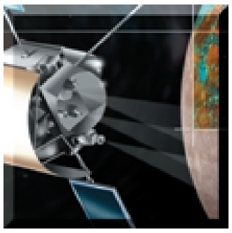

The APL Space Department in the World Community

Carl O. Bostrom and Richard W. McEntire

During more than 40 years of existence, the APL Space Department has contributed significantly to national security and has greatly advanced our knowledge in space and Earth sciences. A strong system engineering capability and an approach to problem solving that stresses innovation have enabled the Department to advance the state of the art in space systems design and to provide cost-effective solutions for a variety of problems of national importance. This article summarizes the lasting impact of these accomplishments. Space Department contributions in science range from pioneering work in satellite geodesy to important discoveries about particles and fields in space. With its early emphasis on reliability and miniaturization of spaceflight instruments and spacecraft, the Department has been a leader in developing space technology and innovative mission designs. Today's slogan of "better, faster, cheaper" describes standard practice for the Department. We expect the next 40 years to be equally productive as we prepare to meet the challenges of the next millennium. (Keywords: Satellite navigation, Space mission design, Space science, Space technology, Spacecraft engineering.)

INTRODUCTION

Who could have imagined in 1958, when Transit was invented, that in 1999 we would have farm cultivators, airlines, and private automobiles routinely finding their way using satellite navigation? That, of course, is but one of the many benefits accrued to mankind as a direct result of the APL Space Department's work. This article attempts to describe the 40 years of space research and development carried out by the Space Department in terms of its immediate and lasting impact on the important events and issues during this period.

It seems appropriate to consider separately the Department's impact in three often intertwined areas: national security, space science and instrumentation, and space technology and mission design. Histories of the Space Department have sometimes listed APL "firsts" in space science, engineering, and technology. These lists are both interesting and impressive, but they do not give a coherent picture of the Department's work. Here, we will describe specific inventions, discoveries, or innovations only as they support or illuminate the bigger picture. The most important of the three impact areas is our contribution to national security, and this area was also the origin of the other two impact areas.

In her new book, *Something New Under the Sun: Satellites and the Beginning of the Space Age*, Helen

Gavaghan chose to tell the stories of the early applications satellites.[1] She selected navigation, meteorology, and communications as the key areas that have had the greatest impact on the largest number of people. They didn't stir the public with the spirit of exploration as the Apollo Program did, nor were they comparable feats of engineering. But the navigation, meteorology, and communications programs were equally challenging and, for those fortunate enough to have been involved, tremendously exciting. As Ms. Gavaghan put it,

> Application satellites have a stealthy, silent influence on our lives. Most of us would notice them only in their absence. But then we *would* notice. . . . It would be a more dangerous and expensive world.[1]

That tractor equipped with a Global Positioning System (GPS) receiver probably also has a NOAA weather radio and a cell phone.

CONTRIBUTIONS TO NATIONAL SECURITY

Between Ms. Gavaghan's book and the recent issue of the *Johns Hopkins APL Technical Digest* commemorating the 40th anniversary of APL's Strategic Systems Department,[2] the early history of the Space Department has been well described. Ms. Gavaghan, in particular, recounts in detail the extraordinary work of William Guier and George Weiffenbach, which led them to conclude that each satellite radio contact (pass) produced a *unique* Doppler-shifted signal, and further that the orbit parameters could be calculated from a single pass of perhaps 10 minutes' duration.

In hindsight, it is almost impossible to overstate the value of the development and operational performance of Transit, the Navy Navigation Satellite System. While its invention and development were exceptional achievements in themselves, the Transit System's ultimate impact was in helping to establish the credibility and enabling the outstanding performance of the Fleet Ballistic Missile System. To quote an August 1998 letter from RADM Shipway to then-Director Dr. Gary Smith,

> The invention of satellite navigation allowed the submarine inertial navigator to be reset anywhere in the world, thereby enabling the weapon system to covertly maintain its accuracy during extended deterrent patrols.

The Laboratory and the Space Department were often at the forefront in the long-running scientific and technological competition between the superpowers during more than four decades of the Cold War. The United States and its allies eventually "won" that war on the basis of economic strength that allowed heavy investment in military and space systems while maintaining a prosperous civilian economy and a strong scientific establishment. From the earliest days of the Polaris Missile System, through the development of Poseidon and Trident, the goal has been to provide a covert, survivable, and reliable missile launch system capable of delivering a retaliatory nuclear strike large and precise enough to make a first strike against the United States unthinkable. To achieve this capability required an enormous effort, drawing on a great many scientific and engineering disciplines and challenging the capabilities of U.S. industry. Extraordinarily large and ambitious programs like Polaris and NASA's Apollo greatly extended the state of the art in many fields and revealed shortcomings in the state of our knowledge that could be addressed only through expanded research.

How important satellite navigation was to the Fleet Ballistic Missile System was revealed when concerns arose about the survivability of the Transit System itself. To deal with potential threats to the satellites, primarily from high-intensity artificial radiation belts, as well as threats to the ground installations, the Space Department undertook the Transit Improvement Program (see Ebert and Hoffman, this issue). The most vulnerable parts of the Transit System were deemed to be the ground-based elements that tracked the satellites, carried out all the orbital calculations and predictions, and loaded each satellite's memory with its navigation messages twice a day. The task was to develop Transit satellites that could supply precise positioning information without any contact to or from the ground stations for a period of several days.

This approach to satellite design was totally different from that used in the earlier days, when the philosophy was to minimize the satellite's complexity by placing as much of the functionality as possible in the ground-based elements of the system. When satellite (and launcher) reliability was a major problem, it made sense to keep the space-based part of the system as simple and inexpensive as possible and keep the complex parts on the ground, where they could be easily upgraded and repaired. By the end of the 1960s, however, many of the satellite reliability issues were understood, so it became possible to consider designing a more autonomous satellite. The technology did not permit the level of autonomy used in today's spacecraft, but the 10 years since the original Transit design had seen great progress in miniaturizing electronics. The improved Transit was to have an extended memory to allow storing some 10 days of navigation data, an onboard clock that kept accurate time for that period, an onboard reprogrammable computer to permit more flexible operations, and redundant and radiation-resistant electronic systems as needed. By this time (about 1970), even though the Earth's gravity field had been determined well enough for us to predict the satellite position 10 days into the future, the variability of atmospheric drag still made such predictions impossible. The solution was to build a "drag-free" satellite.

The satellite itself would not be drag-free, of course; it would be but "drag-compensated." If a small mass is placed in a cavity at the gravitational center of the satellite, shielded from all external surface forces, and if the surrounding satellite is forced (by small thrusters) to move in a way that keeps the mass centered in the cavity, then the mass will travel in a purely gravitational orbit, and so will the satellite. The complexity of the preceding sentence is exceeded only by the complexity of achieving the three-axis Disturbance Compensation System (DISCOS) used on Triad, the first of three satellites in the Transit Improvement Program. The next two satellites, TIP-II and TIP-III, were built with a single-axis DISCOS oriented in the along-track direction, which is all that is needed to compensate for drag. Of course, the along-track orientation for DISCOS placed new requirements on the attitude control system, which were met by adding a momentum wheel to the gravity-gradient system. The single-axis DISCOS was incorporated into the second-generation navigation satellites called Nova, the first of which was launched in 1981.

The Transit Navy Navigation Satellite System was retired from operational service at the end of 1996 after more than 32 years. The Space Department remained a part of Transit's operation throughout the life of the system. Such a "cradle-to-grave" commitment is an important attribute of the Department and the Laboratory. This commitment enabled Transit to meet the demands of the Navy's Submarine-Launched Ballistic Missile System as it implemented several major improvements over nearly four decades.

When the Navy decided to enhance the effectiveness of the Trident System by improving system accuracy, the Space Department collaborated with the Strategic Systems Department in the development of a special tracking system to precisely measure the missile trajectory during the boost phase. The system, known as SATRACK, was described by Thompson et al. as follows:

> SATRACK was developed to validate and monitor the Trident missile guidance error model in the System Flight Test Program. It is the primary instrumentation and processing system responsible for accuracy evaluation of the Navy's Strategic Weapon System.[3]

To achieve the improved accuracy goals of the Trident System, yet another characteristic of nature had to be determined, namely, the spatial variation of "local vertical" at sea. Because of local anomalies in the mass distribution of the Earth, the local gravitational field is distorted slightly. The distortion is small, but it is enough to affect the performance of a missile system that must travel several thousand kilometers. Apart from meteorological and certain oceanographic effects (more about these later), the surface of the ocean should conform to the shape of the local geoid. By measuring the surface shape to an accuracy of 1 m or less using a satellite-borne radar altimeter, the so-called local vertical can be determined and suitable corrections applied to the missile system. This was one of the Navy's principal objectives for the precision radar altimeter APL designed for the NASA Seasat Program. When Seasat (launched in 1978) failed prematurely, the requirement went unmet until the launch of the Navy/APL Geosat satellite in 1985.

As is described elsewhere in this issue, the Space Department has made important contributions to research in support of programs to defend the United States against ballistic missiles. It has also provided system engineering capability to the program office now known as the Ballistic Missile Defense Organization (BMDO). From the earliest quick-response projects (the Delta 180 series that helped get the Strategic Defense Initiative under way) to the development of one of the most sophisticated scientific satellites ever flown (the Midcourse Space Experiment, MSX), the Department has consistently met the mission objectives.

SPACE SCIENCE AND INSTRUMENTATION

Turning now to the Department's contributions to space science and instrumentation, we must first acknowledge our heritage. It goes back to the late 1940s, when James Van Allen was developing sounding rockets to study cosmic rays at high altitudes, and to work in the 1950s on geomagnetism carried out by the late Alfred Zmuda of APL's Research Center. The "modern era" dates from 1960, when the decision was made to make *in situ* measurements of the energetic particles and the magnetic field to be encountered by the Transit satellites. In the early 1960s, if you were fortunate enough to get a good instrument aboard a working satellite in a useful orbit, "discoveries" were almost assured. Even today serendipity plays a more important role in space science than in most other experimental research, because with very few exceptions, you observe only what nature happens to offer. Sometimes nature offers too much at once, and the challenge becomes sorting and interpreting the observations.

The first APL particle experiment was flown aboard the Injun 1 satellite, built by Van Allen's group at the University of Iowa, and launched with Transit 4A in June 1961. It consisted of a set of solid-state detectors sensitive to protons with energy between 1 and 15 MeV. As luck would have it, the Sun became very active in July 1961. A dozen large solar flares that occurred between 11 and 28 July produced copious numbers of energetic protons and major geomagnetic storms. We were thus able to discover that low-energy solar protons had ready access to the Earth's polar regions and that this region of access extended to much lower latitudes than existing models of the Earth's magnetic field allowed.

This APL particle detector was the first to use silicon junction detectors in space. It was quite simple, but two of its characteristics have been used in almost all detector designs since: (1) it measured a specific type of particle over a specific range of energy in a specific direction, and (2) it was designed to minimize the background from radiation outside the range of interest. This ability to discriminate among particle species, with high sensitivity over a wide range of intensities, and to measure angular distributions is essential to understanding the properties of a complex environment of enormous spatial and temporal variation. Over the years, a variety of techniques used in nuclear physics research have been adapted, and sometimes improved, for use in space. Coincidence and anticoincidence detectors, special shielding, shaped electric and magnetic fields, secondary emission devices, and time-of-flight measurements are a few examples. APL researchers and their colleagues have led the development of instruments to measure the composition of the energetic particles emitted by the Sun and trapped in the magnetospheres of Earth and most of the other planets in the solar system. Williams et al. (this issue) discuss the development of such instruments in detail.

Essentially from the beginning of the space age, APL scientists and engineers have been major players in the effort to first characterize and then understand the very intense energetic particle fluxes found in space near the Earth. On spacecraft launched for the Navy to study the low-altitude Transit environment (5E-1), as well as on spacecraft launched by NASA to study the deeper-space environment (the Interplanetary Monitoring Platform [IMP] missions), APL instruments, APL scientists, and their collaborators made major contributions to characterizing the structure, variation, and sources of the intense near-Earth fluxes (the Van Allen belts) and the even higher-energy particles from sporadic events on the Sun. Building on these efforts, in the early 1980s we proposed to NASA and were selected to carry out (along with our collaborating science and engineering teams in Germany and England) the three-spacecraft Active Magnetospheric Particle Tracer Explorers (AMPTE). This mission created a series of artificial comets in space, looked at particle transport into and throughout the Earth's magnetosphere, and for the first time measured the complete elemental composition of magnetospheric particles.

Energetic particles are guided by the magnetic field in space. In addition, *in situ* measurements of the magnitude and direction of the magnetic field can help to determine the orientation (attitude) of a satellite in a low-altitude orbit. Thus, from the beginning, APL has flown spacecraft magnetometers, and scientists have analyzed magnetic field data. In 1966, Zmuda found disturbances in the magnetic field that seemed to be explained by large currents (now known as Birkeland currents) flowing along field lines between the ionosphere and the outer magnetosphere.[4] These field-aligned currents (FACs) are now known to be an essential part of the structure and dynamics of the magnetosphere; they couple solar-wind energy to the Earth's upper atmosphere. International research on the physics of these important current systems continues, with APL playing a major role.

A common theme emerges: space-based research, begun to support a programmatic need (in this case, Transit spacecraft attitude control and radiation dose measurement), developed over time and with several sponsors (Navy, NASA, NSF) into much broader programs of basic research into our natural environment, which produced important contributions to scientific knowledge.

In addition to the direct, *in situ* measurements already described, the Space Department has made major contributions in several areas of remote sensing. Building on our scientific interest in auroral physics (intimately related to FACs), we studied ionospheric disturbances, which have important effects on long-range communications and over-the-horizon radar. Department scientists developed and flew the first auroral imager that operated in the ultraviolet wavelength range, allowing measurements of the aurora under sunlit conditions (on the HILAT spacecraft, 1983). Since then, numerous imagers and spectrometers have been flown, and others are in preparation for flight, to study auroral emissions, atmospheric photochemistry, and the effect of both external energy inputs and atmospheric trace species pollutants on the upper atmosphere, including the ozone layer. At the same time, we studied ionospheric variations from below. Starting in 1983, Department scientists have led the development of a collaborative (10-nation) network of ground-based high-frequency ionospheric radars that now continuously image the state of the high-latitude ionosphere in both the Northern and Southern hemispheres. They monitor the effect of "space weather" on the ionosphere. Space Department science and instrumentation have evolved from initial studies of radio communication disturbances to contributions to the global view of how our upper atmosphere and ionosphere react to external forces.

We have already mentioned the Department's contributions to defining the geoid through ocean surface measurements with APL radar altimeters on Seasat and Geosat. These instruments also measure ocean currents, internal and surface waves, and surface wind fields. Using theory, modeling, *in situ* observations, altimeter data, and synthetic aperture radar (SAR) data, Department scientists have made important contributions, including major advances in the processing of SAR data.

So far we have discussed Space Department contributions to knowledge of the Earth's immediate environment. But our scientists have also become deeply involved in measuring energetic particles in the heliosphere and the outer solar system. In the early 1970s, an APL-led team was competitively selected by NASA to provide the energetic particles instrument suite for the Voyager 1 and 2 spacecraft. These spacecraft have now flown by the planets Jupiter, Saturn, Uranus, and Neptune and are on their way out of the solar system into interstellar space. Our teams were subsequently chosen to provide energetic particles instrumentation on Galileo, now orbiting Jupiter; Ulysses, orbiting over the poles of the Sun; the Atmospheric Composition Explorer (ACE) to study the composition of solar energetic particles; and Cassini, on its way to orbit Saturn. No other institution has such an involvement in measurements of energetic particles throughout the solar system! We also have a new but growing involvement in planetary remote sensing—the Near Earth Asteroid Rendezvous (NEAR) to orbit the asteroid Eros; the Comet Nucleus Tour (CONTOUR) to fly close to three different comet nuclei; and the just-selected mission to orbit the planet Mercury, called MESSENGER.

The APL Space Department has made significant, and often major, scientific contributions in areas from the surface of the ocean to the outer reaches of the Earth's magnetosphere, and from the surface of the Sun to the outer planets and beyond. Our scientific interests and instruments have evolved from that first simple Injun-1 detector to very complex particle detector suites, hyperspectral imagers, and advanced radars, and we continue to pursue research to learn more about the space environment and its effects on the Earth.

MISSION DESIGN AND ADVANCED TECHNOLOGY

The third arena in which the APL Space Department has made major contributions is in space technology and mission design. From the outset, the Department's leadership encouraged innovation and established goals that were beyond the current state of the art. For example, the early decision to use the Scout launch vehicle for the Transit satellites placed severe restrictions on size, weight, and power and drove the design in a great many ways. The goal of achieving a 5-year satellite lifetime was set at a time when satellites rarely lasted more than a few months, but the goal provided a philosophy that guided the selection of technologies and approaches used in every subsystem. Circumscribing the effort in this way focused continual attention to detail and required a constant search for the better solution. One result of this approach was a satellite design that eventually was shown to have a mean lifetime of more than 14 years! Another result was that the production run of the operational satellites, called Oscars and built by (then) RCA Astro-Electronics Division, substantially exceeded the number needed for the system. One of the APL-built satellites, Oscar 13, was in operational service for over 21 years.

While the Laboratory can claim world-class expertise in a number of areas, the design and production of ultrastable oscillators (USOs) for spaceflight stands out. Stable frequencies were essential for achieving the goals of the Transit System. The development of ultrastable oscillators soon surpassed the needs of Transit, but not necessarily the needs of other space programs. *More than 400 USOs have been delivered for use on a variety of spacecraft.* Dr. Alvydas J. Kliore of the NASA Jet Propulsion Laboratory, Radio Science Team leader for the Cassini mission to Saturn, recently wrote in a letter to Space Department Head Dr. Stamatios Krimigis, "The USOs that your division has delivered to us are to our knowledge the finest in the solar system in terms of the cleanliness and stability of their output." Of course, to our knowledge, they are the finest in the entire universe. Several attempts over the years to transfer the technology to industry had not succeeded, but this year a new company (Syntonics, LLC) has been organized to fully commercialize this state-of-the-art device.

Exceptional competence in system engineering, always a hallmark of the Laboratory, has been a particular strength of the Space Department. The benefits of this characteristic cannot be overstated. Expert system engineering allows mission designs to be optimized for performance while retaining flexibility and minimizing cost. To be most effective, this system engineering capability must be coupled with a strong effort in the development and application of new technology and a willingness to accept some level of risk in order to make significant gains. For many years, the U.S. space program was afflicted with the "heritage" requirement for much of its spaceflight subsystems and instruments. The requirement was intended to reduce risks and costs by using, insofar as possible, devices and packages with a proven track record of successful operation in space. There are certainly occasions and programs where that may be the proper course, but in cutting-edge research programs, new technologies and techniques are often what make a mission viable in the first place.

The impact of the APL Space Department in the areas of space technology and mission design is brought home by the fact that we have been consulted or invited by NASA to provide alternative approaches for important missions that for one reason or another, usually cost, had outgrown available resources. In the 1970s, APL was asked to propose its own design for Seasat, and many features of that design were ultimately incorporated into the satellite built by the Jet Propulsion Laboratory and its contractors. Seasat included five major subsystems designed and built by APL. More recently, the Department developed an alternative, much more affordable design that enabled NASA to pursue the Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics (TIMED) mission.

Because of its long history of accomplishing more for less, APL's proposal for the NEAR spacecraft was selected as the first mission in the Discovery Program of low-cost interplanetary missions. In meeting the cost and schedule targets, the Department established the paradigm for future interplanetary missions. Further, despite the disappointment of having to delay the rendezvous for some 13 months because of two unrelated human errors, the fact that the spacecraft was quickly recovered and retargeted attests to the quality of the system engineering and careful planning that went into the original design.

The APL approach to mission and spacecraft design has been proven time and time again over the past 40 years. Some 58 satellites and spacecraft have been designed, built, tested, and launched; more than 150 instruments were provided for other spacecraft. The "better, faster, cheaper" (and that's the right order, by the way) slogan of the 1990s has been standard practice at APL for many years, and that practice has provided low-cost, high-performance systems to the benefit of all our government sponsors, and ultimately the U.S. taxpayer.

Space-based research, begun to support a programmatic need, developed over time . . . into much broader programs of basic research into our natural environment, which produced important contributions to scientific knowledge.

The combination of quality and innovation in both science and engineering has been responsible for the continuing demand for the Department's services and for its enviable success in preparing winning proposals for new missions. In the most recent competition for new Discovery missions, 5 proposals out of 29 submitted were selected for further study. The two proposals submitted by the Space Department and its collaborators were among the five finalists. Both are challenging missions that promised strong scientific return. The Aladdin mission would collect samples of material from the two moons of Mars and return them to Earth. The MESSENGER mission to Mercury will provide the first detailed study of this innermost planet in our solar system. In the final NASA selection, MESSENGER was one of the two missions chosen for flight—with a launch in 2004. Also, in a competition of Midsize Explorer (Midex) concepts, the Department submitted 2 of the 32 proposals offered. One, the Auroral Multiscale Midex (AMM), was among the five selected for further study. The AMM envisions coordinated measurements in Earth's auroral regions using four spacecraft to make three-dimensional measurements of currents and fields.

THE NEXT 40 YEARS

It must have become clear to the reader by now that the APL Space Department occupies a unique position in the spectrum of the space science and engineering enterprise that extends from government laboratories at one end to commercial space companies at the other. The Department, being part of a university laboratory, is able to promote and excel in a number of space science disciplines; in this respect it resembles an academic unit that thrives on basic research. It is also able to maintain and nurture all the basic engineering skills necessary to implement end-to-end space missions; in this respect it resembles a commercial space engineering organization. Being a not-for-profit organization, the Laboratory can pursue one-of-a-kind missions that advance the state of the art and satisfy the needs of government sponsors while working closely with industry to use the best available technologies and to develop those that have not yet matured. This combination enables us to address problems and invent solutions that satisfy the requirements of the Department's sponsors.

It is our strong conviction that this formula, having been exceptionally successful during the first 40 years, will continue to be so during the next 40, with appropriate midcourse corrections along the way. A glimpse into the proverbial "crystal ball" was put together by the Department staff during a strategic planning activity in 1998.[5] Four programmatic goals emerged:

- Strengthen our space research program
- Solve national security problems
- Conduct civilian space missions
- Strengthen our advanced technology development program

To achieve these program goals, we also developed four enabling goals that will help us both to meet our customers' needs and to continually improve as an institution:

- Forge new alliances
- Extend our "better, faster, cheaper" model to new areas
- Enhance our education and outreach programs
- Develop our capabilities

In the years to come, implementation of all of these goals, together with our tradition of pursuing excellence in all we do, will propel APL's Space Department to higher levels of achievement, in science and engineering as well as in service to our country.

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