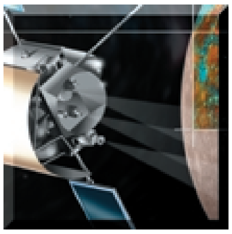

Defining the Problem and Designing the Mission: An Evolutionary Process

Carl O. Bostrom

The APL Space Department was formed to develop an entirely new space-based navigation system essential to the successful operation of the fledgling Submarine Launched Ballistic Missile (SLBM) System, then known as Polaris. The opportunity to carry out this challenging work grew from the insightful research in satellite tracking by George C. Weiffenbach and William H. Guier, and the subsequent brilliant invention and conceptual design presented by Frank T. McClure in a memorandum dated 18 March 1958. However, this important research and innovative concept might never have reached fruition in the form of Transit, the Navy Navigation Satellite System, had it not been for the Laboratory's involvement with Polaris.

APL had been assigned the essential task of evaluating the performance of the Polaris System and all of its elements. To fulfill that responsibility, the Laboratory needed a thorough understanding of the requirements, capabilities, performance, and reliability of all subsystems, as well as a system-level view of trade-offs that might compromise system effectiveness. As a result of this close association between the Laboratory and (what was then) the Special Projects Office, the potential value of a satellite-based navigation system was recognized early on. (I was going to say "was immediately obvious," but almost everything is immediately obvious in hindsight. Throughout this issue of the *Digest* there are dozens, maybe hundreds, of examples of technological and engineering solutions to problems that seem trivial in hindsight, but were in fact major achievements, given the tools available 40 years ago!)

Navigation was and is an important element of the SLBM System to ensure the credibility of the sea-based leg of the U.S. nuclear deterrent. In addition, a space-based navigation system promised to provide an enormous advantage in maintaining the security of the submarine by limiting its exposure during the periodic "fixes" needed to update the inertial navigation systems of that era. The need for system accuracy and covert operations, and the fact that the Polaris System enjoyed the highest national priority, drove the development of Transit at an urgent pace.

The following discussion presents insights into the Space Department's development and evolution over the past 40 years in terms of the kinds of programs and problems that were undertaken. Some of these programs and problems, to paraphrase Shakespeare's remarks on greatness, were "achieved," i.e., invented, developed, and presented by the Department to agencies in need, while others were "thrust upon us," by agencies aware of the Department's and the Laboratory's reputation and capabilities.

From its inception, APL has been most effective when it has had intimate knowledge of the actual operational problems faced by the (military) users of the technologies and systems available to them. A strong partnership between the system operators and the scientists and engineers applying new technologies to enhance capabilities often produces the most potent and practical solutions. Such was certainly the case in the origins of the Transit System as well as many of the spacecraft and instrumentation programs accomplished by the Space Department over its lifetime.

To understand the evolution of the Department, we should take a look at the array of talent that was necessary to implement the design and development of Transit, because it was these people who have guided our course. The success of Transit, and therefore the Space Department, was due to the team of engineers and scientists assembled and led by the late Dr. Richard B. Kershner, a man of enormous intellect, broad knowledge, uncanny vision, and great personal magnetism. Over some 20 years, through a variety of crises and difficult times, his leadership, charm, wit, and powers of persuasion kept programs on course and maintained Department morale at a consistently high level.

I have often asserted that the development of the Transit System was an almost prototypical exercise in "applied physics." The process would have been ever so much easier if nature had been more cooperative. If the satellites were orbiting a homogeneous, spherical Earth; rotating on an absolutely fixed axis; surrounded by a uniform, time-invariant atmosphere and ionosphere; enclosed within an electrically neutral, nearly perfect vacuum with a stable, known magnetic field and no high-energy radiation except the galactic cosmic rays; irradiated by a steady, known spectrum of electromagnetic waves from a stable, well-behaved Sun—Transit System development would have gone much faster. Instead, nature conspired to disallow the possibility of using any simplifying assumptions whatsoever! Many of the properties of the Earth and its environment that seriously affected system performance were poorly known, at best.

The entire field of satellite geodesy grew out of the essential need to measure and describe the Earth's gravity field with sufficient precision to predict the position of a satellite in low-Earth orbit, even a few hours into the future. Although variations in the Earth's atmosphere and ionosphere had long been studied with ground-based instruments, the enormous and rapid variations in response to solar and magnetic disturbances affected both the satellite motion (drag) and the RF transmissions to and from the satellite in unpredictable ways. Real-time corrections to the received satellite signals had to be developed by using two or more coherent frequencies derived from a common source. Initially, atmospheric models were developed to reduce the errors introduced by drag, and later the active Disturbance Compensation System (DISCOS) was developed to compensate for external forces in real time.

When Transit was invented, the Earth's radiation belts were just being discovered. Professor James A. Van Allen had not yet announced the explanation for the peculiar behavior of the Geiger counters flown on Explorer I to measure cosmic rays. This finding added substantial complexity to the satellites by forcing all components to be designed to operate in an environment of high-energy ionizing radiation. Later, when it was demonstrated that artificial radiation belts could be produced with sufficient intensity to destroy satellites in low-altitude orbits, the problem became critical for an operational system such as Transit.

The requirements for the successful prosecution of the Transit Program became the impetus for a number of research efforts aimed at acquiring new knowledge and understanding of physical and environmental phenomena. In addition, those requirements demanded the development and application of new materials and innovative designs and techniques to achieve goals in system accuracy and stability as well as satellite weight, power, cost, and reliability.

Examples are abundant. Consider, for one, the impact of attitude stabilization. For a satellite meant to radiate RF signals to receivers on the surface of the Earth, it is clearly most efficient for the satellite antenna to always point "down." This allows the use of a directional antenna, which minimizes the power needed for the transmitters. Because transmitters are often one of the major users of electrical power, savings there will reduce the size of the solar cell arrays and onboard batteries, conserving weight and cost. Of course, if the method selected for pointing the antenna is sufficiently complex, the advantage is lost.

In the case of Transit, it was also important to avoid using components with known lifetime limitations or ones that might alter the satellite trajectory (e.g., gas jets). The method chosen was gravity-gradient stabilization, so that, like the Moon, one face (end) of the satellite would always point toward the Earth. This method had many advantages, foremost among them the fact that, once achieved, such a system was passive, with no moving parts or consumable materials to worry about.

It is one thing to speak so matter-of-factly about gravity-gradient stabilization in 1999 and quite another to set out to achieve it in the early 1960s. For the method to work, the satellite had to have a mass distribution similar to a dumbbell so that the gravitational force would tend to orient the satellite with its long axis parallel to a line from the center of the Earth. To achieve the desired shape, a long boom had to be deployed with a suitable mass at the end, *and* the boom had to be deployed in such a way that the satellite would stabilize right-side up, *and* some way had to be found to damp the large oscillations about the vertical due to the weakness of the gravity-gradient torque.

Needless to say, these problems were indeed solved. The first gravity-gradient–stabilized satellite, Transit 5A3, was launched in June 1963, and all the operational satellites in the system throughout its 32-year lifetime used the same basic system for attitude control. I have oversimplified this discussion on gravity-gradient stabilization just to emphasize that every activity and program undertaken by the Space Department for the past 40 years was made possible because of the expertise and experience gained in solving the many large and complex problems encountered in developing Transit.

In fact, looking back, the Department's major activities can be divided roughly into three categories, each representing a broad area of expertise developed during the design and implementation of the Transit Program:

1. *Precision time and frequency technologies*. At the heart of much of the Department's work has been our expertise in developing precision time and frequency standards, and in all related technologies enabling the precise tracking, location, and navigation of objects on the Earth's surface and in space.
2. *Space and environmental sciences*. From the early measurements of particles and fields encountered in the Transit satellite orbits, the Department's capabilities have expanded to include important areas of atmospheric and ionospheric science, solar and interplanetary physics, magnetospheres of the Earth and other planets in our solar system, and even comets and asteroids. A continuing interest in gravity research has grown to include those aspects of oceanography amenable to measurement from space.
3. *End-to-end space mission design*. A broad array of exceptional capabilities in all aspects of space mission design—from the highest system-level concepts to the detailed design of instruments, subsystems, and components—allows the optimum use of technology and resources to achieve critical objectives. In today's lexicon, that translates to "faster, better, cheaper."

These three areas of special expertise have been responsible for the Department's success in continuing to attract important and challenging programs. We are particularly proud of the quality and quantity of our contributions to basic research in space and space-related sciences, but it is important to recognize that the Space Department shares the essential attribute of the Applied Physics Laboratory, namely, *we are a problem-solving organization*. As such, we have strength in system engineering and in the conduct of applied research and development. In some instances, we may have to advance the state of the art through research in a particular area of science or through invention and development of new technology, but more often, it is a matter of applying existing technology to achieve the desired answer to the problem at hand. In either case, the primary focus is on finding the most effective and efficient solution.

Our expertise in precision time and frequency matters has been an important ingredient in many of our programs. In addition to some 27 navigation satellites built for the Navy, we have provided literally dozens of precision flight oscillators and tracking beacons to the Air Force, NASA, the Defense Mapping Agency, and the Naval Research Laboratory for use on spacecraft requiring precision clocks and/or tracking.

Of necessity, the Department became a major contributor to early work in satellite geodesy. A worldwide network of Doppler tracking stations was established and operated by the Laboratory, and satellite orbits of six different inclinations were used to develop the models of the Earth's gravitational field needed to meet the Transit requirements. This led rather naturally into a series of geodetic research satellites and instruments designed specifically to measure the detailed shape of the Earth's gravity field.

The series began with the Army, Navy, NASA, Air Force (ANNA) 1B (ANNA-1A failed to orbit) launched in October 1962, and continued with the three NASA-sponsored Geodetic Earth Orbiting Satellites (GEOS) launched between 1965 and 1975. All of these carried multiple tracking systems to ensure that any biases or systematic errors in any one system could be evaluated. GEOS-C carried a radar altimeter to measure the satellite's altitude and ultimately the profile of the ocean surface directly beneath it. That experience led to the Department designing a much-improved series of radar altimeters, which subsequently flew aboard the NASA Seasat mission, the Navy (APL-built) Geosat-A satellite, and the NASA Topex satellite.

In the 1970s and early 1980s, we provided the first precision satellite-to-satellite tracking capability to the Air Force and the Defense Mapping Agency for use in tracking very low altitude satellites. A direct extension of previous work, the system was called NAVPAC (for NAVigation PACkage), and it used Transit satellite signals as received by the lower satellite to precisely determine its position. A later version, also developed by the Space Department, used the Global Positioning

System (GPS) satellite signals for the same purpose. Similar instruments were provided to the NASA Landsat Program. When the Navy's Trident Program set out to improve the accuracy of the SLBM System, a more complete understanding of the errors inherent in the missile guidance and other subsystems during the launch phase was needed. The Space Department, in collaboration with the Strategic Systems Department, developed a precision missile tracking system. Called Satrack, the system was one of the first to use the new GPS satellite signals to measure the trajectory of the missile.

Some missions came to us on the basis of our combined expertise in these areas. Because of our early efforts in miniaturization of spacecraft electronics, required by the decision to use the inexpensive Scout launch vehicle for the operational Transit satellites, we were able to provide cost-effective satellites for several early NASA missions such as Beacon Explorers A, B, and C and the Direct Measurement Explorer (DME-A). These missions had both ionospheric and geodetic research purposes relevant to the Transit System as well.

Among programs and missions that came to APL because of our demonstrated capabilities in space mission, system, and subsystem design, I would include the three NASA Small Astronomy Satellites (SAS) and the NASA magnetic field satellite, Magsat, all launched in the 1970s. There were also a number of subsystems and instruments, ranging from the attitude control systems for Explorers 32 and 38 in the 1960s to the data link for the synthetic aperture radar on Seasat. We have collaborated with our colleagues at the Homewood campus of Hopkins on several programs, including the ultraviolet experiments on Apollo 17 and 18 in the 1970s and the Hopkins Ultraviolet Telescope (HUT) aboard the Space Shuttle in the 1990s.

One characteristic shared by both the Laboratory and the Space Department that has not been highlighted up to this point is a preference for accepting responsibility and accountability for the programs conducted on behalf of sponsoring agencies. The Department functions most efficiently when it is permitted to operate with the minimum essential administrative and management oversight by a sponsor. This approach was used during World War II, when time was the primary consideration, and persisted into the early 1960s and beyond in certain arenas, even as cost became a critical factor. In the space program, fear of failure, particularly during the Apollo and Space Shuttle eras, created expensive processes and procedures, all of which had to be fully documented. Multiple layers of watchers and reviewers introduce delays, increase cost, and effectively obscure accountability. The value of trust earned by a record of accomplishment is thereby diminished.

Having said that, the Department has had the good fortune of working for several sponsoring agencies in its preferred mode. The Transit Program is, of course, the major outstanding example. It included a series of development satellites that permitted the careful evaluation of alternatives for major subsystems and allowed experiments and auxiliary measurements to be made in support of the primary objective. This enlightened approach produced not only the successful Navy Navigation Satellite System, but also made the Department an exceptionally valuable asset for the nation.

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When the Strategic Defense Initiative Office (SDIO), now the Ballistic Missile Defense Organization (BMDO), needed to move quickly in pursuit of its ambitious objectives, we were able to provide meaningful space-based data through our leadership of the rapid development of the Delta 180 Program launched in 1986. The follow-on Delta 181 and 183 spacecraft were similarly fast-paced, and they in turn led to the much larger and more capable Midcourse Space Experiment (MSX) mission launched in 1996. All of these missions were marked by yet another characteristic of the APL approach, namely, to extend the capabilities beyond the minimum requirements whenever such enhancements appear to be prudent and add value. The early decision to extend the spectral measurements of rocket plumes in space into the ultraviolet yielded important new insights into the physics and chemistry of these phenomena.

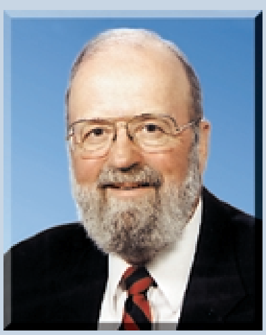
As NASA began its new initiatives to encourage the use of small, focused, low-cost missions for space science instead of large observatory missions, the Department was well positioned to lead the way into this new era. APL won the competition to provide the first of the series of small interplanetary missions in the Discovery Program, the Near Earth Asteroid Rendezvous (NEAR) mission to the asteroid Eros. The NEAR mission and spacecraft design took advantage of all the Department's capabilities and special characteristics established through a long history. The result was a spacecraft built and launched on time and under budget, and one that performed beyond mission requirements by adding a flyby of the asteroid Mathilde along the way to Eros.

The original plan for NEAR called for placing it into orbit around Eros in early 1999 to begin an extended period of detailed study of the asteroid. In December 1998, however, during a scheduled firing of its main propulsion system, NEAR suffered a serious (although not catastrophic) failure. The engine shut down almost immediately and placed the spacecraft in "safe" mode. Instead of orbiting Eros, NEAR had a "flyby" opportunity while the problem was analyzed. In January 1999, the main engine was fired successfully, but the orbital part of the mission has been delayed until early 2000.

One topic that deserves some discussion is the issue of competition. While the Laboratory has had a long-standing policy against responding to government-issued requests for proposals in competition with industry, that prohibition does not extend to the variety of Announcements of Opportunity seeking proposals for research programs. For example, after the Transit requirements for environmental measurements had been satisfied, a strong capability in space science and instrumentation had been developed and documented in a steady stream of research publications. To pursue the research interests of this group of scientists and engineers, we had to seek support from agencies chartered to conduct and fund basic space research, primarily NASA. By the mid-1960s, this group was submitting competitive research proposals and becoming a self-supporting part of the Space Department. Our strength in instrument design was a key element in successful proposals to develop experiments for NASA research spacecraft.

Much of the Department's work in the past 20 years has stemmed from the careful preparation of strong, detailed technical proposals, both solicited and unsolicited, which have been selected and funded on the basis of merit, usually after a rigorous competitive process. We would expect this situation to persist for the foreseeable future. Although the "foreseeable future" for the Space Department has sometimes been measured in months, we have seen remarkably few significant lapses in our overall level of activity. More often, the challenge has been to manage the periodic work overload that results from winning more than the expected share of proposed programs. Fortunately, the Department has successfully followed Dick Kershner's warning about the dangers of offering proposals of any sort: "You've got to be prepared to take 'yes' for an answer." If recent events are any indication, the APL Space Department will continue the traditions of the first 40 years and make equally significant contributions to the nation's space programs for the next 40 years.

THE AUTHOR



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