by the Quebec electric system blackout of 13 March 1989 (Fig. 2b[6] shows the southern extent of auroral activity), which was directly attributed to ionospheric current induction, the so-called geomagnetically induced currents. During that event, excessive Earth potential on the transatlantic telecommunications cable was correlated with an intense ionospheric current measured by ground magnetometers.[14] The graph in Fig. 2a shows the large magnetic disturbances measured by the APL HILAT (high-latitude satellite) Magnetic Field Experiment (MFE). These ionospheric currents are colocated with the auroral light shown in Fig. 2b. Corrective measures to eliminate the problems caused by geomagnetic disturbances can be taken but require continuous real-time monitoring of the geomagnetic system and accurate forecasting.

THE FREJA MFE

The Freja MFE[15] consists of a three-axis ring-core fluxgate sensor mounted on a 2-m boom. Spacecraft-mounted electronics provide lowpassed and bandpassed analog signals, digitized and signal-processed to satisfy the scientific objectives. The analog electronics were designed to significantly lower system noise levels, which are approaching the fluxgate sensor levels. Measurements of the three-axis Earth's magnetic field are taken at 128 vector samples per second (vs/s) and digitized to 16-bit resolution. These measurements are used to evaluate currents and the main magnetic field of the Earth. The additional three-axis "AC" channels (vector wave measurements, which will record all information about the polarization, ellipticity, etc., of the wave field) are bandpass-filtered from 1.5 to 128 Hz to remove the main field spin signal and are amplified. These measurements cover ion gyrofrequency magnetic wave signals up to the oxygen gyrofrequency (≈40 Hz at a 600-km altitude). A separate, seventh channel

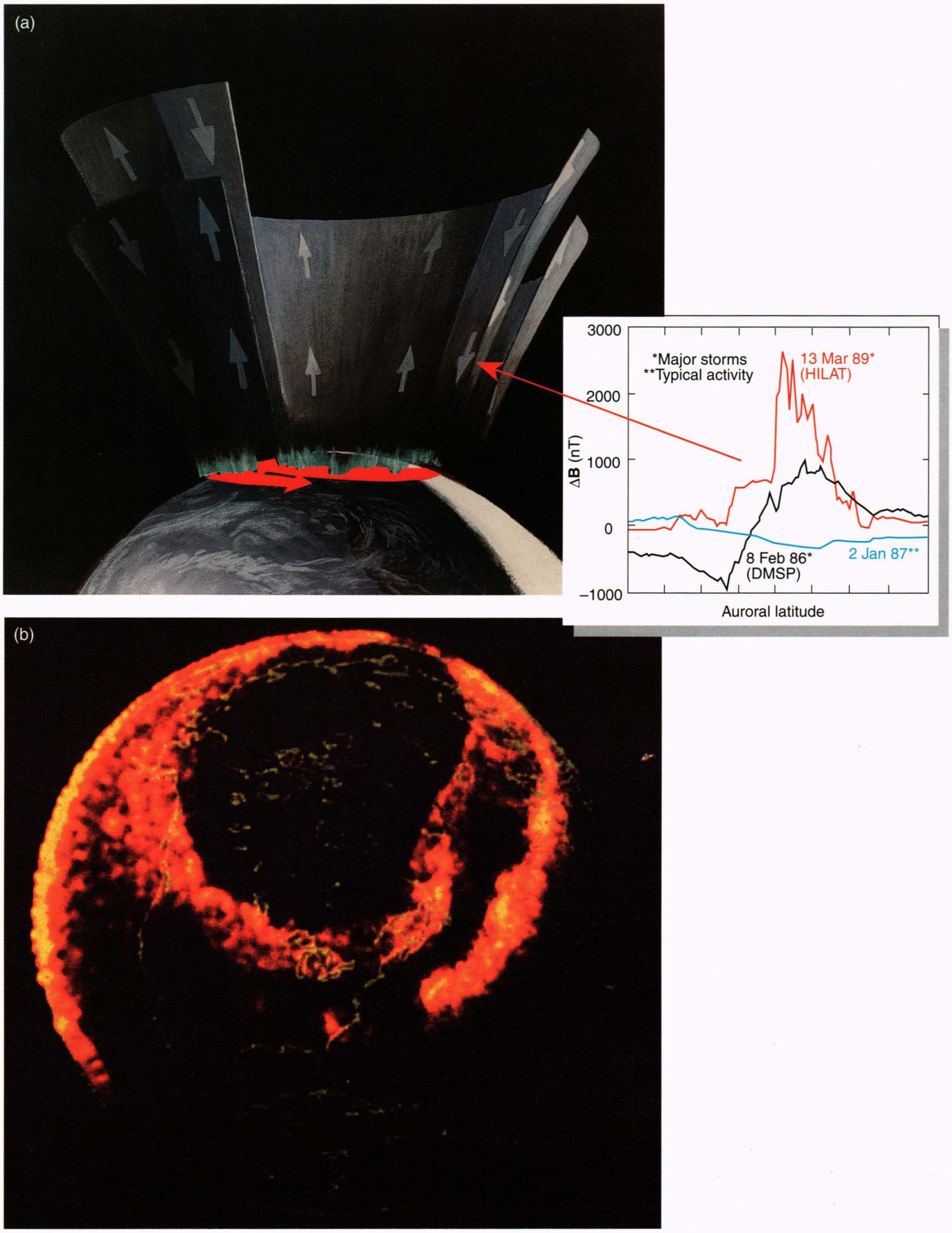


Figure 2. Auroral images. (a) Artist's conception of the field-aligned current system of the ionospheric auroral zone, which transmits the energy from the outer magnetosphere. The red arrow indicates the accompanying horizontal ionospheric current, at times carrying more that 1 million amperes at a 120-km altitude. The graph shows examples of the magnetic field disturbance that accompanies the field-aligned currents, plotted as $\Delta\mathbf{B}$, the change from the Earth's background field, versus position in latitude (HILAT = high-latitude spacecraft, DMSP = Defense Meteorological Satellite Program spacecraft). The example for 13 March 1989 shows a current system producing nearly 3000 nT of disturbance to the Earth's field (10%). (b) An auroral image from the NASA Dynamics Explorer spacecraft, also on 13 March 1989. The entire province of Quebec experienced a 9-h power system blackout due to the induction from the extreme ionospheric currents.[6]

samples the sensor aligned parallel to the satellite's spin axis (relatively insensitive to modulations caused by the spin field) with a permanent bandpass filter of 1.5 to 256 Hz; the signal from this filter is fed to the software fast Fourier transform (FFT) to provide wave spectra that cover the local helium gyrofrequencies (≈160 Hz).

Data are taken throughout the orbit and are stored in reduced form in the MFE's 1.3-Mbit random access memory (RAM). The range and resolution are as previously described but with a variable sampling rate of 0.0625 to 16 vs/s (the nominal rate has been 3-s data). Virtually continuous MFE coverage since launch enhances the correlative aspects of this mission with other satellite and ground-based data sets. Full-orbit storage totals 0.5 Mbit of RAM, which takes a few minutes to transmit during real-time data reception. The AC channel bandwidth allows the full range of measurements to continue uninterrupted. A running standard deviation of the magnetic field fluctuations is computed and is used to trigger a flag when the fluctuations exceed a predetermined (and programmable) threshold. This trigger information indicates the entrance into the strong field-aligned current regions as discussed later. The general characteristics of the MFE system are as follows:

- Summary characteristics
  Triaxial ring-core fluxgate sensor, 2-m boom-mounted
  Low-noise (8-μV) analog, 16-bit A/D, spacecraft-mounted electronics
  Internal 1.3-Mbit RAM, event trigger, software FFT, oversampling
- Telemetry data rate
  14.3 kb/s @ 256-kb/s spacecraft rate; 28.6 kb/s @ 512-kb/s spacecraft rate
  (a) 128/256 vs/s; range, ±65,000 nT; resolution, ±1 nT
  (b) AC: 128/256 vs/s; bandpassed from 1.5 to 128 Hz; range, ±650 nT
  (c) Spin axis, 1.5 to 256 Hz FFT; resolution, 2 Hz
- Weight, 3.5 kg (excluding boom and mount)
- Power, 3.7 W (including DC/DC)
- Size
  Sensor, 10 × 7.5 × 7.5 cm
  Data processor, 18 × 23 × 9 cm

Figure 3 is a block diagram of the MFE, which consists of the boom-mounted, three-axis probe and a spacecraft-mounted data processor and electronics unit. The electronics are contained on four circuit boards:

1. The sensor electronics board drives, processes, and filters analog signals from the probe.
2. The filter–A/D board provides additional anti-alias and bandpass filtering and digitizes the analog signals.
3. The central processing unit (CPU) board, which includes the APL-developed Forth reduced instruction set computer (FRISC) microprocessor, processes the digital data, formats the data for telemetry, and controls the instrument.
4. The DC/DC converter board converts spacecraft power to the voltages required by the electronics.

The improved performance of the Freja ring-core fluxgate magnetometer is a result of advances in sensor design, materials, and electronic systems made at the Goddard Space Flight Center (GSFC) in Greenbelt, Maryland, for missions such as Magsat, Voyager, Ulysses, AMPTE/CCE (Active Magnetospheric Particle Tracer Explorers/Charge Composition Explorer), and others. The fluxgate sensors are constructed utilizing the ring-core geometry, which has been shown to exhibit superior long-term zero-level stability and minimal drive power requirements. In addition, the magnetic material used to manufacture these sensors is the latest in a series of advanced molybdenum–permalloy alloys specially developed in cooperation with the Naval Surface Warfare Center (White Oak Laboratory, Maryland) for low-noise, high-stability applications. It exhibits superior performance characteristics, unmatched by any other type of fluxgate sensor material. Improved formulations of these alloys were developed and used in the Voyager and Ulysses instruments.[16–18] Employed in conjunction with the electronics described in what follows, zero offset stability is better than ±0.1 nT over a temperature range of ±60°C and for periods exceeding 1 year, based on current Voyager data. The system-level stability of the AMPTE/CCE MFE was <1 nT per axis over its 4.5-year lifetime.

The design of the analog electronics associated with these sensors evolved from designs developed for previous missions. Complexity is minimized to improve reliability while reducing power consumption, instrument weight, and experiment cost. The design uses stable, negative-resistance parametric amplification obtainable from tuned fluxgate sensors to sense magnetic fields at the sensor element. This technique eliminates the need for high-gain, low-power, low-noise amplifiers, which can be extremely sensitive to interference and radiation-induced degradation. The sensor element is essentially used as a null detector in a feedback loop; the current required to null the field at the sensor is a measure of the field. This arrangement delivers the high sensor linearity and exceptional noise performance for which the GSFC magnetometers are noted. The inherently low noise design, coupled with the careful layout of the critical analog circuitry, produced system noise levels in the Freja MFE approaching the fluxgate sensor levels (≈10^{-7} nT^2/Hz).

The filter–A/D board filters the analog probe signals from the sensor electronics board, converts them to digital form, and buffers them in a first-in, first-out (FIFO) buffer under control of the onboard,

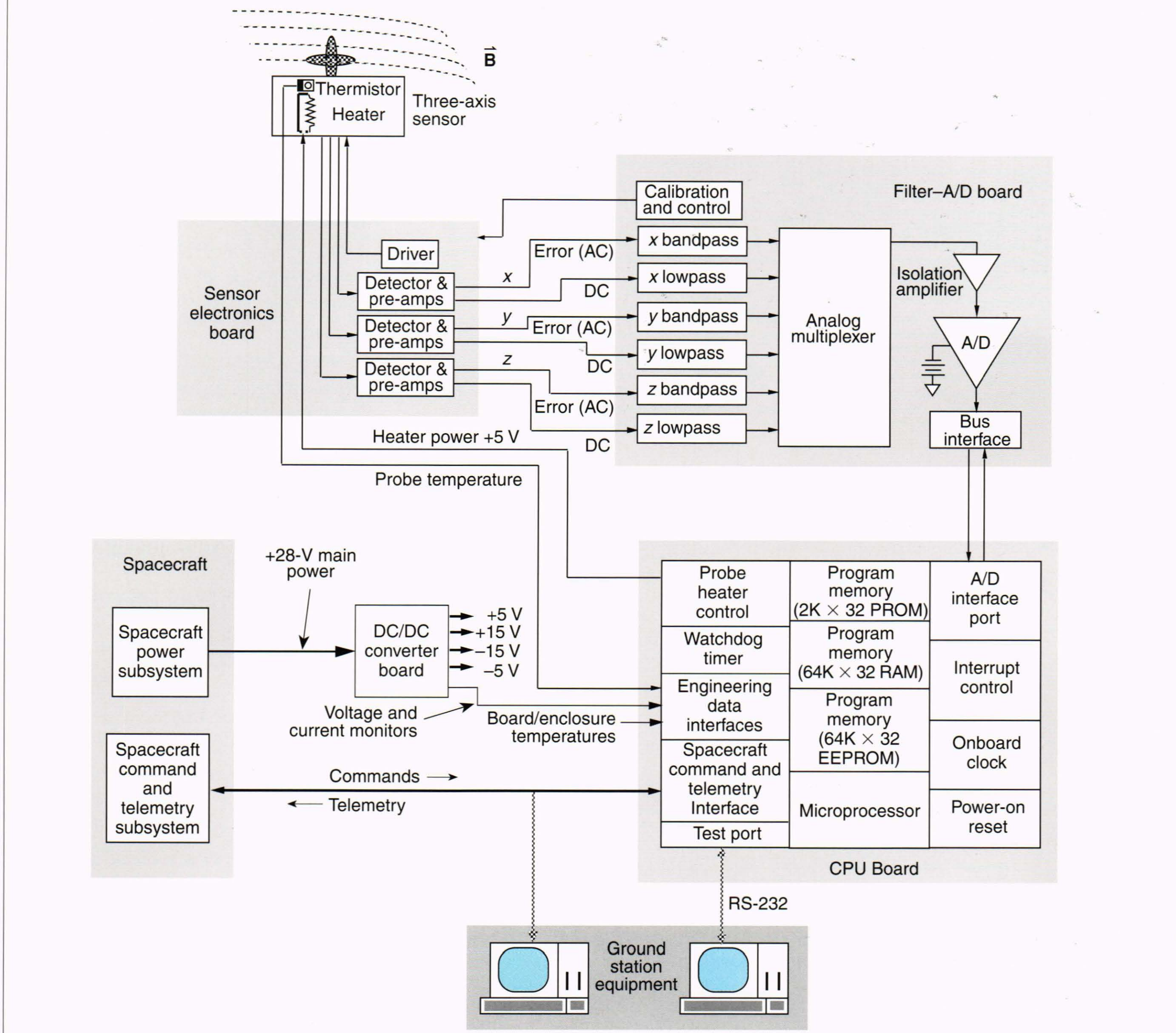


Figure 3. Block diagram of the Magnetic Field Experiment circuit boards and their functions. The boards are mounted in two half-chassis on the Freja spacecraft with the three-axis sensor (top left, measuring the magnetic field $\vec{B}$) at the end of a 2-m rigid boom. (RAM = random access memory, PROM = programmable read-only memory, EEPROM = electrically erasable PROM.

programmable "smart" sequencer. As the sensor is being continuously sampled at 256 samples per second, the hardware anti-aliasing filter corner is set at 128 Hz for the high telemetry rate and is digitally filtered to the 64-Hz frequency for the normal rate. The AC channels are bandpass-filtered (1.5 to 128/256 Hz), amplified by a factor of 100, and digitized to 16-bit resolution. In addition to gathering magnetic wave measurements, this frequency band is proving extremely useful for the automatic detection of the auroral zone Birkeland field-aligned currents, as alluded to previously and discussed later in this article. An analog multiplexer presents one signal at a time to the 16-bit A/D converter, which stores its digital results in an output FIFO for the CPU board to read. The smart sequencer selects the analog multiplexer channel, initiates A/D conversion, oversamples the A/D by up to 16 and averages, and controls FIFO output based on a program stored in its RAM. The CPU board can download various smart sequencer programs, depending on the data collection mode required.

Figure 4 displays system noise levels for near-Earth magnetic field measurements, confirming laboratory calibrations[19] with in-flight data. During a quiet interval (orbit 790) outside the auroral zone, the AC channels were FFT spectrum analyzed, yielding an average noise level of 5×10^{-5} nT^2/Hz in all three channels from 5 to 64 Hz, corresponding to a broadband 60-pT signal in a 0.3-G background field. The noise floor is believed to be limited by the 16-bit A/D's two least

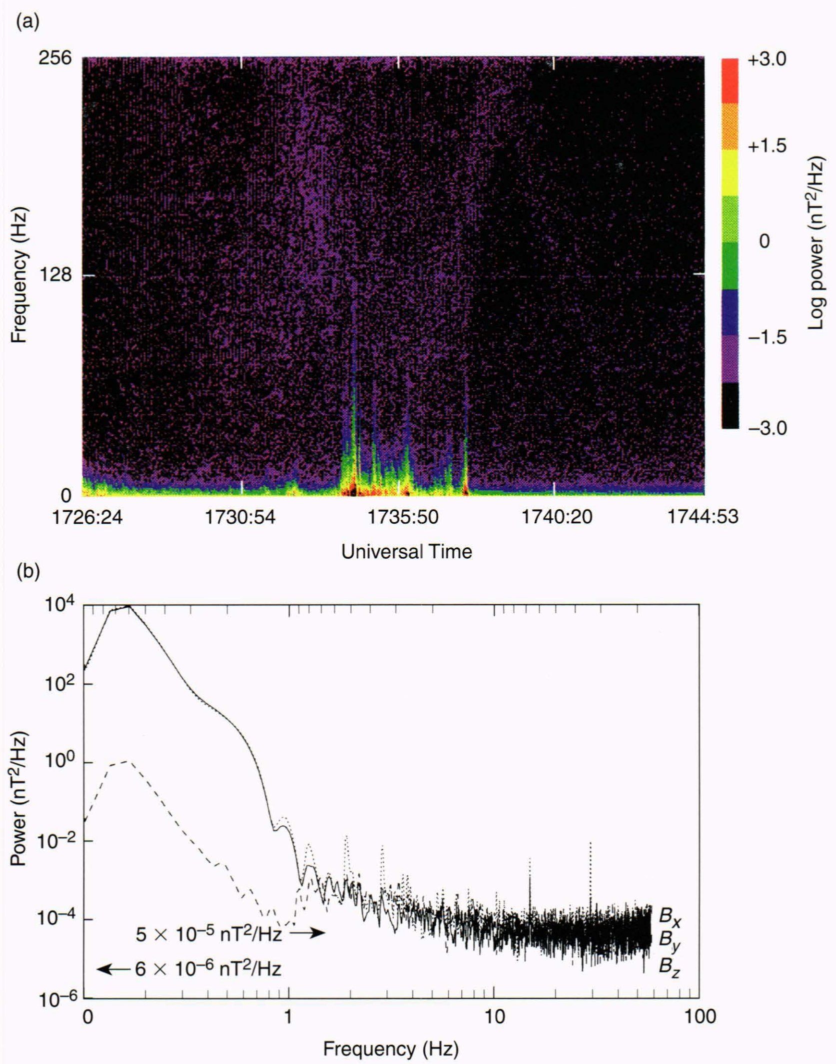


Figure 4. System noise levels for the near-Earth magnetic field measurements. (a) Onboard-processed fast Fourier transform (FFT) spectrogram format (0–256 Hz vs. time) of the spin-axis MFE bandpassed channel during orbit 2437 on 8 April 1993. The V-shaped signature centered at 1735:50 UT is typical of low-frequency magnetic waves accompanying auroral zone activity. (b) A single FFT spectrum (equivalent to one vertical section of Fig. 4a) of the three-axis bandpassed channels (B_x, B_y, B_z) during a quiet interval on 5 December 1992 (orbit 790). The measured system noise level is 5×10^{-5} nT^2/Hz (the higher levels at low frequencies are due to the spin field dominating the highpass filter corner at 1.5 Hz), compared with the digitization level corresponding to the least significant bit (20 pT, 6×10^{-6} nT^2/Hz).

significant bits, and software could be uploaded to simulate the oversampling process used on the DC channels to compensate for this bottom 2-bit noise. The least significant bit produces a noise level of 6×10^{-6} nT^2/Hz.

The heart of the Freja MFE is the custom APL-designed single-chip FRISC microprocessor (Fig. 1) located on the CPU board.[20] An APL patent is pending on this design. APL has licensed the FRISC to Silicon Composers, Inc., Palo Alto, California, which offers the chip as a commercial-grade device designated as the SC-32. The company also markets a single-board computer that plugs into IBM PC-compatible computers, along with its own operating/development system. The integrated circuit foundry (European Silicon Structures, ES2) recently established a Mil-Std-883 line, which was used for our Freja FRISC fabrication. The Laboratory's Reliability Group performed a visual inspection of the parts at the foundry and confirmed ES2's high-quality fabrication process. In addition, APL has an internal testing and screening program that upgrades the parts to a reliability above the Mil-Std-883 level. Data analysis subsystem functions of the FRISC SC-32 microprocessor include the following:

- Magnetometer data collection
- Oversampling and averaging (nominally to ensure 16 bits, potential upgrade to 18-bit analog system noise floor)
- Digital lowpass filtering (switchable anti-aliasing filter corner @14.3/28.6 kb/s)
- Full-orbit data collection (0.0625 to 16 vs/s selectable; 0.3 vs/s = 10-orbit summary data)
- Event detection (standard deviation = 128 vs/s for 1 s, variable threshold, event information, parameters in spacecraft housekeeping)
- Remote data collection (10-s precursor, 40-s total @ 128 vs/s)
- Spin-axis FFT processing (1.5 to 256 Hz, 2-Hz resolution)
- Telemetry rate detection
- Housekeeping data collection (including event information for remote transmission)
- Telemetry formatting
- Command processing

The processor was specifically designed to run the Forth high-level language and take advantage of the structure of the operating system to preserve speed and interactiveness.[21] It can perform 10 million instructions per second when operating at 10 MHz. The use of this powerful 32-bit microprocessor (one of the first 32-bit processors in space aside from a commercial 80386 on the Clementine mission) simplified system hardware design by allowing functions that would otherwise require specialized hardware to be performed using software. For example, the Forth system performs the onboard FFT function using software to provide selected spectral information from data too voluminous to downlink. This software function eliminates separate FFT hardware and the extra power, board space, and design time it would require. The FRISC processor directly executes the high-level Forth language, thus eliminating the penalty of compiling a high-level language to machine code. Furthermore, software development and debugging are performed interactively on the actual target hardware.

A CPU test port connects to a terminal to provide communication and control functions via the interactive Forth language interpreter during system development and testing; even hardware glitches from the high-speed logic are traced with interactive debugging software. The CPU board reads the data from the FIFO, performs the signal processing tasks, calculates the event detector, and stores the reduced full-orbit data in the local RAM. It also formats the resulting data and sends them to the telemetry interface board, which buffers the data and sends them using a serial protocol to the Freja system unit. Concurrent with the data handling tasks, the CPU controls the sampling sequencer, collects and formats the housekeeping data, and executes uplinked commands. The telemetry interface board also receives serial commands and selected telemetry words from the spacecraft. It converts them to parallel and passes them to the CPU board for interpretation and/or execution.

The hardware functions on the CPU board include a fusible link boot PROM (programmable read-only memory) program. It loads itself into RAM after any reset command, turns itself off to save power, and waits for either a telemetry system command or a debug terminal command. If neither occurs within 10 s, the boot program automatically loads the application software stored in the electrically erasable PROM (EEPROM). Included is the capability to uplink new application software into the EEPROM via the command system for programming upgrades. One memory module slot on the CPU board has been chosen for more EEPROM. Other hardware functions on the board include a prioritized interrupt controller, a real-time clock, telemetry timers, a housekeeping A/D converter, and a watchdog timer (used to confirm that the application software is running properly). Programs are stored in the 64K × 32-bit EEPROM. At system initialization the flight program is copied into the 64K × 32-bit RAM, which also contains the buffers referred to earlier for storing the full-orbit and burst data.

Full-flight software was stored in the EEPROM before launch; however, new programs were uplinked and stored in the EEPROM during the mission. This reprogrammability feature of the Freja MFE system offers an ideal and realistic environment in which to adapt to alternate mission requirements and upgrades.[22] These characteristics allow the MFE processor to recover automatically from single-event upsets (SEUs) and even to record when those upsets occurred. Consequently, the MFE is an SEU sensor as well as a magnetic field sensor. Figure 5 shows the locations of upsets experienced by the Freja MFE during December 1993. It confirms that most SEUs occur near South America, where the configuration of the geomagnetic field known as the South Atlantic magnetic field anomaly permits energetic particles from the radiation belts to penetrate to low altitudes and thus cause problems with the satellite microelectronics.

GEOMAGNETICALLY INDUCED CURRENTS

From data acquired by the UARS MFE, magnetic field fluctuations in the 5- to 50-Hz range appear to be good indicators of the locations of large-scale field-aligned or Birkeland currents.[9] The exact response of these channels and filters, as well as the physics behind the wave and fine-scale current structures accompanying the large-scale average current system, is being pursued with both the Freja and UARS MFE data. Nevertheless, the association is clear, and we discuss next the use of the fluctuations to estimate the location of large-scale Birkeland currents.

When a measure of the fluctuations, such as a running standard deviation, exceeds a commandable, preset threshold, a flag is triggered. This event flag tracks the occurrence, boundaries, and intensity of the auroral current region. The correlation presented here demonstrates that spacecraft measurements of fluctuations in the magnetic field that are associated with the auroral zone currents can be used to regionally locate the sharp boundaries of the ionospheric currents. Variations of the large-scale ionospheric currents, also known as auroral electrojets, produce large-scale electric fields (due to Lenz's law) on the Earth's surface, which, in turn, cause large, unwanted currents in power distribution systems. These geomagnetically induced currents (GICs) have produced serious power disruptions and equipment damage. The Freja AC measurements described previously can be acquired in real time and provide an important first step in developing a reliably predictive monitor for warning utility systems of impending geomagnetic disturbances.

Currents induced in Maryland's Chalk Point power generating and transmission system (supplying the Washington, D.C., Potomac Electric Power Company) have been correlated with large-scale ionospheric currents in the auroral region tracked by the Freja MFE as it passed over the eastern United States on 8–9 March 1993.[23] The GIC monitors on the Chalk Point generator step-up transformer and the switchyard autotransformer recorded induced currents as part of Electric Research and Management's Sunburst Project within the Electric Power Research Institute (EPRI) program. The Sunburst Project is now

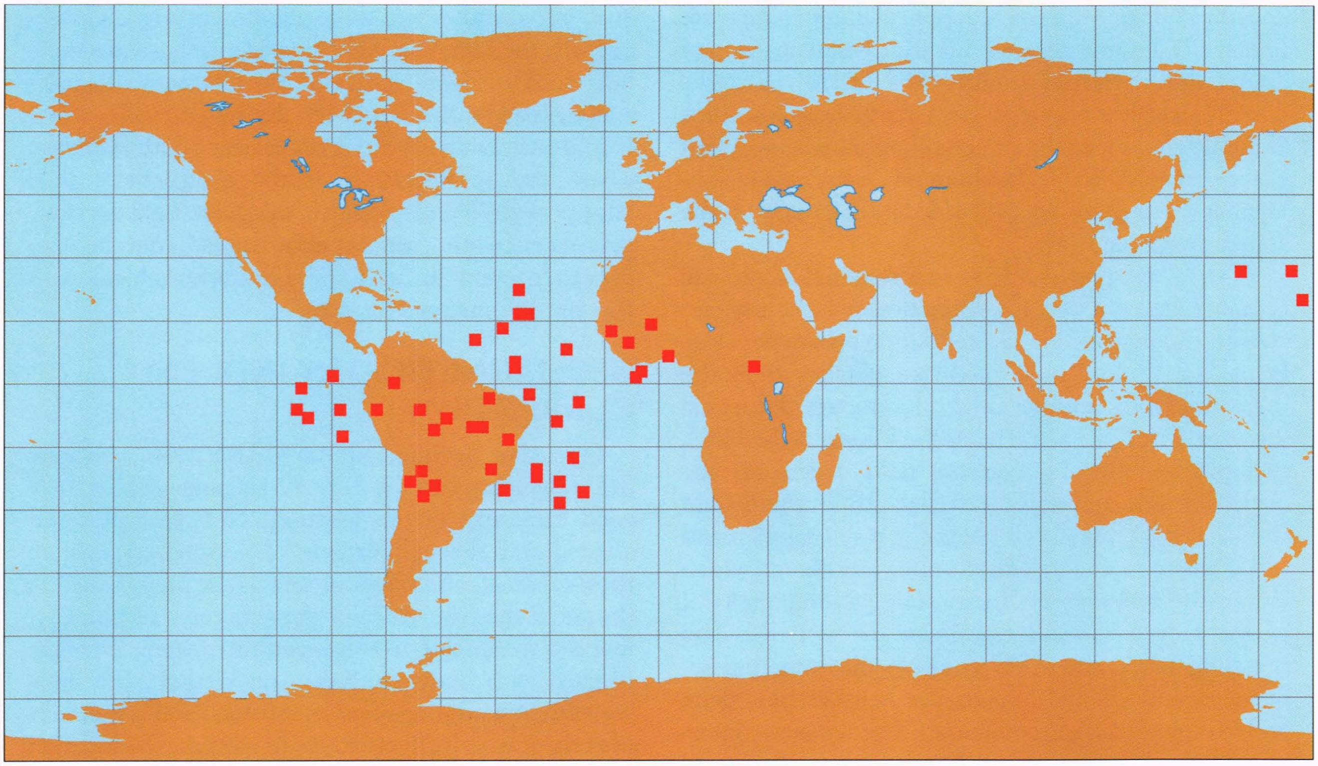


Figure 5. In June 1993, the Freja MFE flight code was reloaded with an error-correcting version in order to survive single event upsets (SEUs) caused by energetic particles in the instrument's RAM. In addition, the SEUs were recorded along with event times. This map (courtesy of James D. Kinnison of APL) shows that most events, represented by squares, for December 1993 cluster around the South Atlantic anomaly, a weak point in the Earth's magnetic field.

concentrating on the tracking and statistics of GICs and their associated harmonics through computer-controlled monitors and communications networks of currents and voltages on transformers. The Sunburst system spans the North American continent and entails 25 installed systems centrally controlled and monitored with bulletin board communication to EPRI subscribers for alerts of predetermined severity levels of GIC activity.[24]

The events near midnight between 8–9 March 1993 produced high levels of GICs and associated 60-Hz harmonics in the power transformer neutrals, which connect the generators to the transmission grid. The GICs enter through these neutral grounding points, depending on the land or land–water interface resistivity, and onto the electric power grid. A moderately active geomagnetic storm was in progress, which expanded the auroral regions and attendant ionospheric current systems to latitudes of about 45° over the east coast of the United States. IMF data (IMP-8, courtesy of R. Lepping, NASA/GSFC and Ref. 25) indicate that an interplanetary shock hit the Earth's magnetosphere at 2130 Universal Time (UT) on 8 March 1993 and was followed by an exceptionally strong southward IMF during the early hours of 9 March. Such conditions generally initiate strong geomagnetic storm activity, and the strong southward IMF maintained the expanded auroral zone and the intensity of the current system.

The Freja MFE perspective of the auroral current system is shown in Fig. 6. Freja's orbital coverage has been held fixed in space with the Earth rotated beneath according to time (time proceeds from left to right and then down). The orbital tracks (orange lines) correspond to receiving station overpasses, and the light blue segments indicate field-aligned current activity detected within the MFE. For the 8 March, 2218 UT and successive passes, the empirical model of the field-aligned current distribution[5] was used to extrapolate the auroral current zone in longitude or local time (local noon is toward the upper left in each frame). In all global views the location of the Chalk Point power generating station is indicated.

The Freja data from the passage at 2025 UT (Fig. 6, top left panel) show only minor activity, and therefore no currents are indicated. Stored Southern Hemisphere MFE data showed a similar lack of significant activity until the auroral zone passage at 2218 UT (top right), which indicates strong, albeit physically contracted, current intensities.

Figure 7 plots the 2-day time series from the Sunburst/GIC monitoring system at the Chalk Point power station. The solid line indicates the GIC (in amperes), which is essentially DC relative to 60 Hz, and the dashed lines are the various harmonics generated by the 60-Hz half-cycle saturation due to the GIC-imposed zero-level offset. These data are regularly collected only at 2-h intervals but are stored at a high rate when activity is detected. For example, the burst of data at 2136 UT on the first day corresponds to the interplanetary shock discussed earlier.

During the early hours of 9 March, we see good correspondence of activity in both the Freja auroral current zone detector (middle panels of Fig. 6) and the Sunburst monitor (Fig. 7). However, the next orbital coverage of the Freja MFE again indicates continued auroral oval activity, yet there is little GIC until 0230 UT (Fig. 7). The overview of the current system in the middle panels of Fig. 6 has changed little and appears to be over the Chalk Point station. The reason for the lack of GIC activity is not known. The orbital passage received at 0340 UT shows strong currents but a somewhat contracted oval, which has retreated from the east coast latitudes of Chalk Point. A few hours later, at 0533 UT, we indeed observe the expansion of the oval as significant GICs are recorded and the MFE auroral current detector identifies a well-developed, expanded, and strong field-aligned (and inferred electrojet) current system.

The horizontal electrojet distribution inferred from this case on 9 March is about 0.5 million A, which would produce on the order of 500 to 1000 nT at the Earth's surface. In addition, this analysis does not solve the detailed interaction between the large-scale currents and GICs, but rather the general correlation of source and induced currents. In fact, the statistical distribution of currents is a static, averaged model developed from steady-state disturbances to the Earth's magnetic field. It is the time variation and fine struc-

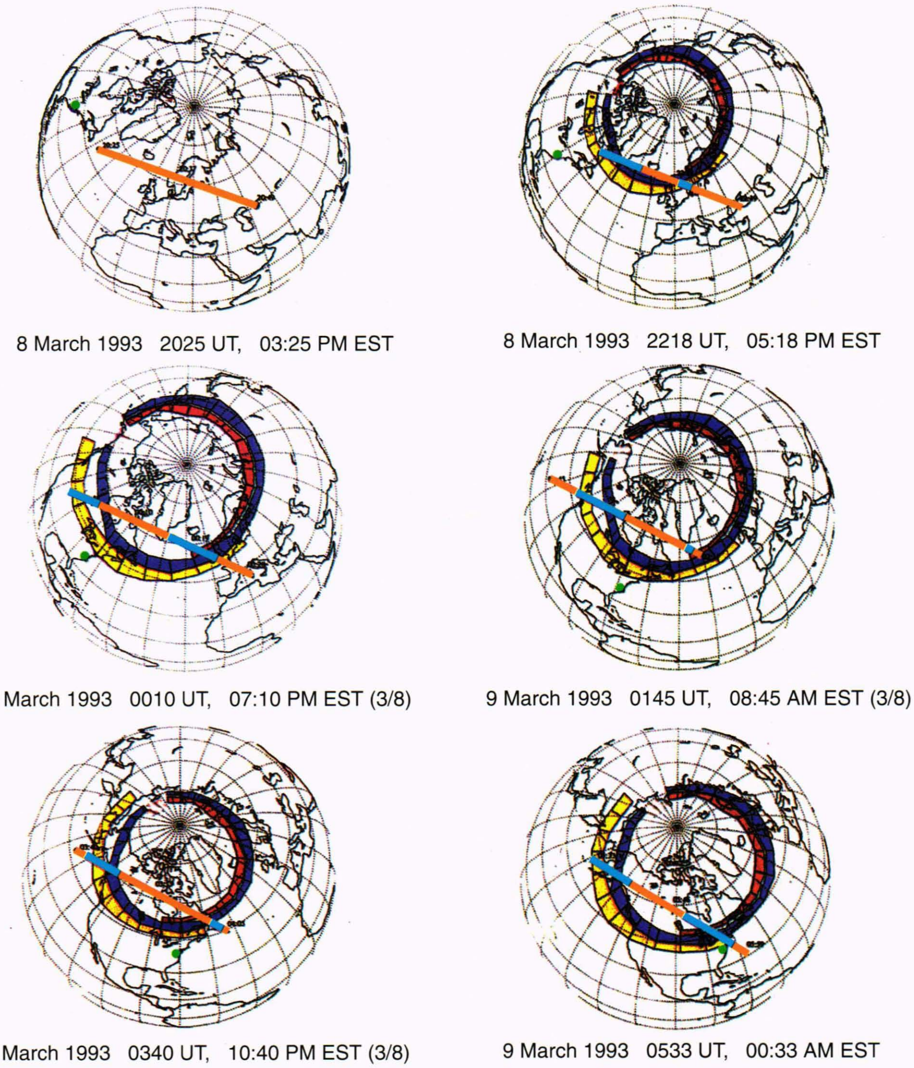


Figure 6. Six global views of the Earth with superimposed Freja orbital tracks (orange lines) and the estimated auroral current zones for 8–9 March 1993. The views are separated by about 100 min (the Freja orbital period) but are all oriented for the same local time. The Sun points to the upper left in each view. The light blue line segments on each orbital track indicate field-aligned current activity. An empirical model of the ionospheric field-aligned current distribution (see Fig. 2a) is superimposed to extend the detected currents in longitude. The Chalk Point, Maryland, power generating and transmission station is indicated by the green dot.

ture of these currents that cause the induction; the "spikes" in these ionospheric systems can certainly be larger than quoted here and vary on typical substorm times, which are on the order of minutes. This magnetic field variation (>1000 nT/min) could produce the observed GIC levels.

Two effects (both evident in Fig. 6) augment the temporal expansion and movement of the auroral zone: (1) the magnetic pole offset from Earth's spin axis and (2) the local time asymmetry of the auroral current zone. The magnetic pole of the Earth's field is in the North American sector, and the auroral current system is fixed to this pole; thus, a given geographic latitude has the highest geomagnetic latitude in the North American sector and is more likely to be within the auroral zone. The auroral current zone maps to the Earth's magnetosphere, which is compressed on the dayside and drawn out into a "tail" on the nightside. This causes the noon local time currents to be located at much higher magnetic latitudes compared with the midnight currents. The midnight sectors are also generally more active, being part of the magnetospheric tail geomagnetic storm circuit. Thus, owing to these two effects, stations such as Chalk Point rotate with the Earth up into the active midnight sector of the auroral current zone throughout the day.

DISCUSSION

The Freja MFE project has led to a generic and flexible instrument design with adaptability to differing mission requirements, high sampling rates, FFTs, filtering, and other onboard processing. Even differing telemetry interfaces can be accomplished, modified, and updated using software, providing direct cost savings for future programs. APL, in conjunction with NASA/GSFC, has built the most capable near-Earth MFE to date.

The onboard processing described in this article was necessitated by increasingly difficult data throughput in ground computer systems, compounded by a 10-fold increase in telemetry rate for the Freja MFE alone compared with any of our previous missions. Freja processing via traditional tape transfer of the full telemetry is 1 Gbyte/day.[26]

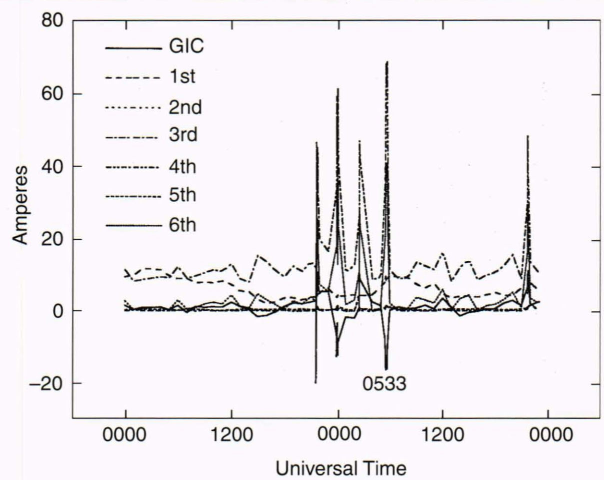
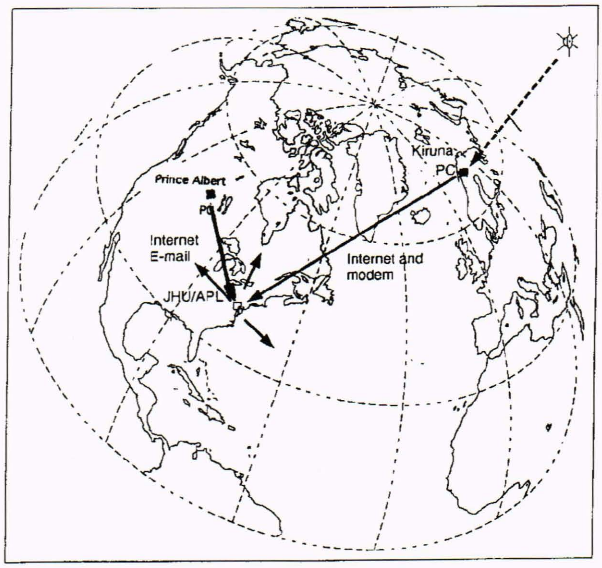


Figure 7. The 2-day time series (8–9 March) of the Sunburst/GIC (geomagnetically induced current) monitoring system data from the Chalk Point power station. The solid line indicates the GIC, in amperes, and the various dashed lines indicate the harmonics (current, amperes) caused by the 60-Hz half-cycle saturation due to the GIC-imposed zero-level offset.



SATELLITE WARNING of AURORAL ZONE INCREASES (SWAZI)

Date: 26/11/94 (d/m/y)

The Freja satellite in low earth orbit has monitored magnetic activity which may be relevant. Detection of these events by the spacecraft means that the auroral zone has expanded as a result of increased geomagnetic conditions. Such increases in space weather activity may result in grcund level disturbances in power grids and interruptions in communications.

Be advised. APL SWAZI Report for North America follows :

OUR ESTIMATED FIELD-ALIGNED CURRENT PATTERN IS AVAILABLE ON WWW through:

http://sd-www.jhuapl.edu/Freja/SWAZI/

Selected Events with Standard Deviations over 100 for DATE FILE 941126.dat

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Event duration: 120 events
Beginning: 12:24:24 UT, Ending: 12:30:57 UT

Event statistics:

Maximum Standard Deviation in Interval (counts): 977
Average Standard Deviation in Interval (counts): 342

Figure 8. A schematic of the automatic alert system, which monitors auroral zone activity. Data processed onboard are captured at the Kiruna, Sweden, receiving station during events and are transmitted via the Internet to APL computers. An operational, automatic e-mail script monitors and validates this transmission and broadcasts a summary report, included at the bottom as an example. The SWAZI (satellite warning of auroral zone increases) report for 26 November 1994 has a standard text description followed by information on the specific event, including directions to a World Wide Web map (Fig. 9).

Although CPU capabilities are increasing tremendously, input/output remains a bottleneck, making it more reasonable to process the information onboard as it proceeds through the instrument. The Kiruna ground station creates summary plots produced in conjunction with data acquisition for immediate distribution via e-mail; the parameters plotted from the MFE (including FFTs) are generated onboard and cover the full MFE bandwidth. Furthermore, these capabilities can actually be iterated with information gained from observations or with new requirements from the spacecraft, operations, or natural phenomena. For example, understanding was gained regarding auroral zone current detection during the UARS MFE data analysis effort; although the Freja MFE had been delivered and was near launch, the flexibility of the MFE FRISC processor allowed us to implement this newly gained information into the Freja MFE flight software post-launch. In March 1993, the MFE auroral current monitor was fine-tuned and upgraded based on the UARS experience. In July 1993, the MFE was completely reprogrammed to track and error-correct excessive RAM SEUs due to the high solar and magnetic activity of this present solar cycle.

The FREJA MFE "senses" geomagnetic activity via onboard processing, and this information is automatically relayed to users through the APL SWAZI (satellite warning of auroral zone increases) report. Figure 8 (top) is a schematic of this PC-based, Internet, and commercial software and communications system. Onboard-processed information products are captured at the receiving site during significant auroral events and transferred via the Internet to APL; the information is then summarized and redistributed through automatic e-mail to users. Freja is generally over Europe during data reception, possibly as far west as Greenland.

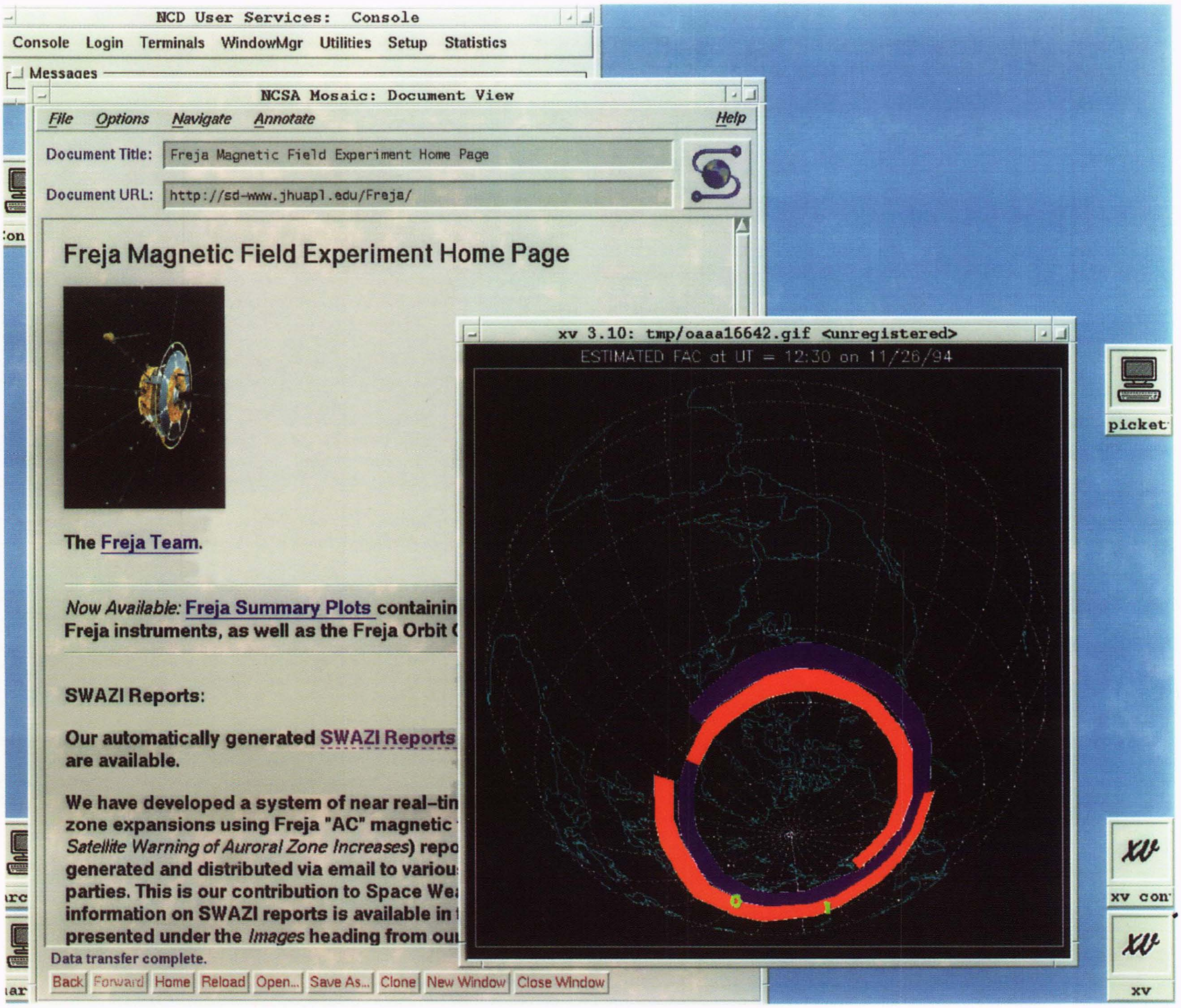

Figure 9. Map of the estimated auroral current zone corresponding to the 26 November 1994 SWAZI alert (Fig. 8), accessed via Mosaic. This World Wide Web entry is created by the software that generates and distributes the SWAZI report. The Sun points toward the upper left, and the fit of the field-aligned current system (concentric circles surrounding the magnetic pole) indicates morning ionospheric currents over the northern United States.

A SWAZI report of 26 November 1994 is also shown (Fig. 8, bottom). The relevant parameter provided in this report is the length of time Freja spends within these intense currents (deduced from the AC fluctuations), which indicates that the auroral zone has significantly expanded.

Events may be recorded once per second; for November 1994, <200 s of events indicates that Freja was within the auroral currents over Europe or ≈55° geographic latitude for North America during evening local times. The SWAZI report is sent hourly for European coverage (about 8 h) during significant geomagnetic events. Estimates of the ionospheric current patterns are also produced automatically each time a SWAZI report is generated, and those estimates are available via the Internet and the World Wide Web using software such as Mosaic or Netscape.

Figure 9 is an example of the estimate of the global ionospheric pattern corresponding to the SWAZI alert generated on 26 November 1994. From the time the spacecraft track intersects the expanded oval, an estimated ionospheric current pattern, based on Ref. 5 for geomagnetically active conditions, has been adjusted and fit to the boundary of the events. The pattern shown in Fig. 9 is from a Mosaic display, with the Sun to the left and the midnight region to the lower right; noon magnetic local time appears as a break in the outer ring. The orange rings denote current traveling along field lines into the ionosphere, and the purple rings indicate current traveling away from the ionosphere. The dawn section of the ionospheric current system is barely approaching the Great Lakes region of the United States.

Established scientific research on ionospheric current systems based on satellite magnetic field data analysis, combined with today's communications technology, can give a global perspective on the location and intensity of geomagnetically active regions in real time. The asymmetry of the current system in local time and the offset of the Earth's dipole allow us to monitor and predict the currents over the European and Atlantic sectors as ground-based operational systems in the North American sector move eastward and rotate up into the auroral current zone.

The 8–9 March 1993 correlation of GICs and auroral zone currents over the east coast of the United States is, we believe, the first direct confirmation of the influence of dynamic geomagnetic storm circuits in the ionosphere on a specific electric power system.

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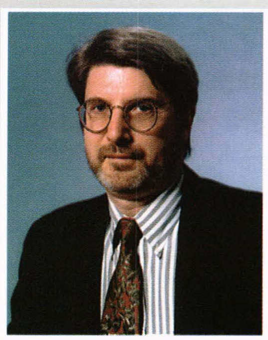

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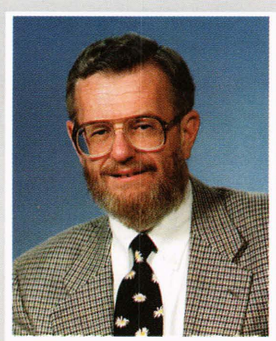

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