The Space Environment

Carl O. Bostrom and Donald J. Williams

The space science program began at the Applied Physics Laboratory in 1960 as an element of the Transit system development. The 1958 discovery of radiation trapped in the Earth's magnetic field, and the growing body of knowledge about the effects of the Sun on the temporal and spatial variations of the Earth's atmosphere, ionosphere, and electric and magnetic fields, led to the conclusion that much more information was needed about the environment of the Transit orbits. The Laboratory's experimental program, which began with solid-state proton detectors aboard the Injun I satellite (June 1961), expanded rapidly because of opportunities to launch research satellites with the Transit development satellites. This article presents selected measurements and discoveries made with satellites and instruments launched in the early 1960s. The science effort has been responsible for much of the work of the Space Department since the Transit system achieved full operational capability in the late 1960s, and it has enhanced the Department's reputation as a leader in developing important space missions from concept and design to the analysis, interpretation, and dissemination of data.

(Keywords: Charged particles, Currents, Radiation belts, Research, Transit program.)

INTRODUCTION

The Transit Navigation System was invented by Frank T. McClure, who disclosed the concept in a memorandum to APL Director Ralph E. Gibson, dated 18 March 1958 (see p. 7). The full-fledged "Proposal for a Satellite Doppler Navigation System,"[1] which included all the essential elements of the system, was dated 4 April 1958, a pretty remarkable achievement even for those "sense of urgency" days. That early proposal contained no mention or concern about the satellite operating environment, except for noting that "imperfect knowledge of the index of refraction function and of the geoid" would require experimental measurement. This omission was understandable because the early satellites that were used to develop the Doppler tracking technique had not yet revealed the existence of the radiation belts or details of the Earth's high-altitude magnetic field.

However, on 1 May 1958, at a special joint meeting of the National Academy of Sciences and the American Physical Society, James A. Van Allen of the University of Iowa announced that, based on observations by satellites 1958 α and γ (Explorer 1 and

Explorer 3), a "belt" of high-intensity radiation appeared to encircle the Earth. Van Allen had led the high-altitude research program at APL immediately following World War II, using captured German V2 rockets and the Aerobee rockets, which were developed under his direction in the late 1940s.[2] When two nuclear physicists from Yale—George Pieper and Carl Bostrom—joined the APL Space Department in September 1960 and were given the charter to measure the particle and field environment of the Transit satellites, it made good sense to approach Van Allen as a possible collaborator. First of all, he was the foremost authority on the belts that bear his name, and second, he had an APL connection.

Within a month or so, APL was committed to carrying a University of Iowa satellite, Injun I, and the Naval Research Laboratory satellite, Galactic Radiation Energy Balance (GREB), on top of Transit 4A, scheduled for launch in June 1961. Injun I was instrumented with an array of particle detectors from the University of Iowa, and a set of solid-state detectors designed and built at APL to measure low-energy protons.[3] For nuclear physicists, designing simple particle detectors was pretty easy, except for figuring out how to make them work for long unattended periods under uncontrollable conditions. To achieve reliable, stable operation, APL called upon two innovative engineers, George Bush and Frank Swaim, as well as the growing experience of the entire Space Department. More importantly, APL's Research Center had one of the world's leading theorists in the field of geomagnetism, the late Alfred J. Zmuda. He became a collaborator early on and began the process of converting nuclear physicists into geophysicists.

Just after the launch of Injun I on 29 June 1961, APL was offered the opportunity to launch Transit 4B on 15 November of that year. In parallel with this effort, the Transit Research and Attitude Control (TRAAC) satellite was designed and built—in just 3.5 months! One of us (DJW) had arrived at APL from Yale on 1 August 1961 and was immediately asked to provide an experiment for the TRAAC launch. It became instantly clear that life outside of graduate school was stressful, difficult, and frustrating—but immensely satisfying. Also at this time, an expanded set of solid-state detectors was developed into a proton spectrometer for the Injun III satellite in December 1962. We were joined by more physicists from Yale—Hans Lie and Andy Smith—and throughout the early 1960s, added Stan Kowal, Dan Peletier, Steve Gary, Dave Beall, John Kohl, the late Jim Armstrong, Pete Verzariu, and Roy Cashion, who had been the payload engineer for Injun I. From inside APL, we attracted Art Hogrefe, John Crawford, Ray Thompson, and Ray Cole. Later in that decade, we were joined by Tom

Krimigis, and Tom Potemra joined Al Zmuda in the Research Center.

Early in 1962, a series of satellites were planned to obtain environmental data in the vicinity of the operational orbit of the Transit satellites. John Dassoulas was the project engineer for these satellites, called the 5E-series, to be launched with early operational Transit satellites. Transit 5E-1 was launched with Transit 5BN-1 in September 1963; 5E-3 was launched with 5BN-2 in December 1963; 5E-2 and 5BN-3 failed to orbit (April 1964); 5E-5 was launched with Oscar 2 in December 1964; and 5E-4 was never built. (Oscar was the name of a series of operational Transit satellites.) Of the three 5E satellites launched successfully, 5E-3 was devoted to measuring ionospheric effects and a number of transistor tests, and 5E-1 and 5E-5 were designed to make particle and field measurements. Transit 5E-5 contained an ultraviolet telescope that made the first survey of celestial UV sources in the 1300 to 1650 Å wavelength range. Transit 5E-1, also known as 1963 38C, operated for more than a solar cycle ($\approx$11 years), and some of its many contributions to our knowledge of the Earth's environment will be described in a later section.

At least two histories of the Space Department have been published,[4,5] and some of the material in this article is drawn from them. At the end of this article, we present what we believe is a complete list of publications in space science by APL investigators stemming from the instruments and satellites of the early (pre-1965) Transit program. Investigators from the University of Iowa and elsewhere published extensively using data from Injun 1, Injun 3, and TRAAC; however, no attempt has been made to include that work. In the summary discussions that follow, we have chosen not to clutter the text with all the specific references. Instead, sources are contained in the list of publications.

INJUN I

The Injun I satellite was launched on 29 June 1961 along with Transit 4A and GREB into an orbit of approximately 67° inclination with apogee of 998 km and perigee of 881 km. The three satellites were supposed to separate after being placed in orbit; Injun did separate from Transit 4A, but unfortunately, did not separate from GREB. That failure meant that the planned magnetic orientation was only partially achieved, complicating the data analysis, but it turned out to have little effect on the number of significant discoveries from this 40-lb spacecraft.

Although Injun was launched during a quiet period of solar and magnetic activity, the period from 11 July to 28 July was extremely active, with some 12 major
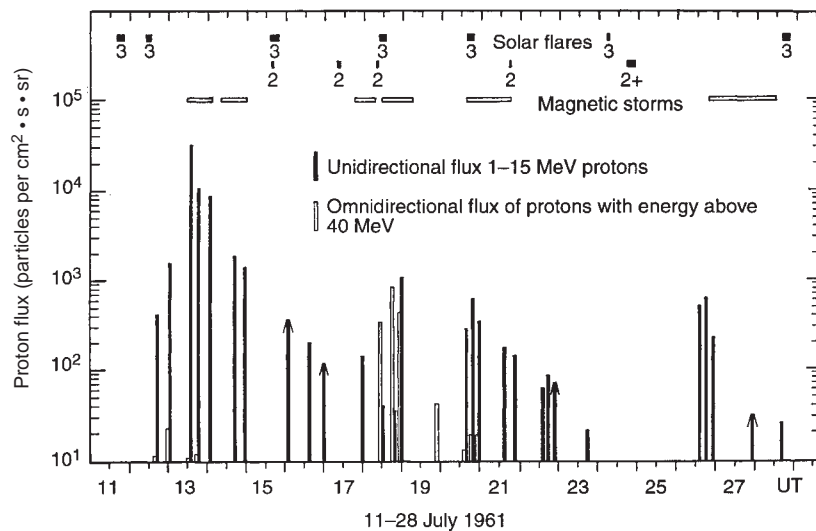
Figure 1. Solar flares, magnetic storms, and some of the proton fluxes observed by Injun 1 for 11–28 July 1961. [Adapted from Pieper, G. F., Zmuda, A. J., and Bostrom, C. O., "Solar Protons and Magnetic Storms in July 1961," *J. Geophys. Res.* **67**, 4959–4981 (1962). © 1962 American Geophysical Union.]

spacecraft and on six National Oceanic and Atmospheric Administration weather satellites in the late 1960s and early 1970s.

Despite the excitement over the July 1961 activity, and subsequent solar events in September 1961 and February 1962, the radiation belts were not ignored. The first two weeks of data showed that the outer belt contained no low-energy protons (>1 MeV) at Injun altitudes.[3] It was known from earlier measurements that the outer belt had no protons with energy above 30 MeV. Our initial studies of inner-zone protons used Injun I data from the region of the South Atlantic magnetic anomaly for July–December 1961. They examined the spatial distribution of 1–15 MeV protons and >40 MeV

solar flares and six major magnetic storms. As shown in Fig. 1, these flares produced copious fluxes of low-energy protons (our detectors were sensitive to 1–15 MeV protons) observable at high latitudes. Suddenly, our interests were diverted (temporarily) from the measurement of the Van Allen radiation belts to learning about the characteristics of solar cosmic rays and the implications of these measurements for the configuration and dynamics of the geomagnetic field. First of all, these were the first confirmed measurements of low-energy solar protons entering the polar cap regions, and they left little doubt as to the particles causing the phenomenon known as polar cap absorption (PCA). Higher energy particles (>40 MeV) were observed in significant numbers only following the flares on 18 July.

Further, the concept of geomagnetic cutoff for cosmic rays was undergoing considerable modification as more became known about the distortion of the magnetosphere by the solar wind. The low-energy solar proton measurements allowed direct observation of the location and movement of the "edge" of the polar region as a function of local time and phase of the magnetic storm. Observations of the geomagnetic latitude dependence of the proton fluxes during various phases of the storm of 13 July are shown in Fig. 2. Both the sharp rise at the cutoff and the relatively uniform particle flux at all latitudes above the cutoff enhanced our understanding of the configuration of the magnetosphere. The July 1961 observations led to numerous studies of many other solar particle events using a variety of detectors aboard different spacecraft. The APL-designed solar proton monitor was flown on three of the Interplanetary Monitoring Platform (IMP)

protons, measured the energy spectrum as a function of position, and determined that these inner-zone
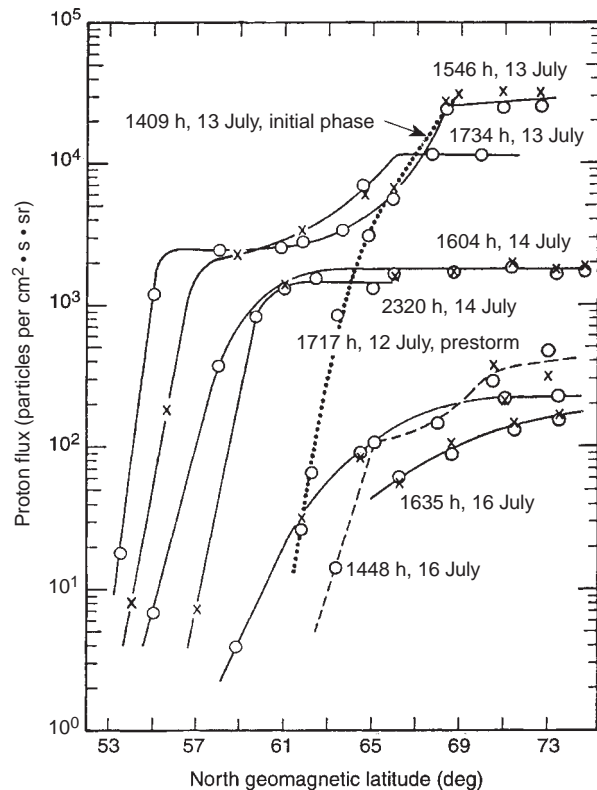

Figure 2. Latitude dependence of 1- to 15-MeV solar protons observed by Injun 1 in relation to the storm of 13 July 1961. Circles and crosses are data from different detectors. [Adapted from Pieper, G. F., Zmuda, A. J., and Bostrom, C. O., "Solar Protons and Magnetic Storms in July 1961," *J. Geophys. Res.* **67**, 4959–4981 (1962). © 1962 American Geophysical Union.]

protons were basically unaffected by the major solar and magnetic disturbances of that period.

Injun I was in position to measure the artificial radiation belt created by the Starfish high-altitude nuclear test in July 1962. However, the APL detectors, having little sensitivity to electrons, were not useful in these studies. Unfortunately, Injun I was one of several satellites that came to an untimely end, because the intense Starfish belt of high-energy electrons severely damaged the solar cells.

TRAAC

Following the 3.5-month concept-to-launch schedule mentioned previously, TRAAC was launched on 15 November 1961 into an orbit with apogee of 1100 km, perigee of 951 km, inclination of 32.4°, and period of 105.8 min. Designed to extend the measurements

of the Transit environment begun by Injun I, it carried a variety of charged-particle detectors along with an experiment to explore the origin of the radiation belts by measuring the flux of neutrons produced by the impact of cosmic rays with the atmosphere. Like Injun I, TRAAC's lifetime was shortened considerably by the Starfish high-altitude nuclear test. The degradation of the solar cells caused a final loss of signal on 12 August 1962.

At launch, TRAAC provided a first-of-a-kind contribution to the space program—the first original poem dedicated to space research placed in Earth orbit (see the boxed insert). This perhaps is one reason why the bits and bytes from space do not seem as impersonal to us as they may to others.

The TRAAC data showed that not only did the detonation directly inject electrons into the radiation belts, it also established a secondary radiation belt

---

FOR A SPACE PROBER

The atmosphere of working at the forefront of a new and developing field of research was exhilarating, so much so that we were inspired to commemorate these initial forays into space. Given the strong (and recent) ties of our young group to Yale University, it seemed only natural for George Pieper, Head of the Space Research and Analysis Project, to approach Thomas G. Bergin, then Professor of Romance Languages and Master of Timothy Dwight College at Yale, to compose and dedicate a poem to the newly developing field of space research. He responded with alacrity, and the poem, "For a Space Prober," was received, inscribed upon an instrument panel, and launched onboard the TRAAC satellite, 1961 $\alpha\eta2$, on 15 November 1961. Signatories of this first poem into space were George F. Pieper, Carl O. Bostrom, George Bush, Hans Lie, Frank Swaim, and Donald J. Williams. Following launch, a copy of the poem as engraved on the instrument panel was presented to Professor Bergin, then reigning Poet Laureate of Outer Space.

FOR A SPACE PROBER

From Time's obscure beginning, the Olympians
    Have, moved by pity, anger, sometimes mirth,
Poured an abundant store of missiles down
    On the resigned, defenceless sons of Earth.

Hailstones and chiding thunderclaps of Jove,
    Remote directives from the constellations:
Aye, the celestials have swooped down themselves,
    Grim bent on miracles or incarnations.

Earth and her offspring patiently endured,
    (Having no choice) and as the years rolled by
In trial and toil prepared their counterstroke—
    And now 'tis man who dares assault the sky.

Fear not, Immortals, we forgive your faults,
    And as we come to claim our promised place
Aim only to repay the good you gave
    And warm with human love the chill of space.

Thomas G. Bergin
Professor of Romance Languages
and Master of Timothy Dwight College
Yale University
New Haven, Connecticut

(Fig. 3) created from decay electrons emanating from the fission fragments that fell back into the atmosphere. Because of the low-injection altitude and asymmetries in the magnetic field of the Earth, these decay electrons lasted at most a few hours. The lifetime of this secondary radiation belt was controlled by the source, the fission fragment population at the top of the atmosphere. Unfortunately, signals from TRAAC stopped before an accurate time history of the atmospheric fission fragment source could be collected.

A second TRAAC study of the artificial radiation belts created by Starfish provided information on its time evolution. It was observed, for example, that electron fluxes obtained at $B = 0.23$ G and $L = 1.216$ Earth radii had decayed by roughly a factor of 50 between 1.0 and 9.5 h after the detonation. [Note that early in the study of the radiation belts, it was found that the observations were best organized by using a special coordinate system. In this system, a particular magnetic field line (or shell) was labeled by its effective equatorial crossing distance in Earth radii, and the location along the field line was specified by the magnetic field strength in Gauss. This (B,L) system has north–south symmetry and is independent of longitude, appropriate for mirroring drifting charged particles.] Data from many satellites over an extended period were required to map the time and spatial behavior of the artificial

belts. The TRAAC data also showed a shift in the spatial structure of the new belts as seen at low altitudes some 5 days following the explosion. It is not known whether this shift was a result of enhanced scattering of the electrons by electromagnetic radiation or the appearance of an additional source.

The information emerging on the strength and behavior of the radiation belts made them a factor in the design and operation of Earth-orbiting satellites. Information about their source(s) could provide increased accuracy in predicting expected mission radiation doses. For this reason, TRAAC carried a neutron detector to test whether cosmic ray impact on the atmosphere produced enough neutrons to supply the radiation belt particles observed, especially at low altitudes where Transit was designed to operate. Data were collected for 240 days before the Starfish detonation obliterated further observations. The neutron measurements showed spatial and time variations in the neutron intensity that were in general agreement with model calculations. On the basis of these results, a major conference on the Earth's albedo neutron flux was sponsored by and held at APL in 1963. It is now agreed that the Earth's albedo neutrons do constitute the major source for protons greater than ≈10 MeV and at altitudes less than ≈1.4 Earth radii. However, most of the particle populations trapped in the Earth's magnetic field display time and spatial variations that cannot be supported by the neutron source. TRAAC was one of the first (if not the first) satellites to test the viability of the neutron albedo source.

TRANSIT 5E-1 (1963 38C)

Solar Particle Events

The Transit 5E-1 satellite, launched in September 1963, provided an extremely valuable data set for the study of the Transit system environment. At 1100-km altitude and in polar orbit, 5E-1 was used extensively in the continuing research on solar energetic particles in the polar regions. Nearly one-third of the publications based on data from 5E-1 are concerned with the analysis of the observations of solar particle events. Because the satellite had a useful life of more than a solar cycle, there were numerous opportunities to compare and correlate
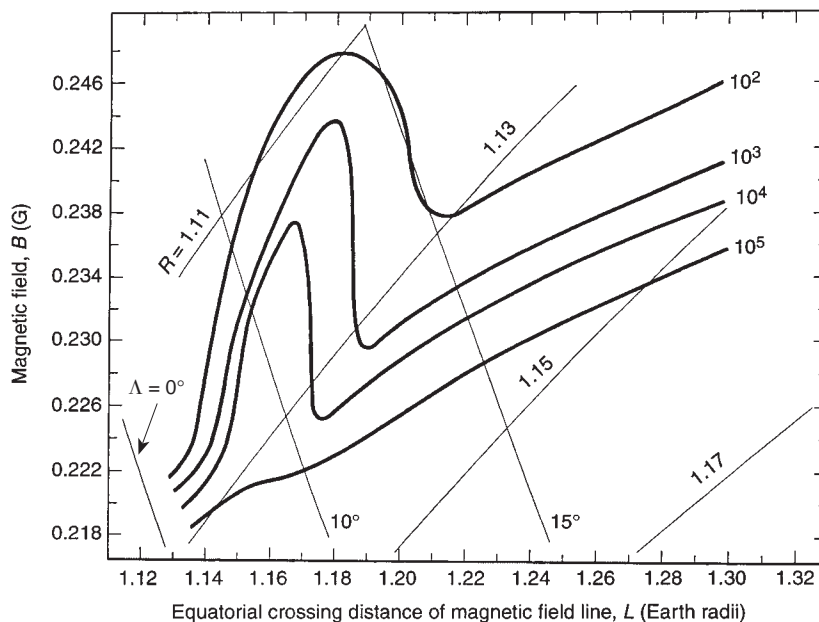
Figure 3. Flux contours in *B–L* space determined by the TRAAC 302 Geiger counter between days 192 and 199 in 1962 in the longitude region ≈180° E to ≈230°. Contours refer to the omnidirectional flux of electrons of energy >16 MeV in units of particles/cm²·s. A grid in *R–Λ* space is also shown to aid in visualizing the second artificial radiation belt created by the 9 July 1962 nuclear explosion. *R* is the radial distance, and Λ is the magnetic latitude. [Adapted from Pieper, G. F., Williams, D. J., and Frank, L. A., "TRAAC Observations of the Artificial Radiation Belt from the July 9, 1962, Nuclear Detonation," *J. Geophys. Res.* **68**, 635–640 (1963). © 1963 American Geophysical Union.]

measurements with many other spacecraft in the magnetosphere and in the interplanetary medium. The 5E-1 measurements had relevance to studies of solar flare processes, the interplanetary medium, the magnetosphere, the ionosphere, and the upper atmosphere.

As one example, the solar proton event of 5 February 1965 was rather modest in terms of its intensity; however, a combination of circumstances allowed it to contribute to our understanding of a variety of phenomena. The location of the flare and simultaneous observations by the Mariner 4 and Injun 4 spacecraft led to information about the topology and time variations of the high-latitude magnetosphere, and also indicated that particle motion across interplanetary field lines was necessary to explain the proton arrival times in the vicinity of Earth. These same polar region proton data were used to develop a model ionosphere that was then used to explain the observed VLF phase perturbations during the course of the magnetic storm produced by the event.

Field-Aligned Currents

The 5E-1 satellite used a passive magnetic attitude stabilization system, which contained a set of three orthogonal vector magnetometers. The magnetic stabilization maintained the z axis of the satellite parallel to the Earth's magnetic field (within about 5°), allowing the particle detectors to measure particles moving parallel and perpendicular to the local field direction. The magnetometers were oriented so that the z-axis magnetometer was parallel to the local magnetic field and thus provided an approximate measure of the total field strength. The x- and y-axis magnetometers were approximately perpendicular to the Earth's field and, because they were expected to measure field strengths near zero, were designed to have greater sensitivity.

In February 1964, Al Zmuda suggested using the transverse magnetometers to search for evidence of hydromagnetic waves at high latitudes by commanding the telemetry system to dwell on either the x or y magnetometer during a satellite pass over APL. After several attempts, a disturbance was indeed found, and over the next two months disturbances were found in about 85% of the passes. Zmuda and colleagues reported

this phenomenon in 1966 and launched a major new field of research. Although reported as "transverse magnetic disturbances," there was early speculation that the observed disturbances were the magnetic signatures of electrical currents flowing along the magnetic field lines in the vicinity of the auroral oval. A particularly striking observation that occurred on 1 November 1968 is shown in Fig. 4.

Zmuda's discovery was soon confirmed to be the field-aligned currents that had been postulated by Kristian Birkeland in the early 1900s. The large body of observations from 5E-1 led to the flight of improved magnetometers on TRIAD, the first satellite in the Transit Improvement Program, and later on a number of other polar orbiting satellites.

The Radiation Belts and Magnetospheric Modeling

Transit 5E-1 also included energetic electron detectors in its payload to determine the magnitude and distribution of penetrating fluxes that the Transit Navigation System would encounter. As we began our studies to meet this objective, we quickly realized that the 5E-1 data represented a unique resource and had the potential to provide vital new information on the spatial distribution and time variations of the Earth's low-altitude trapped particle populations.

Our initial studies established the variation of energetic electron fluxes as a function of universal time and L value. Satellites like 5E-1, in polar near-circular
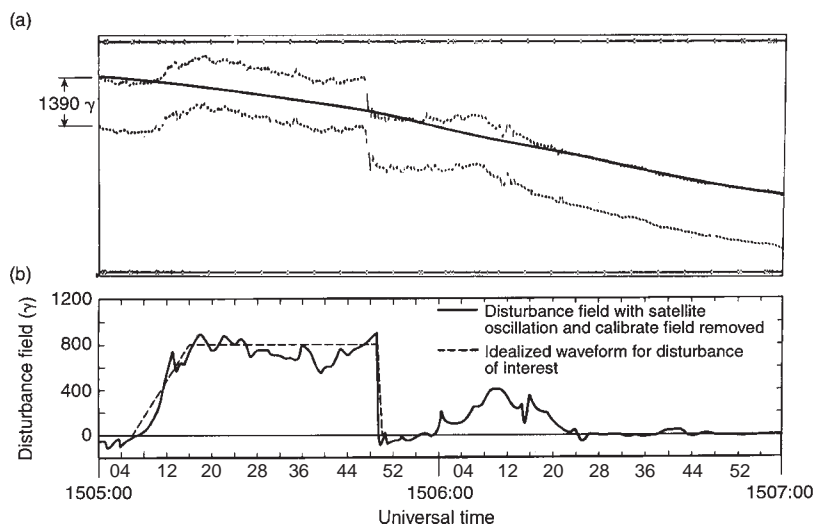
Figure 4. (a) The transverse magnetic disturbance detected by satellite 1963 38C on 1 November 1968 at a local time of 0851 h. The magnetic activity index was 8[+], indicative of highly disturbed conditions. (b) Reconstruction of disturbance field and idealized waveform for disturbance of interest. [Adapted from Amstrong, J. C., and Zmuda, A. J., "Field-Aligned Current at 1100 km in the Auroral Region Measured by Satellite," *J. Geophys. Res.* **75**, 7122–7127 (1970). © 1970 American Geophysical Union.]

orbits, sample L values ranging from satellite altitude at the magnetic equator to very large values in the high-latitude portions of the orbit. Our first study showed that variations in energetic electron fluxes ranged from no correlation with magnetic activity at magnetic latitudes less than $\approx45°$ (L values <≈2 Earth radii) to very strong correlation with magnetic activity at latitudes greater than $\approx55°$ (L values >≈3 Earth radii). By correlating our data over several months with simultaneous data obtained near the geomagnetic equator, we were also able to show that such variations occurred both at low and high altitudes, i.e., throughout the magnetic flux tubes sampled. These were global variations occurring throughout the radiation belts.

During these initial studies, we noticed that the latitude profiles of the electron fluxes at local noon and local midnight were displaced in the sense that a given electron flux was observed at a lower latitude at midnight than at noon. This observation resulted in a series of more globally oriented studies and led to the development of the first quantitative model of the Earth's magnetosphere to explain the observed flux displacements (Figs. 5 and 6). This model, although stemming from low-altitude electron measurements and confined to the noon–midnight plane, was similar to empirical models developed at the time using magnetic field data obtained throughout Earth's high-altitude magnetic field from the NASA IMP satellites.[6] The model also turned out to be successful in explaining the relative motion of the low-altitude, high-latitude electron trapping boundary during magnetic storm periods and agreed with the observed L-value displacements seen between measured low- and high-altitude electron fluxes during magnetic storms. This model has long since been superseded by greatly improved, three-dimensional magnetic field models that incorporate within them models of the Earth's charged-particle populations. However, the data from 5E-1 were what led to one of the first successful efforts to provide a quantitative explanation for trapped particle variations by configuration changes in the global magnetic field.

Continuing investigations showed the dramatic loss of trapped particles in the South Atlantic anomaly region of the Earth's surface magnetic field, the reappearance of particles just outside that region due to electromagnetic scattering along the field line from higher altitudes, and the relationship of electron fluxes in the radiation belts to solar wind parameters. These studies all contributed to our growing knowledge and understanding of the environment in which satellite systems had to operate. The 5E-1 data often provided either the first direct observations of their kind or analyses yielding new results and insights in magnetospheric physics that went far beyond the initial goal of simply charting the low-altitude space environment.
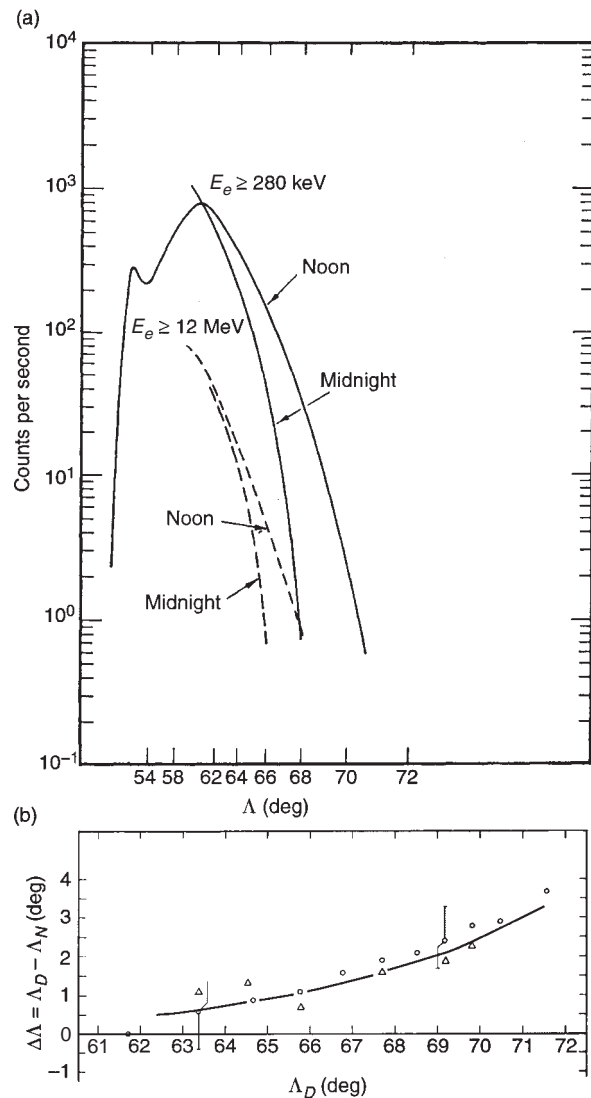

Figure 5. Example of maintenance of charged-particle trapping even in the highly distorted geomagnetic field. (a) Intensity versus invariant latitude (Λ = arc cos $L^{-1.2}$) profiles at 1100 km on the noon–midnight meridian for outer-zone energetic electrons. (b) Diurnal variation, $\Delta\Lambda = \Lambda_D - \Lambda_N$ (Λ_D, Λ_N = dayside and nightside latitude of observation, respectively) from data in (a) plotted versus dayside latitude, Λ_D. Solid curve is expected variation based on adiabatic motion of electrons trapped in the distorted geomagnetic field; $\circ$, trapped electrons E_e > 280 keV, matched pass data; $\triangle$, trapped electrons E_e > 280 keV—daily averages. [Adapted from Williams, D. J., and Mead, G. D., "Nightside Magnetosphere Configuration as Obtained from Trapped Electrons at 1100 Kilometers," *J. Geophys. Res.* **70**, 3017–3029 (1965). © 1965 American Geophysical Union.]

The Starfish Artificial Radiation Belt and the Inner Radiation Zone

The long life of 5E-1 allowed it to examine long-term changes in the radiation belts, both natural and artificial. Several important questions regarding the trapped particles had to do with the stability and variability of the natural belts, and with the lifetimes
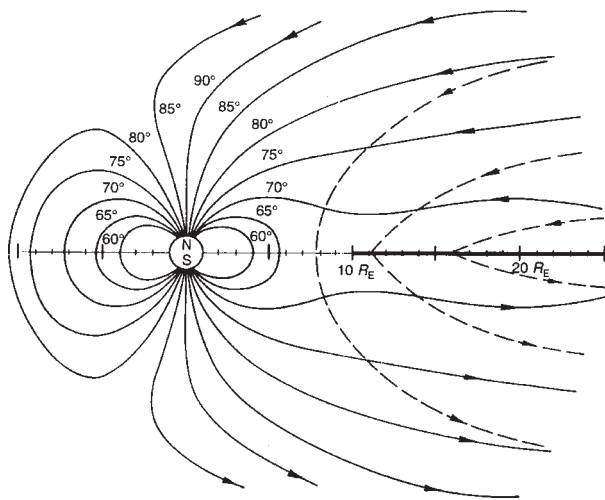
Figure 6. Geomagnetic field model used to explain trapped electron distributions. Solid lines show the distorted geomagnetic field as made up of components due to the Earth's dipole B_d, surface currents at the magnetopause B_s, and a current sheet in the nightside hemisphere B_{cs}. The dashed lines show the field due to the current sheet B_{cs} alone. [Adapted from Williams, D. J., and Mead, G. D., "Nightside Magnetosphere Configuration as Obtained from Trapped Electrons at 1100 Kilometers," *J. Geophys. Res.* **70**, 3017–3029 (1965). © 1965 American Geophysical Union.]
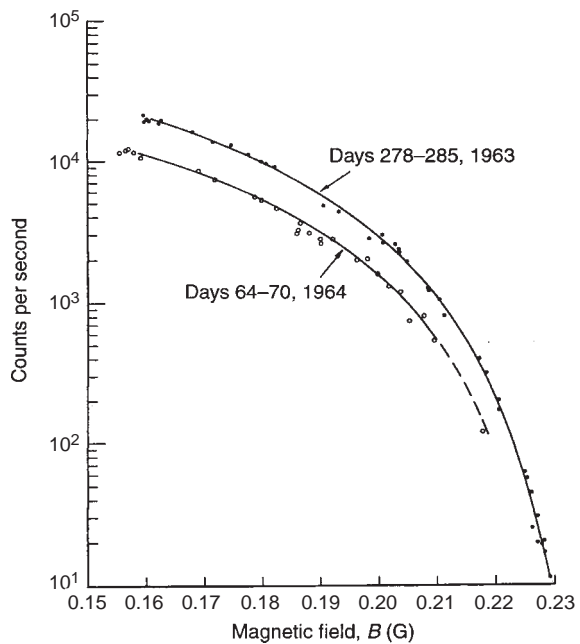

Figure 7. Intensity of electrons $E > 12$ MeV, measured by instrumentation onboard APL satellite 1963 38C, as a function of B at $L = 1.30$ for two epochs 151 days apart. [Adapted from Bostrom, C. O., and Williams, D. J., "Time Decay of the Artificial Radiation Belt," *J. Geophys. Res.* **70**, 240–242 (1965). © 1965 American Geophysical Union.]

of the energetic electrons introduced into the inner belt region by Starfish. Figure 7 shows the intensity of electrons with energy >1.2 MeV on the magnetic field line that crosses the equator at 1.3 Earth radii ($L = 1.3$) at two different time periods separated by 151 days. Similar measurements for a number of field lines yielded lifetimes (assuming exponential decay) between 120 and 460 days, with the longest lived electrons at about $L = 1.5$. A more comprehensive study using 27 months of data was conducted to determine electron lifetime variations as a function of energy and location.

Finally, a long-term study of the inner radiation zone was conducted using a variety of 5E-1 data channels (two electron channels, >0.28 MeV and >1.2 MeV; and four proton channels, 1.2–2.2 MeV, 2.2–8.2 MeV, 8.2–25 MeV, and 25–100 MeV). Figure 8 shows the 10-day average counting rates for the highest energy proton channel from October 1963 to December 1968 on several inner-zone magnetic field lines. The stability of these protons in the heart of the inner zone ($1.2 < L < 1.5$) is fairly obvious; at higher L-values, there is evidence of response to major solar

and magnetic disturbances, particularly around the events in May 1967.

It should be pointed out that all of these early satellites were BOBS (before on-board storage). All the data were acquired in real time from an array of ground stations scattered around the globe. Much of
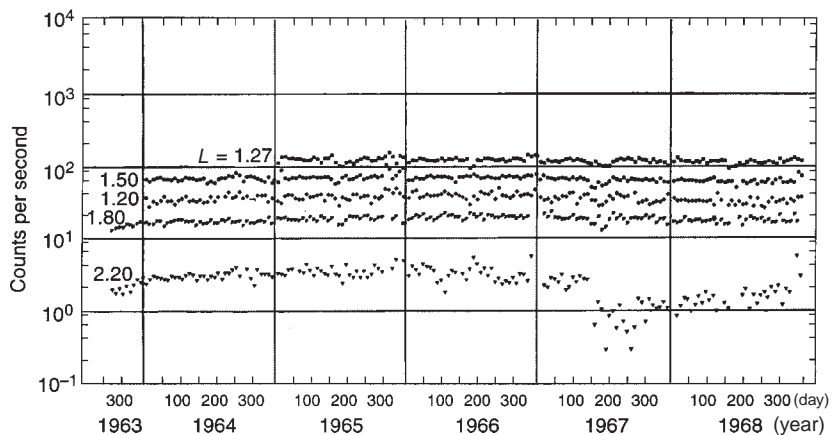

Figure 8. Ten-day average counting rates for P4, the highest energy proton channel ($25 \leq E \leq 100$ MeV) from October 1963 through December 1968 at $L = 1.20$, 1.27, 1.50, 1.80, and 2.20 Earth radii. [Adapted from Bostrom, C. O., Beall, D. S., and Armstrong, J. C., "Time History of the Inner Radiation Zone, October 1963 to December 1968," *J. Geophys. Res.* **75**, 1246–1256 (1970). © 1970 American Geophysical Union.]

the inner-zone data came from stations in Brazil, Ascension Island, and South Africa; most of the high-latitude data were received by stations located at APL and in Alaska and England.

LEGACY

The Transit space science research effort was successful beyond its original stated objective of charting the charged-particle fluxes in the low-altitude space environment. Through the establishment of numerous joint efforts in experiment development and data analysis, the early small group of space researchers at APL fully integrated into the young and expanding space research community. This integration led to scientific investigations well removed from Transit. In hindsight, we believe that this was expected by Department management at the time—that is, research supported by a real need was encouraged to expand into related areas.

What perhaps was not expected was the ultimate success of this expansion. Today, the Space Department is noted for its development of space research programs, satellites, and experiments; it is staffed with internationally known scientists and engineers; and it continually provides innovative and state-of-the-art space technology. From the early effort comprising 15 to 20 people who worked on Transit, APL's space research program has grown to well over 200 people supported by more than 100 external programs. From the early task to map the Earth's low-altitude radiation belts and its low-altitude magnetic field has come the present Space Department research efforts in atmospheric, ionospheric, magnetospheric, and heliospheric physics, spanning the solar system and including asteroids, comets, the planets, and their moons. A truly remarkable legacy, indeed!

REFERENCES

[1] *Proposal for a Satellite Doppler Navigation System,* TG 305A, JHU/APL, Laurel, MD (1958).
[2] Van Allen, J. A., "My Life at APL," *Johns Hopkins Tech. Dig.* **18**(2), 173–177 (1997).
[3] Pieper, G. F., "INJUN, A Radiation Research Satellite," *Johns Hopkins Tech. Dig.* **1**(1), 3–7 (1961).
[4] *History of the Space Department, The Applied Physics Laboratory, 1958–1978,* JHU/APL SDO-5278, Laurel, MD (1979).
[5] *The Space Program at the Applied Physics Laboratory,* JHU/APL, Laurel, MD (1985).
[6] Ness, N. F., "The Earth's Magnetic Tail," *J. Geophys. Res.* **70**, 2989 (1965).

The following are APL space science publications stemming from the early Transit program listed in chronological order.

Pieper, G. F., Zmuda, A. J., Bostrom, C. O., and O'Brien, B. J., "Solar Protons and Magnetic Storms in July 1961," *J. Geophys. Res.* **67**, 4959–4981 (1962).

Zmuda, A. J., "Solar-Terrestrial Disturbances and Solar Protons in July 1961," *Johns Hopkins Tech. Dig.* **2**(2), 14–19 (1962).
Pieper, G. F., Williams, D. J., and Frank, L. A., "TRAAC Observations of the Artificial Radiation Belt from the July 9, 1962, Nuclear Detonation," *J. Geophys. Res.* **68**, 635–640 (1963).
Pieper, G. F., "A Second Radiation Belt from the July 9, 1962, Nuclear Detonation," *J. Geophys. Res.* **68**, 651–655 (1963).
Pieper, G. F., Zmuda, A. J., and Bostrom, C. O., "Solar Protons and the Magnetic Storm of 13 July 1961," *Space Res.* **3**, 649–661 (1963).
Zmuda, A. J., Pieper, G. F., and Bostrom, C. O., "Solar Protons and Magnetic Storms in February 1962," *J. Geophys. Res.* **68**, 1160–1165 (1963).
Williams, D. J., and Bostrom, C. O., "Albedo Neutrons in Space," *J. Geophys. Res.* **69**, 377–391 (1964).
Bostrom, C. O., and Williams, D. J., "Time Decay of the Artificial Radiation Belt," *J. Geophys. Res.* **70**, 240–242 (1965).
Bostrom, C. O., Zmuda, A. J., and Pieper, G. F., "Trapped Protons in the South Atlantic Magnetic Anomaly, July through December 1961, 2. Comparisons with Nerv and Relay 1 and Discussion of the Energy Spectrum," *J. Geophys. Res.* **70**, 2035–2043 (1965).
Guier, W. H., and Newton, R. R., "The Earth's Gravity Field As Deduced from the Doppler Tracking of Five Satellites," *J. Geophys. Res.* **70**, 4613–4626 (1965).
Pieper, G. F., Bostrom, C. O., and Zmuda, A. J., "Trapped Protons in the South Atlantic Magnetic Anomaly, July through December 1961, 1. The General Characteristics," *J. Geophys. Res.* **70**, 2021–2033 (1965).
Williams, D. J., "Outer Zone Electrons," Radiation Trapped in the Earth'a Magnetic Field, Billy M. McCormac, ed., Proc. of the Advanced Study Institute, Bergen, Norway (16 Aug–3 Sep 1965).
Williams, D. J., "Studies of the Earth's Outer Radiation Zone," *Johns Hopkins APL Tech. Dig.* **4** (6), 10–17 (1965).
Williams, D. J., and Kohl, J. W., "Loss and Replacement of Electrons at Middle Latitudes and High B Values," *J. Geophys. Res.* **70**, 4139–4150 (1965).
Williams, D. J., and Meade, G. D., "Nightside Magnetosphere Configuration as Obtained from Trapped Electrons at 1100 Kilometers," *J. Geophys. Res.* **70**, 3017–3029 (1965).
Williams, D. J., and Palmer, W. F., "Distortions in the Radiation Cavity as Measured by an 1100 Kilometer Polar Orbiting Satellite," *J. Geophys. Res.* **70**, 557–567 (1965).
Williams, D. J., and Smith, A. M., "Daytime Trapped Electron Intensities at High Latitudes at 1100 Kilometers," *J. Geophys. Res.* **70**, 541–556 (1965).
Zmuda, A. J., Pieper, G. F., and Bostrom, C. O., "Trapped Protons in the South Atlantic Magnetic Anomaly, July through December 1961, 3. Magnetic Storms and Solar Proton Events," *J. Geophys. Res.* **70**, 2045–2056 (1965).
Ness, N. F., and Williams, D. J., "Correlated Magnetic Tail and Radiation Belt Observations," *J. Geophys. Res.* **71**, 322–325 (1966).
Williams, D. J., "A Diurnal Variation in Trapped Electron Intensities at $L = 2.0$," *J. Geophys. Res.* **71**, 979–981 (1966).
Williams, D. J., "A 27-Day Periodicity in Outer Zone Trapped Electron Intensities," *J. Geophys. Res.* **71**, 1815–1826 (1966).
Williams, D. J., and Ness, N. F., "Simultaneous Trapped Electron and Magnetic Tail Field Observations," *J. Geophys. Res.* **71**, 5117–5128 (1966).
Zmuda, A. J., "Ionization Enhancement from Van Allen Electrons in the South Atlantic Magnetic Anomaly," *J. Geophys. Res.* **71**, 1911–1917 (1966).
Zmuda, A. J., "The Auroral Oval," *Johns Hopkins APL Tech. Dig.* **6**(2), 2–8 (1966).
Zmuda, A. J., Martin, J. H., and Heuring, F. T., "Transverse Magnetic Disturbances at 1100 Kilometers in the Auroral Region," *J. Geophys. Res.* **71**, 5033–5045 (1966).
Arens, J. F., and Williams, D. J., "Examination of Storm Time Outer Zone Electron Intensity Changes at 1100 Kilometers," *Proc. of the Conjugate Point Symposium,* IV-22-1–IV-22-4 (Jan 1967).
Beall, D. S., Bostrom, C. O., and Williams, D. J., "Structure and Decay of the Starfish Radiation Belt, October 1963 to December 1965," *J. Geophys. Res.* **72**, 3403–3424 (1967).
Bostrom, C. O., Kohl, J. W., and Williams, D. J., "The Feb. 5. 1965 Solar Proton Event: 1. Time History & Spectrums Observed at 1100 Km," *J. Geophys. Res.* **72**, 4487–4496 (1967).
Fischell, R. E,, Martin, J. H., Radford, W. E., and Allen, W. E., *Radiation Damage to Orbiting Solar Cells and Transistors,* JHU/APL TG 886 (1967).
Potemra, T. A., Zmuda, A.J., Haave, C. R., and Shaw, B. W., "VLF Phase Perturbations Produced by Solar Protons in the Event of February 5, 1965," *J. Geophys. Res.* **72**, 6077–6089 (1967).
Smith, A. M., "Stellar Photometry from a Satellite Vehicle," *Astrophys. J.* **147**, 158–171 (1967).
Williams, D. J., "On the Low Altitude Trapped Electron Boundary Collapse During Magnetic Storms," *J. Geophys. Res.* **72**, 1644–1646 (1967).
Williams, D. J., and Bostrom, C. O., "The Feb. 5, 1965 Solar Proton Event: 2. Low Energy Proton Observations and Their Relation to the Magnetosphere," *J. Geophys. Res.* **72**, 4497–4506 (1967).
Zmuda, A. J., Heuring, F. T., and Martin, J. H., "Dayside Magnetic Disturbances at 1100 Km in the Auroral Oval," *J. Geophys. Res.* **72**, 1115–1117 (1967).

Beall, D. S., "The Artificial Electron Belt, October 1963 to October 1966," *Earth's Particles and Fields*, B. M. McCormac, ed., Reinhold Book Corp., New York (1968).

Bostrom, C. O., "Solar Protons Observed at 1100 km during March 1966," *Annales de Geophysique* **24**, 841–845 (1968).

Heuring, F. T., Zmuda, A. J., Radford, W. E., and Verzariu, P., "An Evaluation of Geomagnetic Harmonic Series for 1100 Kilometer Altitude," *J. Geophys. Res.* **73**, 2505–25114 (1968).

Williams, D. J., Arens, J. F., and Lanzerotti, L. J., "Observations of Trapped Electrons at Low and High Altitudes," *J. Geophys. Res.* **73**, 5673–5696 (1968).

Zmuda, A. J., Radford, W. E., Heuring, F. T., and Verzariu. P., "The Scaler Magnetic Intensity at 1100 km in Middle and Low Latitudes," *J. Geophys. Res.* **73**, 2495–2503 (1968).

Potemra, T. A., Zmuda, A. J., Haave C.R., and Shaw B.W., "VLF Phase Disturbances, H. F. Absorption, and Solar Protons in the Events of August 28 and September 2, 1966, "*J. Geophys. Res.* **74**, 6444–6458 (1969).

Williams, D.J., and Bostrom, C. O., "Proton Entry into the Magnetosphere on May 26, 1967," *J. Geophys. Res.* **74**, 3019–3026 (1969).

Armstrong, J. C., Beall, D. S., and Bostrom C.O., "Response of Electrons ($E_e \geq 0.28$ Mev) at $1.2 \leq L \leq 1.3$ to the November 1968 Magnetic Storm," *World Data Center A Report UAG-8*, Vol. II (1970).

Armstrong, J. C., and Zmuda, A. J., "Field-Aligned Current at 1100 Km in the Auroral Region Measured by Satellite," *J. Geophys. Res.* **75**, 7122–7127 (1970).

Bostrom, C. O., "Entry of Low Energy Solar Protons into the Magnetosphere," *Intercorrelated Satellite Observations Related to Solar Events*, V. Manno and D.E. Page, eds., D. Reidel Publishing Co., Dordrecht, Holland (1970).

Bostrom, C. O., Beall, D. S., and Armstrong J.C., "Time History of the Inner Radiation Zone, October 1963 to December 1968," *J. Geophys. Res.* **75**, 1246–1256 (1970).

Potemra, T. A., and Zmuda, A. J., "Precipitating Energetic Electrons as an Ionization Source in the Midlatitude Nighttime D Region," *J. Geophys. Res.* **75**, 7161–7167 (1970).

Potemra, T. A., Zmuda, A. J., Shaw, B. W., and Haave, C. R., "VLF Phase Disturbances, HF Absorption, and Solar Protons in the PCA Events of 1967," *Radio Sci.* **5**, 1137–1145 (1970).

Zmuda, A. J., Armstrong, J. C., and Heuring F.T., "Characteristics of Transverse Magnetic Disturbances Observed at 1100 Kilometers in the Auroral Oval," *J. Geophys. Res.* **75**, 4757–4762 (1970).

Potemra, T. A., and Lanzerotti, L. J., "Equatorial and Precipitating Solar Protons in the Magnetosphere, 2. Riometer Observations," *J. Geophys. Res.* **76**, 5244–5251 (1971).

Potemra, T. A., "The Empirical Connection of Riometer Absorption to Solar Protons During PCA Events," *Radio Sci.* **7**, 571–577 (1972).

Potemra, T. A., and Zmuda, A. J., "Nightglow Evidencs of Precipitating Energetic Electrons in the Midlatitude Nighttime D Region," *Radio Sci.* **7**, 63–66 (1972).

Potemra, T. A., and Zmuda, A.J., "Solar Electrons and Alpha Particles During Polar-Cap Absorption Events," *J. Geophys. Res.* **77**, 6916–6921 (1972).

Zmuda, A. J., and Potemra, T. A., "Bombardment of the Polar-Cap Ionosphere by Solar Cosmic Rays," *Rev. Geophys. and Space Phys.* **10**, 981–991 (1972).

Armstrong, J. C., "Field Aligned Currents in the Magnetosphere," *Earth's Particles and Fields*, *Proc. of the Summer Advanced Study Institute*, Sheffield, England (13–24 Aug. 1973).

Williams, D. J., and Heuring, F. T., "Strong Pitch Angle Diffusion and Magnetospheric Solar Protons," *J. Geophys. Res.* **78**, 37–50 (1973).

Zmuda, A. J., and Potemra, T. A., "HF Absorption Near the Polar-Cap Edge during PCA Events," *J. Geophys. Res.* **78**, 5818–5821 (1973).

THE AUTHORS

CARL O. BOSTROM is a retired Director of APL, having served in that position from 1980 to 1992. He earned degrees in physics from Franklin and Marshall College (B.S., 1956) and Yale University (M.S., 1958; Ph.D., 1962). In 1960, Dr. Bostrom joined APL as a senior staff physicist and helped start a group to conduct research on the space environment. Between 1960 and 1980, Dr. Bostrom had a variety of responsibilities ranging from instrument design and data analysis to management of satellite development and space systems. Most of his more than 60 publications are based on measurements of energetic particles in space. From 1974 to 1980, he was the Chief Scientist of the Space Department and later became the Department Head. Dr. Bostrom has served on a variety of advisory boards, committees, and panels, and has also received numerous awards and honors. Since retiring in 1992, he has worked as a consultant in the areas of R&D management and space systems. His e-mail address is carl.bostrom@jhuapl.edu.
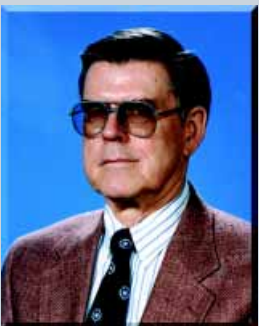
DONALD J. WILLIAMS is the Chief Scientist of APL's Milton S. Eisenhower Research and Technology Development Center. He received a B.S. degree in physics from Yale University in 1955 and, after 2 years in the Air Force, received M.S. and Ph.D. degrees in nuclear physics, also from Yale, in 1958 and 1962, respectively. He joined the Space Department in 1961, where he participated in developing APL's early space research activities. In 1965, he went to NASA Goddard Space Flight Center, and in 1970, he was appointed Director of NOAA's Space Environment Laboratory. In 1982, he rejoined the Space Department. He was appointed Director of the Research Center in 1990 and held that position through September 1996. Dr. Williams has worked on various NASA, NOAA, DoD, and foreign satellite programs. He has been a member of and has chaired numerous committees advising and defining the nation's space research program. His research activities, which have resulted in over 200 publications, are in space plasma physics with emphasis on planetary magnetospheres. His e-mail address is donald.williams@jhuapl.edu.