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THE VIKING SATELLITE PROGRAM: PRELIMINARY RESULTS FROM THE APL MAGNETIC FIELD EXPERIMENT

Sweden's first satellite, Viking, was successfully launched from French Guiana in February 1986 with an Ariane 1 booster. It is conducting scientific observations of plasma processes in the earth's magnetosphere and auroral regions with instruments supplied by Sweden, Canada, Denmark, France, Norway, the United States, and West Germany. The APL Magnetic Field Experiment, the only instrument supplied completely by the United States, is being used to determine characteristics of field-aligned Birkeland currents in a region of space never before sampled.

INTRODUCTION

Viking, Sweden's first satellite, was successfully launched on February 22, 1986, at 0144 universal time (UT). It was carried into orbit with the French remote sensing satellite Spot by an Ariane 1 booster launched from French Guiana. Viking's perigee boost motor placed the relatively small satellite (approximately 520 kilograms) into a final 817 by 13,527 kilometer polar orbit, where it is conducting scientific observations of complex plasma processes in the earth's magnetosphere and ionosphere. The satellite carries experiments to measure electric fields, magnetic fields, charged particles, waves, and auroral images. The experiments were supplied by scientific teams from Sweden, Canada, Denmark, France, Norway, the United States, and West Germany.

The Magnetic Field Experiment is the only instrument supplied completely by the United States; it was built at APL with the support of the Office of Naval Research. F. F. Mobley, K. J. Heffernan, L. Scheer, and H. T. Henline of APL were responsible for the engineering, construction, and testing of the instrument with the assistance and guidance of M. H. Acuña of NASA's Goddard Space Flight Center. The science team consists of T. A. Potemra, L. J. Zanetti, and R. E. Erlandson of APL, M. H. Acuña of the Goddard Space Flight Center, and G. Gustafsson of the Uppsala Ionospheric Observatory in Sweden.

Telemetry data from Viking are received and processed on a real-time basis at the Esrange tracking station located near Kiruna, Sweden, above the Arctic circle. The data are reduced and displayed by computer graphics techniques immediately after reception at the ground station. Scientists engage in collaborative analysis of the space plasma phenomena at nearly the instant they are observed. Special "campaigns" are conducted that focus on special scientific topics, and coordinated observations are made with surface projects and balloon, rocket, and other satellite programs. The Viking program is unique because experiment modes can be changed on a nearly real-time basis in order to concentrate on special phenomena that may be occurring at the moment. Another unique feature is the system for distributing data to the international community of scientists. For a small charge, a series of quick-look plots is produced and distributed on a weekly basis to any scientist in the world. The plots contain summaries of the information acquired by all Viking instruments. The goal is to inspire interest in the Viking data among the international scientific community.

SCIENTIFIC OBJECTIVES

Northern Scandinavia is one of the most favorable places on earth to conduct measurements of phenomena related to the coupling of energy between the sun and outer space with the lower atmosphere and ionosphere. This is because the auroral zones are the focal points of the energy deposition, which can reach 10^{11} watts. The most spectacular manifestation of the phenomenon is the northern lights, or aurora borealis, which have been studied for centuries by Scandinavian scientists, including such prominent scientists as Celsius, Birkeland, Hansteen, Ångström, and Alfvén.

The auroral regions are a dynamic and complex system of plasmas interacting with magnetic fields and electric currents. Figure 1 is a schematic view of some of the complicated phenomena involved. The Viking program is directed toward an understanding of such large-scale processes as plasma convection, global current systems, and auroral morphology, and of small-scale and microphysical problems including particle acceleration processes, wave–particle ineractions, shock structure, fine-structured currents, and auroral kilometric radiation. Viking was specifically designed to perform high-resolution measurements of electric and magnetic fields, energetic particles, plasma waves, and ultraviolet emissions. The principal purpose of the APL Magnetic Field Experiment is to detect the field-aligned Birkeland cur-

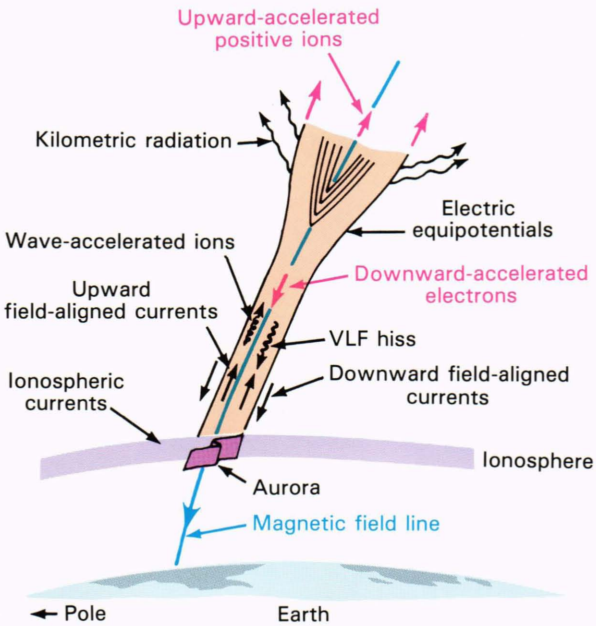

Figure 1—A schematic view of the complex plasma processes occurring on geomagnetic field lines that couple the distant magnetosphere to the lower ionosphere. Viking passed over such a region of upward-flowing ions and wave activity on March 25, 1986, at approximately 2040 UT.

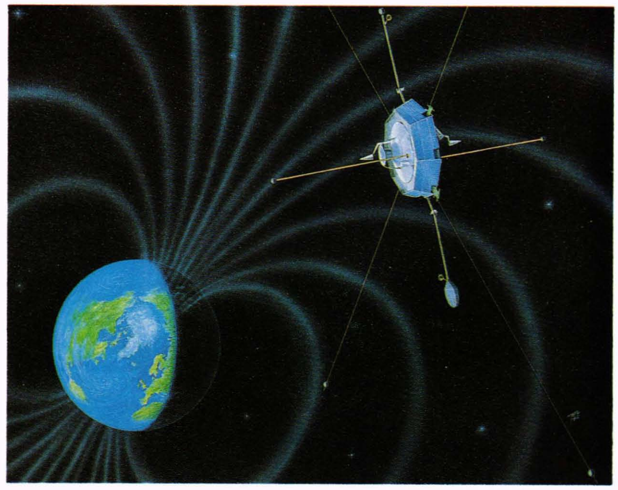

Figure 2—An artist's view of the Viking satellite in polar orbit above the earth. The fluxgate sensor for the APL Magnetic Field Experiment is located at the end of the thick boom pointing up, and the search coil sensor for the low-frequency experiment is located at the end of the thick boom pointing down. The 40-meter-long wire booms are used for the Electric Field Experiment, and the particle detectors and ultraviolet camera are mounted around the outside edge with the solar panels.

rents that flow into and away from the auroral regions above the earth. The presence of the currents was first confirmed by A. J. Zmuda and his colleagues[1] with data acquired by the APL-built satellite, 1963-38C (5E-1). The APL Magnetic Field Experiment on Viking and some early measurements are described in the following paragraphs.

THE VIKING SPACECRAFT

An artist's view of the Viking spacecraft in its deployed configuration is shown in Fig. 2. The figure shows the four 40-meter-long wire booms and two 4-meter-long axial booms used for the electric field experiment. Also shown are two 2-meter-long radial booms used for the magnetic field and plasma wave experiments. In its stowed launch configuration, Viking is about 0.5 meter high and 2 meters in diameter and it weighed 520 kilograms, including 263 kilograms for the perigee boost motor.

Power is supplied by eight body-fixed solar arrays with a battery providing backup power during eclipses. Telemetry is provided with an S-band link at a 55-kilobit-per-second data rate. Data are received on a real-time basis at the Esrange ground station. A spin rate of 3 revolutions per minute is maintained by magnetic coil torquers commanded from the ground.

THE VIKING SCIENTIFIC INSTRUMENTS

The five principal experiments on board Viking and some of their characteristics are described in Table 1.

The Magnetic Field Experiment includes a fluxgate magnetometer system with the sensors mounted on a 2-meter radial boom to reduce spacecraft-related measurement errors. The experiment has four automatically switchable ranges from ± 1024 to $\pm 65{,}536$ nanoteslas (full scale) and resolutions commensurate with a 13-bit analog-to-digital converter in each range (± 0.25 to ± 8 nanoteslas). Approximately 53 vector samples are acquired each second. The experiment is similar to the Magnetic Field Experiment on the Charge Composition Explorer satellite, part of the Active Magnetosphere Particle Tracer Explorers program (AMPTE),[2] except that the latter instrument has three additional ranges extending to ± 16 nanoteslas.

EARLY RESULTS FROM THE VIKING MAGNETIC FIELD EXPERIMENT

Figure 3 shows the orbital track of the Viking satellite for a pass beginning at 2010 UT on March 25, 1986 (just over a month after launch), plotted on a magnetic latitude–magnetic local time (MLT) polar plot. The statistical pattern of field-aligned Birkeland currents determined by Iijima and Potemra[3] from their analysis of Triad magnetic field data is shown on this plot to provide a reference frame. Noon is at the top of the polar plot and midnight is at the bottom. As shown by the orbital track, Viking passed over the evening auroral zone near 2100 MLT, then over the magnetic pole, and finally over the dayside auroral zone near 0900 MLT. The satellite was at approximately 5600 kilometers altitude when it passed over the evening auroral zone and at about 13,000 kilometers (near apogee) when it passed over the morning side.

Figure 4 is a survey plot of the magnetic field observations during the Viking pass on March 25, 1986, shown in Fig. 3. The three traces in Fig. 4 show the mea-

Table 1—Viking scientific instruments.

Experiment	*Range*	*Resolution*	*Principal Investigator*
V1. Electric field	0–0.5 V/m	0.1 mV/m	L. Block, Royal Institute of Technology, Stockholm
V2. Magnetic field	± 1,024 nT ± 4,096 nT ±16,384 nT ±65,536 nT 53 samples/sec	±0.125 nT ±0.5 nT ±2 nT ±8 nT	T. A. Potemra and L. J. Zanetti, JHU/APL
V3. Hot plasma electron spectrometer	10 eV–300 keV	16–128 energy steps ΔE/E (energy resolution) = 0.05–0.25	R. Lundin, Kiruna Geophysical Institute
Positive ion spectrometer	1 eV–40 keV	16–64 steps ΔE/E = 0.05–0.10	
Ion composition (low energy)	1 eV/g–70 keV/g	8–32 steps ΔE/E = 0.03–0.06	
Ion composition (high energy)	10 eV/g–10 MeV/g	16–64 steps ΔE/E = 0.07–0.25	
V4L. Low-frequency waves	0–15 kHz		G. Gustafsson, Uppsala Ionospheric Observatory
Plasma density	1–3,000 cm^{-3}		
V4H. High-frequency waves	10–512 kHz		A. Bahnsen, Danish Space Research Institute
V5. Ultraviolet auroral imager	1250–1400 Å 1345–1900 Å 1 image every 20 to 80 sec	<50 km	C. D. Anger, University of Calgary

sured magnetic field transformed from the spinning satellite reference frame to geographic north–south, east–west, and radial components (in the top, second, and third panels, respectively). The bottom panel shows the magnitude of the measured field. The satellite moved higher in altitude and therefore into regions of progressively smaller geomagnetic field, as this panel shows.

The major perturbations in the east–west component (BE), which appear between approximately 2030 and 2040 UT and 2135 and 2145 UT, are significant because they can be used to determine the density, direction, and location of Birkeland currents that flow into and away from the auroral zones. This is done with the formula from Maxwell's equation $\mathbf{J} = (1/\mu_0)$ curl $\Delta\mathbf{B}$ (where $\mathbf{J}$ is the current density and $\Delta\mathbf{B}$ is the magnetic perturbation). For currents flowing parallel to the geomagnetic field and in sheets aligned in the east–west direction (with infinite extent), this vector formula reduces to the scalar gradient, $J_z \equiv (1/\mu_0)(\partial/\partial x)(\Delta B_y)$ where J_z is the Birkeland current flowing along the main geomagnetic field in the z direction, ΔB_y is the perturbation in the east–west y direction, and x is the north–south direction. Since $\mu_0 = 4\pi \times 10^{-7}$ henry per meter, $J_z = 8 \times 10^{-4} (\partial/\partial x)(\Delta B_y)$ ampere per square meter, where ΔB_y is in nanoteslas and x is in meters. When combined with the speed of the spacecraft (v measured in kilometers per second), which is assumed to pass perpendicularly through the current sheet (in the y direction), $J_z = 0.8 (1/v)(\partial/\partial t)(\Delta B_y)$ microamperes per square meter. The speed of the Viking satellite varies from about 9.1 kilometers per second at perigee to 3.3 kilometers per second at apogee.

The current "intensity," $\int J dy$, is given directly by the amplitude of the magnetic disturbance by $\int J dy =$

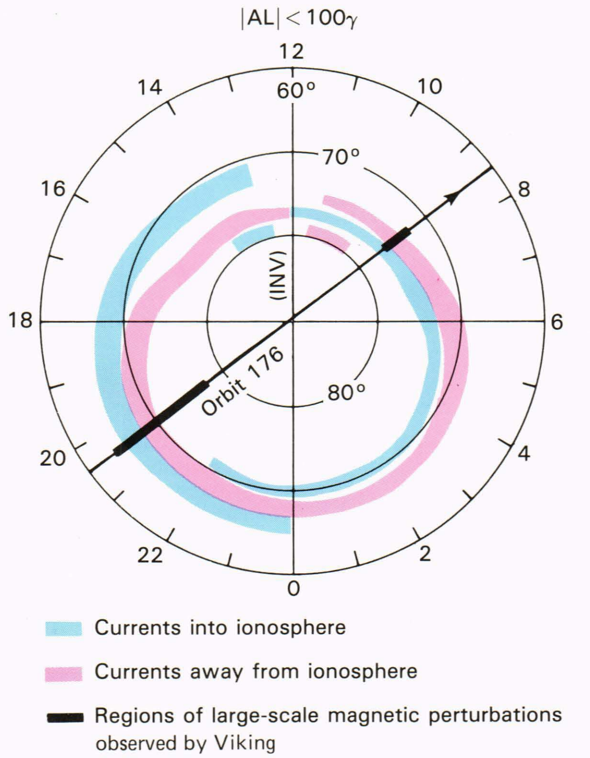

Figure 3—Projection of Viking's orbit 176 on March 25, 1986, on the invariant magnetic latitude-magnetic local time plot of the statistical location of Birkeland currents.[3] The regions of large-scale magnetic perturbations detected by Viking (see Fig. 4) are denoted by wide black lines on the orbit track.

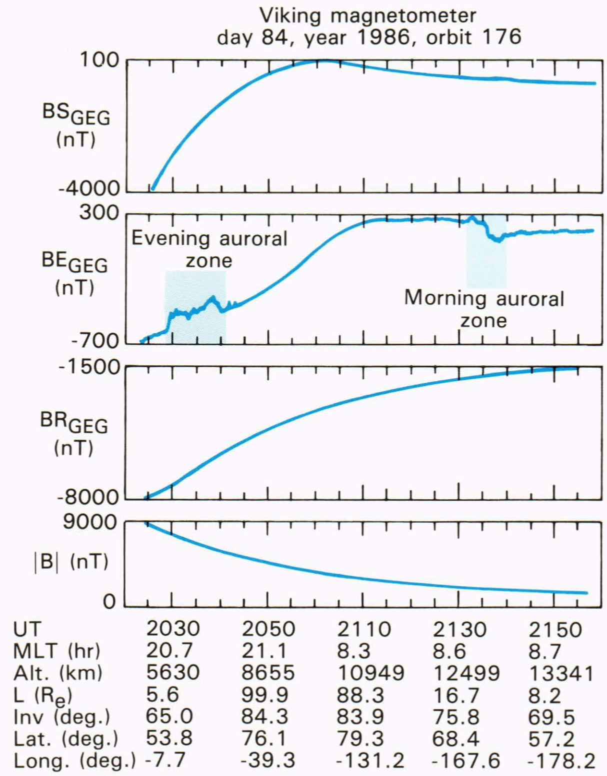

Figure 4—A survey plot of the magnetic field components measured by Viking on orbit 176 shown in Fig. 3 transformed to the geographic north-south, east-west, and radial directions (from the top, second, and third panels). The bottom panel shows the magnitude of the measured field.

$(1/\mu_0)\Delta B_y$. A 100-nanotesla perturbation corresponds to a current intensity of 0.08 ampere per meter.

The perturbations in BE shown in Fig. 4 occur as Viking passes over the evening and morning auroral zones and are very close to the statistical location of those regions as shown in Fig. 3. An expanded view of the east-west magnetic perturbation in the evening auroral zone is shown in Fig. 5. The 20-minute segment of data shown, beginning at about 2025 UT, illustrates the detail available with the high-resolution Magnetic Field Experiment instrument.

The data in Fig. 5 show a series of four large-scale gradients in the magnetic field with smaller scale fluctuations superimposed. These perturbations can be attributed to a system of large-scale Birkeland currents flowing into and away from the evening auroral zone. The positive gradients (increases in the eastward direction) are due to current flowing into the auroral ionosphere, and the negative gradients indicate currents flowing away. The steepest gradient (about 200 nanoteslas in 1 minute) occurs at the equatorward edge of the system between 2028 and 2029 UT and corresponds to a downward flowing current with an intensity of 0.16 ampere per meter. The satellite's speed at that time was about 6 kilometers per second, so the gradient corresponds to a current density of 0.4 microampere per square meter, using the formula derived earlier. This perturbation is followed by a much smaller negative gradient of less than

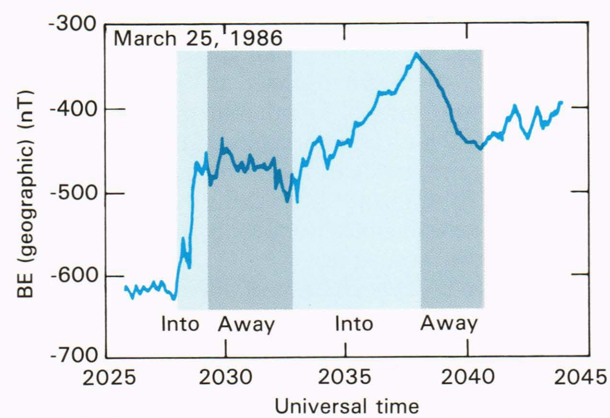

Figure 5—A 20-minute detail of the east-west magnetic field measurement over the evening auroral zone.

50 nanoteslas over nearly 4 minutes (corresponding to an upward flowing current of 0.04 ampere per meter), a positive gradient of about 150 nanoteslas in 5 minutes (0.1 ampere per meter downward current), and a negative gradient of 100 nanoteslas in 2.5 minutes (0.08 ampere per meter upward flowing current).

Past studies have indicated that the current carriers for the downward flowing Birkeland currents are upward flowing low-energy (less than 100 electronvolts) electrons from the auroral ionosphere. The upward flowing Birkeland currents are carried by downward flowing electrons that originate in the earth's magnetosphere. If they are sufficiently energetic (approximately 1 kiloelectronvolt or greater), these precipitating electrons will produce visual or ultraviolet auroral forms such as shown in Fig. 6.

The auroral image in Fig. 6 was obtained by the Viking ultraviolet auroral imager at approximately 2047 UT, about 7 minutes after the last large-scale magnetic field perturbation shown in Fig. 5. The picture, supplied through the courtesy of C. D. Anger and the Canadian imager team, shows a distinctive auroral form over the southern tip of Greenland. The correlation of the in-situ measurements, such as magnetic fields, at Viking's altitude with the auroral emissions produced at a much lower altitude in the ionosphere (about 100 kilometers) is complicated because it requires tracing of geomagnetic field lines from the satellite to the ionosphere. A preliminary attempt to determine the field-line projection of Viking's orbit on the image in Fig. 6 is shown as the line passing over Iceland and up the east coast of Greenland. Considerable work must be done before the Birkeland currents in Fig. 5 can be positively identified with the emissions shown in Fig. 6. An ultimate result of this study will be the validation of the geomagnetic field line model that is used.

An example of a higher resolution magnetic field measurement made during the same Viking orbit is shown in Fig. 7, a 1-minute plot of the east–west component of the magnetic field beginning at 2135 UT when Viking was crossing the pre-noon auroral zone (see Figs. 3 and 4) at about a 13,000-kilometer altitude (near apogee). The sampling rate of 53 hertz for the Magnetic Field Experiment corresponds to a spatial resolution of 60 meters at Viking's apogee when combined with the satellite speed of about 3.3 kilometers per second. A 60-kilometer horizontal distance at Viking's apogee altitude of approximately 2 earth radii projects along geomagnetic field lines to a horizontal distance of about 12 meters near the earth's surface. Consequently, the Magnetic Field Experiment has an equivalent spatial resolution of 12 meters in the auroral ionosphere when making measurements near apogee.

The sharp positive gradient of about 80 nanoteslas in 2.4 seconds near 2135:10 UT shown in Fig. 7 corresponds to a downward flowing Birkeland current with an intensity of 0.06 ampere per meter and a density of 8 microamperes per square meter. When projected from Viking's 2-earth-radii altitude to the lower ionosphere, that density becomes about 27 times larger or approximately 200 microamperes per square meter. This is one of the largest Birkeland densities ever observed and may be related to an intense beam of upward flowing ionospheric electrons associated with a conductivity gradient as determined by Bythrow et al.[4] from their analysis of HILAT data.

SUMMARY

In this article, we have concentrated on the APL Magnetic Field Experiment on the Swedish Viking satellite, but the ultimate scientific rewards will result from the combination of the data from that instrument with those acquired from the other Viking instruments. For example, the correlation of electric field and magnetic observations will determine which of the magnetic perturbations result from stationary currents and which from plasma waves. The combination of magnetic field, particle, and wave measurements will shed some light on understanding auroral plasma instabilities that can accelerate particles and are driven by Birkeland currents. And the ultraviolet auroral imager plays a very important role in combining all in-situ observations with auroral forms. We look forward to a very productive program in association with Sweden's first satellite, Viking.

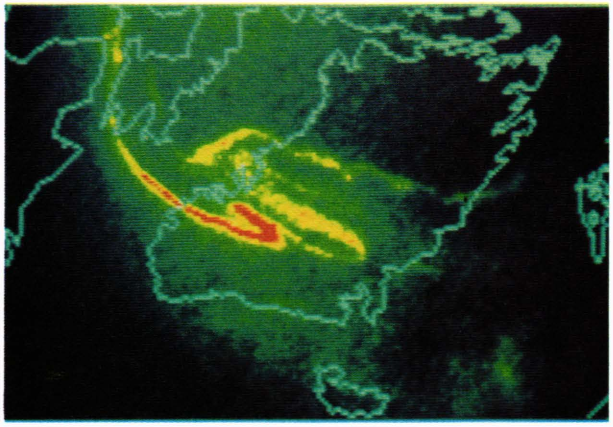

Figure 6—The image acquired by the ultraviolet auroral imager in the 1345 to 1900 angstrom band on March 25, 1986, at 2047 UT when Viking was over the evening auroral zone (see Fig. 3). The outlines of Greenland and Iceland are included in this computer-produced image, which was made available through the courtesy of C. D. Anger, University of Calgary.

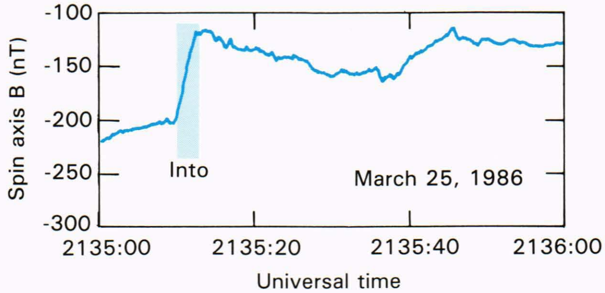

Figure 7—A 1-minute segment of magnetic field data from the spin axis sensor (approximately in the east–west direction) over the morning auroral zone.

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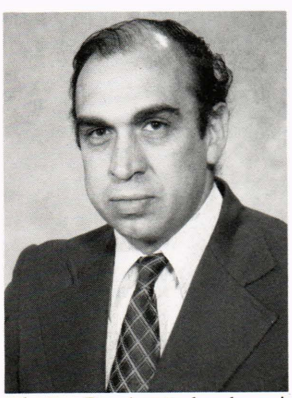
THOMAS A. POTEMRA (right) was born in Cleveland in 1938 and received his Ph.D. degree from Stanford University in 1966. He was a member of the technical staff of Bell Telephone Laboratories from 1960-62, and he joined APL in 1965. During 1985-86, he worked on special assignment as a senior policy analyst in the Office of Science and Technology Policy, Executive Office of the President. He is presently supervisor of the Space Physics Group and conducts research on magnetospheric current systems. He is the principal investigator for numerous satellite magnetic field experiments and has served on several committees of the National Academy of Sciences and the American Geophysical Union. He is a member of the faculty of The Johns Hopkins University G.W.C. Whiting School of Engineering and has been a guest lecturer at the U.S. Naval Academy.

LAWRENCE J. ZANETTI (left) was born in Huntington, N.Y., in 1949. He received a Ph.D. in physics from the University of New Hampshire. Since joining APL in 1978, he has conducted near-space research using the satellite data resources within the Space Physics and Instrumentation Group. His most recent magnetospheric research has included the development of analysis methods for inferring the three-dimensional global Birkeland and ionospheric current systems, as well as the analysis of wave spectral characteristics of magnetic vector measurements from AMPTE and Viking. Dr. Zanetti is presently principal investigator in the above programs, as well as being involved in magnetometer analyses and requirements for the HILAT, POLAR BEAR, Defense Meteorological Satellite Program, and UARS satellite projects.

ROBERT E. ERLANDSON (center) is a physicist in APL's Space Department. Born in Minneapolis, he obtained a B.A. degree in physics from Augsburg College (1982) and M.S. and Ph.D. degrees in physics from the University of Minnesota (1984 and 1986). His research interests include experimental investigations of ion acceleration in the earth's magnetosphere, generation and propagation of hydromagnetic waves, and the relationship between Birkeland currents and plasma instabilities. Dr. Erlandson has a postdoctoral research appointment at APL.



MARIO H. ACUÑA was born in 1940 in Cordoba, Argentina, where he received his undergraduate degree from the University. He earned the M.S.E.E. degree from the University of Tucuman (1967) and the Ph.D. degree in space science from The Catholic University of America (1974). In 1969, he joined the Goddard Space Flight Center, where his research interests have centered around instrumentation for geophysical and space research as well as studies of magnetic fields and plasmas in interplanetary space and in magnetospheres. Dr. Acuña has been involved with Explorers 47 and 50, Mariner 10, Pioneer 11, Voyagers 1 and 2, Magsat, the International Solar Polar Mission, Project Firewheel, and AMPTE as instrument engineer, principal investigator or engineer, or project scientist. He has received many awards in recognition of his contributions to NASA programs.

GEORG GUSTAFSSON was born in Umeå, Sweden, in 1932. He joined the Kiruna Geophysical Institute in 1958 and the Uppsala Ionospheric Observatory in 1983. Dr. Gustafsson received his Ph.D. degree in 1970 and became professor of space physics in 1985. Sabbatical periods have been spent at NASA's Goddard Space Flight Center, APL, and the University of California, San Diego. He has conducted research in ionospheric/magnetospheric physics based on particle data from the ESRO, GEOS, OGO-4, and ATS-6 satellites and on magnetometer data from Triad, as well as optical data from ground-based observations. He is now principal investigator for the low-frequency wave experiment and coinvestigator of APL's magnetometer experiment on Viking.