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THE POLAR BEAR MAGNETIC FIELD EXPERIMENT

A primary route for the transfer of solar wind energy to the earth's ionosphere is via large-scale currents that flow along geomagnetic field lines. The currents, called "Birkeland" or "field aligned," are associated with complex plasma processes that produce ionospheric scintillations, joule heating, and auroral emissions. The Polar BEAR magnetic field experiment, in conjunction with auroral imaging and radio beacon experiments, provides a way to evaluate the role of Birkeland currents in the generation of auroral phenomena.

INTRODUCTION

Less than 10 years after the launch of the first artificial earth satellites, magnetic field experiments on polar orbiting spacecraft detected large-scale magnetic disturbances transverse to the geomagnetic field.[1] Transverse magnetic disturbances ranging from ~ 10 to 10^3 nT (1 nanotesla = 10^{-5} gauss) have been associated with electric currents that flow along the geomagnetic field into and away from the earth's polar regions.[2] These currents were named after the Norwegian scientist Kristian Birkeland who, in the first decade of the twentieth century, suggested their existence and their association with the aurora. Birkeland currents are now known to be a primary vehicle for coupling energy from the solar wind to the auroral ionosphere.

Auroral ovals are annular regions of auroral emission that encircle the earth's polar regions. Roughly 3 to 7° latitude in width, they are offset $\sim 5°$ toward midnight from the geomagnetic poles. As shown in Fig. 1, the large-scale Birkeland currents generally flow in a stable pattern that is roughly coincident with the auroral oval.[3] On the morning side of the auroral oval, Birkeland currents flow into the ionosphere at higher latitudes and away from the ionosphere at lower latitudes. The flow pattern is reversed on the afternoon side. The system of Birkeland currents in the auroral zone has been referred to as "Region 1" in higher latitudes and "Region 2" in the lower latitudes. The total integrated current carried by the Region 1 and 2 Birkeland current system is on the order of 10^6 A. Considering an average auroral zone conductivity of 10 S (1 S = 1 mho), this amounts to $\sim 10^{11}$ W of power being dissipated via joule heating (i.e., $P = \mathbf{E} \cdot \mathbf{J}$ in the auroral ionosphere).

Over the past four years, the instrument complement on board the HILAT satellite (built at APL for the Defense Nuclear Agency) has yielded extensive information concerning the interrelationship of auroral phenomena.[4] During its limited lifetime, the Auroral Ionospheric Mapper experiment on HILAT generated data that were combined with magnetic field information to show that intense UV emissions are generally associated with upward-directed Birkeland currents. The brightest emissions are often associated with the more intense, small-scale currents, some of which can be generated by plasma instabilities in the distant geomagnetic tail.[5,6]

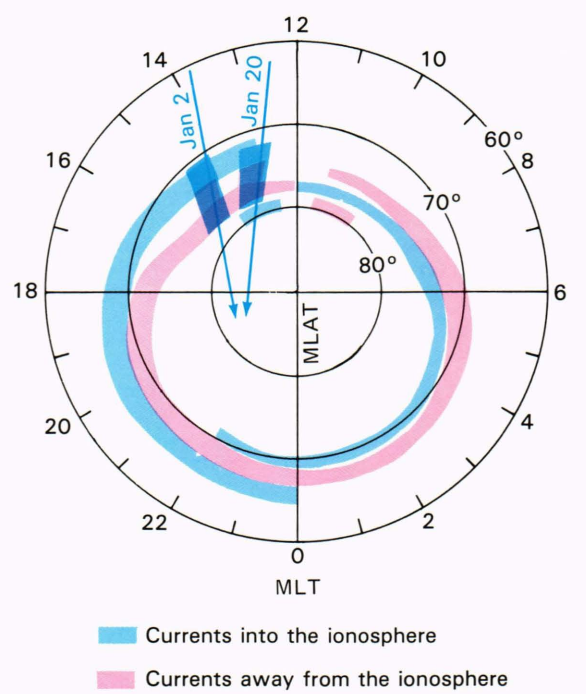

Figure 1—A statistical pattern of large-scale Birkeland currents plotted on a magnetic local time versus magnetic latitude dial (see Ref. 3). The pattern roughly outlines the region of auroral emission. The orbit footprints of two Polar BEAR passes from Fig. 5 are superimposed on the pattern, with the direction of Birkeland current flow indicated.

The objective of the Polar BEAR Program is to extend and improve on the HILAT mission. To this end, the Auroral Ionospheric Mapper was replaced by the Auroral Imaging and Remote Sensing (AIRS) experiment. AIRS measures auroral UV emissions simultaneously at four wavelengths (see the article by Meng and Huffman in this issue). The Polar BEAR magnetic field experiment was fitted with an improved, integrated sensor unit for the three orthogonal axes. The sensor unit also was located at the end of the +y solar panel to minimize interference from spacecraft-generated magnetic fields.

The Polar BEAR magnetic field experiment is described below, and some preliminary results from simultaneous measurements of Birkeland currents and UV auroral emissions are presented.

INSTRUMENTATION

Although the Oscar satellite that constitutes the body of Polar BEAR is over 25 years old and was recovered from the Smithsonian Air and Space Museum, the scientific instrumentation is of recent design. The magnetic field experiment, which consists of three components (sensor, analog electronics, and digital electronics), was assembled at APL. The integrated sensor head and analog electronics units comprise a model SAM-63C-24 vector-flux-gate magnetometer acquired from the Schonstedt Instrument Co. A block diagram of the sensor, analog electronics, and digital electronics components is shown in Fig. 2. The integrated sensor head is a single unit containing sensor windings for each of the three orthogonal axes. After extensive laboratory testing that incorporated the Polar BEAR solar panel array, it was determined that the optimum location for mounting the sensor head was at the end of the +y solar panel (see Ref. 7 and the article by Peterson and Grant in this issue). At that location, magnetic interference from spacecraft operations and from the AIRS scan mirror was minimized to less than about ±15 nT. The sensor axes were oriented parallel to the spacecraft coordinates. Nominally, this is the same as orbit normal coordinates with +x in the direction of the velocity vector, +y perpendicular to the orbit plane, and +z radially outward. In that orientation, z is nearly along the geomagnetic field in polar regions. Thus the x and y components are most sensitive to transverse magnetic field perturbations that result from Birkeland currents.

The digital electronics package, which is essentially identical to that flown on HILAT, was designed and fabricated at APL. A signal processor, modeled after the RCA 1802 microprocessor, digitizes the analog outputs of the three orthogonal axes of the flux-gate magnetometer to a 13-bit resolution, giving a magnetic field range of ±63,000 nT and a resolution of 15.2 nT. With a data-compression-differencing scheme, the Polar BEAR magnetometer processor yields 20 vector-magnetic-field samples per second, with a telemetry data rate of only 348 bits/s. (Without the processor, the required data rate would be 780 bits/s.) This is accomplished by computing "difference values" between successive samples in a given sensor and retaining the four least significant bits (plus sign) of the differences. The format of the telemetered

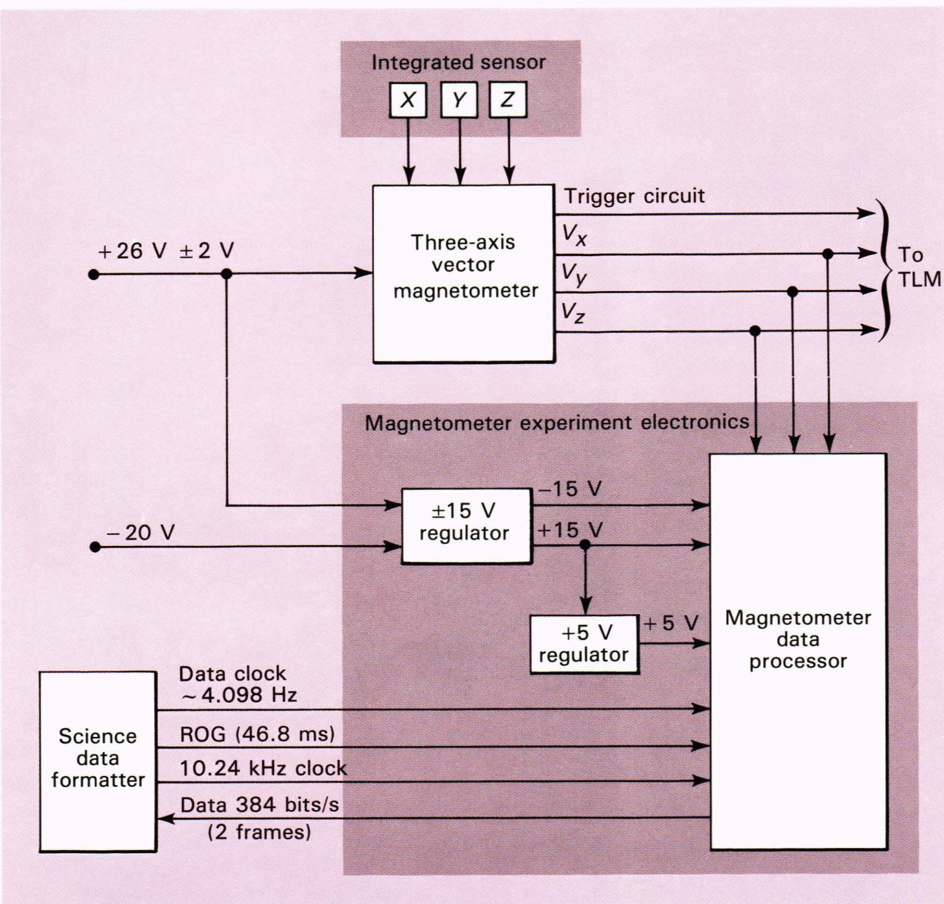

Figure 2—A block diagram of the Polar BEAR magnetic field experiment. The x, y, and z sensors are housed in the integrated sensor head. Sensor output is transmitted to the analog circuitry. Analog voltages are transmitted to the analog telemetry and to the magnetometer digital processor. The digital data are routed to the science data formatter and to the magnetometer test fixture.

data is a full 13-bit sample followed by nine 5-bit difference values. Therefore, 10 samples are transmitted for each sensor in a 0.5-s period, producing the 20 vector samples per second. The full-resolution magnetic field values are recovered by data processing techniques on the ground. The characteristics of the magnetic field experiment are summarized in Table 1.

Table 1—Polar BEAR magnetic-field experiment parameters.

Range	±63,000 nT
Resolution	15.2 nT (13 bits)
Sampling rate	20 vector samples/s
Antialiasing filter	10 Hz, low pass
Data rate	348 bits/s (using an RCA 1802-based on-board data processor)

PRELIMINARY RESULTS

Before Polar BEAR was turned over to the Navy Astronautics Group for routine monitoring, it underwent a post-launch phase in which command and tracking operations were carried out from the APL Satellite Tracking Facility. Science data were transmitted to APL on the 400-MHz transmitter during the period. Science and housekeeping telemetry data were recorded in analog form and were simultaneously processed into the digital science format through the Polar BEAR ground-support equipment. Each 0.5-s science telemetry frame, which contained magnetic field, AIRS, digital solar attitude, and instrument housekeeping data, was then stored on disk for immediate analysis at the completion of each Polar BEAR pass. Figure 3 shows typical magnetic field data acquired during post-launch operations. Here, data are plotted at two samples per second (1/10 full resolution). The vertical scale, ΔB_y, is the magnetic field component measured perpendicular to the orbit plane with a baseline field removed. ΔB_y is, therefore, a transverse perturbation of the geomagnetic field that can be ascribed to a field-aligned Birkeland current.

The magnetic disturbances associated with Birkeland currents occur predominantly in the geomagnetic east-west direction (B_y) so that from the time-independent Maxwell's equation for curl **B** (i.e., $\mathbf{J} = 1/\mu_0 \, \nabla \times \mathbf{B}$), one derives

$$J_\parallel = J_z = \frac{1}{\mu_0} \frac{\partial}{\partial x} B_y \ , \quad (1)$$

where **B** is the vector perturbation magnetic field determined by removing the baseline geomagnetic field from the measured field. The orientation of the components is such that x is directed toward the north, y is directed toward the east, and z is positive downward and parallel to the main geomagnetic field. The Birkeland current, $J_\parallel$, is uniform in the east-west (y) direction (i.e., the Birkeland current sheets are aligned in the east-west direction and are "infinite").

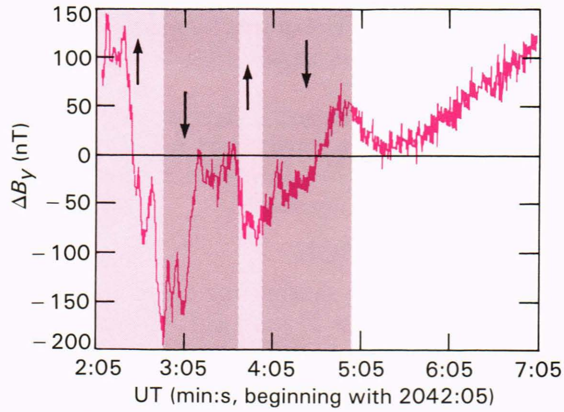

Figure 3—Preliminary data from the y axis of the Polar BEAR magnetic field experiment. For clarity, the data sampling rate shown is 2 samples per second. (The full sampling rate is 20 per second.) A baseline field has been removed from the raw data, and the resultant large-scale perturbations are transverse to the geomagnetic field. Transverse magnetic field perturbations are attributed to Birkeland currents flowing parallel to the geomagnetic field. The digitization level is ~15 nT, corresponding to the least significant bit in the 13-bit A/D converters.

$$\text{Since } \mu_0 = 4\pi \times 10^{-7} \text{ H/m} \ ,$$

$$J_\parallel = 8 \times 10^{-4} \frac{\partial B_y}{\partial x} \text{ A/m}^2 \ , \quad (2)$$

where B_y is in nanoteslas and x is in meters.

Since the speed of the Polar BEAR spacecraft is approximately 8 km/s,

$$J_\parallel = \frac{1}{\mu_0} \left(\frac{\partial x}{\partial t} \right)^{-1} \frac{\partial B_y}{\partial t} = 0.1 \frac{\partial B_y}{\partial t} \ \mu\text{A/m}^2 \ , \quad (3)$$

where $\partial B_y / \partial t$ is in nanoteslas per second.

With the above background, analysis of the data shown in Fig. 3 can be accomplished, and gradients in the transverse field can be interpreted as the signature of Birkeland currents. The large-scale negative gradient in B_y from 2042:23 to 2042:50 is ~11 nT/s. From Eq. 3, this represents a Birkeland current with a density of 1.1 μA/m^2 directed out of the ionosphere. That current is the post-noon Region 1 current system located at about 1600 MLT (magnetic local time) and 70° MLAT (magnetic latitude). The positive gradients in ΔB from ~2042:50 to 2044:45 UT are equal to an average $\partial B_y / \partial t$ of ~2 nT/s or 0.2 μA/m^2 directed earthward. The earthward-directed current corresponds to the afternoon Region 2 current system.

BIRKELAND CURRENTS AND UV EMISSIONS

Polar BEAR can simultaneously monitor magnetic field perturbations and image the aurora at four different wavelengths in the UV. Thus, a unique way is available to examine auroral ionospheric processes and to deduce how they couple to the magnetosphere by studying relationships between Birkeland currents and UV emissions from various points on the UV spectrum. One region of the auroral zone of special interest to investigators is the local time sector between 1300 and 1500 MLT at about 75° MLAT. Previous satellite observations have shown that intense outward-directed Region 1 Birkeland currents flow in that sector and reach peak intensity at about 1400 MLT. Precipitating charged particles in the auroral zone also show a peak in flux there.

Figures 4a and 4b show plots of magnetic field data collected from Sondre Stromfjord, Greenland, at about 1400 UT on January 2 and 20, 1987. The MLT in Fig. 4a is from 1550 to 1420 and the MLT in Fig. 4b is from 1425 to 1252. The plots show the residual magnetic field components from each sensor axis in nominal spacecraft coordinates. The x component is positive in the direction of the velocity vector (north). The y component is perpendicular to the orbit track and positive to the left (west), and the z component is radially away from the earth. The transverse magnetic perturbations measured on both days are qualitatively similar, but the amplitude of the perturbation on January 20 is about a factor of 2 greater than that observed on January 2. There is a westward perturbation at the highest latitude followed by an eastward perturbation and then again by a westward return to baseline values. The transverse variations correspond to a triplet of Birkeland currents. In each case, an intense current (indicated by the positive gradient in B_y) flows out of the ionosphere. The intense outward-flowing current is flanked at higher and lower latitudes by less dense currents flowing into the ionosphere. On January 2, the outward-directed current is interrupted in latitude by two narrow, embedded, earthward-directed currents. On January 20, embedded currents are not as clearly observable. The orbit tracks for each pass are overlaid on the statistical Birkeland current pattern shown in Fig. 1.

In the afternoon auroral zone, the charge carriers of the large-scale, outward-flowing Birkeland currents are predominantly precipitating electrons in the 10- to 10^5-eV range. The precipitation of energetic electrons in that energy range into the auroral ionosphere is expected to produce UV emissions observable with the AIRS experiment. UV images of the aurora acquired from AIRS on January 2 and 20, 1987, which correspond to the magnetic field traces in Figs. 4a and 4b, are shown in Figs. 5a and 5b. Geographic latitude, longitude, and land mass features are superimposed on the image. The orbit track is shown superimposed on the center of each image to aid in comparing in-situ measurements of the magnetic field with the UV image.

Magnetic field data are in-situ measurements made at an altitude of ~1000 km; the UV images from AIRS are from emissions that peak in intensity between ~100 to 200 km. In Figs. 5a and 5b, we have plotted the regions of outward- and earthward-directed Birkeland currents along the orbit track as determined from the magnetic field data. After correcting for the difference in altitude between Polar BEAR and the emission region, we found the region of outward-directed current flow to be coincident with the brightest UV emissions. This leads to the conclusion that the energetic electrons responsible for generating UV emissions also carry the outward-flowing Birkeland current in the afternoon sector.

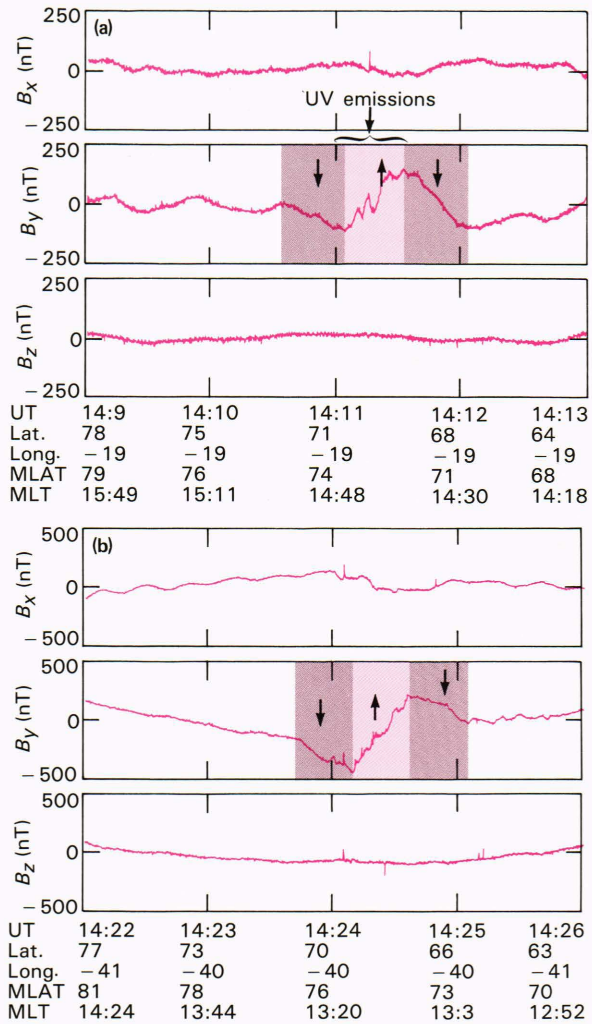

Figure 4—Three-axis magnetic field perturbations from Polar BEAR on (a) January 2 and (b) January 20, 1987. Three large-scale gradients in the y component of the field are interpreted as three current sheets. Current flow is directed out of the ionosphere in the center and into the ionosphere at higher and lower latitudes.

SUMMARY

Low-altitude auroral phenomena are intimately related to plasma processes in the distant magnetosphere and to energy transfer to the magnetosphere/ionosphere system from the solar wind. It is now well-established that a significant fraction of the energy transfer to the ionosphere from the solar wind takes place via the medium of large-scale Birkeland currents. The ultimate disposition of the transferred energy in generating auroral processes (e.g., plasma instabilities and auroral emissions) is not yet fully understood. An improved understanding of this process is one goal of the Polar BEAR mission. We have shown above that the magnetic field experiment

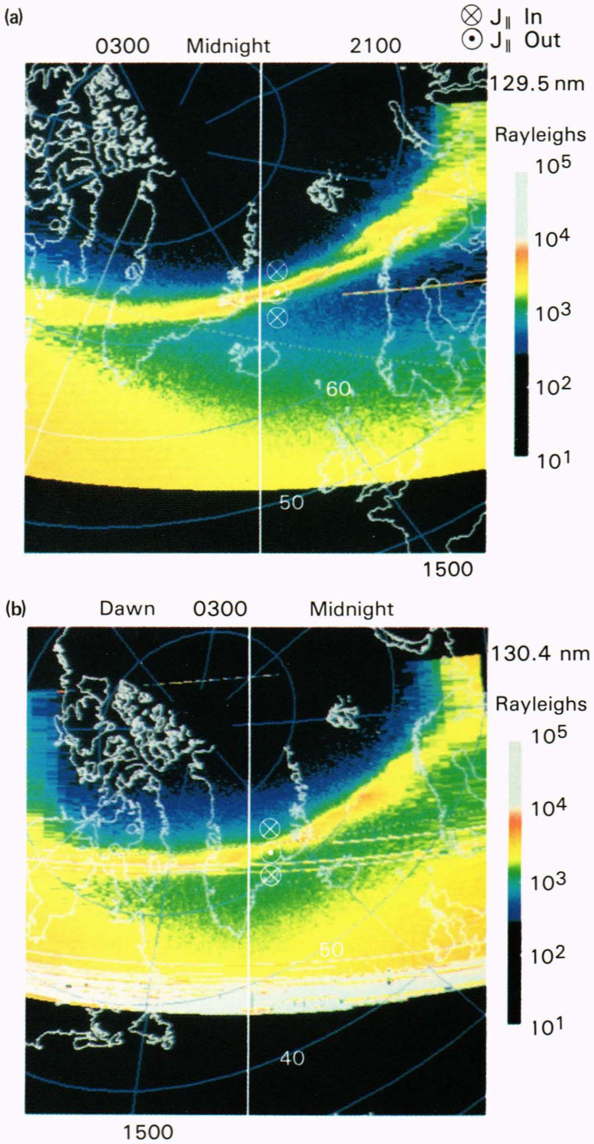

Figure 5—UV images of the post-noon auroral zone from the AIRS instrument. The orbit track is overlaid on the image. The positions along the orbit of earthward- and outward-flowing Birkeland currents are marked. The locations were corrected for the dipole field-line tilt between the emission altitude and the altitude of Polar BEAR. (Images were provided by C.-I. Meng of JHU/APL and R. E. Huffman of the Air Force Geophysics Laboratory.)

used in conjunction with the AIRS instrument is a powerful tool for furthering these studies.

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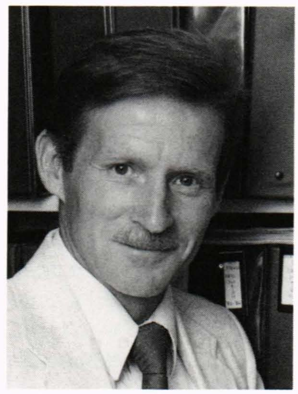
THE AUTHORS



PETER F. BYTHROW was born in Quincy, Mass., in 1949. He received his B.S. in physics from Lowell Technical Institute in 1970. After serving as a USAF pilot from 1970 to 1975, he received his M.S. and Ph.D. in space physics from the University of Texas at Dallas.

Since joining APL in 1981, Dr. Bythrow has been involved in ionospheric and magnetospheric studies using data from the Atmosphere Explorer, Triad, and MAGSAT Programs. In addition, he is co-investigator on the HILAT magnetometer experiment and has done research on data from the Voyager Saturn encounter. Dr. Bythrow is program manager for the DMSP-F7 magnetic field analysis program and co-investigator for the Polar BEAR and Upper Atmosphere Research Satellite magnetic field experiments.

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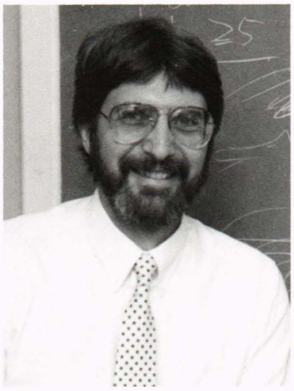

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Mr. Radford has had experience in satellite power system design, scientific instruments for spacecraft, and post-launch operation of scientific satellites. Since 1969, he has been program manager for the development of several implantable medical devices at APL and is program manager for the Programmable Implantable Medication System. Mr. Radford is also section supervisor of the Spacecraft Attitude Control and Detection Section.